



Improving the understanding of water availability and use by vegetation of the Lower-Balonne Floodplain.

Final research report for the project 'Watering requirements of floodplain vegetation asset species of the Northern Murray-Darling Basin'.

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Abbreviations

General abbreviations	Description
BOM	Bureau of Meteorology
BEWS	Basin-wide Environmental Watering Strategy
CEWO	Commonwealth Environmental Water Office
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	Digital elevation model
DNRM	Department of Natural Resources and Mines
DSITI	Department of Science, Information Technology and Innovation
EM	Electromagnetic
ERT	Electrical resistivity tomography
EWKR	Environmental Watering Knowledge and Research (project)
FAA	Floodplain Assessment Area
FPC	Foliage projective cover
GDE	Groundwater dependent ecosystem
GIS	Geographical Information System
HVV	High vegetation vigour
LBF	Lower–Balonne Floodplain
LiDAR	Light Imaging, Detection, And Ranging
MDB	Murray–Darling Basin
MDBA	Murray–Darling Basin Authority
MDFRC	Murray–Darling Freshwater Research Centre
NDVI	Normalised Difference Vegetation Index
NSW	New South Wales
PCT	Plant Community Type
Qld	Queensland
RE	Regional Ecosystem
RS	Remote sensing
RV	Remnant vegetation
SDL	Sustainable diversion limit
SILO	Scientific Information for Land Owners
UEA	Umbrella Environmental Asset

A glossary is provided in Appendix 6.

Executive summary

Floodplain vegetation is an important component of the ecology of the Lower Balonne floodplain system in the northern Murray-Darling Basin. Of course, plants need water to grow and survive, and it is often the case that on floodplains a vital component of this need is provided by regular inundation by floods. There has been a general, but until now untested, assumption that the dominant vegetation species of the Lower Balonne floodplain also depend on occasional flooding to grow, survive and maintain good plant condition. However, almost all of the knowledge of these requirements, including species-specific tolerances for the maximum period between floods, has been derived from research undertaken in the southern Murray-Darling Basin, in rivers with climatic and hydrological regimes far removed from those of the Lower Balonne region.

This raises the possibility of a different relationship between flooding and vegetation condition between northern and southern parts of the extensive Murray-Darling Basin. Indeed, previous investigations by the Queensland Government in the northern Basin have suggested this to be the case. In particular, assumptions that plants of a given species require flooding with a certain frequency to maintain their condition have been shown to be over-simplifications of a much more variable ecology, with other water sources in addition to flooding likely to be playing significant parts in the story. These alternative water sources include in-channel river water, rainwater and shallow groundwater.

Understanding of this was summarised by Holloway et al. (2013) as a series of hypotheses presented as conceptual models of water availability and use by floodplain vegetation, which were tested by the current project. The conceptual models were structured by landscape units (land-systems) to understand the water cycle, since the hydro-morphological characteristics of the floodplain landscape influence potential direct access to river water, the expected frequency of flooding and the availability and quality of groundwater accessible by vegetation.

The current project aimed to address the recognised knowledge gaps pertaining to the water use of floodplain vegetation in the Lower Balonne. Results confirmed that vegetation on this floodplain utilise water from all available sources with a complex spatial and temporal dynamic related to landscape. The project concluded that flooding is not the dominant source.

The approach of the project was to combine multiple lines of evidence to address specific research questions in relation to plant water availability and use on the floodplain. It utilised analyses of long-term time series of satellite images, interpretation of patterns of water availability from floods, rainfall and groundwater and mapped landscape characteristics. This interpretation was validated by detailed field measurements of water source availability, landscape attributes and vegetation physiology and morphology. The project considered the dominant, iconic, and presumed flood dependent plant species ('assets') of this floodplain; being the trees river red gum, coolabah and black box, and the shrub lignum.

Remote sensing and spatial analyses

Analysis of satellite image time series identified patches of the floodplain that maintained high vegetation vigour, a surrogate for vegetation condition, during the driest times between 1988 and 2014. These patches remained in relatively good condition even after long periods without both river flooding and rainfall, suggesting vegetation here accessed and used groundwater or river water. While such patches were relatively rare (occupying less than 1% of the total floodplain area), they were found to occur in all of the dominant land-systems and included patches of each of the asset plant species. The majority of these patches closely fringe the river channels and correspond closely to distribution of river red gum, suggesting likely use by these plants of water in (or associated with) river channels. Away from the river channels, patch locations were considered likely Groundwater Dependent Ecosystems (GDEs) accessing water from shallow aquifers.

On the remaining 99% of the floodplain area, where vegetation condition varied more through time, coolabah was the dominant floodplain asset species in the region, occupying over 20% of the study area, with most in more frequently flooded, lower elevation parts of the floodplain. This implied potential for coolabah to be reliant on flooding. Black box was very restricted to less than 1% of the floodplain area. As well as fringing river channels, river red gum occurred in river meander bends. There was insufficient mapping of lignum to consider spatial patterns in its distribution.

Time-series of canopy greenness, (derived from satellite images), and local climate, (derived from data on rainfall and evaporation from available sources), were used to investigate condition response to rainfall and flooding of coolabah, as the dominant asset species on the Lower Balonne floodplain. This process concluded that there was no evidence that flooding is a major driver of coolabah condition on this floodplain, with climate explaining trends in seasonal greenness to the same degree despite frequency of exposure to flooding. Condition responses to floods was neither greater nor longer lasting than responses to rainfall events, and rainfall occurred much more frequently than flooding. This suggests that rainfall is the dominant water source for coolabah in the region.

Field assessments

Various geomorphological, hydrological, geochemical and plant physiological investigations were conducted at selected field sites to characterise patterns of variability in availability and use of water by vegetation on the floodplain. These results complemented and vindicated results of remote spatial assessments described above.

The role of flooding in providing water to asset species could not be directly investigated due to a lack of flood events during the life of the project. However, multiple, indirect lines of evidence suggested that inundation via floods or ponded rainfall are unlikely to cause significant groundwater recharge over much of the floodplain. Sand ridges and streambed connectivity through meander bends were found likely to be the primary locations of shallow aquifer recharge from in-channel flow events, floods or rainfall. The degree to which recharge spreads laterally into intermediate or regional scale aquifers is still poorly understood. Where shallow aquifers were present, coolabah roots were found accessing this water, confirming remote-sensed GDE assessments.

Results indicated that while both floods and large rainfall events sporadically recharge the soil water on the floodplain, it is the character of the surface two metres of soil that has the strongest controlling influence over the composition and structure of vegetation present. Soil type is more influential than the occurrence of floods, primarily due to its role in governing infiltration and water availability.

Conclusions

Results of this study have greatly advanced understanding of water use from different sources by key vegetation species on the Lower Balonne floodplain system. They confirm that this is complex and variable. In summary, these species of plants can be categorised into four eco-hydrological units, with individuals of the same species potentially belonging to different units at different places and times in response to variability in water sources and availability:

- Fringing (dependent on access to river water),
- Meander/paleochannel (in-channel flow dependent),
- Floodplain (rainfall and/or flooding dependent) and
- GDEs (true shallow aquifer dependent)

Trees in the fringing zone were both taller and in persistently better condition than those in other areas because of constant access to in-channel or associated water, and are therefore 'flow dependent'.

Meander/paleochannel trees in meander bends accessed shallow aquifers formed in paleo-channels and connected to the river during flow events. Whilst the recharge mechanisms of the aquifers still need further clarification, these communities can also be considered flow dependent.

On the floodplain beyond the riparian zone, coolabah condition was mostly influenced by rainfall and evaporation with response to flooding not pronounced.

River red gum and coolabah used groundwater when it was available to them, in which case they are GDEs. GDEs were widespread but patchy on the floodplain, likely in response to spatial variability in aquifer depth, quality and recharge potential. The recharge processes of shallow aquifers were different in clay and sandy soils, with sand ridges potentially representing important recharge conduits via both rainfall and flooding, but with considerable spatial variability according to local topography.

While advancing understanding as outlined, the project has also identified a number of key knowledge gaps with regards to both water needs of vegetation and incorporating learnings into water management. Recommendations are made for future work to address these gaps.

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1 Project purpose

This is the final technical report of the project 'Watering requirements of floodplain vegetation asset species of the Northern Murray-Darling Basin'. This project was undertaken jointly by the Queensland Departments of Science, Information Technology and Innovation (DSITI) and Natural Resources and Mines (DNRM).

1.1 Background

The Commonwealth Water Act 2007 introduced key reforms in the Murray-Darling Basin (the Basin), to manage water in the basin in an integrated and sustainable way (Hale et al. 2014). The Murray-Darling Basin Authority (MDBA) was established under the Act and was required to prepare a strategic plan for water resource management in the Basin. The Murray-Darling Basin Plan (Basin Plan) (Commonwealth of Australia 2012) came into effect in November 2012.

An important aspect of the Basin Plan is the introduction of new limits on the amount of water taken for consumptive uses to ensure there is a healthy working basin. New long-term average Sustainable Diversion Limits (SDLs) have been set for surface and groundwater systems across all catchments in the Basin. The SDLs were determined based on environmental, social and economic factors, and through an assessment of the environmentally sustainable levels of take (ESLT) for each catchment (MDBA 2011). A shared reduction amount was also set for the five zones within the Basin Plan - one of which is the Northern Basin zone (Section 6.05 Murray-Darling Basin Plan 2012).

Section 6.06 of the Basin Plan flagged the intention of the MDBA to "conduct research and investigations into aspects of the Basin Plan in the northern Basin, including the basis for the long-term average SDLs" in recognition of uncertainty in the knowledge on which the determination of the SDLs was based. This research and investigative effort occurred through the Northern Basin Review.

The aim of the Northern Basin Review was to address knowledge gaps through research projects, hydrologic modelling of water recovery scenarios, and social and economic assessments (Hale et al. 2014). Information generated by the Northern Basin Review was used in a review of the SDLs in the catchments of the Northern Basin.

Several floodplain vegetation species were used as indicators of ecosystem flow requirements during the development of the *Basin Plan 2012*. The water requirements of these plants were considered in terms of the magnitude and frequency of flood events and, to a lesser extent, the duration and depth of inundation needed to maintain them in good condition. A review of the science (Hale et al. 2014) identified a need for improved understanding of floodplain vegetation water requirements in the northern Basin. SDLs for the Northern Basin relied on estimates of vegetation water requirements from research undertaken largely in the southern Basin, where hydrology and climate regimes are quite different to the northern Basin.

The Lower Balonne Floodplain System in Queensland was identified as a priority in the Review, and consequently a commitment was made to improve knowledge and information on the floodplain vegetation watering requirements. The 'Watering requirements of floodplain vegetation asset species of the northern Murray-Darling Basin' project was undertaken to fill some of the knowledge gaps as a part of the Australian Government's larger Murray-Darling Basin Environmental Water Knowledge (MDB EWKR) project administered through the Murray Darling Freshwater Research Centre (MDFRC).

Queensland's Department of Natural Resources and Mines (DNRM) and Department of Science, Information Technology and Innovation (DSITI) were engaged by the Commonwealth under the MDB EWKR Project to develop and undertake the research presented here.

1.2 Project objectives

This project aims to improve understanding of the water use of four key floodplain vegetation species in the Northern Murray-Darling Basin with particular emphasis on the Lower Balonne Floodplain (LBF) (Figure 1). The knowledge will help to fill gaps identified in the Northern Basin review and will also contribute to the overall understanding of vegetation water use in the northern Murray-Darling, where region-specific knowledge on floodplain vegetation is limited.

An Interim technical report (Senior et al. 2016) contributed project findings to the MDBA's review of SDLs in the northern Basin. The final project outputs presented here aim to support environmental assessments of Queensland's Water Resource Plans and ultimately to increase confidence in managing water resources for the benefit of all users in the region.

Within the original project proposal, the project had five key objectives:

1. Identify eco-hydrological correlates of floodplain vegetation distribution and change in vegetation condition through time in the study area
2. Quantify vegetation water use and identify sources
3. Identify and quantify the influence of river flooding on water availability in shallow aquifers and unsaturated root zones
4. Identify variation in water requirements among vegetation communities with different characteristics
5. Apply eco-hydrological understanding to develop capacity to predict tree condition responses to alternative flow management scenarios

Project outputs were expected to include:

- Maps of modelled inundation extent and frequency for vegetation patches of asset species
- Assessment of relationships between inundation, vegetation, and landscape components of the floodplains
- Refined shallow hydrogeological conceptualisation of study areas
- Quantifying the detailed water pathways described in the conceptual models
- Refined description of groundwater dependency of species under investigation
- Ecological response models to assess the potential risk to communities of key floodplain vegetation species as a consequence of flow regime alteration, particularly those species not being maintained in good condition, and to inform mitigation actions to reduce risks where they have been identified.

1.3 Project scope

The project scope was defined within the original proposal to examine the water requirements of floodplain vegetation for maintaining condition in mature trees. While many factors other than water availability may influence vegetation condition, these were not the focus of the current study and thus not included in this project.

Additionally, tree recruitment factors (e.g. seed dispersal, germination and seedling survival etc.) were excluded from the study. While important for determining the overall water requirements for

floodplain vegetation in the region, this component of the 'water requirements' was specifically excluded from the scope of the project since many floodplain species, including those that were the focus here, have highly specific eco-hydraulic requirements for recruitment success. Addressing tree recruitment factors reduced the ability to properly address the primary agenda of watering requirements in mature trees. Whilst the original project proposal was titled 'Watering requirements of floodplain vegetation asset species of the Northern Murray Darling Basin' this report has been retitled 'Improving the understanding of water availability and use by vegetation of the Lower-Balonne Floodplain' to better reflect the research conducted within the project.

Each component of the project is bounded by assumptions and data limitations. These assumptions and limitations have generally related to aspects such as the temporal and spatial scales of data sets used within each analysis and hence the conclusions based on them. The implications of temporal scale in a land of drought and flooding rain is clearly critical to conclusions and is discussed within individual chapters with regard to the specific questions and data sets addressed.

The geographical scope for this project was the Lower Balonne Floodplain (LBF) portion of the Northern Murray-Darling Basin, specifically as was delineated by the LIDAR data set captured by the MDBA for provision of a Digital Elevation Model (DEM) (MDBA 2013) (Figure 1). This spatial delineation was based on the association of the project with the CSIRO flood inundation model (which was to use the specified DEM as its source data set).

1.3.1 Project dependencies

There were a number of dependencies that this project relied on in its initial design. The most important of these were;

- Provision of the Lower-Balonne flood inundation model commissioned by the MDBA from CSIRO
- a natural flood event to occur during the course of the project

Flood inundation model

As stated within the project proposal, and as was highlighted as a specific risk throughout the course of the project, the floodplain inundation model was flagged as a critical dependency for the outcomes of this work and three main purposes were cited:

1. to inform understanding of remote-sensed vegetation condition responses to inundation history;
2. to contribute to selection of field sites;
3. to form a key input to ecological response models derived by the project.

When the project proposal was first developed, it was on the understanding that the MDBA floodplain inundation model was due for completion in September 2014 and would spatially represent inundation across the study area based on flows at specific gauges (Gavin Pryde, pers com). However, the model eventually provided in September 2016 was not capable of translating volumetric flows at specific gauges into predictions of area of inundation.

During the course of the project, the scope was adjusted to account for not having the flood inundation model, and whilst work-around solutions were developed for some tasks, certain objectives and deliverables for the project could not be achieved. This related specifically to the capacity for ecological response modelling and the defined objective of:

- Applying eco-hydrological understanding to develop capacity to predict tree condition responses to alternative flow management scenarios

This also applied to the associated outputs, which depended on this modelling capacity, namely:

- Maps of modelled inundation extent and frequency for vegetation patches of asset species
- Ecological response models to assess the potential risk to communities of key floodplain vegetation species as a consequence of flow regime alteration, particularly those species not being maintained in good condition, and to inform mitigation actions to reduce risks where they have been identified.

Flooding during the project

No natural overbank flooding occurred during the course of the project. This has hampered the ability of the project to directly study flood effects on vegetation and soils.

The original project proposal acknowledged the potential for ‘no flood’ as a significant risk, and the risk was managed through the project. A large-scale artificial flooding experiment was considered, which would have flooded an entire detailed vegetation monitoring site enabling measurement of vegetation water use and soil recharge processes in situ. Ultimately, however, the proposed work was too costly and logistically difficult within the project schedule and budget. The overall project timelines were also extended, in part to allow for a greater chance of a natural flood event occurring, but this did not occur.

Several smaller-scale flood inundation experiments were carried out. This included studies of soil wetting and drying rates, to help inform project research questions regarding the potential for groundwater recharge from inundation.

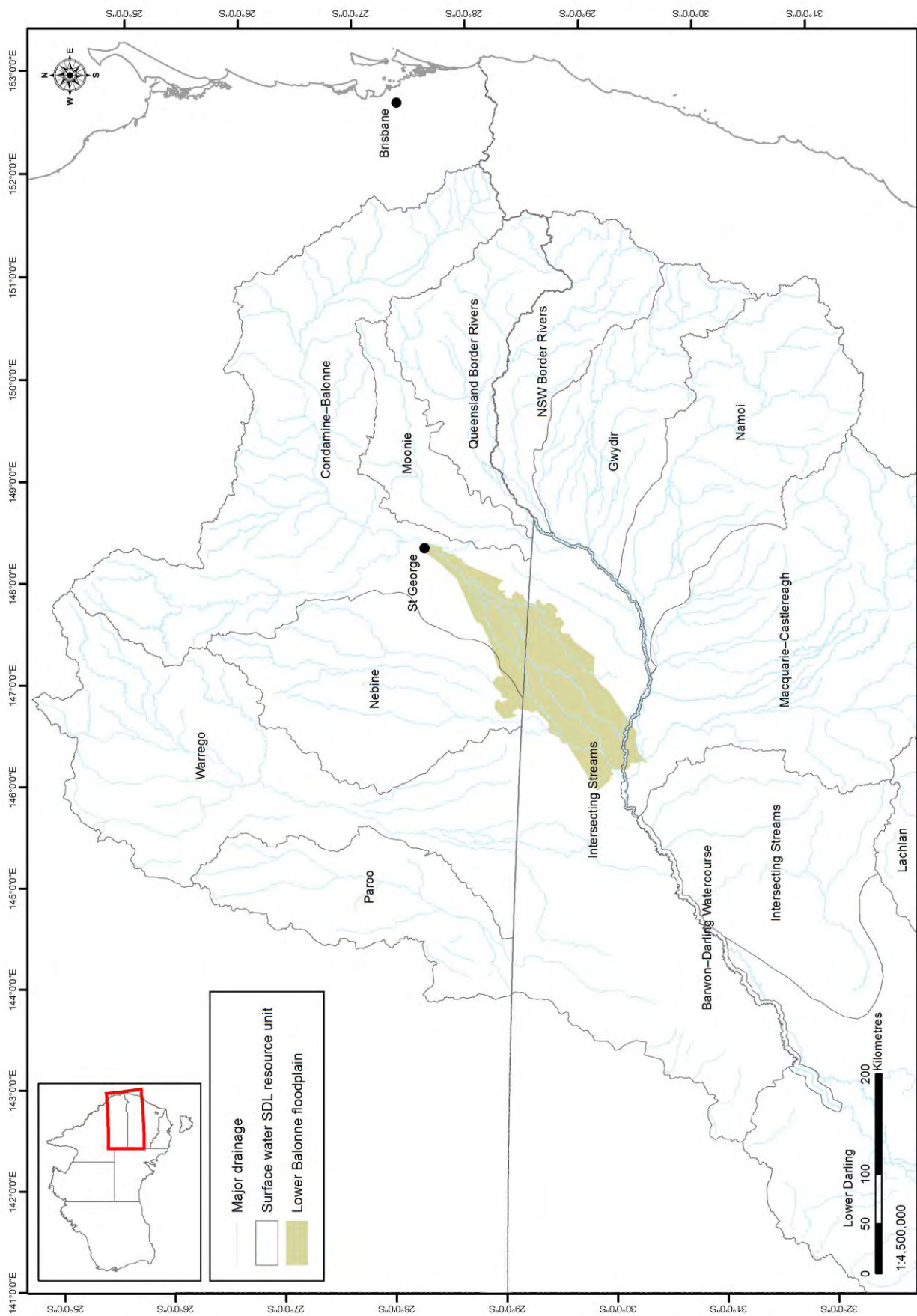


Figure 1 MDBA SDL resource units and the Lower-Balonne Floodplain study area extent within the Northern Basin zone

2 Introduction

The Murray-Darling Basin (MDB) is Australia's largest river system and covers nearly one seventh of the continent. It is also an important agricultural region. Due to the large geographical area of the MDB, there are distinct differences in the environment, climate and hydrology between its northern, southern, eastern and western extremes. The regulation of water also varies geographically across the Basin. Most rivers within the southern part of the basin are highly modified and regulated. By contrast, there is less water regulation in the northern basin.

The Condamine–Balonne catchment, within the northern MDB, is one of the largest Basin catchments spanning areas of Queensland and New South Wales. The landscape of the Condamine–Balonne catchment is diverse; however flat expansive floodplains cover the majority of the catchment. Rainfall throughout the catchment is summer-dominant and the hydrological connectivity of the rivers within the Condamine-Balonne is highly variable and in comparison to other catchments in the Basin, the extent of river regulation in the Condamine–Balonne is low (mdba.gov.au).

2.1 The Lower-Balonne floodplain

The Lower-Balonne system is a distributary river network within the Condamine-Balonne catchment that extends from St. George in Queensland to the Barwon River in northern New South Wales, and includes the channels, waterholes and floodplains of the Culgoa and Narran rivers (Figure 2 Geographical location and major channels of the Lower-Balonne Floodplain). The Lower Balonne Floodplain (LBF) is a complex series of braided channels, floodplains and waterholes. It is dominated by clay soils but with occasional sandy ridges (Galloway et al. 1974). The degree of flooding varies with elevation and the highest geomorphic elements (particularly the sand ridges) are essentially flood free. The clay back-plains form wide areas that are prone to flooding during high river flow events and are vegetated by coolabah (*Eucalyptus coolabah*) or belah (*Casuarina cristata*) open-woodland interspersed with grassland. The ridges, which are dominated by sandy soils, support woodlands dominated by cypress pine (*Callitris* spp.), Moreton Bay ash (*Corymbia tessellaris*) and poplar box (*Eucalyptus populnea*) (Galloway et al. 1974).

The LBF's northern limit is at the town of St. George in southern inland Queensland. Below St. George, the Balonne River breaks into a number of distributary channels and discharges either to the Barwon (via the Culgoa, Bokhara, Birrie Rivers), or to the terminal lakes at Narran (via the Narran River) (Figure 2). The floodplain is roughly 300 kilometres long from St. George to just north of Bourke and spans 100 kilometres at its widest. Approximately 30% of the system is in Queensland and 70% in New South Wales (MDBA 2012a).

The MDBA chose a number of focal locations within rivers, floodplains and wetlands across the Basin for targeted study. These locations are known as Umbrella Environmental Assets (UEA). The term 'UEA' refers to an area or environmental asset for which there is relatively rich knowledge with respect to flow-ecology relationships when compared to the broader region within which it sits (MDBA 2016). The LBF and Narran Lakes are considered separate UEAs in their own right (MDBA 2016).

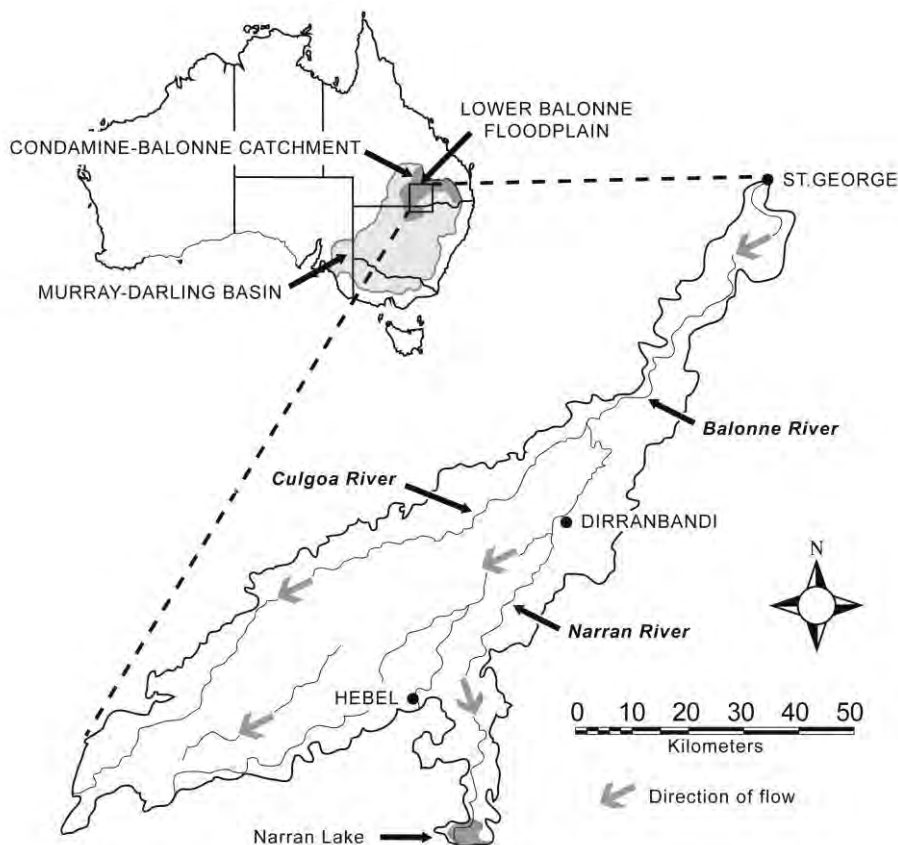


Figure 2 Geographical location and major channels of the Lower-Balonne Floodplain

2.2 Floodplain vegetation of the Lower Balonne

Floodplain vegetation is a key ecosystem component of the LBF and has its own intrinsic value, but also provides an important food source and habitat for a range of terrestrial and aquatic species. Floodplain vegetation relies on permanent and periodic flooding, to a greater or lesser extent, depending upon its type and position in the landscape (Holloway et al. 2013).

Four iconic floodplain species, 'asset species', were selected for this project. These included three eucalypts and one shrub:

- Coolabah (*Eucalyptus coolabah*),
- River red gum (*Eucalyptus camaldulensis*),
- Black box (*Eucalyptus largiflorens*) and
- Lignum (*Duma florulenta*).

Focusing on these four asset species aligns with the Basin-wide environmental watering strategy (BEWS), developed in 2014 as a requirement of the Basin Plan (MDBA 2014). Specific regional targets for the maintenance of condition of existing populations were developed for each of these species for the LBF (MDBA 2012a).

These species are described briefly below with summaries of existing knowledge of their watering requirements in terms of flood frequency and duration. The majority of the research undertaken within the project has been directed to studying Coolabah as of all the asset species it encompasses a far greater proportion of the LBF (see Chapter 4) and was considered to have the largest knowledge gaps in relation to its water use.

2.2.1 Coolabah (*Eucalyptus coolabah*)

Coolabah is a tree of medium height (~15–20 metres) and is assumed to live for hundreds of years (Figure 3) (Roberts & Marston 2011). It is a very common floodplain tree, occurring widely in the northern Basin, particularly in occasionally flooded areas as well as beside river channels and around waterholes (Roberts & Marston 2011). Coolabah has a number of sub-species whose ecological preferences are not well understood. The species is considered drought tolerant (Roberts & Marston 2011) compared to the other asset species and a flooding frequency of between 10–20 years is cited for the maintenance of existing trees. Holloway et al. (2013) suggest that modelled pre-development flows within certain Northern Basin catchments do not deliver the duration (as opposed to frequency) of flooding cited (Roberts and Marston 2011) as being necessary to maintain good condition.

Coolabah has been the main focus for this study as it is the most common large eucalypt species in the LBF (being mapped as being present on more than 20% of the study area - see Chapter 4) and is the least studied.

2.2.2 River red gum (*Eucalyptus camaldulensis*)

River red gum (Figure 4) is a medium to tall (12–45 metres) long-lived tree species (Roberts & Marston 2011). River red gum is usually found very close to the river's edge or in nearby floodplain areas that experience periodic flooding. There are a number of sub-species and it is currently unclear exactly what their relative distributions are, or whether they may have distinct watering requirements.

In the Southern MDB, river red gum is found in large patches of forest on high-volume river floodplains (Roberts & Marston 2011), but in the northern part of the basin, and in the Lower Balonne in particular, generally occurs in much smaller patches and strips in floodplain pockets close to the channel. Roberts & Marston (2011) suggested that in a woodland form, this species needs two to four months of inundation by floodwaters every two to four years to persist in good condition, and that flooding is important for vigorous growth. However, Marshall et al. (2011) showed that modelled pre-development flows within some Northern Basin catchments did not consistently provide these requirements and this therefore raised questions about the eco-hydrology of these northern populations (Holloway et al. 2013).

From observation during this project, particularly in the Queensland portion of the Lower Balonne system, river red gum distribution is almost entirely directly associated with the river channel and is mapped as less than 1% of the study area (see Chapter 4).

2.2.3 Black box (*Eucalyptus largiflorens*)

Black box (Figure 3) is a short to medium height tree (10–20 metres) tall and is thought to be long-lived (Roberts & Marston 2011). It is common in New South Wales and in the Moonie catchment to the east, but it is not common in the LBF (based on project mapping outputs it covers less than 1% of the study area (see Chapter 4), and its distribution is restricted to the far western portion of the study area.

Literature suggests this species needs two to three months of flooding every three to seven years to maintain moderate to good canopy cover and flowering (Roberts & Marston 2011). Its distribution overlaps with coolabah but there are some areas in which it is the sole tree canopy species.

2.2.4 Lignum (*Duma florulenta*)

Lignum is a multi-stemmed, woody shrub (Figure 5) that can form a low shrub layer within an open woodland or may be the predominant layer in shrublands on the floodplain and ephemeral swamps and wetlands (Roberts & Marston 2011). It can grow in drainage lines that are prone to inundation, but is usually not in areas with frequent or prolonged flooding (Roberts & Marston 2011).

Roberts & Marston (2011) suggest that it requires a flooding frequency of somewhere between one and ten years to maintain health (dependent on size and vigour of the plant). Whilst this species is common throughout the LBF and is often present as an understorey species in association with coolabah (it has been mapped as present in just under 20% of the study area – see chapter 4), it is often sparse and patchy. Lignum may be relatively shade intolerant, preferring ephemeral wetlands with low tree cover.

Dense patches of lignum, which are often associated with high ecosystem values such as providing critical breeding habitat for waterbirds (MDBA 2012b), are generally much rarer across the LBF and are not well mapped out from the open woodlands of coolabah with scattered lignum widespread on the LBF. This has been noted as a particular issue within the project that adversely affects the potential for the monitoring, assessment and subsequent management of this species as an environmental asset.



Figure 3 Coolabah (left) and Black Box (right) growing on the LBF Photo by A. Biggs



Figure 4 River red gum community in the LBF riparian zone Photo A. Biggs



Figure 5 Lignum on the LBF showing contrast between different condition states Photos by B. Senior

2.3 Water requirements of floodplain vegetation

In the past, there has been a strong focus on defining ‘watering requirements’ of floodplain trees purely with inundation from flood events (e.g. species X must be inundated at least once every Y years for at least Z weeks). Investigations by the Queensland Government (Marshall et al. 2011) had previously suggested that current understanding of the flow requirements of coolabah in the region were insufficient and showed that in some cases floodplain terrestrial vegetation asset species persisted through periods without flooding that were much longer than their published tolerance thresholds. Additionally, Holloway et al. (2013) identified shallow groundwater as a likely key resource of these assets in the region between flooding. Collectively this indicates that the watering requirements for maintaining communities of floodplain vegetation in good condition in the northern MDB potentially differ from those derived from the literature from the southern MDB.

A recent review of literature pertaining to the watering requirements of all the asset species listed here, generally supported the findings of Roberts and Marston (2011) regarding the watering requirements for long-term maintenance of key species in the Northern Basin (Casanova 2015). The review did note that ongoing studies, specifically including this project, could provide new and more targeted information.

3 Overall approach

The overall approach used within the project was to examine the availability of water sources in different areas of the floodplain, and to examine the use of water from different sources by floodplain vegetation asset species. At a basic level, tree condition is influenced by access to water, which is derived, from either rainfall, flow (surface water) or groundwater (although these sources are connected). Tree condition response to inundation and rainfall is influenced by soil type, which affects the availability of water to vegetation as accessible soil moisture and also affects infiltration and deep drainage. Potential direct access to groundwater by vegetation is also influenced by soil type, elevation and geology (Figure 6).

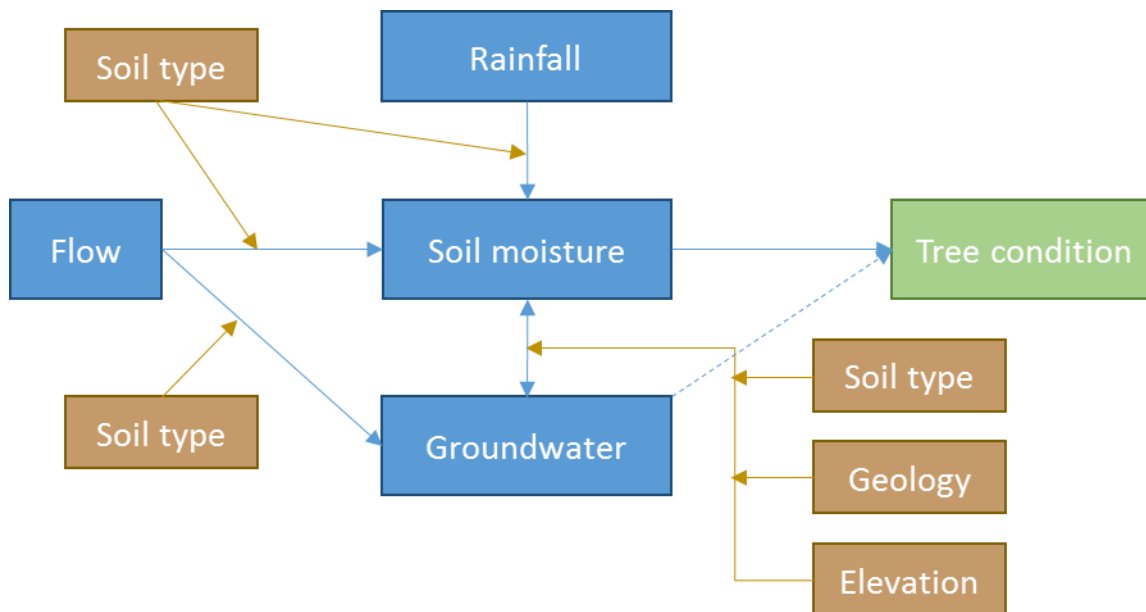


Figure 6 Conceptual model describing key components contributing to tree condition

To accommodate the different potential sources of water, this study was designed to capture data at two distinct spatial scales using multiple lines of evidence. At the site level, we collected detailed field measurements of vegetation physiology and morphology, soil, water source availability and landscape attributes. This was to understand vegetation water usage and its source, as well as validating and quantifying the water pathways between river flooding, groundwater and rain. At the larger scale, we have used remote sensing techniques across the entire floodplain to provide a long-term time series of vegetation condition, as measured from satellite images, with interpretation of patterns of water availability from floods, rainfall and groundwater.

To bring these two scales together, we have used mapped landscape characteristics such as vegetation community types, soil types, elevation, proximity to waterways and other geomorphological features to classify the floodplain and link the information from the different spatial scales.

3.1 Linking research questions to project objectives

Previous work undertaken by the Queensland Government and the basis for this project (Holloway et al. 2013) suggested an overarching hypothesis ***that maintenance of condition of floodplain vegetation asset species is not reliant on flooding alone*** due to the length of time that some areas received no flooding even under predevelopment conditions.

We aimed to evaluate the extent to which this overarching hypothesis is true, and the extent to which the different water pathways (in particular ***access to shallow groundwater*** and ***how rainfall and floods recharge these shallow aquifers***) are contributing to vegetation condition. These broad hypotheses regarding the relative importance of different water sources were then formulated into specific questions linked to project objectives that have formed the basis for the research conducted within the project (Table 1). Note that the original project objective related to eco-hydraulic modelling is omitted (see section 1.3).

Table 1 Project objectives and associated research questions

Chapter	Project objective	Key research questions	Summary of approach for addressing research questions	Spatial scale
4	Identifying eco-hydrological correlates of vegetation response	<p>How does asset species distribution relate to the flooding extent?</p> <p>Can changes in vegetation greenness (condition) be related to rainfall, flooding or groundwater availability?</p>	<p>An evaluation of asset species distribution (using best available vegetation distribution mapping) compared to the conceptual model zones and estimates of flood frequency.</p> <p>Remote sensing analysis of changes in vegetation greenness through time relating to fluctuations in climate and water availability.</p> <p>Remote sensing analysis to assess likelihood of potential groundwater use across the study area.</p>	Remote sensing/ GIS analysis (site based)
5	Identifying and quantifying vegetation water use	<p>Do tree species express visible and quantifiable responses to different sources of available water?</p> <p>Do trees use groundwater?</p> <p>Does groundwater use vary between tree species?</p>	<p>Field measurement of vegetation water use/tree condition using multiple lines of evidence.</p> <p>Assessment of groundwater use through field evaluation using multiple lines of evidence (including sap flow, water potential, isotope signatures, allometric methods, tree condition scores, DNA analysis of tree roots, etc.)</p>	Field based measurement

Chapter	Project objective	Key research questions	Summary of approach for addressing research questions	Spatial scale
6	Identifying the influence of flooding on ground water availability in shallow aquifers and unsaturated root zones	<p>What is the expected relationship between flooding and groundwater in the LBF?</p> <p>What is the potential rate of shallow groundwater recharge and root zone saturation from flooding in the LBF?</p>	<p>Desktop review of groundwater and surface water hydrology.</p> <p>Modelling of potential groundwater recharge across the floodplain (using 2D Hydrus modelling techniques).</p> <p>Field based inundation experiments to examine groundwater recharge and soil drying rates. Desktop review of existing soils data sets (e.g. previous airborne geophysical surveys and research into deep drainage rates within the study area).</p> <p>Ageing of groundwater within riparian transect bores to provide evidence of surface/groundwater connectivity (pending).</p>	Field measurement <i>and</i> desktop modelling techniques
7	Identifying variation in water availability among vegetation communities	<p>How does vegetation greenness vary between different vegetation communities?</p> <p>Does the variation in landscape unit explain differences in tree height?</p>	<p>Comparing greenness of floodplain and riparian communities through remote sensing techniques at a landscape scale.</p> <p>Analyses of tree height information from LIDAR capture across the study area, in relation to distance to water sources as defined by landscape classification units.</p>	Remote sensing /GIS analysis (landscape scale)

3.2 Conceptual model of floodplain vegetation water availability

As a precursor to this project, Holloway *et al.* (2013) introduced the idea of using land-systems as a way to understand the complexity of the water cycle within the landscape of the LBF. The hydro-morphological characteristics of each land-system influence the expected frequency of river flooding and the availability and quality of sub-surface water used by floodplain vegetation species. The proposed conceptual model included each of the prevalent land-systems found within the Queensland portion of the LBF, namely Land-systems 33, 32, 31, 30 and 28 which are listed according to distance they are found away from the river channel. The conceptual model of Holloway *et al.* (2013) has formed the basis for this study and was also used to derive decision rules used to map the potential terrestrial GDEs in the area (Glanville *et al.* 2015).

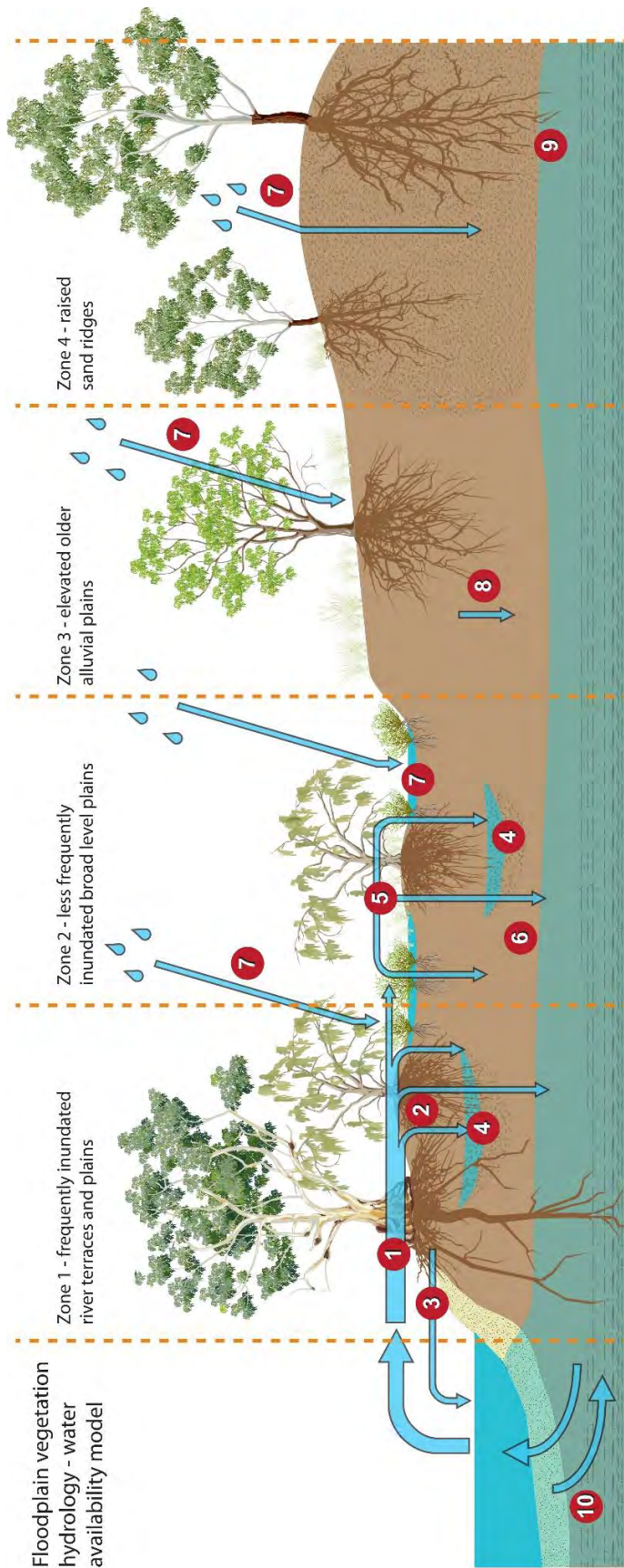
Landscape classification (Land-systems and Regional Ecosystems (REs) and Plant Community Types (PCTs)) also provide a way of linking localised, site-based information with regional landscape remote-sensed data, allowing extrapolation at larger geographic scales across the landscape more generally, and narrowing down to specific elements of the conceptual model.

3.2.1 Development of the model

Based on emerging project results, we have reviewed the original conceptual model and updated it during the course of the project (Figure 7). This model and the subsequent descriptions of the model zones, represents our current understanding of the water cycle pathways on the LBF. The field and remote sensing studies used within this project aim to understand, and in some cases quantify, the specific elements of the water cycle pathways. This enables us to understand the likely availability of water from various sources in each model zone and how plants respond to it. This conceptual model provides the frame within which the rest of the report is to be viewed and interpreted.

A significant change to the model has been a transition from the term 'land-system' to the use of the more generic term 'model zone'. This widens the definitions used in the original conceptual model (Holloway *et al.* 2013) based solely on the Queensland Land-system classification system enabling the inclusion of New South Wales Land-system definitions under a single terminology (see section 3.3.2).

Two new models of floodplain vegetation water availability have also been developed and documented during the course of the project. One model describes terrestrial GDEs occupying buried sand ridges on the floodplain, and the other details surface water/groundwater connectivity in meander bend riparian communities. These models are among the key learnings from the project (Chapter 8).



- 1 The landscape is more frequently inundated by local run-off and river floods.
- 2 Aquifer recharge does take place but is limited by physical soil characteristics.
- 3 The process of bank fill/discharge occurs.
- 4 Shallow fresh perched aquifers exist in this landscape and are likely to be tapped by vegetation and may dry/wet on a regular basis.
- 5 Overland flow/run-off can recharge soil water, shallow perched aquifers and deeper groundwater.
- 6 Deep drainage and recharge is limited by the soil characteristics.
- 7 Rainfall – widespread rain can lead to inundation of the landscape. Contributes to groundwater recharge (especially in Zone 4 due to soil characteristics).
- 8 Lower groundwater recharge rates (in comparison to zones 1 and 2).
- 9 Groundwater depth and characteristics unknown and need to be confirmed.
- 10 Groundwater/surface water connectivity and exchange.

Figure 7 Conceptual model of water availability to floodplain vegetation. Each number represents an ecological process acting on water availability in the region.

Model zone 1

This zone applies to the lowest elevation areas of the floodplain and is characterised by vegetation of river red gum, coolabah and lignum on non-saline, non-sodic black and grey cracking clay soils (vertisols). The landscape is frequently inundated by local runoff and river floods (Figure 7, Process 1). The lower salinity/sodicity of the soils indicates they are 'flushed' by regular leaching (Figure 7, Process 2) but their physical characteristics (shrink/swell) fundamentally limit their hydraulic conductivity and subsequently limit aquifer recharge. In these areas, we also expect zones of rapid recharge, bank fill/discharge (Figure 7, Process 3) and the potential presence of shallow fresh-perched aquifers (Figure 7, Process 4). It is likely these aquifers are tapped by vegetation and may dry/wet on a regular basis. Widespread rain can also lead to inundation of the landscape (Figure 7, Process 7), and there is the potential for connectivity between in channel flows and groundwater (Figure 7, Process 10).

In the Queensland portion of the Lower Balonne, this applies to land-system 33, and in Western New South Wales, this is characterised by the land-systems Dumble, Mid- Darling, Upper Darling, Rotten Plain, Eurie and Warrego.

Model zone 2

This zone is the back-plain environment that is inundated in larger floods, but not small events. Soils generally consist of black, brown and grey vertisols with vegetation typically of coolabah woodland in association with grassland and lignum. In certain areas this environment is distinguished by the presence of black box (for instance in land-system 32 where sodosols are more common and the salinity of the soils is generally greater). This environment receives overland flow/runoff (Figure 7, Process 5), and as with the other clay-dominated units, infiltration (Figure 7, Process 6), deep drainage and recharge is limited in the first instance by the clay soils. Due to the low surface gradient and soil types, widespread rain can also lead to inundation of the landscape (Figure 7, Process 7), as against inundation from channel over-bank flooding.

In the Queensland portion of the Lower Balonne this applies to land-system 31 and 32 and in Western New South Wales this is characterised by the land-systems Goodooga, Llanillo, Long Meadow, Wongal, Wombeira, Ledknapper and Nidgery.

Model zone 3

This zone is the most elevated of the clay-dominated parts of the floodplain (effectively a terrace plain environment). These areas are no longer inundated by flood events (except in extreme events) and the soils are indicative of an extended period of stability and related pedogenetic processes. Accumulation of salts is a feature and hard-setting, texture contrast soils (sodosols) generally dominate. Vegetation is typically not dominated by floodplain vegetation asset species and commonly consists of poplar box woodland with an understory of species such as cypress pine, wilga, false sandalwood and leopard wood. Deep drainage rates (and therefore potential groundwater recharge) (Figure 7, Process 8) in these areas would be lower than that on other areas of the floodplain, because of the soil type, denser vegetation, and the lack of flooding.

In the Queensland portion of the Lower Balonne, this applies to land-system 30 and in Western New South Wales, this is characterised by the land-systems Gingie, Hermidon, Rostella and Rugby.

Model zone 4

These areas comprise elevated, sandy ridges on the floodplain. The sand ridges are fluvial in origin (essentially levees) but no longer active, and many have been partially re-worked (windblown) during arid climatic phases. These reworked deposits are referred to as source-bordering dunes and are distinguished by a finer grain size and narrower particle size distribution than the fluvial deposits.

The sand ridges are generally sinuous/linear in the flow direction (north-south) but vary from tens of metres to hundreds of metres wide and the longest exceed 20 km in length. It is hypothesised that many are quite deep (> 20 m) rather than being a surficial ridge deposited over clay, which will allow for the infiltration of rainfall (Figure 7, Process 7) (or extreme flooding events which may reach the foot of the ridge) to recharge shallow, fresh groundwater within the ridge deposit.

This zone does not typically include floodplain vegetation, including the asset species defined in this study. The vegetation of this zone while generally similar across all areas does show some significant variation in species distributions. For example, while cypress pine is common on all examples, Moreton bay ash and inland red box are not. It is possible, although unproven, that the presence of Moreton bay ash and the size of the trees (which can exceed 25 m in height – much higher than any other tree found on the sand ridges) is indicative of areas with frequent access to groundwater (Figure 7, Process 9).

In the Queensland portion of the Lower Balonne, this applies to land-system 28 and in Western New South Wales, this is characterised by the Tatala land-system.

3.3 Project assessment techniques

The project has utilised a large number of field data collection techniques, remote sensing, GIS and other desktop analyses with the aim of examining multiple lines of evidence to address the key research questions. An overview of the techniques is provided in the following section with more detailed methods presented within each chapter or in the appendices as appropriate. These different project techniques were:

- Field based assessment
- Landscape classification
- Gauged flow and hydrology
- Remote sensing analysis
- Desktop modelling of potential groundwater recharge

These techniques are represented in Figure 8, which relate to specific sections within this chapter.

3.3.1 Field based assessment

Field based measurement of numerous parameters relating to vegetation, water and soils was conducted at sites across the study area to provide direct evidence of vegetation water use and water availability. There were five types of field studies within the project. These were:

- Detailed vegetation monitoring sites
- Riparian transect sites
- Structural vegetation survey sites
- Rapid vegetation condition sites
- Infiltration assessment sites

Detailed vegetation monitoring sites

A comprehensive suite of environmental studies was conducted at the detailed monitoring sites. This included characterisation of the vegetation community composition and structure, plant eco-physiology (including measurement of sap flow, vegetation water potential and stable isotopes), soil coring and analysis, geophysical investigations and monitoring of climatic variables. Three detailed monitoring sites were established and operated continuously between November 2014 and December 2015.

These detailed sites were at Nelyambo, which had a single site, while two sites were within the locale of Euraba Road (Figure 9). The Euraba Road sites were differentiated and named by their soil type; one was located on a grey vertisol (GV) and another located on a sand ridge (SR). All three sites were within coolabah vegetation communities.

Riparian transect sites

To investigate the presence/absence of groundwater and the potential surface water-groundwater interaction in riparian zones, five transect sites were investigated in differing riparian zones across the Queensland section of the floodplain (Figure 9). One was in the upper floodplain (Balonne River at Whyenbah), two on the mid-floodplain (Toobee Creek and Balonne Minor, west of Dirranbandi) and two in the lower floodplain (Ballandool River and Briarie Creek at the cross-border gauging stations). More detailed information regarding transect sites is found in Appendix 2.

Structural vegetation surveys

Detailed vegetation structural analysis was undertaken using the State-wide Land and Tree Survey (SLATS) methodology for circular plots at the detailed vegetation monitoring sites as well as four nearby ancillary sites. Less detailed measurements of vegetation structure were undertaken at twenty-one sites across the wider study area (Figure 9 Project vegetation survey site locations, Appendix 2). The locations of the latter sites were dictated by locations of Landsat pixels selected by the remote sensing analysis (see 3.3.4).

Rapid vegetation condition surveys

A protocol for rapid assessment of vegetation condition was developed based on a field method originally designed by Tucker (2004), which was refined for use specifically for coolabah communities within this project. A pictorial classification of individual tree condition for *Eucalyptus coolabah* was developed (Appendix 2) following field observations in November 2016. Its application was then extended to an area based assessment, which was implemented at multiple sites across the study area (Figure 9 Project vegetation survey site locations, Appendix 2), in conjunction with but not restricted to the vegetation structural survey sites. The primary aim of this rapid assessment was to ground truth the remote sensing work.

Infiltration assessment sites

The lack of a significant flood during the project necessitated the establishment of artificial wetting experiments to evaluate the depth and duration of infiltration in a typical soil of the floodplain. An initial short-term plot was established at the Euraba Road GV site and a longer-term one established nearby on a grassland. The plots used established methods for saturating the soil and soil moisture was monitored at a range of depths over time.

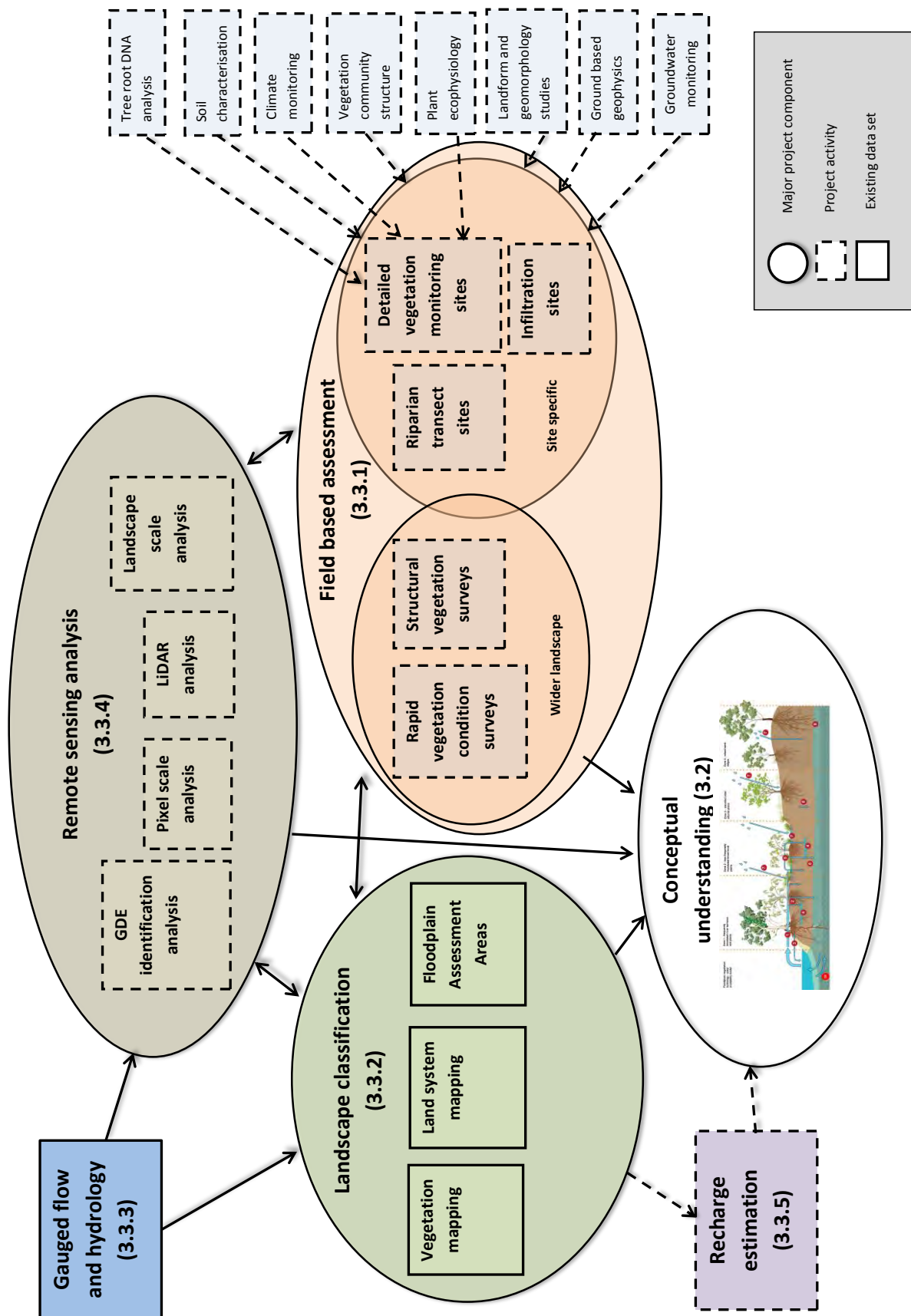


Figure 8 Diagram of project assessment techniques and components (numbering in the diagram refers to section headings within this chapter for further explanation)

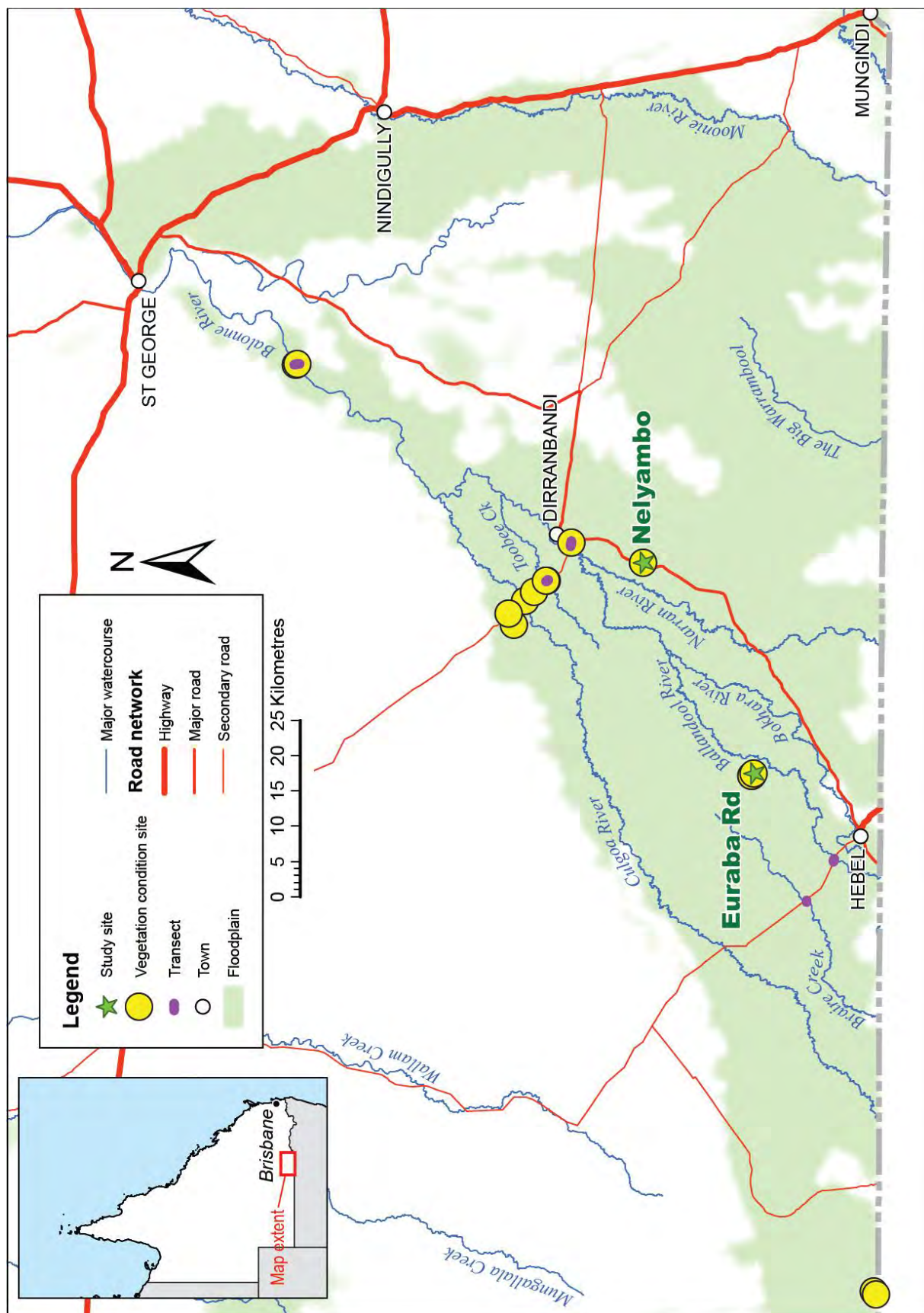


Figure 9 Project vegetation survey site locations

3.3.2 Landscape classification

Within the project, classification of the landscape using existing mapping data sets has provided the basis for defining remote sensing reporting units and extrapolating results from the site-based investigations of water availability and water use to the broader study landscape if appropriate.

The classification was structured according to the best available existing mapping of:

- Vegetation
- Land-systems
- Floodplain assessment areas

Vegetation

There is currently no detailed species-specific mapping for the study area and vegetation community mapping has been used as a surrogate for the distribution of the asset species.

Within Queensland, vegetation mapping for the region is at the scale of 1:100 000 and is represented as Regional Ecosystems (REs) (Sattler & Williams 1999). REs are vegetation communities within bioregions that share species compositions, geology, landform and soil. The edition of the RE description database current at project commencement was used throughout this project (Version 9.0 RE mapping; Queensland Herbarium 2015). The database, which is maintained by the Queensland Herbarium, provides descriptions of each RE, including information on which species dominate and which other species are often present. REs were used as a surrogate for the distributions of the four floodplain species of interest because they represent the most detailed vegetation mapping for the area and are considered the point of truth for the distribution of terrestrial vegetation in Queensland. They also form the basis for Queensland's mapping of wetlands and groundwater dependent ecosystems.

Within the study area an assessment of the RE mapping and classification was conducted by searching the full RE descriptions within the database (REDD version 9) and constrained geographically by the relevant bioregions which occur within the study area. This was used to generate a list of potential RE types that potentially contain any of the asset species. This list was subsequently filtered to produce a list for each asset species, including only REs where the asset species are considered a 'dominant' component of the flora. This decision process was based on consideration of the full RE descriptions and included input and advice from the Queensland Herbarium (D. Butler, *pers. comm.*). A spatial layer of the distribution of each asset species was then produced by selecting individual mapped RE polygons that were mapped as containing a majority (greater than or equal to 50 per cent) of a single asset type or a mixture of asset types (where present as mixed RE communities).

The RE mapping does not extend into New South Wales. A separate Northern Basin Review project (funded by the MDBA) mapped the New South Wales portion of the LBF to the scale of 1:10 000 (Eco Logical Australia 2015) and this has been used to delineate asset species distribution in this area. Within New South Wales, vegetation community mapping is defined using Plant Community Types (PCTs) and as part of the MDBA mapping project an equivalence table linking PCTs to comparable Queensland REs was produced (Eco Logical Australia 2015). This PCT and RE equivalence, and the corresponding spatial data sets, has allowed the production of a seamless vegetation mapping layer across the whole of the study area. The PCT mapping in New South Wales does not contain mixed polygons (as each polygon represents a single PCT due to the finer spatial scale at which this mapping was conducted).

The REs/PCTs that were used to define the distribution for each asset species are given in Appendix 1 and form the basis for mapping the distribution of the asset species across the study area that have been used in project analyses.

Land-systems/Model zones

Land-systems (LS) are recurring patterns of geology, landform, vegetation and soils that are uniform and predictable. The LS have formed the basis for the definition of the model zones in this study as defined in the conceptual model for water availability (Figure 7). Within Queensland, different land-systems and component land units of the Queensland section of the LBF were mapped by Galloway et al. (1974). While they were mapped at a reconnaissance scale (1:500 000), they remain a useful tool for conceptualising the landscapes and functional hydrology of the sites of interest. Although the mapping of Galloway et al. (1974) does not extend past the Queensland/New South Wales border, similar land-systems were also mapped for northern New South Wales (Walker 1991).

Whilst these two data sets are not directly comparable, during the course of the project an equivalence table of the Land-system information between QLD and New South Wales was developed (Table 2). Expert opinion and cross border line-work matching allowed the provision of a uniform data set across the study area that has been used as the basis for defining model zones used in this project (Figure 11).

The model zones make up eighty three per cent of the study area with seventeen per cent being composed of other land-system types that are not considered to represent the floodplain environment (Figure 10).

Floodplain assessment areas

This project applied a Floodplain Assessment Area (FAA) approach that divided the floodplain into areas associated with specific flow gauging stations in the river (Figure 12).

FAAs delimit the area of floodplain and the length of river channel for which water flows can be reasonably represented by variation in water flows recorded at a particular stream gauging station, based on local topography, geomorphology, and river network features. Defining FAAs improves the confidence in the spatial relationship between gauged flow data and the hydrological or hydraulic conditions experienced by ecological assets.

Within the LBF, these were identified by the following step-wise process:

1. Identifying gauging stations within the study area
2. Floodplain lateral extent was then defined as the areas identified as floodplains by the Queensland Reconstruction Authority Interim Floodplain Assessment Layer (IFAO). As there was no equivalent floodplain extent mapping layer for New South Wales, conservative lateral estimates were used for floodplain assessment areas in the Culgoa and Narran Rivers in New South Wales.
3. Expert workshops with Queensland government hydrologists and hydrographers were undertaken and each FAA was determined by estimating the upstream and downstream limit of the river reach represented by the gauge and the adjacent floodplain areas.
4. The boundaries of each FAA were then delineated and digitised.

FAAs enable use of historical flow data as a surrogate for local flooding, and these relationships have been used to define periods of flood and dry across the time-series of available gauged flow

information (see Section 3.3.3). Such analysis has subsequently allowed for targeted selection of dates for imagery used in remote sensing analysis.

Table 2 Equivalence between QLD and New South Wales land-system classification and project model zones

Vegetation hydrology model zone	Western New South Wales Land-system code	Western New South Wales Land-system name	QLD Land-system code (ZBA classification)
1	Db	Dumble	33
1	My	Mid - Darling	33
1	Rp	Rotten Plain	33
1	Ud	Upper Darling	33
1	Ur	Eurie	33
1	Wg	Warrego	33
2	Le	Ledknapper	32
2	Ni	Nidgery	31
2	Gd	Goodooga	31
2	LI	Llanillo	31
2	Lm	Long Meadow	31
2	Wq	Wongal	31
2	Wx	Wombeira	31
3	Gi	Gingie	30
3	Hd	Hermidon	30
3	Rs	Rostella	30
3	Ru	Rugby	30
4	Ta	Tatala	28

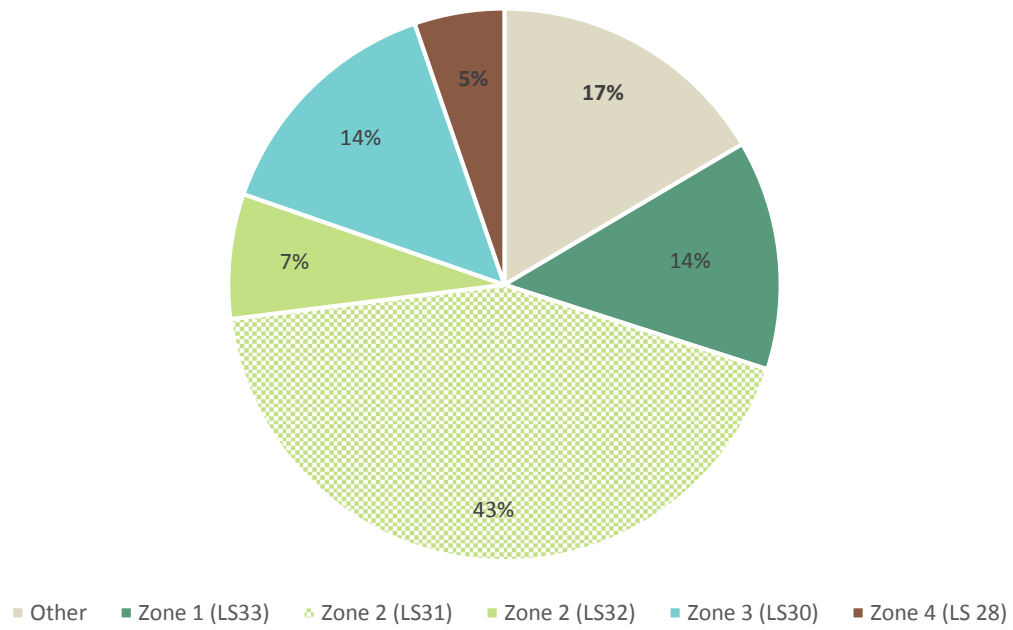


Figure 10 Proportion of each model zone across the study area

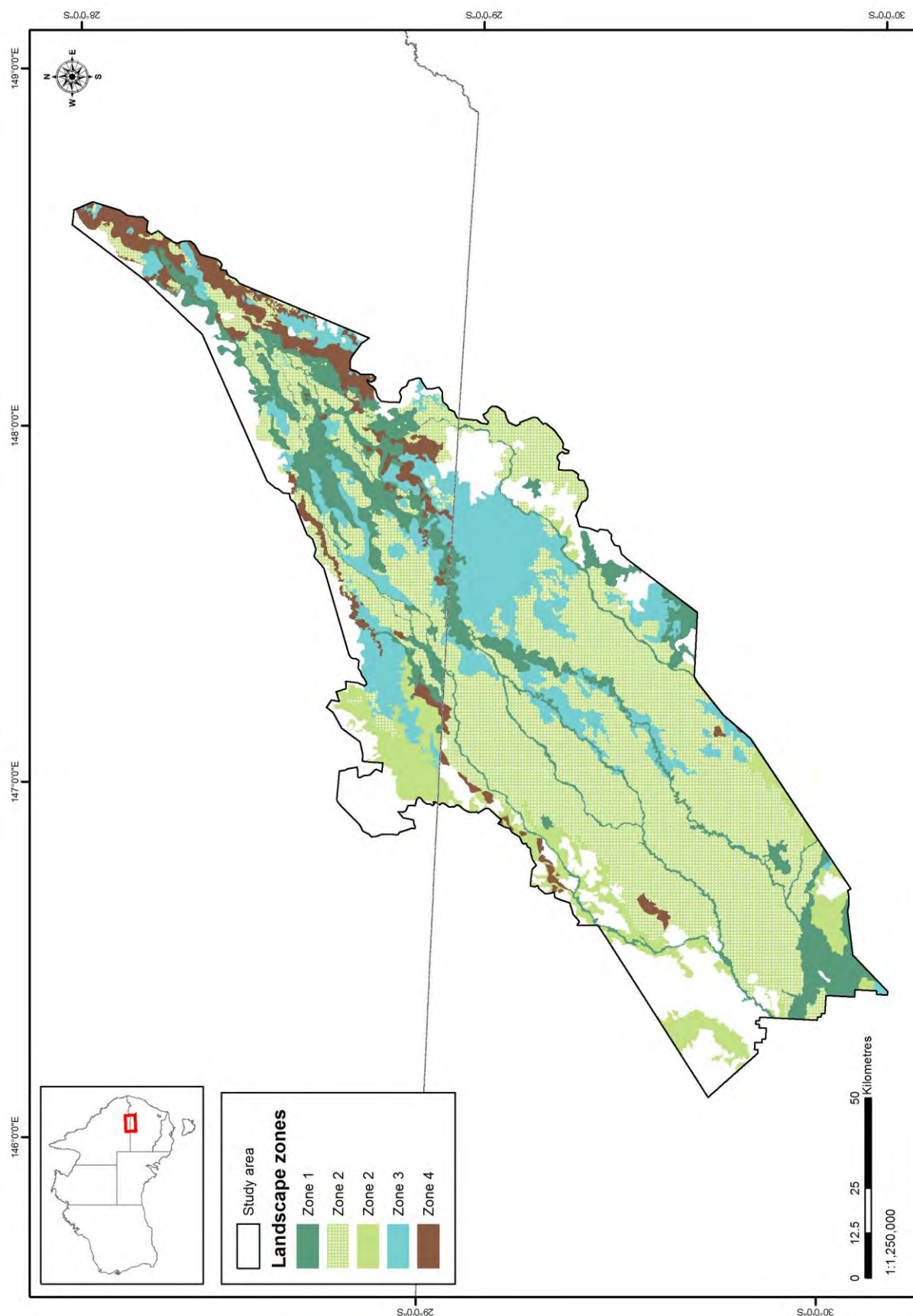


Figure 11 Model zone boundaries across the QLD and New South Wales portions of the Lower Balonne Floodplain (as derived from Land-system mapping using equivalence as defined in Table 2)

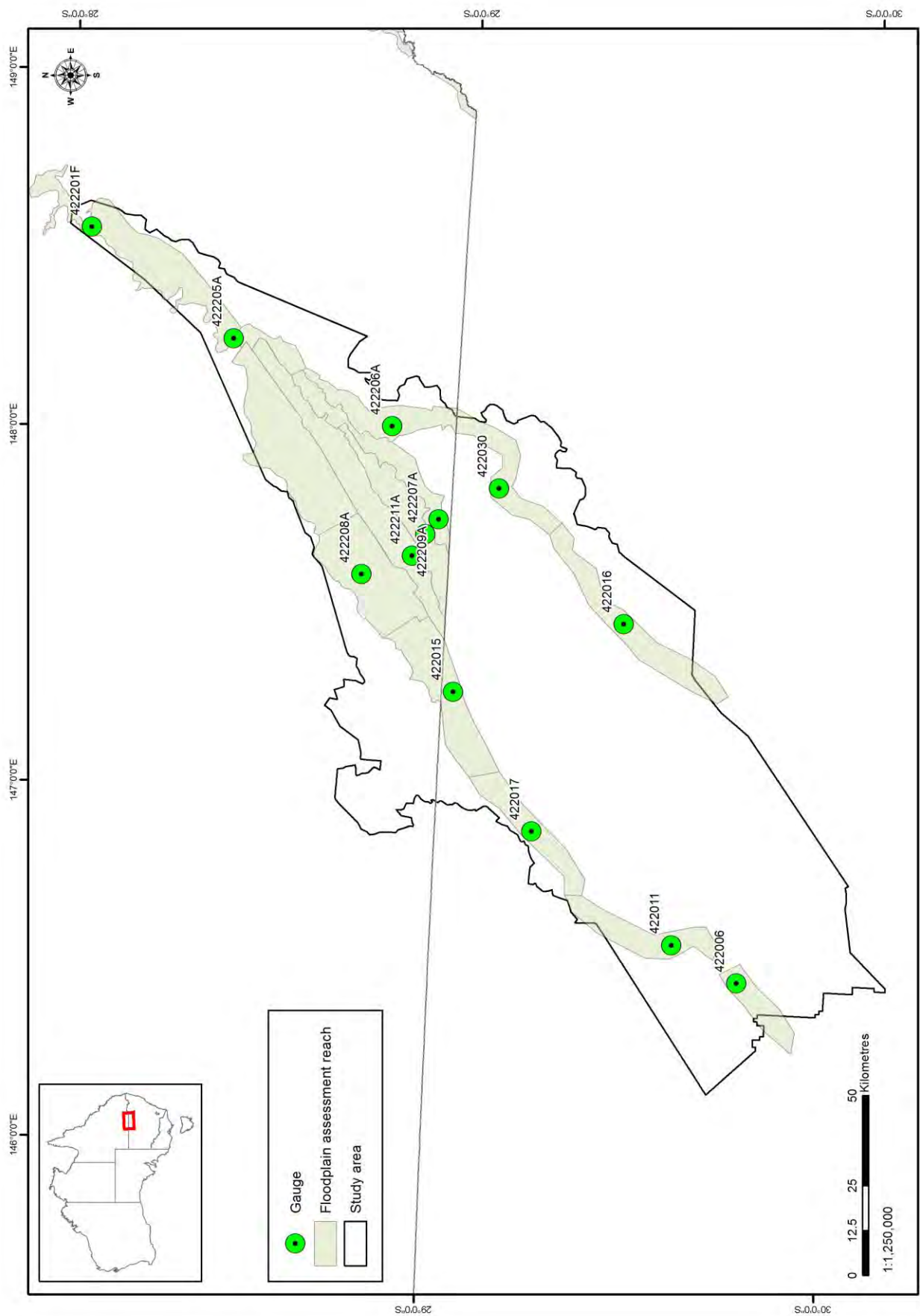


Figure 12 Location of gauging stations within the study area. Gauging stations were used to evaluate Floodplain Assessment Areas.

3.3.3 Gauged flow and hydrology

In the absence of detailed flood inundation modelling, alternative methods related to hydrological data were applied. Dry spells were used to identify vegetation patches potentially accessing groundwater and flood spells were used in the determination of a flood frequency classification within the pixel scale analysis (see section 3.3.4).

A step-wise process (Figure 13) was applied using available hydrological information from Queensland and New South Wales gauging stations within the study area (Figure 12) to determine potential flood dates and dry periods over the Landsat time-series. These dates/periods were then targeted within the remote sensing analysis to assess vegetation response to differing historical hydrological regimes.

Multiple lines of evidence were used to initially determine 'top of bank' thresholds for each of the gauging stations in the study area. This method used cross-sectional data, ratings curve interpretation, interrogation of the DEM in relation to the channel and remote sensing imagery, and was coupled with a comparison of overbank/flood estimates from a variety of sources (DSITI interpretation, Bureau of Meteorology: BOM, Commonwealth Scientific and Industrial Research Organisation: CSIRO) and expert opinion from local hydrographers.

Following conversion to a standardised height datum, flow records from each gauge were compared to the defined top of bank threshold and dates and duration of likely floodplain inundation periods were determined. The longest low flow periods were also identified.

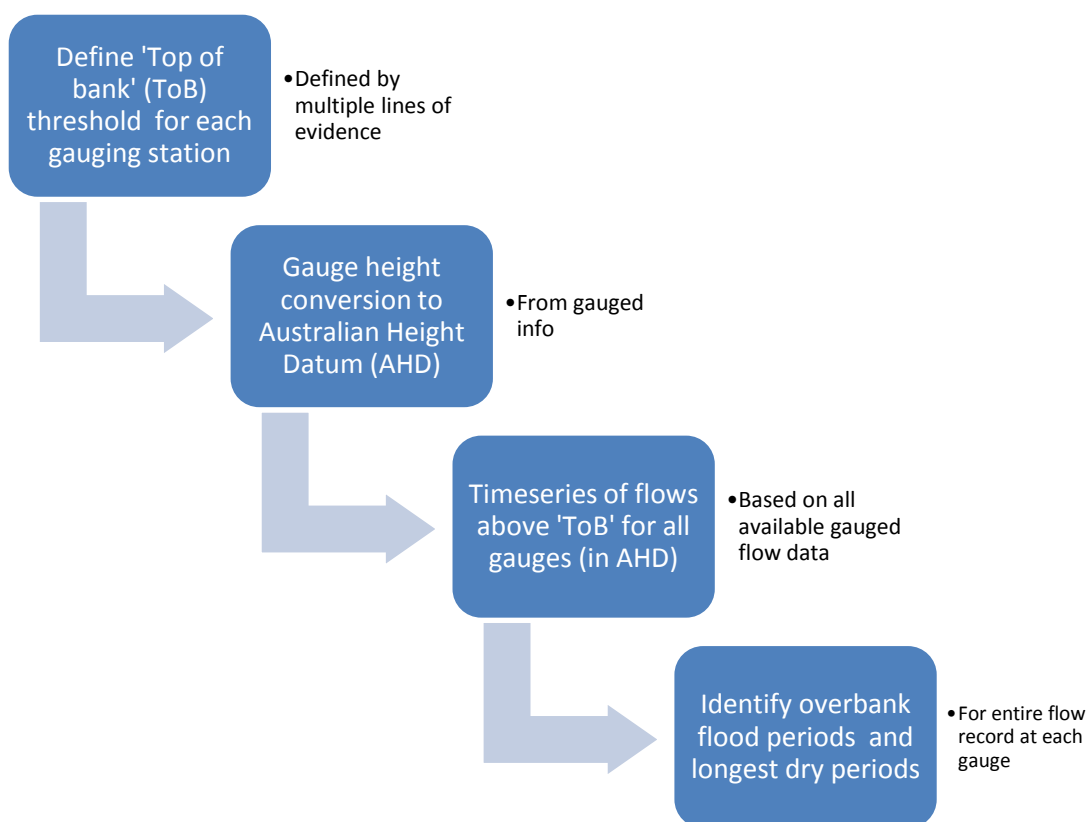


Figure 13 Overview of step-wise process for defining flood frequency, duration and magnitude for all gauging stations in the study area

3.3.4 Remote sensing analysis

The overall aim of the remote sensing/GIS component of the project was relate water availability (multiple sources) to the 1) distribution of floodplain vegetation asset species, and 2) changes in their condition through time. This involved analysing vegetation distribution and temporal changes in vegetation condition (using a seasonal greenness product applied to the long-term Landsat time-series) in relation to occurrences of dry spells, river flooding and also rainfall and evaporation data.

Correlative evidence highlights the relative importance of water from flooding, rainfall and shallow groundwater in supporting vegetation condition. There have been four major steps to the remote sensing analysis:

- Identifying vegetation patches potentially accessing groundwater
- Pixel scale analysis.
- Landscape scale remote sensing analysis.
- LiDAR data analysis.

Different steps of the spatial analysis are described in more detail in chapters related to specific research questions, with more detailed methods contained in appendices where appropriate.

Identifying vegetation patches potentially accessing groundwater

An analysis across the whole study area using remote sensing vegetation response indices identified vegetation patches showing consistently high vigour (high greenness) during dry periods. This was integrated with other information, such as the variability of the long-term signal of vegetation greenness and water indices, to identify patches where greenness and apparent vigour persisted despite climate variability. This provided a multiple lines of evidence approach to classify vegetation patches that are likely accessing groundwater.

Pixel scale analysis

Pixel selection provided for indirect flood frequency analysis and thus for inferences regarding the reliance on flooding for vegetation persistence. Landsat pixels (283 in total) were selected as a stratified sample of the floodplain vegetation in the study area based on their location within the mapped vegetation communities and model zones represented in the project (see Appendix 3 for pixel details). Pixels were spatially dispersed across the study area. For each selected pixel, a time series of seasonal greenness (representing vegetation condition) was derived from the Landsat data set.

The spatial distribution of the pixels selected for coolabah (the majority of the pixels selected) were constrained by the spatial extent of the FAAs. Pixel locations within FAAs were used in conjunction with dates derived from the hydrological analysis (see section 3.3.3) and remote sensing techniques to detect water on the floodplain (see Chapter 4). This provided an estimate of flood frequency for each pixel. Seasonal rainfall and climate variables were also determined across the study area and a statistical analysis was then undertaken to assess the extent to which weather/climate or flooding explained the variation in seasonal greenness at each pixel location.

Landscape scale remote sensing analysis

Landscape scale analysis was conducted to determine if the patterns of weather/climate versus flooding at the pixel scale were suitably extrapolated to a larger spatial scale. Therefore a similar assessment to the pixel scale analysis was also undertaken at the broader landscape scale. We

defined landscape analysis units by intersecting asset species distribution with model zones and also a delineated 'fringing' zone. Analysis units were then filtered to only include 'woody' vegetation based on LiDAR information. Vegetation greenness and rainfall metrics were averaged and analysed at the landscape analysis unit scale.

LiDAR data analysis

An analysis of LiDAR data was undertaken to examine tree heights across the whole study area. Maximum and average maximum tree heights were determined at both the pixel locations and also across the landscape scale units. These data were used to determine any links between tree size and water availability.

3.3.5 Groundwater recharge estimation (desktop modelling)

Modelling of estimated groundwater recharge across the Queensland portion of the LBF was undertaken using a combination of spatial extrapolation, 2D hydrus modelling and interpretation of the updated land-system mapping combined with historic flood imagery (see Chapter 6). This work was commissioned as part of the project and undertaken by Elad Dafny from the University of Southern Queensland (Dafny 2017). The NSW portion of the LBF was not included as updated land-system mapping was only available for the QLD portion.

The work attempted to determine the potential rate of shallow groundwater recharge from flooding and the relative contribution from the different land-systems/model zones within the study area.

3.4 Project generated data

A large volume of data has been collected during the course of this project, and the different data sets generated have been catalogued within a data inventory (Appendix 4 and Appendix 5). These appendices give meta-data for the data sets collected including their spatial and temporal context, method of collection, details of storage locations and archiving arrangements for remote sensing and field data respectively. In accordance with the contractual agreements pertaining to the publication of project material, all data will be available via publically accessible websites or databases where possible, or be available through other means which will be identified.

Large amounts of data have been collected for this project, and whilst all project generated data have been considered in the production of this report, the data of direct relevance to the research questions has been reported here. Consequently, there is significant data that will be further analysed, that is expected to be published in the form journal articles. This will add value, and produce ongoing outputs from the research conducted within this project, beyond its current end date. This will be specifically explored through a number of avenues including via:

- Publications from project team members where time and resources allow
- Via existing research arrangements with university collaborators and contractors established as part of the project
- In collaboration with members of the project steering committee;
- In collaboration with researchers from the MDB EWKR team

4 Identifying eco-hydrological correlates of vegetation response

The purpose of this part of the research is to consider the LBF at a broad scale to explore the correlative relationships between floodplain vegetation distribution/response and eco-hydrological factors that may be explanatory. This is in contrast to the following chapter, which considers the scale of sites and individual trees, in which actual water use is measured over short time scales.

The large-scale approach consists of two parts. The first part addresses a straightforward question about the location and distribution of different floodplain tree species in the LBF. The second part uses remotely sensed data to consider the potential water available to floodplain vegetation through the inferred response to various water sources. Floodplain asset species included river red gum, black box, coolabah, and lignum.

4.1 How does asset species distribution relate to the flooding extent?

The distribution of different asset species across the floodplain is likely to provide clues to their dependence upon water from the river channels and flooding. Spatial data indicative of tree species distributions and flooding regimes were related to each other to investigate how well the hypotheses from earlier studies (Holloway et al. 2013, see Figure 7) are actually supported across the LBF. The following hypotheses derive from Holloway et al. (2013), but these were not specifically tested or confirmed by them through mapping, which is what we do here.

Specific hypotheses for asset species are:

- *Hypothesis 1. The distribution and abundance of river red gum is expected to be greater in riparian areas (model zone 1).*
- *Hypothesis 2. The distribution of black box is expected to be associated within certain land system types within the floodplain model zone 2 (in particular land system 32 for Queensland / Ledknapper for New South Wales).*
- *Hypothesis 3. The distribution of coolabah is expected to be more ubiquitous and found across riparian and floodplain areas (both model zones 1 and 2).*

Note that no hypothesis relating to lignum was considered because of insufficient data on the distribution of this species (but see Lignum case study section 4.3). Lignum is generally an understorey plant in the LBF, which means that it is included in conjunction with other species (mostly coolabah) in plant communities (REs, PCTs). In some places lignum does exist as dense, monocultural stands, however these are not mapped as separate units. The distribution of mapped plant communities that contain lignum mirrors that of coolabah, and so is not particularly reliable for identification and mapping of these dense lignum areas. These areas are potentially of greater interest when considering lignum as an asset in its own right.

4.1.1 Methods

Species Distributions

To define the distribution of the asset species across the landscape of the Lower Balonne Floodplain, different distribution sources were initially used for Queensland and New South Wales. In Queensland, Regional Ecosystems (RE) (REDD version 9; Queensland Herbarium 2015) were used to represent species distributions, whereas in New South Wales Plant Community Types (PCT; Eco Logical Australia 2015) were assessed and then were associated with their RE equivalent to bring the two datasets together (see 3.3.2 and Appendix 2).

Flooding Extent

The relative frequency of flooding was inferred with reference to model zones, which, like species distributions, were derived from different datasets for the two states, Land-systems for QLD (Galloway et al. 1974) and Western New South Wales Land-system for New South Wales (Walker 1991). These datasets were also aligned and combined (see 3.3.2). As model zone 1 is the closest to the river channel and model zone 4 the most distant, the relative rates of inundation were assumed to correlate with model zone (see Figure 7).

Analyses

Maps were generated by intersecting species distributional data with model zone in ArcGIS version 10.4.1 for desktop. Data were extracted to Excel where pie charts were created showing the percentage each model zone makes up of the total distribution of that species across the Lower Balonne Floodplain.

4.1.2 Results

- *Hypothesis 1. The distribution and abundance of river red gum is expected to be greater in riparian areas (model zone 1).*

Within the four model zones, 67% of the distribution was within model zone 1 (Figure 14). River red gum were distributed across only 0.5% of the entire study area, covering only 93 km² (Figure 15).

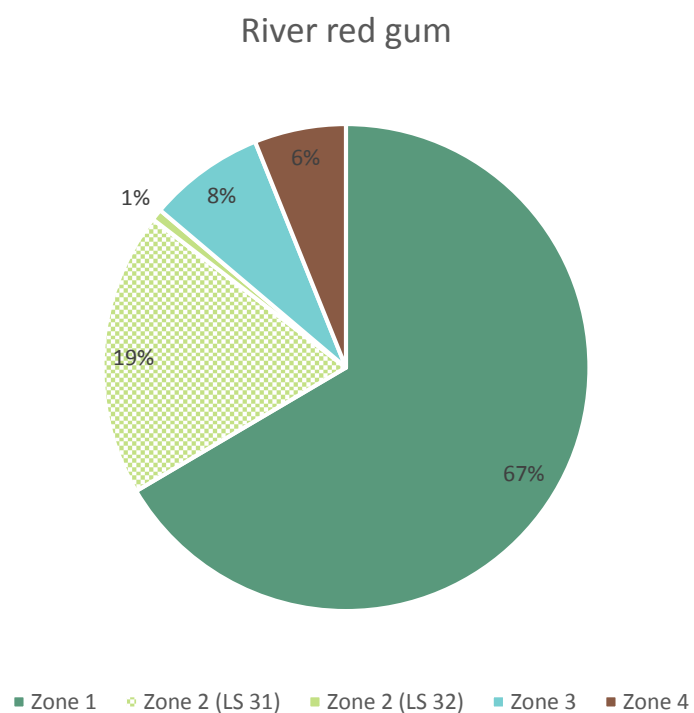


Figure 14 River red gum distributional percentages across the Lower Balonne Floodplain model zones

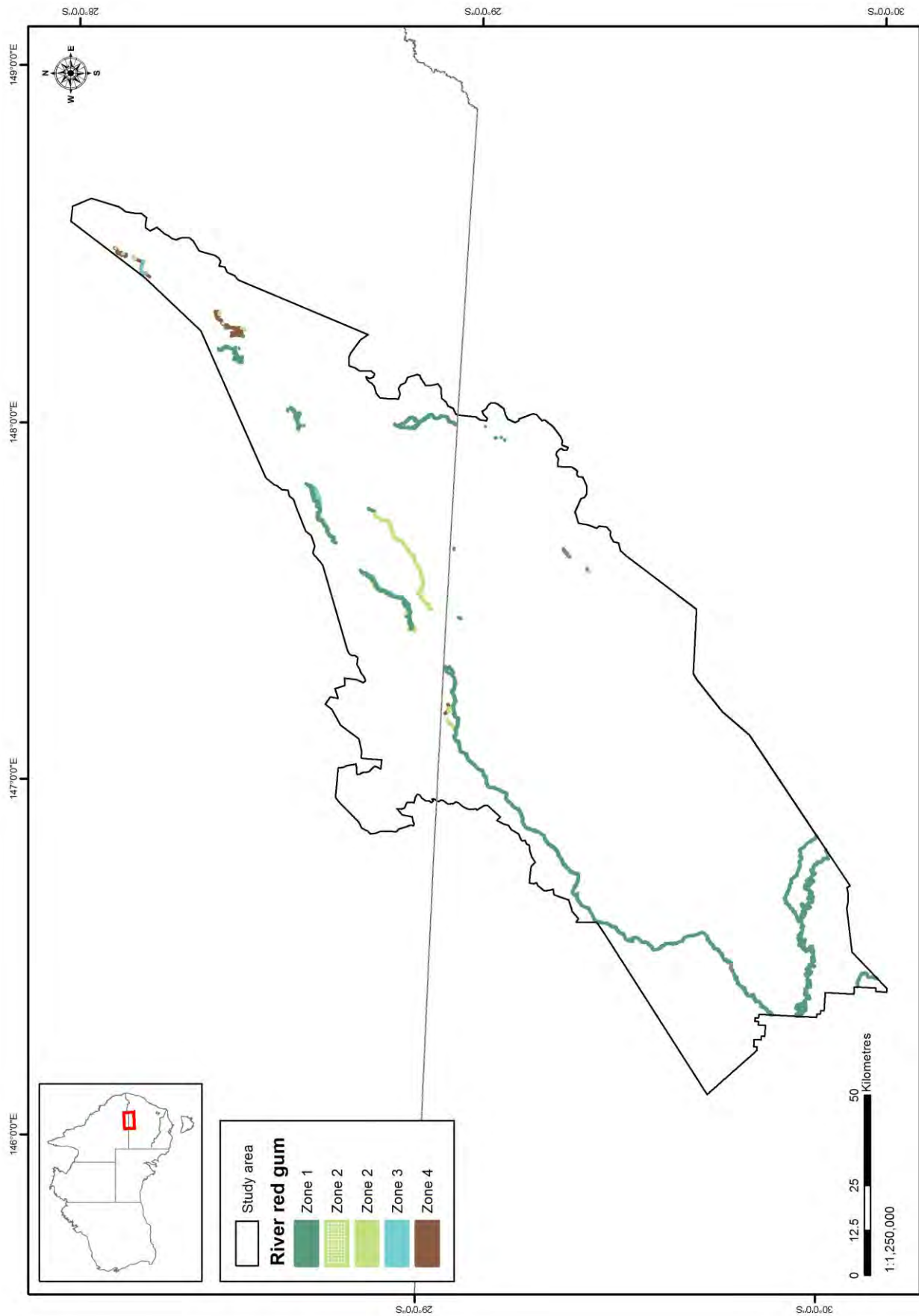


Figure 15 River red gum distribution in Lower Balonne Floodplain within four model zones

- *Hypothesis 2. The distribution of black box is expected to be associated within certain land system types within the floodplain model zone 2 (in particular land system 32 for Queensland / Ledknapper for New South Wales).*

Within the four model zones, 85% of the distribution was within model zone 2, with 83% found in LS32 alone (Figure 16). Black box total area was similar to red gum, and was across only 0.6% of the entire study area, covering only 112km² (Figure 17).

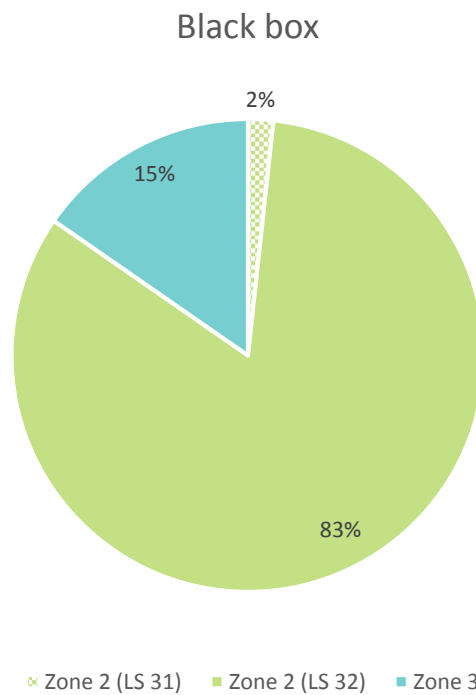


Figure 16 Black box distributional percentages across the Lower Balonne Floodplain model zones

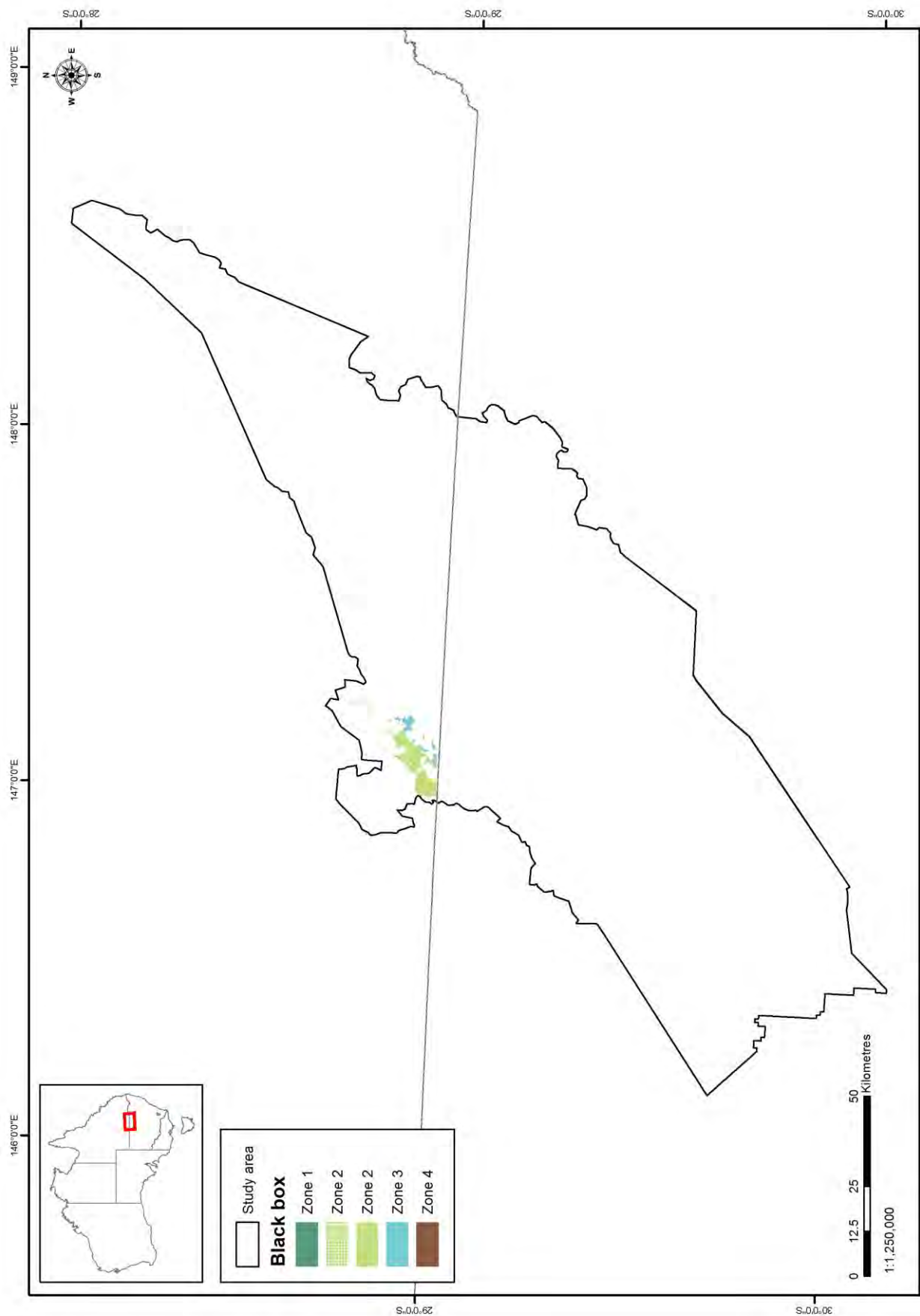


Figure 17 Black box distribution in Lower Balonne Floodplain within four model zones

- *Hypothesis 3. The distribution of coolabah is expected to be more ubiquitous and found across riparian and floodplain areas (both model zones 1 and 2).*

Within the four model zones, 84% of the distribution was within either model zone 1 or zone 2 (Figure 18). Coolabah had a greater distribution than either red gum or black box, accounting for 20.5% of the study area and covering 3551 km² (Figure 19).

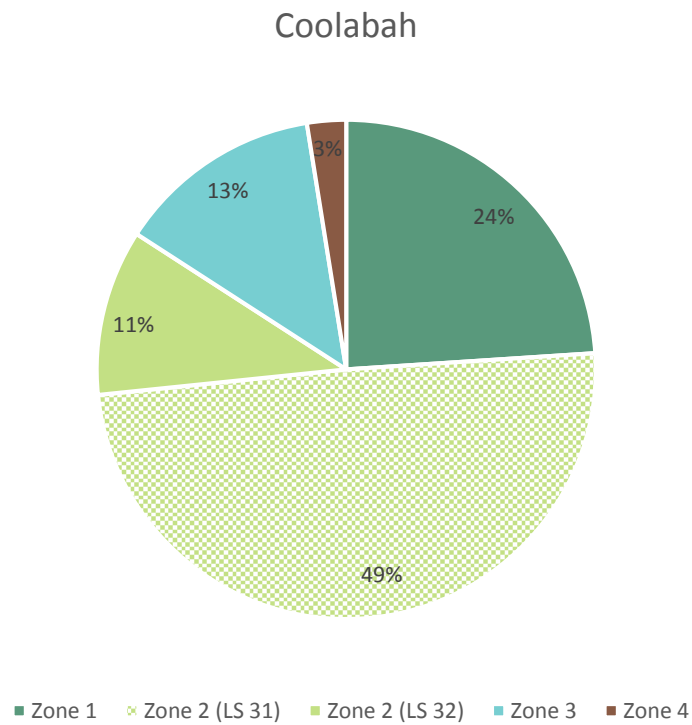


Figure 18 Coolabah distributional percentages across the Lower Balonne Floodplain model zones

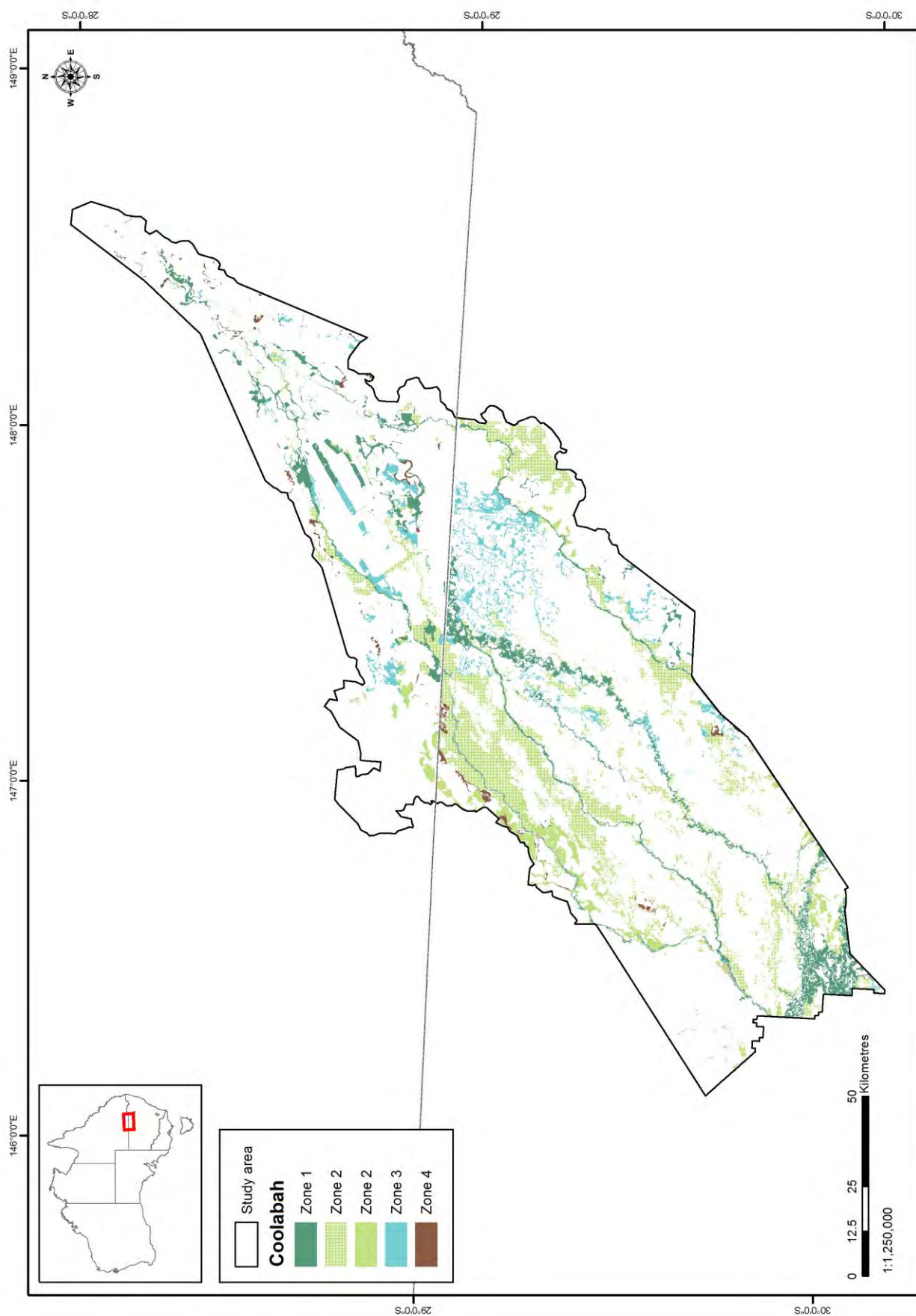


Figure 19 Coolabah distribution in Lower Balonne Floodplain within four model zones

4.1.3 Discussion

- *Hypothesis 1. The distribution and abundance of river red gum is expected to be greater in riparian areas (model zone 1).*

This hypothesis is largely supported, with river red gum indeed mainly found along the river (i.e. mostly in model zone 1). The distribution map closely mirrors the watercourses across much of the study area (Figure 15) and accords with written accounts and field observations of river red gum in this region. One implication of this is that river red gum is not really a major inhabitant of the floodplain in its strictest sense. Because many of these trees likely have roots that intersect directly with the river channel, this species probably does not need to rely on either overbank flood events or local rainfall, because it can instead count on in-channel water to meet much of its watering needs.

- *Hypothesis 2. The distribution of black box is expected to be associated within certain land system types within the floodplain model zone 2 (in particular land system 32 for Queensland / Ledknapper for New South Wales).*

This hypothesis is also largely confirmed given the overwhelming percentage of its distribution being located within model zone 2. However, black box is not a major component of the floodplain vegetation of the Lower Balonne (see Black box case study section 4.3). The distribution map did not display any black box in the New South Wales portion of the study area (Figure 17), however this does not mean that it is not found there, merely that it does appear in plant community type mapping within the four studied model zones. A further issue for more detailed flood-based analyses of black box in this area is that black box occurs largely outside the Floodplain Assessment Areas (see Figure 22) and so it is difficult to assess its flooding history since we cannot use gauge measurements to estimate overbank flow here. Further, since black box is largely restricted to a single model zone, it means that we cannot estimate a relative flooding frequency by comparing with other model zones, as we can do for coolabah.

- *Hypothesis 3. The distribution of coolabah is expected to be more ubiquitous and found across riparian and floodplain areas (both model zones 1 and 2).*

This hypothesis is also confirmed for the study area, with most of the coolabah located in the lower elevation areas, and not in the more elevated floodplain (model zone 3) or raised sand ridges (model zone 4). This could imply that coolabah may be more reliant on overbank flow than species that have an inverse distribution (i.e. in elevated and not lower areas), since at least coolabah could access any overbank flow given their distribution.

4.2 Can changes in vegetation greenness be related to rainfall, flooding or groundwater availability?

The original plan for the second part of this chapter aimed at examining the relationship between floodplain vegetation response and flooding by directly relating remote-sensed data with inundation frequency/duration as derived from a dynamic flood inundation model of the Lower Balonne Floodplain. This method proved impossible using the model provided (see section 1.3.1); consequently, an alternative method was developed in collaboration with Ozius Spatial and considering advice from the project steering committee.

The method entailed selecting a sample of LANDSAT pixels and undertaking a time-series analysis of floodplain vegetation response in relation to historic flooding and weather/climate data (e.g. rainfall and evaporation) to test the following specific hypothesis:

- *That local rainfall rather than flooding is driving changes in tree response (as measured by temporal variability in tree greenness) (H_0)*

In this case, the assumption is that rain is the primary determining factor in the greenness response of floodplain vegetation, which implies relatively limited reliance upon overbank floodwater for tree maintenance. To consider this, regression models were developed for a tree response variable (greenness) as a function of weather/climate variables. Our assumption is that if rain rather than flooding really is key, then the models based on rainfall will fit variation in tree response equally well in frequently flooded areas as in infrequently flooded parts of the floodplain. If true, there should be no relationship between flood frequency and the variance in tree response that remains unexplained by a model on rainfall (Figure 20).

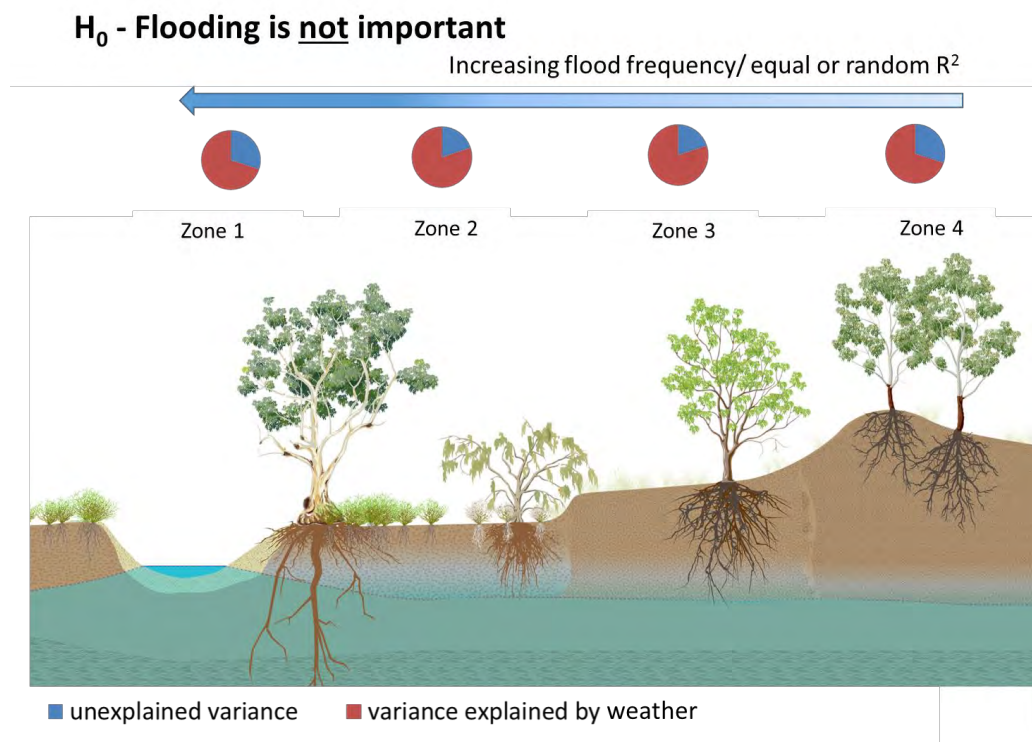


Figure 20 Expected result if rainfall and not flooding is driving changes in tree response

An alternative hypothesis to the above was further considered:

- *Flooding as well as rainfall drives changes in tree response (H_1)*

This version of the hypothesis, which is the inverse of the previous, assumes flooding is a key determinant of the greenness response of floodplain vegetation, which is the canonical view amongst many researchers (Roberts & Marston 2011). However, it is challenging to test H_1 directly due to an incomplete knowledge of where and when floods have inundated different parts of this landscape. This was not possible due to the lack of a suitable dynamic flood model that would allow direct relation of gauged flows to area of inundation. Therefore, our aim was to infer the extent to which this hypothesis is true by testing the alternative hypothesis H_1 . Given this, if H_1 is the more valid, then we would expect that the amount of variance in greenness left unexplained by weather/climate would be correlated with surrogates of flooding frequency (Figure 21).

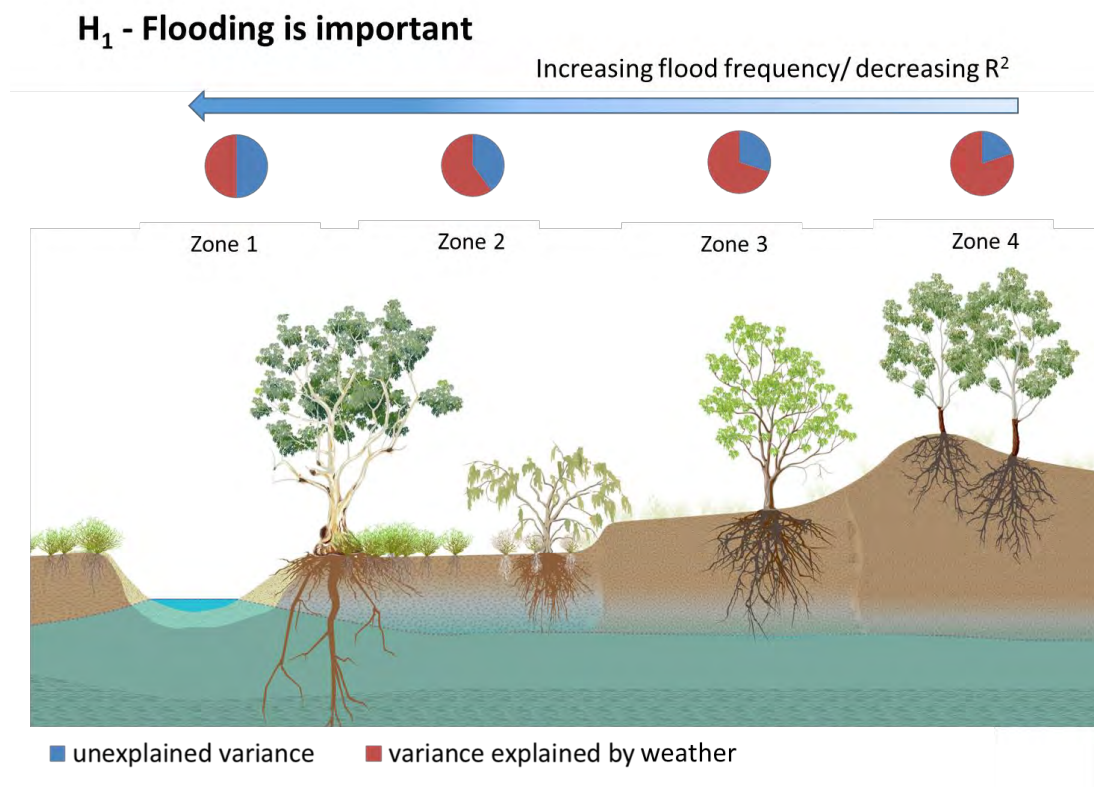


Figure 21 Expected result if flooding as well as rainfall drive changes in tree greenness response

4.2.1 Methods

Sites

Multiple sites were selected from a wide spatial distribution across the study area. Site locations were stratified across vegetation communities (as defined by RE/PCT type) and model zones. Most sites were selected based on the desktop GIS assessment of vegetation community information, but some sites were selected from existing field sites or because they represented riparian study sites. Preliminary analysis of variation in greenness suggested that a minimum level of tree cover was necessary to give confidence that the variance was related to tree responses rather than flushes in the ground stratum. Google Earth was also used to confirm that selected pixels within vegetation community patches supported more than this minimum level of tree cover. This was particularly important given the open vegetation structure across the LBF. Final sites were selected to represent relevant site-specific flooding regimes and tree minimum greenness response data.

A total of two hundred and eighty three sites were selected to represent three of the species: coolabah (252 sites), lignum (11 sites), and black box (20 sites) (Figure 22). There was a strong focus on coolabah because of its wide relative distribution (Figure 19), with stratified sampling within coolabah communities. River red gum was not included because its strictly 'fringing' distribution means that its response was likely to reflect in-channel water and not overbank floods or local climate. Lignum and black box were included but only as case studies (see text boxes below) due to insufficient mapping (lignum) and restricted distribution and flooding data (black box).

Floods

Two different proxies for flood frequency were used. Firstly, model zone was used to represent relative flooding (see 4.1.1). Secondly, each pixel site was assigned a flood frequency value representing the number of times floodwaters had reached the site during a number of specific periods of flooding (1989 – 2013). Relative flood frequency was calculated for each site within a Floodplain Assessment Area by calculating the periods of overbank flow for the relevant local gauges (see 3.3.2) and then analysing relevant Landsat scenes for these periods using a water mask (Danaher and Collett 2006). A count of the number of times that water was detected at each pixel site was then assigned to the site as its flood frequency. This assessment was used to provide indicative sample sites across a sample of the LBF flooding regime, however, it was not an in-depth flood inundation study. Only 8-12 flood events were selected (depending on location of site on the floodplain) as these were the floods that were measured at a gauge as an overbank flood onto the LBF. The dates varied from north to south and also with availability of Landsat images observing the flood event given the historical assessment approach (using best available data at the spatial and temporal scale appropriate to this study).

Weather/climate

Rain data covering each pixel site was downloaded from SILO (Scientific Information for Land Owners; www.longpaddock.qld.gov.au/silo), which interpolates data in 0.05 degree blocks across the landscape. Daily rain data (in mm) was aggregated to season total. Evaporation data for the same sites were downloaded from Australian Water Resources Assessment landscape (AWRA-L) model (registry.it.csiro.au/sandbox/csiro/oznome/AWRA-L/potential-evapotranspiration). The Potential evapotranspiration variable (Penman 1948) was used from the AWRA-L data (also calculated on a 0.05 degree grid), and is also represented as total mm in a season. A deficit value

was also calculated for each season, which was rain minus evaporation, making a total of three categories (rain, evaporation, deficit).

Because it was unclear if vegetation would respond to the current climate or antecedent conditions, the three categories of climate data (rain, evaporation, deficit) were considered over three time periods: the current season, the previous season and the previous year (preceding four seasons). This generated a total of nine variables (the three lags above for rain/evaporation/deficit) and their in-season observations (see Appendix 1).

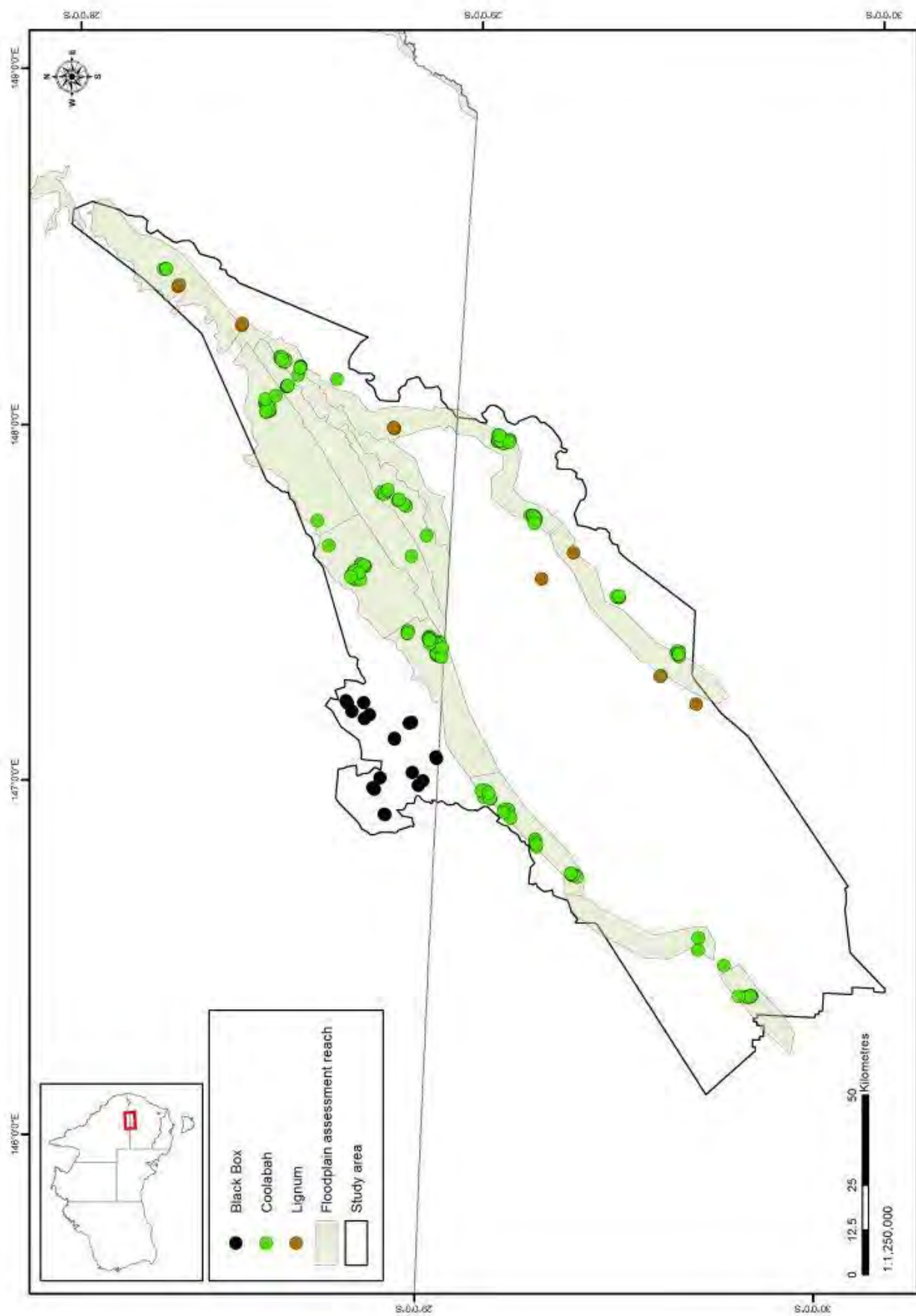


Figure 22 Pixel Analysis Site Locations

Tree Response

Landsat Seasonal Greenness (Flood 2013) data were extracted for the sites from Autumn 1989 to Autumn 2013. Only sites with an average green fractional cover (GFC) (Scarath et al 2010) of greater than or equal to 12% were sampled in order to avoid any grass-dominated sites. Coolabah sites were stratified into Medium GFC (greater than 20% and less than 35%) and High GFC (greater than or equal to 35%) to capture a range of green cover variation.

Previous studies (Holloway et al. 2013) have suggested that some floodplain vegetation in the Lower Balonne are accessing groundwater, which would mean these areas would not necessarily show a direct response to flooding or rainfall and would contribute unwanted noise in the data. To avoid this situation, areas deemed as “High vegetation vigour” (HVV) and classified with a likelihood of accessing groundwater (potential, likely, highly likely) were excluded from later analyses (see Appendix 2 for method details and GDE case study – section 4.3).

4.2.2 Analyses

Regressions

Multiple stepwise regression analyses were done in R (R Development Core Team 2008) using the climate variables (nine in total) over the data for the seasonal greenness for each pixel site to explain temporal greenness variability. For each stepwise regression (forward and backward), an AIC function (Akaike information criterion; Akaike 1974) was applied to identify the model with the best balance between fit and complexity. The proportion of the variance in greenness explained by this best-fit model was then assessed using adjusted R^2 values, which takes into account the number of variables included in the chosen model.

The outputs included the model applied for each site, the best fitted values, the upper and lower 95th percentile confidence intervals, and the adjusted r^2 .

ANOVAS

All sampled pixels were filtered to select only those specifically classified as coolabah because the representation of both black box and lignum (see 4.1.3 and case studies section 4.3) was inadequate for statistically significant results. Only coolabah sites not deemed HVV progressed to this stage (212 sites).

Two separate analyses were then performed on the non-HVV coolabah pixel sites using the two flood surrogates (a) model zone classifications (209 sites in zones 1-4) and (b) flood frequency (180 sites within FAAs). Regression R^2 values, which measure the variance explained by models based on weather data were then averaged for each classification. For the model zones (a), data were grouped into model zones 1, 2, 3, 4. For flood frequency (b), the classifications were 0,1,2,3,4,5, 6+, which represent the number of observations when that particular pixel was classified as being inundated (as explained in section 4.2.1). They actually ranged from 0 to 9, however sample sizes for 6 and greater were small and thus data were pooled into a single category, which really represents a relative incidence of flooding (see Limitation section of 4.2.4).

R^2 represents the variance in the greenness that is explained by our regression models with weather/climate variables. Whereas the unexplained component of the variance (1 minus R^2) is that which was not explained by weather, and thus potentially could be explained by overbank flooding. This value was calculated for each flood frequency classification or model zone and plotted into a separate bar graph for both flood measures respectively.

A single factor ANOVA (using MS excel data analysis function) was performed on both groups of data to test for statistical difference between the averages and variances for each classification.

4.2.3 Results

Model Zone vs Flood Frequency Groupings

To check that model zones actually represent a higher increased chance of flooding with proximity to the channel, the flood frequency counts from the water mask were binned by model zone to see if model zone 1 to 4 represented a declining probability of flood (Table 3). Average Flood Frequency Values are really a relative measure of the probability of flood and not an actual count of all floods over the relevant time period, and so a higher number means more floods and so more flood prone. The assumption that model zones represent a predictable range of flooding frequency was supported, with an average of fewer floods counted in model zones more distant from the channel (i.e. zones 3 and 4) than those closer (zones 1 and 2).

Table 3 Average Flood Frequency Value by Model Zone

Model Zone	Average Flood Frequency Value
1	2.90
2	1.69
3	1.27
4	0.86

Model zone Groupings

The 1 minus R^2 value for each model zone did not show a pattern of larger unexplained variance (i.e. not climate, so presumably flood) for zones nearer to the channel (zones 1-2) than zones more distant from the channel (3-4), which would receive relatively less floodwater. There was no statistically significant difference between the groups ($P = 0.197$) (Figure 23).

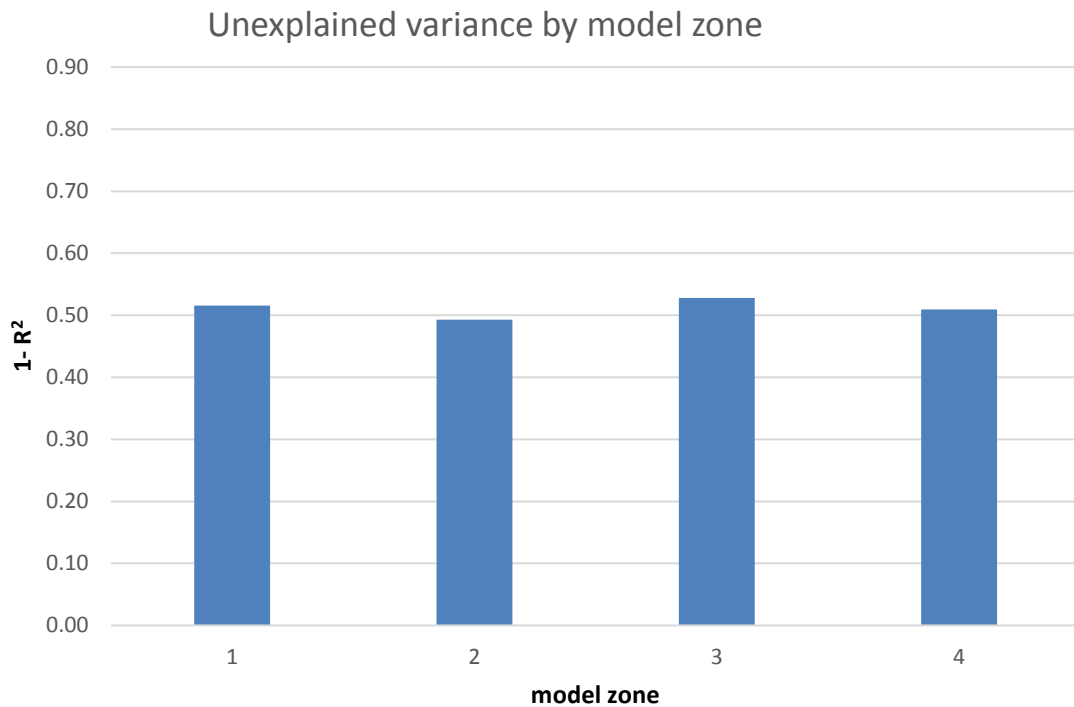


Figure 23 Histogram of unexplained variance for climate/greenness regressions for coolabah sites by model zone

Flood Frequency Groupings

As above, the 1 minus R^2 value for each flood frequency group did not show a pattern of larger unexplained variance (i.e. not climate, so presumably flood) for pixels that had received floodwaters more often than those that had not. There was again no statistically significant difference between the groups ($P = 0.734$) (Figure 24).

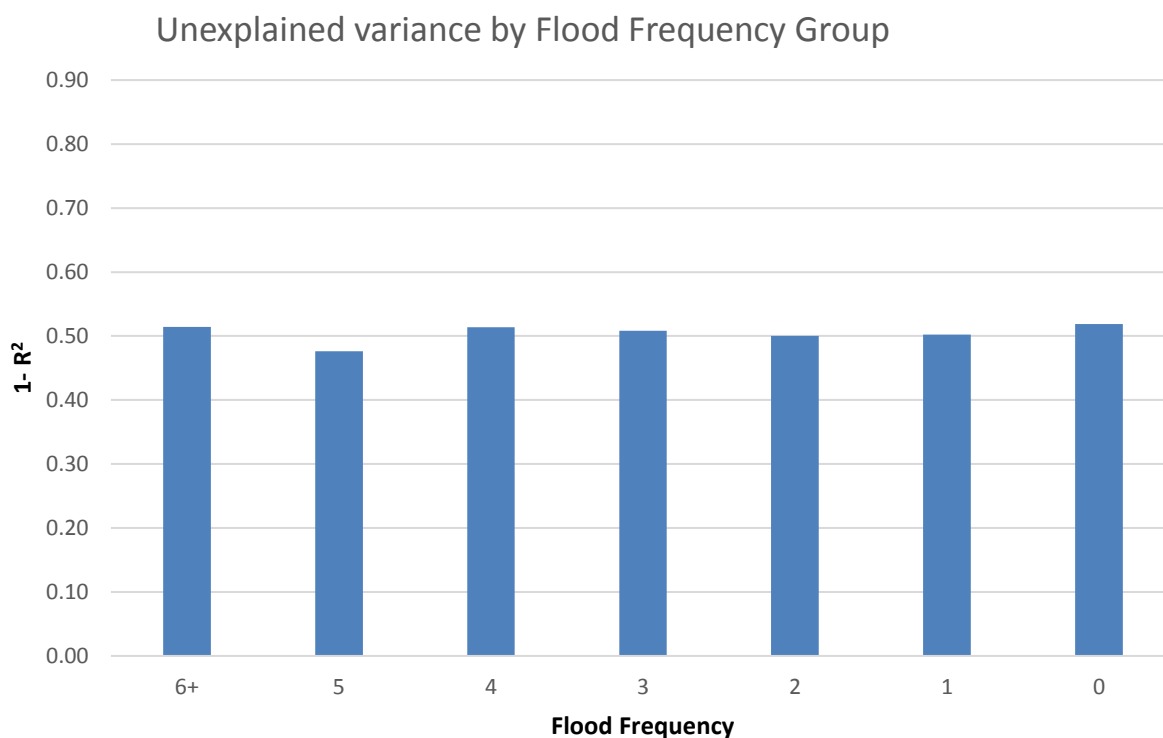


Figure 24 Histogram of unexplained variance for climate/greenness regressions for coolabah sites by flood frequency group

Best-Fit Models

Different combinations and numbers of climate variables were included in the best-fit regression models chosen for each pixel site. The number of variables per site ranged from two to six. A deficit variable was included only once (0.4% sites), with the remainder being either rain or evaporation variables (Table 4).

Table 4 Climate variables included in best-fit models

Climate Variable	% sites variable in best-fit model
Evaporation Current Season	97.50%
Rain Current Season	79.90%
Rain Previous Season	79.90%
Evaporation Previous Year	71.40%
Rain Previous Year	65.00%
Evaporation Previous Season	48.80%

4.2.4 Discussion

The objective of this component of the overall project was to assess the relative importance of three different water sources (rainfall, floods, groundwater) for coolabah condition in the LBF by using remote sensing of the trees' greenness response to available water. However, groundwater as an independent water source is not addressed by these approaches. Rather, potential groundwater sites were removed as "too green". It was deemed that groundwater dependent sites would not show a clear response to rain or flood and would thus bias the overall assessment. Groundwater as an independent source is specifically assessed at the smaller scale in Chapter 5 and also considered within the case study in section 4.3.

So the main question dealt with here is whether rain or flood is driving the greening response of coolabah on the Lower Balonne Floodplain over a 25-year period. The specific hypotheses are:

- *"That local weather/climate rather than flooding is driving changes in tree response (as measured by temporal variability in tree greenness) (H_0)". Or its counterpoint "That flooding as well as rainfall drives changes in tree response (H_1)".*

The results presented here (Figure 23, Figure 24) suggest that the null hypothesis, that weather/climate (rain) is driving the tree response, is supported. There was no strong signal of the influence of flood as inferred by either simple landscape position (model zone) or flood frequency. If flooding were a significant influence on the trees' greenness over this time, we would expect a pattern of a diminution of the influence of weather/climate with an increased signal of unexplained variance (presumably the influence of floods) for areas deemed to flood more often (Figure 21). However the different relative flood categories did not show any difference, suggesting that flooding has not been particularly influential, and that overbank floods may not be the keystone for these dryland species. Despite the LBF being a reasonably dry area, it does seem to receive regular rain, even during the millennial drought of 2001 – 2009 (see Figure 27).

Limitations

Unexplained variance

While weather/climate variables did appear to explain much of the greenness response, it actually explains only about half of the observed variation in greenness (average $R^2 = 0.49$ for non-HVV sites), which means that about half the story remains untold. Flooding may be very important for areas that do flood reasonably regularly, but this signal may not be clear in our results because flooding may only be one amongst many other unmeasured factors that together explain the other half of the variation. The possibility that a strong flooding signal is hidden would probably require that areas that do not flood also have some other sort of highly influential factor that remains unconsidered here, or else we should still see greater unexplained variance in flood areas.

It could be that phenology might also contribute noise to these analyses and mask any obvious greenness signal relative to water availability. This is because trees tend to flush in spring/summer, regardless of rainfall. It may also be that the unexplained variance is largely random, meaning that there is no simple explanation based on discrete measurable variables. Any unexplained variance could result from a complex combination of many local factors that vary in space and time (for example human influence), and so simple analyses would be unlikely to fully explain them.

Data sources

Much of the data used here was abstract, in that it did not represent a direct measurement of water use in a specific tree (as in Chapter 5), but required many different high level sources of data at

large scales (temporal and geographical) and many assumptions. A potential weakness is that these time-series analyses were restricted to relatively recent times when satellite data were available (after 1989 in this case). However, there is no guarantee that the climate, flooding or vegetation response during this time period is typical. If there were relatively fewer or more floods or rain than is usual over the long term, this would not be evident.

Vegetation mapping

The REs and PCTs, in QLD and NSW respectively, are by definition mapping of mixed vegetation communities (although they have been specifically chosen as those communities which are dominated by a particular species). It is therefore assumed that they represent the best available knowledge of where these species exist and have been used as a surrogate for the location of a particular species. This means that, with the exception of some locations where ground-truthing has taken place (e.g. at rapid vegetation assessment sites), we cannot guarantee that selected Landsat pixels are looking only at a particular asset species.

The accuracy of the vegetation mapping data sets is also a potential limitation. Within Queensland the RE mapping across the study area has been highlighted as a potential issue, and indeed a specific project to improve RE mapping across the Queensland portion of the Northern MDB, was proposed in 2015 to coincide with delivery of this project, however it was not resourced. In comparison, the New South Wales vegetation mapping was carried out at a finer scale and is more up to date.

Defining the distribution of lignum is a particular problem. When defining the potential distribution of lignum, REs and PCTs were included where the descriptions of the vegetation community listed lignum as a major understory species. In nearly all cases the distribution of lignum is aligned with that of coolabah (and this is supported by field observations), however whilst lignum is nearly always present, it is not in large and dense stands that have traditionally been used to define lignum as an asset in other parts of the Murray-Darling Basin. Specific mapping of clusters of dense lignum would be required to accurately represent its extent and location across the study area.

Weather/climate data

The rainfall data used in the project is based on SILO daily rainfall gridded datasets (which are at the scale of approximately 5 km x 5 km). These values are derived from observational data (i.e. rain gauging stations) which is then interpolated between gauges to generate the data grids. Whilst this is the best available information to enable an estimate of rainfall at any given point in the study area, the rainfall across landscape is likely to be highly variable and potentially localised, e.g. storm cells in spring and summer, and therefore might not accurately represent amount of rainfall at a particular pixel location.

However, the SILO rainfall data does show sensible spatial trends, including a correlation between latitude and rainfall (weak R^2 0.44), where the north is wetter and south drier, with a maximum difference of 18% between the wettest and driest pixel sites (Figure 25). Therefore, local variation may not be random across the landscape and may be predictable. There is an even tighter relationship between east (wetter) and west (drier) (R^2 = 0.77).

The evaporation data set used in this project (CSIRO Penmans evaporative potential) is similarly interpolated across the landscape, however an evaluation of the data set shows little spatial

variation across the study area (maximum 6% difference). In contrast to rainfall, this is felt likely to accurately represent the conditions across the study area (as the potential evaporation metric is based on broad variables such as air temperature, wind-speed etc.). However, the lack of overall spatial variation potentially hampers its usefulness as a predictor variable, despite there being a clear relationship between latitude and evaporation ($R^2 = 0.82$) with the north more evaporative, and it may be that temporal variation is more important than spatial.

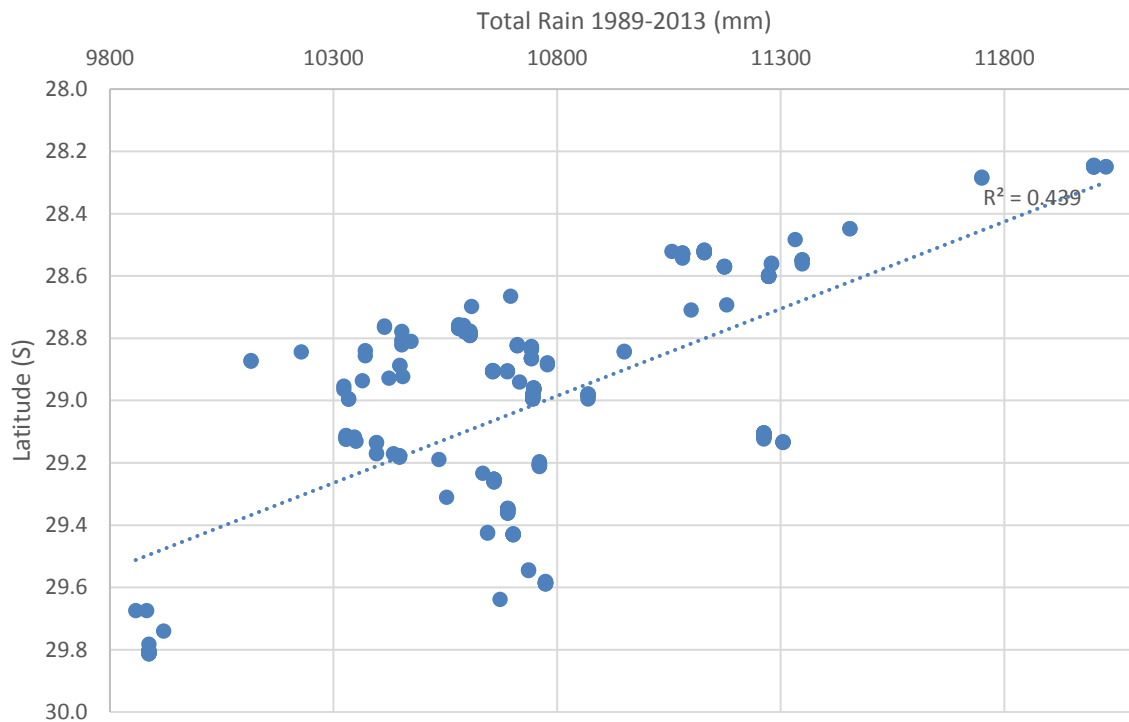


Figure 25 Variation in Rain at Pixel Sites across the Lower Balonne Floodplain

Floods

A major limitation within the project has been the inability to accurately represent flood inundation across the study area in relation to the remote sensing time-period. Whilst the flood frequency metrics used within the pixel-based analysis provide an indication of flood frequency, they cannot be considered to be truly representative of the inundation regime at a specific location. The two metrics are themselves highly correlated (see Table 3), although this is as it should be if they are actually measuring flooding probability.

The flood frequency metric is only indicative and provides a relative Landsat-scale snapshot of floods represented in the Landsat time-series in-lieu of a calibrated flood model. Because of the localised nature of flooding on the floodplain, flood events often being coincident with widespread rain and cloud (which obscures satellite sensors), and limited gauge data available to select relevant flood dates, the flood frequency assessment is only indicative. It provided a relative insight for the purpose of sampling pixels exposed to different flood inundation regimes across the floodplain. Although the flood frequency is a count of the number of times the site was observed as wet, the flood frequency site attribute is really a relative measure of inundation to provide an indication of the relative incidence of inundation through time due to overbank flow.

4.3 Case Studies

While coolabah provided a great deal of usable data, that for lignum and black box were restricted by insufficient mapping and flooding data, and these species' restricted distributions across the LBF. However, this project has produced some potentially indicative data for these two species for smaller-scale case studies. Similarly, while GDE identification was initially done simply to remove certain sites from the main pixel analyses (4.2.1), this process provided some potentially interesting results worth reporting here, and considering more in future.

Lignum case study

During dry periods that can extend for multiple years, lignum can appear lifeless or dead, but remain viable as underground rootstock (Freestone et al 2016). Healthy Lignum was observed in the field following above average spring autumn rainfall (April 2017) and is shown in Figure 26 compared to dormant lignum from a nearby site after an extended dry period (April 2016).



Figure 26 Comparison between 'green' and 'dormant' lignum *photos B. Senior and A. Biggs*

Landsat pixels were selected at eleven locations (Appendix 3) across the study area to specifically look at the condition of lignum monocultures. Sites were chosen by direct observation in the field where possible (or in some cases by using vegetation distribution mapping combined with Google Earth imagery) to select only dense stands of lignum rather than treed locations. Landsat-derived seasonal greenness time-series plots were generated for each site.

An example of one of these time-series plots in comparison to seasonal rainfall (derived from interpolated SILO data) is shown in Figure 27. Examining the trend in greenness over time there is generally correlation with rainfall and several examples in the time series where lignum has gone from its 'greenest' to 'brownest'.

The time-series the plots were analysed and periods identified where there was seen to be a continuous decline in condition between the 75th and 25th percentile of GFC values (derived from the whole lignum pixel data set). These values were taken to represent 'green' lignum and 'dormant' lignum respectively. The number of seasons taken for this decline to occur was recorded in each case (this process is also highlighted in the Figure 27).

Examining these specific periods gives an indication of how long it takes for lignum to lose condition. In all identified cases this was between one and five seasons with the average observed time for this to occur being approximately 2.5 seasons or 225 days. This suggests a seasonality, whereby without a significant rainfall or flooding event, lignum will have lost condition over the course of a year.

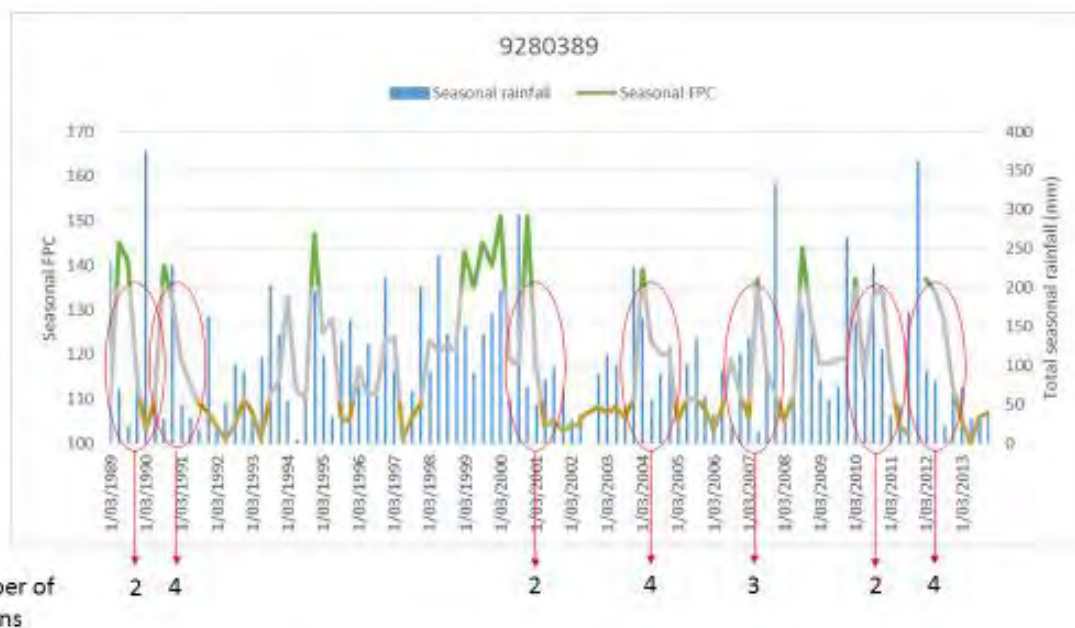


Figure 27 Seasonal GFC and seasonal rainfall over time at lignum site 9280389 with periods highlighted by the red ovals where there was a continual decline in response from ‘green’ to ‘dormant’.

Freestone et al (2016) found that although lignum can regenerate from dormancy, the likelihood of successful regeneration diminishes with increasing length of dormancy. Whilst the period of dormancy was found to be dependent on location they presented evidence that after five or more years of ‘dormancy’ no plants would survive (Figure 28).

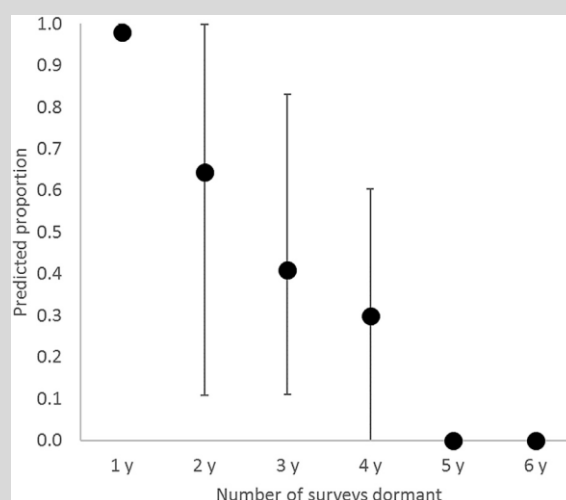


Figure 28 Predicted proportion of dormant lignum plants that regenerated over a seven year survey period for all locations ($\pm 95\%$ confidence intervals). (Reproduced from Freestone et al 2016).

This information suggests a threshold value of four years from ‘dormancy’ to enable regeneration. Combining these findings with knowledge from this project we can set a potential threshold of concern for lignum that could be then be applied within an ecological modelling context.

Black box case study

Black box of the Lower Balonne Floodplain is one of the asset species identified for study in this project (Figure 29). However, issues relating to a limited distribution and a lack of reliable information about flooding in this small area make this challenging (see 4.1.3).



Figure 29 Black box (*Eucalyptus largiflorens*)

Despite this, a limited number of black box sites (twenty) were located for the pixel analyses (Figure 22). One site (Site 9380375, 28.89 S., 147.17 E.) was identified as HVV, and so possibly a GDE (see 4.2.1), and was thus removed from the analyses.

Of the remaining sites, most were located in model zone 2 as expected (see 4.1.3) but four were in model zone 3, and so a simple comparison was possible between model zones as a surrogate for flooding. Model zone 2 showed a slightly lower average unexplained variance (0.47 vs 0.49), but with no significant difference ($P = 0.39$).

A comparison was also made between black box in model zone 2 and coolabah from the same zone. This was to see if there may be any species-specific differences in tree responses to a theoretically similar flooding regime. Black box had a slightly lower average unexplained variance (0.47 vs 0.49), but this also was not statistically significant. ($P = 0.34$).

Very small sample sizes meant that it was unlikely that trends would be identified even if they were there. To better understand the potential influence of flooding on LBF black box, it will be necessary to better understand the hydrology of the area, in particular the potential for flooding from other adjacent river systems such as the Nebine to the west.

Groundwater Dependent Ecosystems via remote sensing

A previous study by Holloway et al (2013) suggests that some of the floodplain vegetation of the LBF was likely accessing groundwater because of the many long periods when they had not benefited from water provided by floods. But identifying precisely where groundwater is located can be problematic, with many different methods, such as remote sensing (chapter 4), various direct measurement site-based methods (chapter 5), experimental plots (chapter 6) and modelling (chapter 6). Obviously direct evidence of groundwater and its use by vegetation is the strongest, but is also the most difficult to obtain and is only relevant over very small scales. A consistent theme of this project is that vegetation (and its response) might serve as a surrogate for the presence of water, and this is especially so for groundwater which is inherently difficult to locate and map. Thus a remote-sensing approach, as used in chapters 4 and 7, may help as a first cut to identify patches of vegetation across the entire floodplain that are greener than they should be, given their rainfall and flooding history.

In chapter 4, a method to identify areas of “High vegetation vigour” (HVV; see Appendix 1 for method details) was developed to remove pixel sites from regression analyses because the presence of groundwater would confound the water balance signal between rain and flooding that was the focus of those analyses.

However, the distribution of these HVV’s across the landscape are of interest as they represent possible groundwater dependent ecosystems (GDE), and were classified as “highly likely”, “likely”, or “potential” (Figure 31). Approximately 122 sq. km. was identified as HVV or one sort or another and thus possible GDEs, which is about 0.84% of the land area of the four model zones. These potential GDE sites were not evenly distributed across the landscape, with many closely following the river channels (model zone 1). This finding may justify not including river red gum in the main pixel analysis, since its distribution (Figure 15) closely matches parts of the of the potential GDE map (Figure 31).

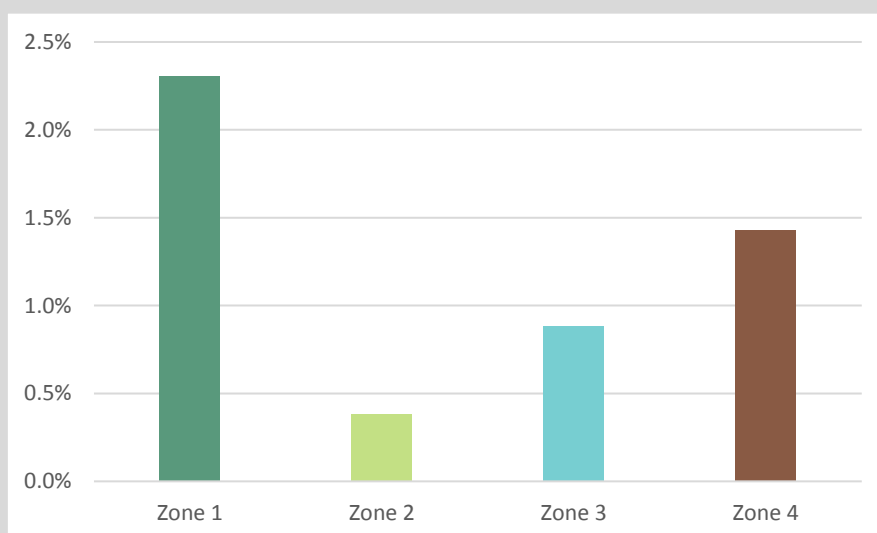
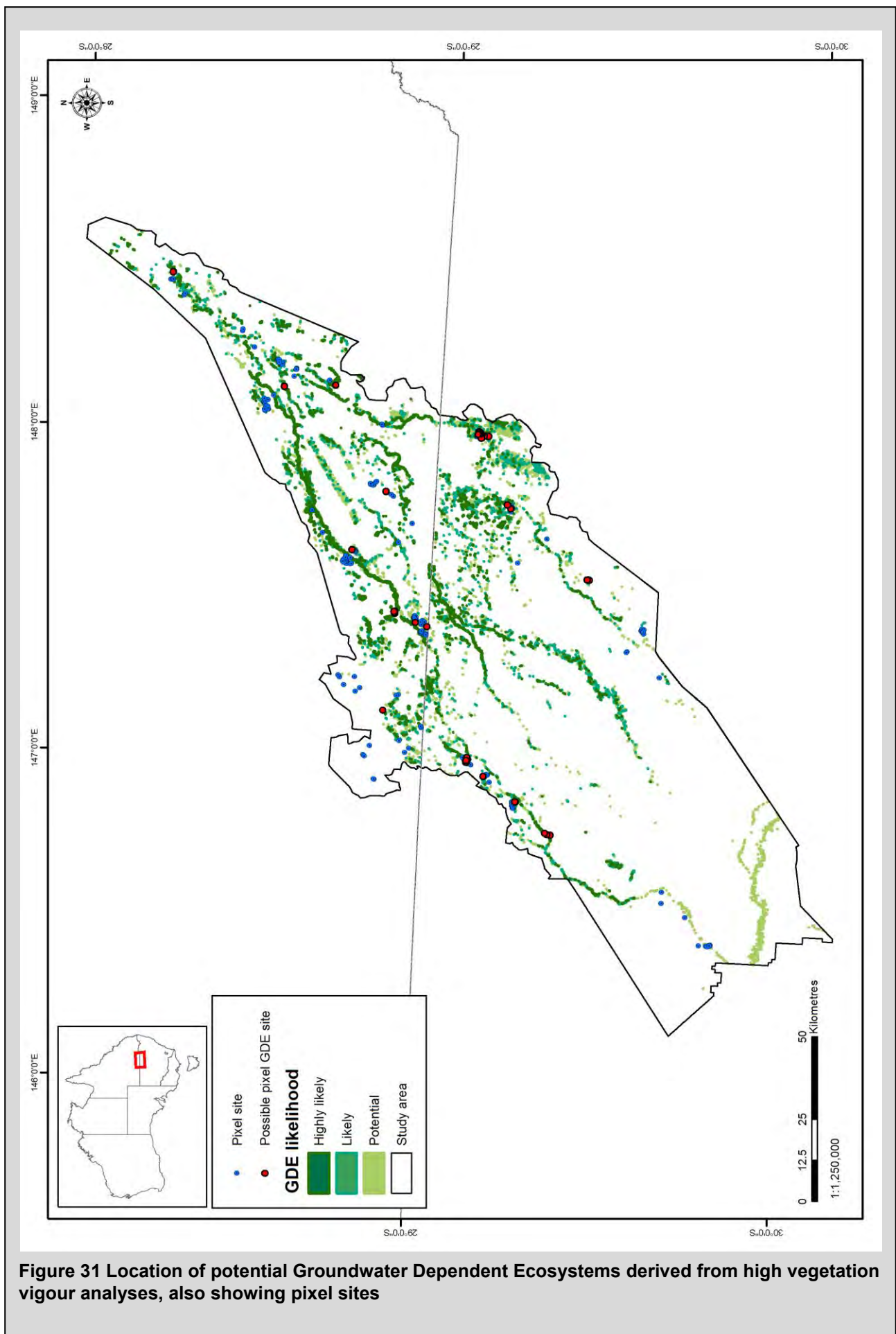


Figure 30 Percentage of model zone land area representing possible Groundwater Dependent Ecosystems (all categories)

Model Zone 1 had the highest percentage of possible GDE land area (Figure 30), which may represent the influence of in-channel water on nearby vegetation, as well as meander bend zones (chapter 5). Model zone 4 had the next highest percentage, and this may represent GDEs associated with sand ridges of that zone.



Zones 2 and 3 are characterised by clay soils and so may not be as conducive to GDEs. Zones 1 and 4 also had the highest percentage of highly likely GDEs (Table 5).

Table 5 Breakdown of percentage of different likelihoods for land areas identified as possible GDEs by Model Zone

Model Zone	Highly Likely	Likely	Potential
1	25.2%	30.4%	44.4%
2	8.3%	20.0%	71.7%
3	16.4%	32.0%	51.6%
4	28.6%	30.6%	40.8%
All 4 Zones	19.4%	27.9%	52.8%

Sites that had been identified in chapter 4 as possible GDEs were removed from the greenness/climate regressions, because of the noise they could add to the analyses. However, it is possible that a comparison of coolabah sites identified as potential GDEs, with those that were not, might highlight important differences in the nature of their greenness responses. The average R^2 for unexplained variance (thus not weather/climate related) was slightly higher for non-GDE (0.511) than possible GDE sites (0.489) but not statistically different ($P = 0.12$). If this difference is meaningful, it could result from non-GDE sites relying more on flood, and GDE sites relying more on rain to recharge their aquifers. However, the sample size is not large enough nor the theory well enough developed as yet.

This tool is too blunt to be used in isolation, however when used in combination with other sources of data on groundwater, it may prove effective. For example, as shown above with the model zone GDE percentage breakdown (Table 5) that actually make sense when compared to the real nature of those zones.

While the impetus of using remote sensed data is often to increase the scale being considered, this can go too far (see section 7.1.3). It is also possible to go the other way and look at smaller scales, which is particularly effective in combination with on-the-ground studies (chapter 5) that provide context, explanations and proper ground-truthing.

A good place to try this approach is at the pair of adjacent Euraba Road sites (chapter 5). One of these, Euraba Road SR (sand ridge), has a vibrant coolabah community, and for which there is a great deal of direct evidence of available groundwater (see chapter 5), making it very likely a GDE. Whereas the other nearby site, Euraba Road GV (grey vertisol), has a struggling coolabah community and no evidence of groundwater input.

A time-series of vegetation response (Landsat Seasonal Greenness; see chapter 4) and total rainfall for both Euraba Road sites were directly compared (Figure 32), as were greenness statistics for both sites (Table 6 and Table 7).

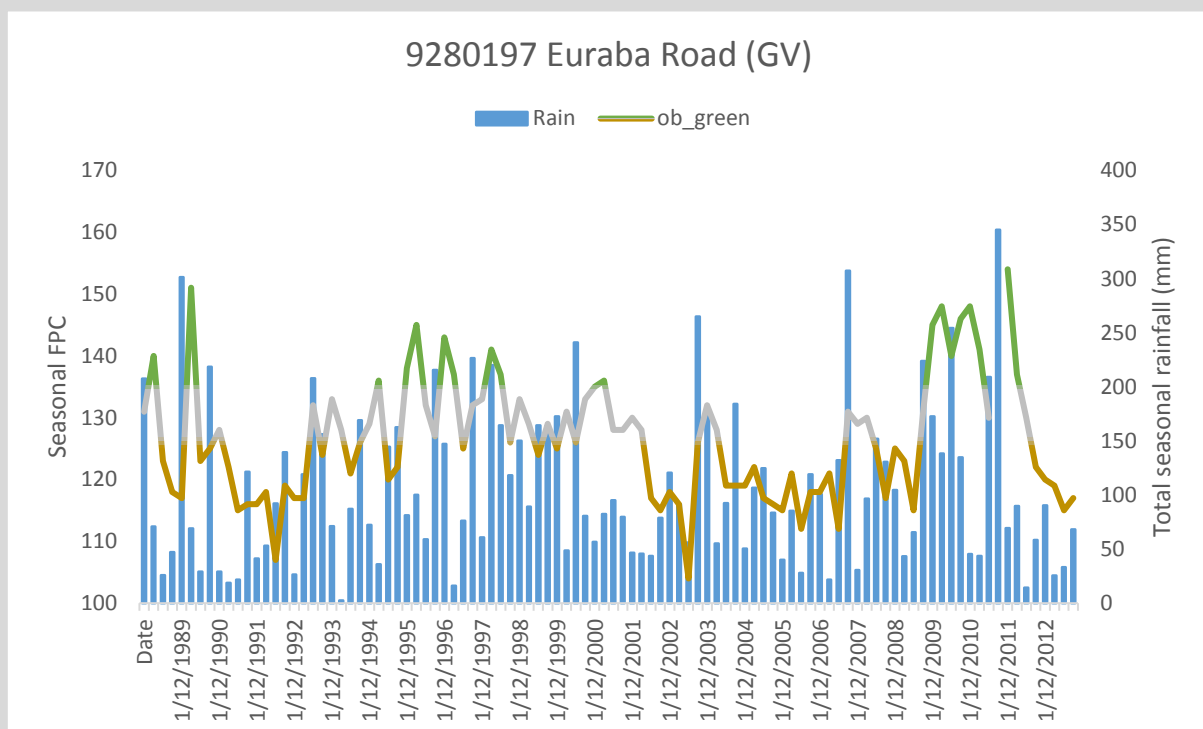
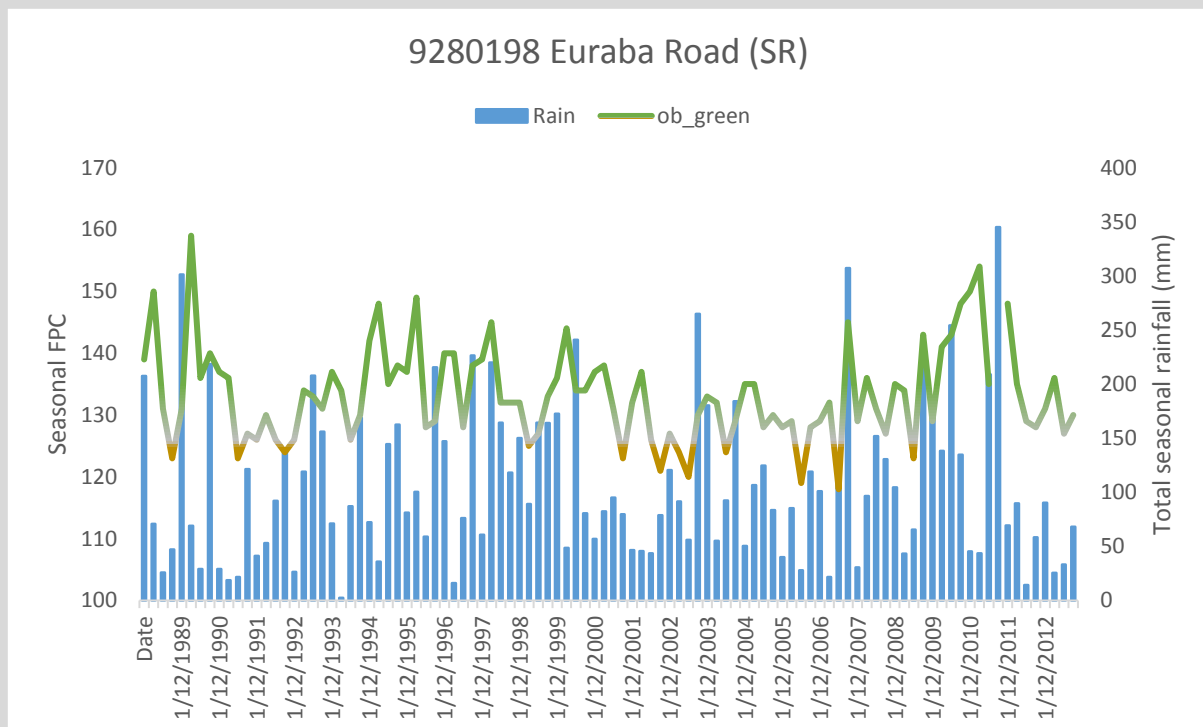


Figure 32 Time-series of vegetation response (Landsat Seasonal Greenness) and total rainfall for Euraba Road sites. Green and brown boundaries on the observed greenness line set using the averaged 25th and 75th percentiles of values from all coolabah pixel analysis sites (126 and 137 FPC respectively).

Table 6 Comparison of seasonal GFC statistics between the Euraba Road SR and GV sites and averaged figures for all coolabah pixels

Seasonal GFC	Euraba Road SR	Euraba Road GV	All coolabah pixels
Average	133.29	126.55	132.06
Max	159	154	161
Min	118	104	115
Range	41	50	45
25 th percentile	128	118	126
75 th percentile	137	132	137

Table 7 Comparison of percentage of seasons that vegetation condition signature is “brown” or “green” based on average 25th and 75th percentile figures for whole coolabah pixel data set

% seasons	Euraba Road SR	Euraba Road GV	All coolabah pixels
“green”	28 %	16 %	30 %
“brown”	17 %	53 %	31 %

The higher average greenness, higher maximum greenness, and perhaps most importantly, higher minimum greenness and lower range of variation at Euraba Rd SR (Table 6 **Error! eference source not found.**) over the 25 year period suggests that there is an alternative water source for Euraba Rd SR vegetation. Seasonal differences between the sites (Table 7), in particular the much lower percentage of seasons “brown” at the Euraba Rd SR site compared to Euraba Rd GV or the all coolabah pixel average is telling.

Because of the very close proximity of the two sites, the rainfall regime and flooding regimes are probably the same for both sites, hinting that groundwater is available to Euraba Rd SR vegetation. This is derived entirely from inferred remote sensed greenness data, but accords well with site-based direct observations at the sites (chapter 5), and thus suggests the combination can be very informative.

5 Identifying and quantifying vegetation water use

5.1 Introduction and research questions

The local assessment of groundwater use by vegetation in the LBF via field investigations was a core component of this project. A number of common ecohydrological variables were evaluated using direct and indirect field methods. The studies were primarily focussed on coolabah, as it is the most common tree species on the LBF. Black box was not studied due to its limited extent. The water use patterns of the species have been evaluated elsewhere in the Murray-Darling Basin (Jolly and Walker 1996; Akeroyd et al. 1998; Holland et al. 2006). Similarly, river red gum is very limited in its extent in the LBF, thus direct field investigations of it were restricted. It too has been extensively studied elsewhere. Lignum by contrast is widespread but only exists as a scattered shrub layer within coolabah communities thus an assumption was made that evaluation of coolabah communities would provide information relevant to lignum. It is acknowledged that the field investigations within this project do not encompass all of the vegetation communities or landscapes that exist within the LBF.

Based on initial findings of the project, a single research question was developed to address variation in water sources. At a smaller localised scale of study, groundwater was identified as a primary focus for consideration and thus has two targeted research questions.

The key research questions posed were;

- Do tree species express visible and quantifiable responses to different sources of available water?
- Do trees use groundwater?
- Does groundwater use vary between tree species?

The field methods used to answer these questions overlap significantly.

5.2 Methods

A multi-scale/multi-method approach was used to evaluate direct and indirect evidence of groundwater use by trees. At the site scale, direct methods included stable isotope analysis, DNA analysis and measurement of elements of the water balance (sapflow, water potential and climatic variables). At the site and landscape scale, an indirect assessment was made via community structural attributes. The use of structural attributes to infer water availability was predicated on the established understanding of the relationship between water supply and tree structure (Eamus et al. 2006; Klein et al. 2015; Specht et al. 1999) i.e the greater the water supply, the larger the size of the tree that can be supported – whether that be expressed as height, canopy area, leaf area or basal area. Which of the structural attributes correlated best with water availability was unknown, thus evaluation of all was required. Tree height in particular was evaluated as there were observable differences in tree height across the floodplain and tree height statistics for the whole study area could be derived from LiDAR data.

Water availability on floodplains is concentrated around flow paths, the most obvious of which are river channels. A conceptualisation of relative water availability on the LBF was therefore derived to support the selection of sites. Trees on riverbanks were considered to exist in an environment of relatively high water supply (either as quantity and/or reliability) whereas trees on the backplain were considered to exist in an area of lesser water supply – particularly in the case of the more elevated, relict backplain elements of the floodplain. Riparian zones were further conceptualised

on the basis of geomorphology and vegetation pattern, comprising two major forms (Figure 33) at either end of a spectrum. One form is represented by complex meander bends with high heterogeneity in soil type, microtopography related to distinct arcuate levee/channel elements. These possess a distinctive riparian vegetation forest up to ~500 m in width (Figure 33a). Given the frequent presence of sandy soils in these areas and the apparent connectivity of meander features to the stream, this form was conceptualised as having a high likelihood of shallow groundwater that would be accessible to trees. The riparian forests include trees >20m height and are floristically diverse. They relate to Land Unit 75 from Galloway et al. (1974).

The other main form was generically termed the “one tree wide” type (Figure 33b) as it is comprised of a very narrow riparian zone – typically <20 m wide. Occasional river red gum and western tea tree are present, but the form is dominated by scattered large coolabah and is floristically similar to the adjacent backplain woodlands – the most obvious difference being the greater size of coolabah on the bank compared to the backplain, which presumably reflects greater water availability at the river bank. The ‘one tree wide’ form is generally evident in lower energy streams incised into clay rich, often relict components of the floodplain. They are more common in the southern part of the LBF as the bifurcations of the main channels result in lower energy streams. Soils in the southern LBF are also more likely to be sodic clays, with very low hydraulic conductivity that limits infiltration and deep drainage. It was conceptualised that there was little bed/bank recharge in these areas and that shallow groundwater was absent. This form relates to Land Unit 76 from Galloway et al. (1974).

These conceptualisations represent end-members of a wide spectrum but both are commonly represented on the floodplain. Study sites were selected to represent both end-members as well as intergrades and investigations were undertaken to validate the models.



a)



b)

Figure 33 Examples of complex meander bend riparian zones with dense, floristically diverse forest (a) and narrow, 'one tree wide' riparian zones comprised of large coolabah (b)

5.2.1 Sites

A total of 37 sites were investigated across the LBF (Figure 9). A brief summary of the more detailed vegetation monitoring sites and riparian transects is provided below and further location data for all sites is given in Appendix 2 (Table 24). The greatest detail was collected from three sites (Euraba Rd SR, Euraba Rd GV, Nelyambo) established early in the project. These 'detailed sites' encompassed isotopic, sapflow, tree structure, geophysical and soil investigations in coolabah communities. The sites were selected on the basis of accessibility, presence of existing groundwater bores, visible differences in vegetation structure/health and their representativeness of different land units/systems. The two Euraba Rd sites constitute a pair in terms of contrasting landscape position (and inferred flooding frequency), tree size/vigour and soil

type. Close to the Euraba Rd detailed sites, 5 ancillary sites were used for tree structural measurements. These additional sites were selected on the basis of landform/soil/vegetation in an attempt to represent similar pairs to the detailed sites (site details are provided in Table 8).

Five riparian transect sites were established between St George and the New South Wales border to investigate the presence/absence of shallow groundwater adjacent to rivers and the potential for riparian vegetation to access shallow groundwater. Transects were selected to evaluate the two main forms (Figure 33) as well as intermediate examples. The transects utilised a rectangular plot 10 m wide, rather than the circular plot utilised at other sites, as the intent was to examine the changes in vegetation structure with distance away from the stream – on the basis of the aforementioned conceptualisation that trees on the river bank experience ‘maximum’ water supply and those further away experience a lesser water supply. Tree structure measurements in rectangular transects were undertaken in the same manner as in circular plots. Transect length varied from 320 - 635 m depending on landscape complexity/geomorphology. A 100m riverbank transect was also undertaken at each site. Detailed geophysical and soil investigations were undertaken in these transects. At the Balonne-Minor transect, a line of shallow groundwater bores was established for detailed monitoring and geochemical investigations (see below). Two shallow bores were also established close to the river at Whyenbah (site details are provided in Table 9).

Eighteen further sites were selected in coolabah across the floodplain on the basis of remote sensing criteria, for limited measurement of structural attributes using the SLATS circular plot field protocol (and repeat surveys were also conducted at the two Euraba Rd sites). Measurements at these sites include an estimate of mean height, basal area and canopy intercept. Twenty-six sites were assessed using the rapid vegetation condition assessment method including some of the SLATS sites (Table 24 - Appendix 1). At the floodplain scale, tree height was derived from LiDAR data provided by Geosciences Australia.

The Nelyambo site

The Nelyambo site was located approximately 13 km south of Dirranbandi in an ungrazed road reserve mapped as land system 33 and RE 11.33/11.3.28 (Figure 34). The area was quite complex from a soils/surface drainage perspective and local landholders report an increased frequency and duration of flooding over the last few decades. Overstory vegetation was dominated by coolabah with isolated belah (*Casuarina cristata*). The understorey was dominated by dogwood (*Eremophila bignoniiflora*) with a shrub layer of scattered small lignum. Ground cover was high and comprised primarily of Warrego summer grass (*Paspalidium jubiflorum*). Soil type was a gilgaied grey Vertosol (vertical interval ~ 0.2 m, horizontal interval 5-10 m) with varying surface condition (pedal to crusty).

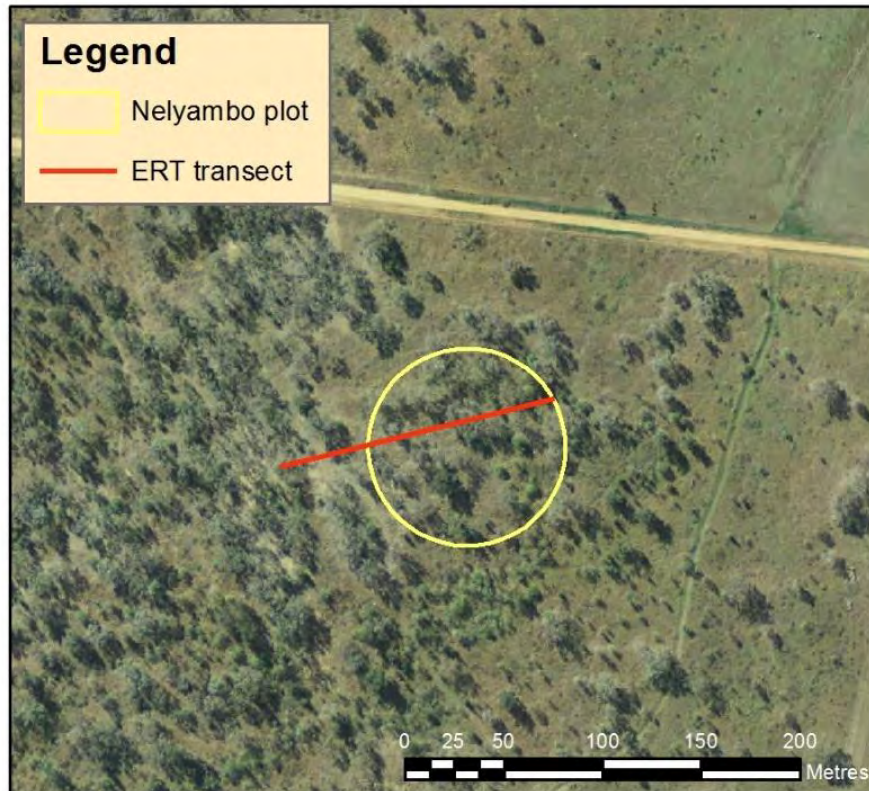


Figure 34 Nelyambo detailed plot and related features

The Euraba Road sites

The pair of sites at Euraba Road lie approximately two-thirds of the way between Dirranbandi and Hebel on the New South Wales border (Figure 35). The western site (Euraba GV) was in a woodland of coolabah on a self-mulching to crusting grey Vertosol in a lower element of the floodplain (Land system 33). The coolabah was pre-dominantly small single stem trees (< 20 cm DBH) with isolated large trees possessing a distinct growth form – a central old dead core (with axe marks from ringbarking) surrounded by multiple large stems originating in the lower 1 m of the tree. 1951 aerial photography indicated that the site was previously a grassland/sparse woodland but the isolated large trees could be identified. Much of the LBF was cleared by ringbarking prior to 1950. Mid storey at the site was comprised of large dogwood (up to 9 m in height) and the lower storey consisted of occasional juvenile river cooba (*Acacia stenophylla*) and scattered lignum. Ground cover was very low – essentially completely absent – and remained so for the duration of the study. At establishment, many trees showed signs of mortality and poor vigour. Recruitment (seedlings <0.3 m height) was evident at the SR site but not the GV site.

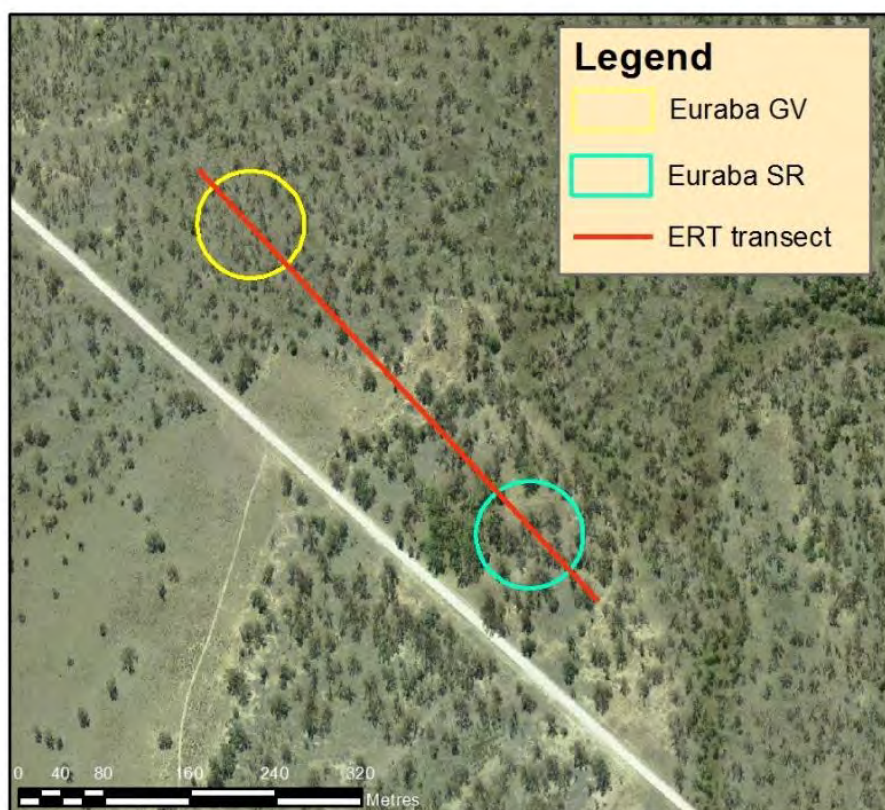


Figure 35 Euraba Rd detailed plots and related features

To the east of the GV plot was a low sand ridge vegetated with large coolabah in which a paired site was established – known as the SR plot (Figure 35). Stem density at SR was lower than in the GV plot and trees were larger and showed no signs of mortality or poor vigour. Other tree species present included clumps of Moreton Bay ash (*Corymbia tessellaris*), primarily outside of the plot and isolated vine tree (*Ventilago viminalis*) and boonaree (*Alectryon oleifolius*). Ground cover was sparse and included species such as galvanised burr (*Sclerolaena birchii*) and scattered *Aristida* spp. Soil type varied across the plot from Tenosols to black Sodosols. To the west, north and east of the sand ridge, the landscape dropped into drainage depressions of grey Vertosol.

Table 8 Summary features of the three detailed study sites (in blue) and nearby ancillary plots

Site	Vegetation community	RE	Landform	Soil type	Land system
Euraba GV	Coolabah/dogwood/ lignum woodland	11.3.25/11.3.15	Backplain drainage depression	Grey Vertosol	33
Euraba SR	Coolabah/Moreton Bay ash	11.3.19	Low sand ridge	Tenosol/ Sodosol	28 (atypical)
Euraba 1	Coolabah	11.3.19/11.3.3	Drainage depression between two sand ridges	Grey Vertosol over sand	31
Euraba V1	Coolabah	11.3.19/11.3.3	sand ridge	Grey Vertosol over sand	28 (atypical)
Euraba V2	Coolabah	11.3.19/11.3.3	Backplain	Grey Vertosol	33
Euraba V3	Coolabah	11.3.25/11.3.15	skinny low sand ridge	Brown Vertosol over sand	28 (atypical)
Euraba V4	Coolabah	11.3.25/11.3.15	channelized backplain	Grey Vertosol	33
Euraba wet-up	Grassland	11.3.21	Relict backplain	Grey Vertosol	30
Nelyambo	Coolabah/belah/dogwood/ lignum	11.3.3/11.3.28	Backplain	Gilgaied grey Vertosol	31

Table 9 Summary features of the riparian transect study sites

Site	Vegetation community	RE	Landform	Soil type	Land system
Whyenbah	RRG, coolabah fringing forest grading to coolabah woodland and cypress pine/ironbark	11.3.25/11.3.2 11.3.19/11.3.2	Young and old alluvia grading to sand ridge	Sodosol/ Vertosol	28, 33
Balonne Minor	RRG, coolabah forest grading to grassland	11.3.25/11.3.2 8/11.3.27b	Young alluvia	Grey Vertosol	33, 31
Toobee Creek	Coolabah fringing forest grading to coolabah woodland, chenopod shrubland, grading to /Moreton Bay ash woodland	11.3.28/11.3.1 7	Young and old alluvia grading to sand ridge	Tenosol/ Sodosol/ Vertosol	33, 31, 28
Ballandool River	Coolabah, RRG fringing forest grading to collibah woodland, chenopod shrubland, grading to Moreton Bay ash and <i>Acacia</i> spp. woodland	11.3.15/11.3.1 9/11.3.17/11.3. .16; 11.3.19	Young and old alluvia grading to sand ridge	Gilgaied grey Vertosol	33, 30, 28
Briarie Creek	Coolabah fringing forest grading to coolabah/ dogwood woodland, chenopod shrubland. Scattered gidgee.	11.3.37/11.3.3	Young alluvia grading to old alluvia	Grey Vertosol	33, 30

Whyenbah riparian transect

The Whyenbah transect at ~600m (Figure 36), was the longest of the 5 transects. Located on the western side of the Balonne River, about one third of the way between St George and Dirranbandi, it traversed gentle meander bends associated with a large, incised river in the upper, higher energy part of the floodplain. Very tall river red gum (>30 m) were present on the river bank with an adjacent riparian forest of coolabah, sally wattle (*Acacia salicina*) and occasional river red gum. The forest graded to coolabah woodland to open woodland on a landform of repeating relict levees and semi-active drainage depressions. The latter were vegetated by sedges and grasses. The distal end of the transect transitioned into a relict sand ridge of cypress pine (*Callitris glaucophylla*) and silver leaf ironbark (*Eucalyptus melanophloia*). Soils were heavy textured Vertosols in the drainage depressions and lighter textured Vertosols on the levees, with the exception of the distal end of the transect, which was comprised of Sodosols and Tenosols.

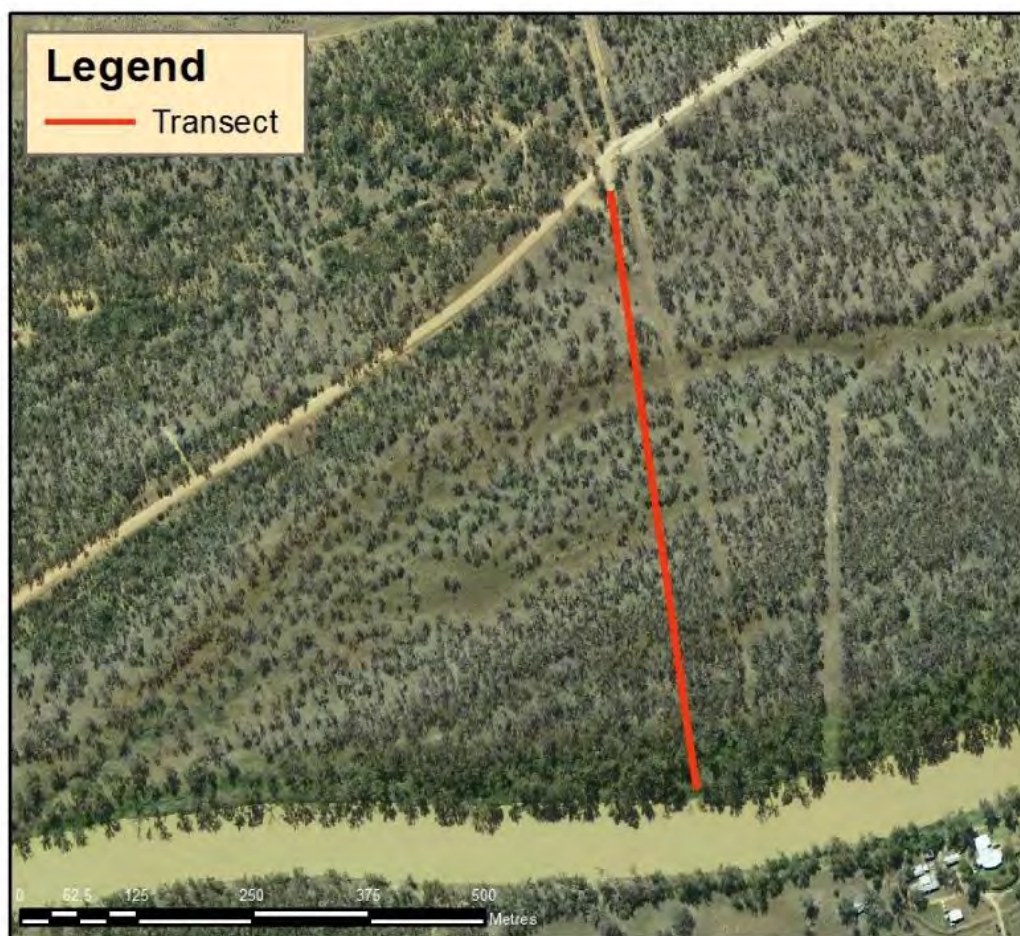


Figure 36 Whyenbah riparian transect

Toobee Creek transect

Toobee Creek is a small creek to the west of Dirranbandi, between the Culgoa and Balonne Rivers. While it is only a narrow, shallow creek it possesses complex fluvial features cut into a backplain of coolabah on a grey Vertosol (Figure 37). The transect traversed levee and oxbow drainage depression features, vegetated with coolabah and dogwood, before rising up about 1 m onto the backplain and ending on the margin of a sand ridge vegetated with Moreton Bay ash. The

riparian vegetation zone was very narrow and comprised primarily of scattered large coolabah on the river bank. It was unknown whether the chenopod shrubland was a feature of historical clearing at the site.

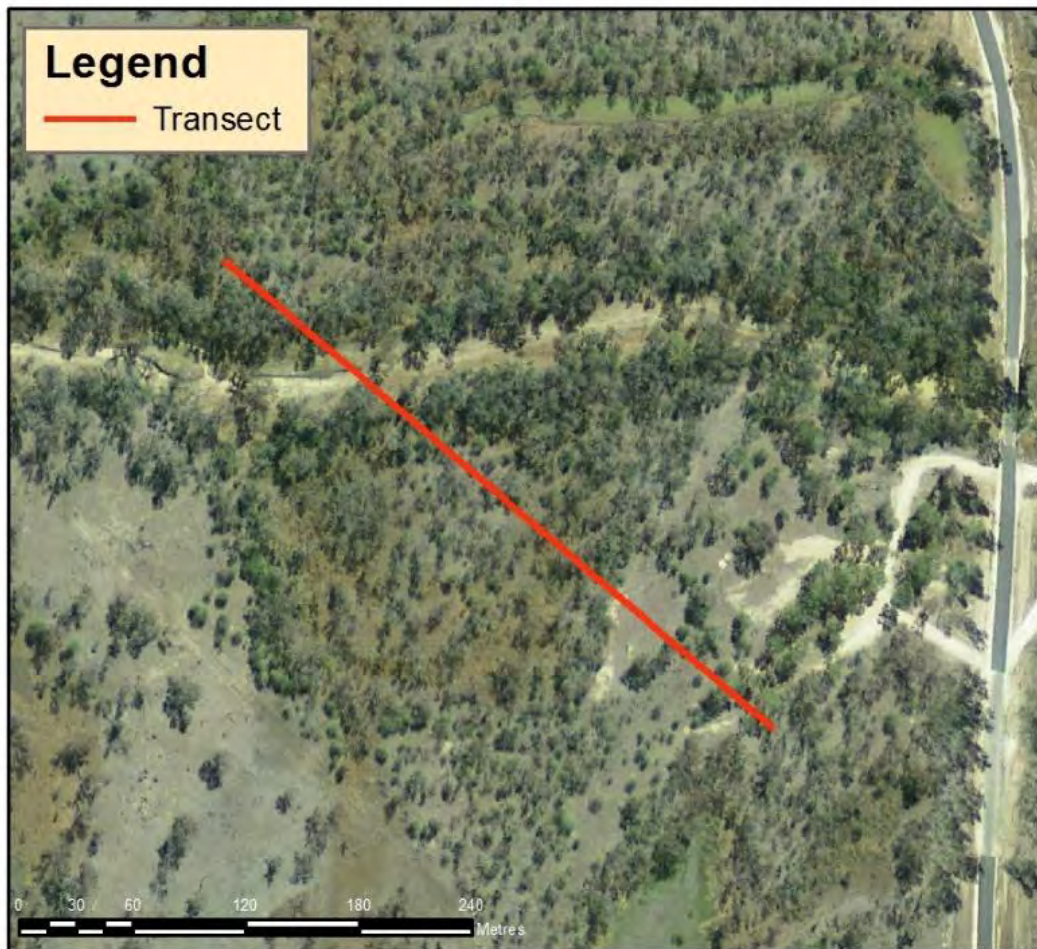


Figure 37 Toobee Creek riparian transect

The Balonne-Minor River transect

This transect was in a well-defined meander bend on the Balonne-Minor River just upstream of the bifurcation to the Narran River. The transect represents a typical meander bend form and was dominated by black Vertosols. The transect spanned obvious arcuate levee/drainage depression features that were vegetated with a riparian forest of coolabah, white wood (*Atalaya hemiglauca*), native sandalwood (*Santalum lanceolatum*), sally wattle and occasional river red gum closer to the river. Understorey was dense dogwood, prickly wattle (*Vachellia farnesiana*¹), river cooba and minor wilga (*Geijera parviflora*). A transitional coolabah woodland was evident towards the western edge of the obvious fluvial features, beyond which was a grassland. The degree of anthropogenic influence on the grassland presence is unclear. The earliest aerial photographs (1950) suggest that the grassland was present then and was a widespread feature on both sides of the river. Interestingly the vegetation on many of the meander bends, including the one studied, were considerably sparser in 1950 than now.

¹ Formerly *Acacia farnesiana*

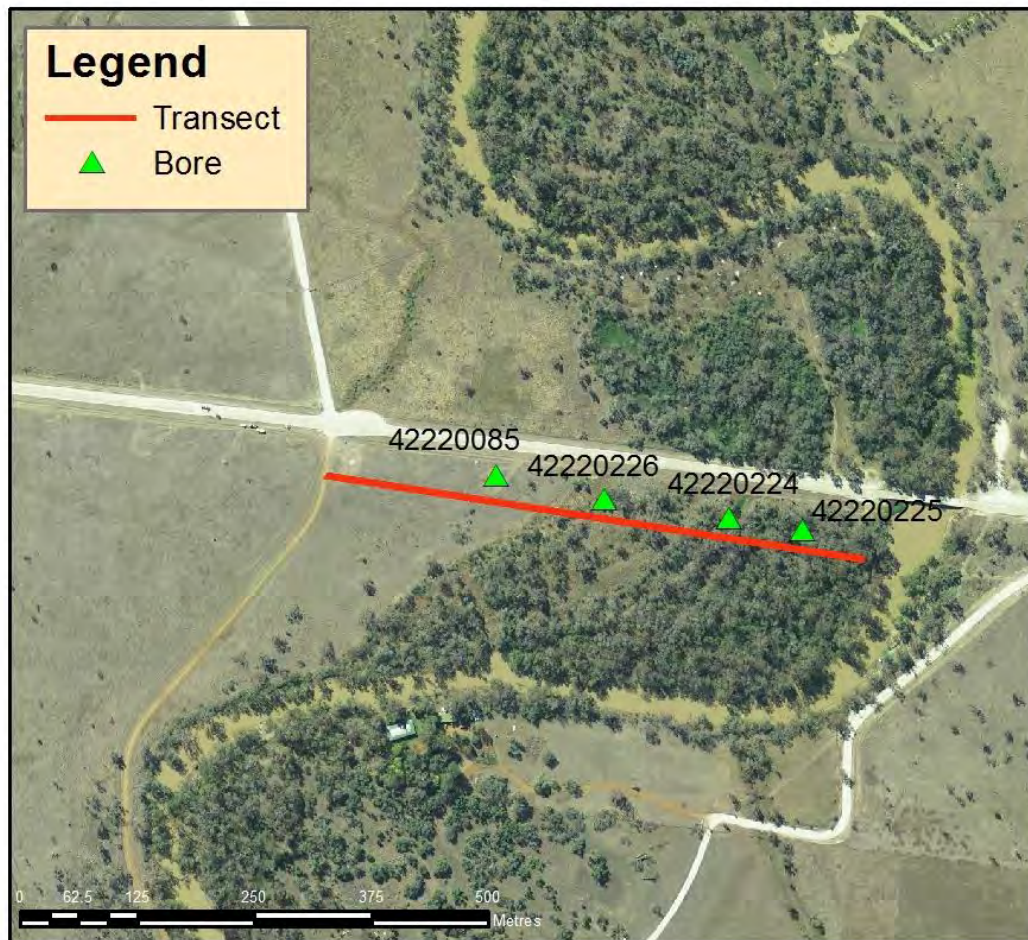


Figure 38 Balonne-Minor River riparian transect

Ballandool River transect

The transect on the Ballandool River spanned a relatively low energy river cut into a complex landscape of relict backplains and sand ridges (Figure 39). Oxbows and cutoffs are evident but there is little modern depositional material either side of the channel. Western tea tree (*Melaleuca trichostachya*), large coolabah and occasional large river red gum were present on the river bank, with an understory of whitewood and dogwood. The riparian zone was very narrow, giving way to chenopod shrubland and open woodland of coolabah and dogwood on grey Vertosols. The western end of the transect slopes up through a sheetwash eroded area with dense coolabah before grading into *Acacia* spp. and Moreton Bay ash on a sand ridge.

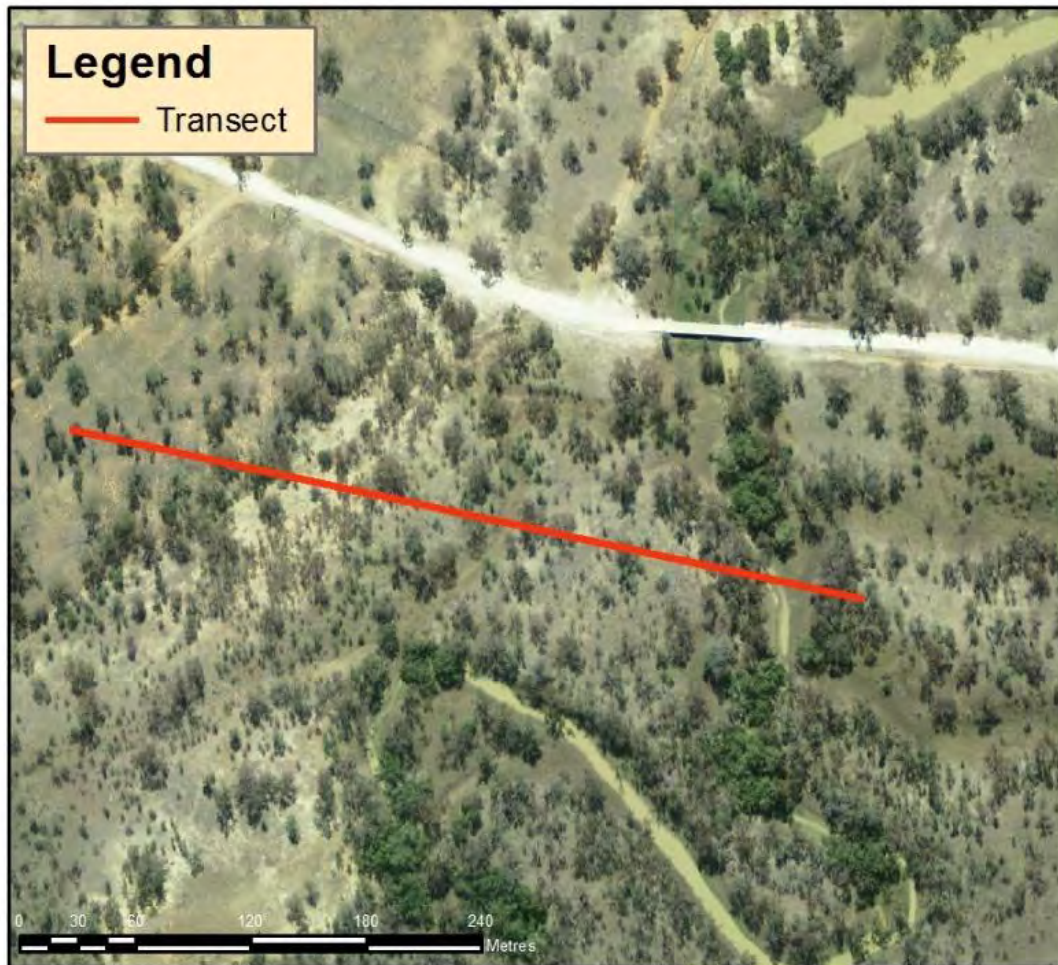


Figure 39 Ballandool River riparian transect

The Briarie Creek River transect

The Briarie Creek transect represents a smaller, lower energy version of the Ballandool transect (Figure 40) and was selected to represent a 'one tree wide' form of riparian zone. The channel is cut into a relict backplain of sodic grey Vertosols. Minor local re-working and deposition of the backplain was sporadically evident but there were few significant meanders. Large coolabah were scattered on the river bank, giving way to an open coolabah/dogwood woodland and chenopod shrubland – the latter dominant in a large shallow drainage depression mid-way along the transect. The western end of the transect sloped up to the higher surface of the relict backplain. Scattered gidgee (*Acacia cambagei*) was present in the immediate surrounds of the transect.

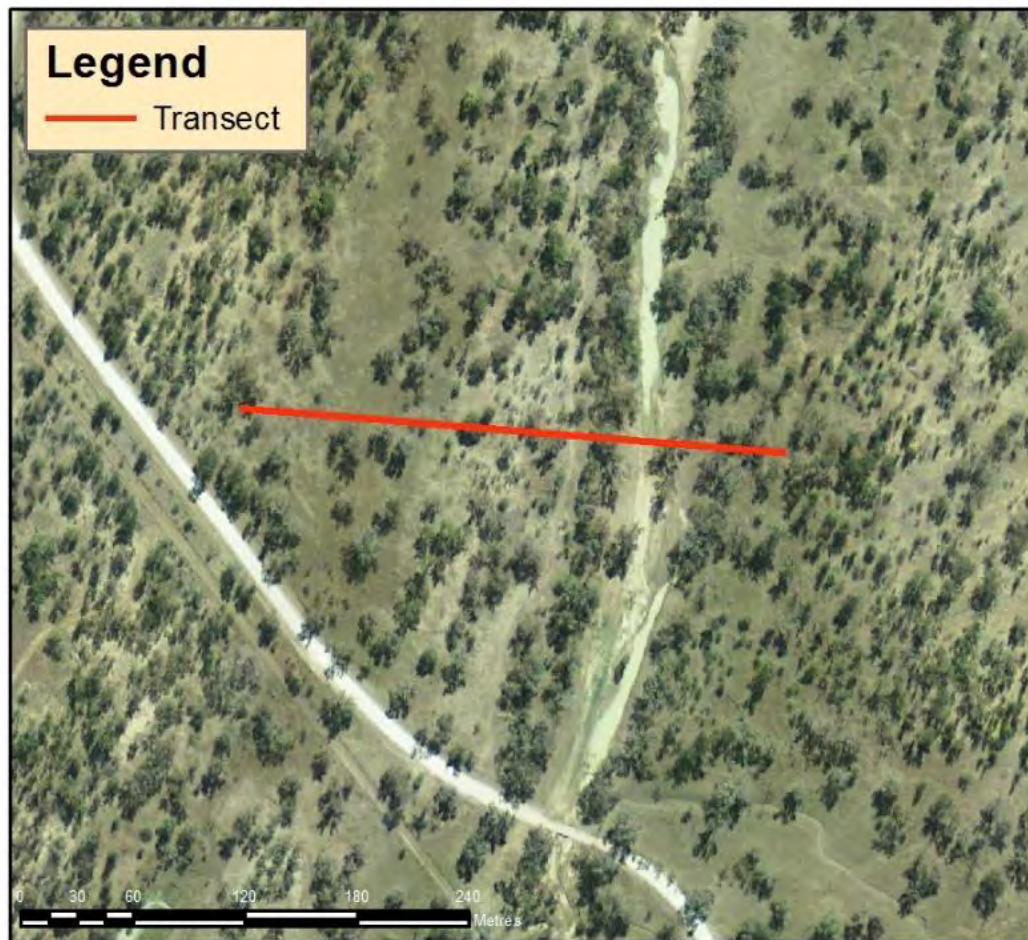


Figure 40 Briarie Creek riparian transect

5.2.2 Field Methods

Climatic variables

Weather stations were established in an open area at the Nelyambo and Euraba Rd SR plots for the duration of the project (Dec 2014 to Jun 2017). Variables measured included precipitation, solar radiation, temperature, humidity and wind speed/direction. Details of instruments are provided in Appendix 2. Thirty three bulk rainfall samples for chemical analysis were collected via a Winchester bottle connected to the outlet of the pluviometer. Sample bottles were changed on a monthly basis.

Stable isotopes

Comparison of stable isotopes values in vegetation with differing possible water sources is a methodology that has been applied to species such as black box and river red gum within the lower MDB (Akeroyd et al. 1998; Doody et al. 2009; Jolly et al. 1994; Mensforth et al. 1994). The method relies upon isotopic differences between the water sources and use of mixing models to establish the potential contribution of each source to the vegetation signature. Sampling and analysis of stable isotopes of hydrogen and oxygen (^2H , ^{18}O) in soil, vegetation and groundwater occurred at four sites (the three detailed plots and the Balonne-Minor transect). The work utilised

established methods for sampling and analysis of vegetation (Thorburn et al. 1993a,b) and an improved azeotropic analytical method for soils to account for the presence of gypsum – a common feature in soils of the Lower Balonne. Sampling at Nelyambo encompassed both mound and depression elements of the gilgai. Further details of sampling and analytical methods are provided in Appendix 2. Limited sampling was initially undertaken at the three detailed sites in summer 2014/2015 to establish field protocols and provide initial data on variability in water signatures. This was followed by a more detailed sampling in autumn 2015. The Balonne-Minor transect was sampled once in winter 2017, at the same time as detailed geochemical sampling of groundwater. The local meteoric water line (LMWL) of Liu et al. (2010) is used as a reference throughout this report and all data is presented in standard delta (δ) notation. Delta notation provides information on the ratio of heavy (^2H and ^{18}O) to standard isotopes (^1H and ^{16}O) relative to a standard. Larger positive delta values indicate samples are 'enriched' in heavy isotopes relative to the standard. Enrichment may arise due to higher evaporation rates of water molecules composed of lighter isotopes, for example. Enrichment and depletion processes result in a different isotopic composition in water from different sources (soil, vegetation, rainfall, surface water and groundwater).

DNA analysis

During the geochemical sampling of the new shallow bores drilled in the Balonne Minor transect, roots were retrieved at a depth of 7-8 m. The roots were obtained from above and within the water column – a bore camera was used to confirm the location of roots in the bores. Representative samples (leaves) of surrounding vegetation were also collected. DNA matching of root and leaf samples was undertaken by the University of Queensland (A. Toon) to determine the species present in the bores.

Sapflow and tree water potential

Determination of sapflow enables quantitative comparison of water use between sites as well as analysis of temporal influences e.g floods on tree water use. It is a widely used method in ecohydrology and forestry (e.g Ford et al 2004; Steppe et al. 2010; Vertessy et al. 1995). Measures of sapflow velocity were converted to a flow rate (mm/hour) and a daily flux (L/day) via knowledge of the conducting area (sapwood area) of the tree. Tree water use is determined primarily by the climatic conditions (atmospheric water demand), the leaf area of a tree and attributes such as stomatal conductance. Normalisation of data against leaf area (e.g flux/m² leaf area/day) allows comparison between trees. Individual tree data can be used to scale up to an estimate of water use per hectare of the vegetation type, but this requires assumptions and/or data regarding allometric relationships for the species concerned, e.g relationship between sapwood area and basal area; relationship between water use and canopy area or basal area.

Sapflow monitoring of coolabah was undertaken at the three detailed sites (Nelyambo and Euraba Road GV, SR). Sensors were ICT International SFM models which utilise the heat ratio method (Burgess et al. 2001). A single sensor was installed in the southern side of the trunk at approximately 1.3 m above ground. Trees were selected to encompass a range of tree sizes at each site. Axial variability was investigated in a limited number of trees using four sensors installed at cardinal points around the trunk of the selected trees. Sites were established in Nov-Dec 2014 and closed in March 2016. A total of 36 trees across all sites were monitored. Tree water potential was measured in a limited number of trees at each site using an ICT stem

psychrometer installed according to manufacturer's instructions in a branch < 5cm diameter and <5 m above ground. Bark and sapwood thickness of all instrumented trees was determined using a drill and plunge gauge. The same measurements were made on all other coolabah within the plots. Sapwood samples for density and water content were obtained using a 25-35 mm diameter hole-saw at various times during the measurement period – primarily at the end of the measurement period – the sample holes were located just below the sensors and served a secondary purpose of creating a zero flow condition. Tree health scores (1-10) were recorded at all sites to provide a relative measure of condition over the duration of the measurement period. Further detail of methods is provided in Appendix 2.

Soil water

Soil water content and water potential was determined during the period of measurement of tree water potential at the three detailed plots and the Balonne Minor transect. At the Nelyambo site, gilgai necessitated two sets of samples (mound and depression). Samples were obtained via 45-50 mm hydraulically driven soil coring to a depth of at least 1.5 m. Samples were typically in 10cm increments and wrapped in clingfilm and stored in airtight containers. Gravimetric water content and bulk density was determined on one component of the sample, while water potential was determined on a subsample using a laboratory psychrometer or tensiometer depending on water content (Campbell et al. 2007; Foley 2017). More detail of soil sampling methods are provided in Appendix 2.

Soil and regolith architecture investigations

At both the detailed plots and the riparian transects, geophysical investigations were coupled with shallow and deep soil coring to characterise the regolith and evaluate the presence and potential for recharge of shallow groundwater. Geophysical investigations were primarily via electrical resistivity tomography (ERT) although electromagnetic induction (EMI) was also used in the detailed plots. Further detail of geophysical and related methods is provided in Appendix 2. Soil coring was to a maximum depth of ~16 m and utilised push tube or percussion hammer core tubes depending on depth. Rotary augering was undertaken at some sites to a maximum depth of 19m. Cores were described according to the standards set out in NCST (2009) and all soil core data is stored in the Queensland Government soil database. Selected cores at each plot/transect were analysed for standard soil chemical and physical parameters (pH, electrical conductivity, chloride, exchangeable cations, particle size). All analyses of soil samples and all isotopic analyses of soil, water and vegetation samples was undertaken at the Ecosciences Precinct Laboratory (DSITI) in Brisbane. Further detail on sampling and analytical methods is provided in Appendix 2.

Given the use of the land systems of Galloway et al. (1974) as part of the conceptualisation of GDEs for the Lower Balonne, revision of the land systems mapping was also undertaken as part of this project. The original mapping was 1:500 000 scale and the digital data contained some known geographic registration issues. One hundred and ninety polygons were originally mapped in the LBF. Utilising LiDAR DEM, radiometric data and satellite imagery, desktop revision generated 1123 polygons. To fully validate and finalise this linework will require further work beyond the scope of this project but the draft revised linework was utilised in the remote sensing component of this project. More detailed soil maps of each riparian transect and detailed plot were also developed.

Surface and groundwater investigations

Sampling of surface water and groundwater for ionic chemistry and stable isotopes occurred opportunistically throughout the project – particularly focussed towards sampling flow events. 22 surface water samples encompassing event and non-event periods were collected in streams of varying sizes, from small flood runners to major rivers across the floodplain but primarily close to the detailed site locations (Figure 41). Twelve groundwater samples were obtained from 10 bores. Six new shallow groundwater bores were constructed – three in the Balonne-Minor transect, two at Whyenbah and one at Euraba Rd. Depth to water in these and a number of other bores were monitored daily with water level loggers. A detailed geochemical investigation (H. Hofmann, University of Queensland) was undertaken in the riparian zone bore network established on the Balonne-Minor at Dirranbandi (results still pending).

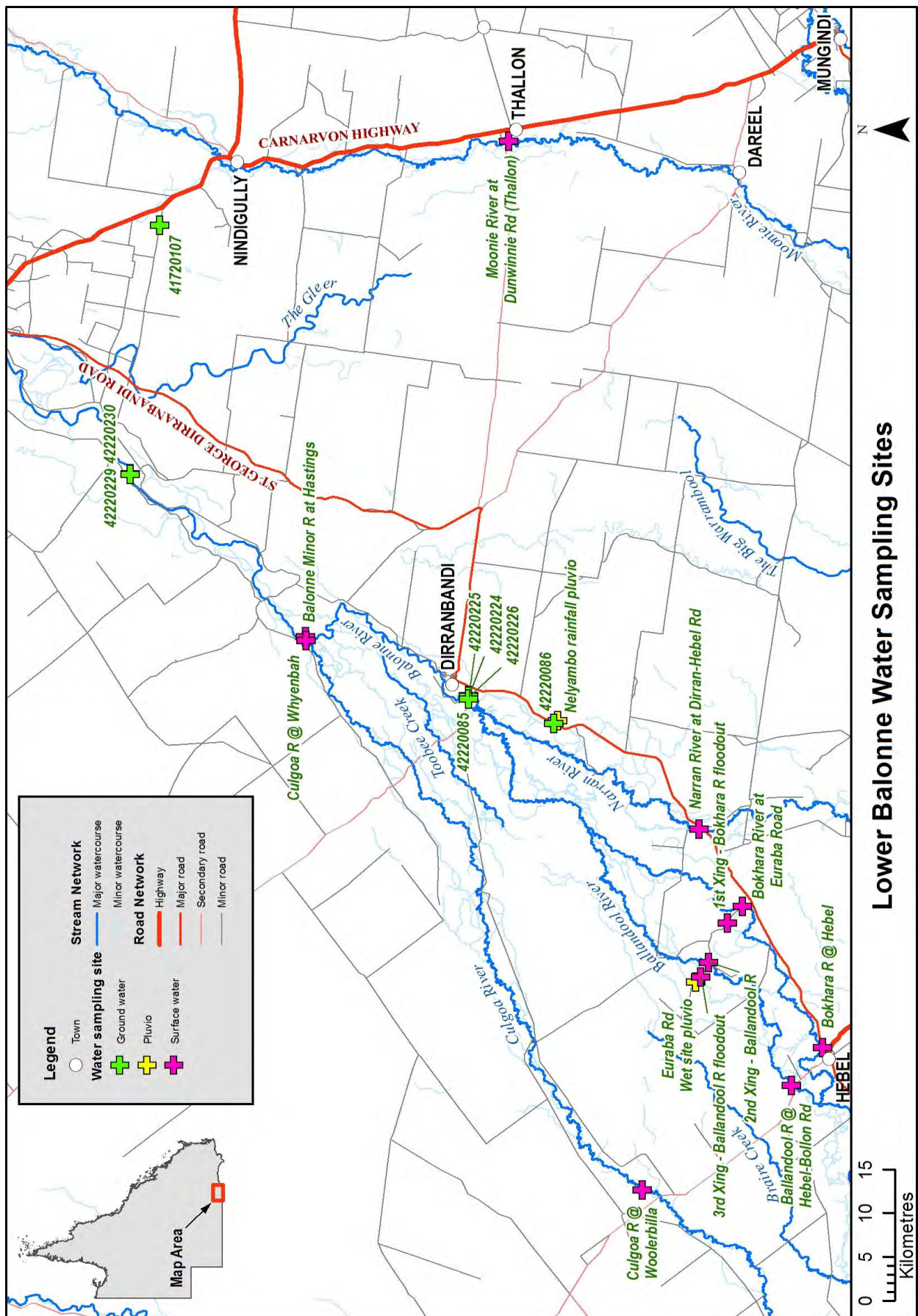


Figure 41 Location of surface and groundwater sampling sites

Tree structural attributes and related data

The approach to measuring tree structural characteristics at all circular plot sites (the detailed, ancillary and SLATS sites) generally conformed with the AUSCOVER SLATS methodology (www.auscover.org.au/xwiki/bin/view/Field+Sites/Data+Collection+Resources) thus providing extra value to the sites as calibration points for the SLATS remote sensing program. The method assesses ground cover and tree canopy intercepts at 1m intervals along a series of radiating transects within circular plots. The method was varied slightly for the rectangular riparian transects, in which intercepts were assessed along three parallel lines spaced 5 m apart. The centre line was used for geophysical investigations. The location of every tree >2 m height was recorded within the transect using a local co-ordinate system. A riverbank rectangular plot was also created perpendicular to the transect start point on the riverbank. The riverbank plot was 100 m long by 10 m wide.

At all plots, trees in which the crown overhung the plot but the trunk was outside the plot were also included in intercept measurements. All trees >2 m height within the plots were measured for girth at breast height (GBH), height (height meter and tape) and canopy area (major and minor axes by densitometer and tape). In the riparian sites, quadrats for surface cover and floristics were also recorded along the centre line (data not reported in this project).

During the site selection process, the centre of circular plots was adjusted to ensure that soil/land type uniformity was achieved whereas riparian transects deliberately spanned a range of soil/vegetation types. Length of riparian transects varied – the intent being to span the riparian zone and into the backplain. Summary details of the detailed, ancillary and riparian sites are provided in Table 8 and Table 9.

At closure of each detailed site (Nelyambo, Euraba Rd GV & SR), a selection of the monitored trees were sampled for biomass measurement (trees were not killed). Trunks and branches were weighed in the field using a hanging digital scale while leaves were bagged and kept cool for laboratory measurement of leaf area via planimeter (LiCOR 3100C). For small trees, the area of the whole leaf component was measured but for larger trees, a subsample of leaves (13-50%) was measured and the area/weight ratio utilised to calculate the total leaf area. Leaf area index (m^2/m^2) was determined for the harvested trees. Three samples of trunk from these trees (two at Nelyambo, one at Euraba SR) were aged via dendrochronology (H. Haines, Griffith University – data not reported here). Branch samples along the length of some harvested trees were also taken to evaluate isotopic variation within trees. Further details of sampling methods are provided in Appendix 2.

5.3 Results

The following section provides relevant results from the varying methods and sites – not all results from within the project are discussed. It has been organised in terms of the lines of evidence/methods. Greater detail of results will be provided in subsequent journal articles.

Roots and DNA

Roots have been anecdotally observed in shallow bores in the region previously and DNA analysis of samples from a bore in the Border Rivers catchment (Biggs unpub) has confirmed the presence of myall (*Acacia pendula*) in saline groundwater at ~12 m depth (Biggs et al. unpub).

Roots were manually retrieved from the three bores in the Balonne-Minor riparian zone during a dry winter (2017). The location of the roots in the bores was visually confirmed with a downhole bore camera – roots were found to be present both above the water table (Figure 42) and in the water column, suggesting there was sufficient oxygen for root growth in at least the upper part of the aquifer. This is not surprising as the aquifer is shallow and there is about 6 m of dry sand before the saturated zone is encountered. DNA matching of the roots² revealed that not all tree species recorded above-ground at each bore were evident in the respective bores (Table 10), although coolabah was found throughout. The representativeness of the samples has no doubt been influenced by the exact location of bores with respect to trees and to a lesser degree the method of retrieval of roots from the bores. For example, river red gum was only present east of 4220225 – the nearest tree was about 30 m east of that bore. The lack of confirmation of river red gum roots in that or any other bore was more likely a result of the limited distribution of the species in the transect and its proximity to any bore rather than a lack of roots of that species at the aquifer fringe.



Figure 42 Roots (marked with arrows) visible above the water table in RN42220224 at Dirranbandi

² Analysis conducted by Alicia Toon, University of Qld

Table 10 Species presence in aquifers determined by DNA analysis of roots retrieved from the water column

Bore	Species present in bore
42220225 (closest to river)	<i>E. coolabah</i> , <i>A. salicina</i>
42220224 (drainage depression)	<i>E. coolabah</i>
42220226 (edge of backplain)	<i>E. coolabah</i> , <i>A. salicina</i>

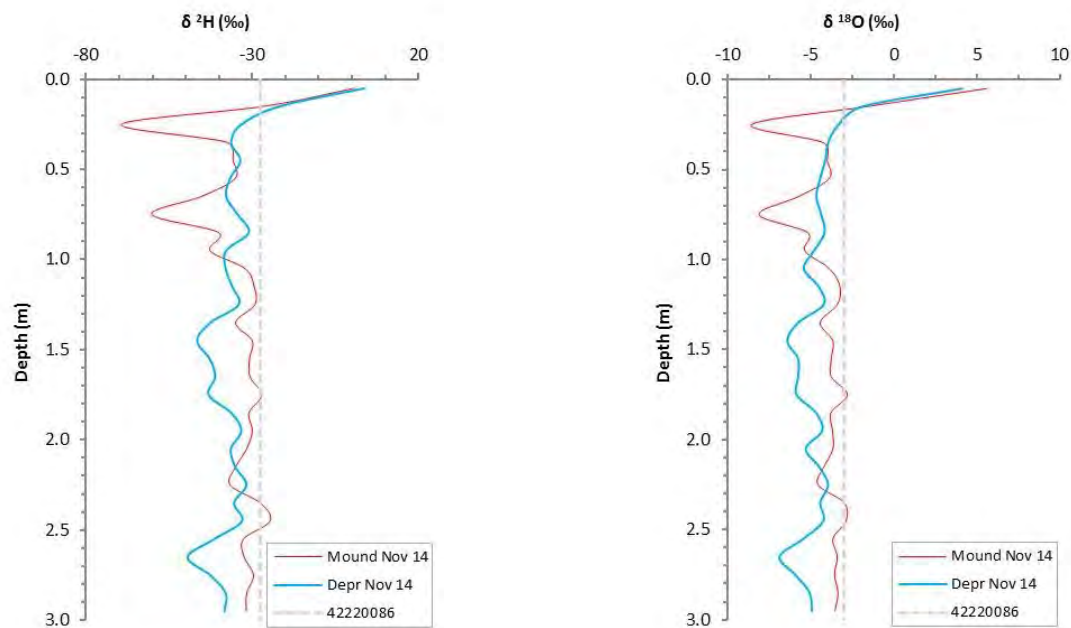
The presence of roots of any species at the aquifer interface does not automatically imply substantive or obligate groundwater use. Further investigations such as sapflow and stable isotope measurements (see below) would be required at this site to confirm the degree of exploitation of groundwater by the tree species. This is however the first time that DNA analysis has been used to confirm the species present at the watertable for a GDE in semi-arid Queensland and more detailed sampling and analysis will be undertaken to further verify species with roots at the aquifer.

Stable isotopes ($\delta^{18}\text{O}$, $\delta^2\text{H}$)

Sampling of stable isotopes of trees and soil at detailed sites occurred initially in November 2014 during dry conditions, with a subsequent more extensive sampling in February 2015, after a period of summer rainfall. Limited sampling of vegetation isotopes was also undertaken in July 2015 during biomass harvesting.

Nelyambo

Soil water isotope profiles from Nelyambo in November 2014 display an obvious zone of surface enrichment i.e less negative delta values at the top of the profile (Figure 43). The upwards trending profile is consistent with experimental trends observed by Barnes *et al.* (1988). Overall the depression profile was slightly depleted relative to the mound, which fits with a conceptual model of depressions having higher infiltration by virtue of their microtopography. Distinct peaks of depleted water (more similar to fresh rainfall) were present at 0.35 m, 0.6 m, 1.45 m and 2.7 m depth. These most likely correspond to specific recharge events. $\delta^2\text{H}$ varied in a similar manner to $\delta^{18}\text{O}$ although the ratio of $\delta^{18}\text{O}$ to $\delta^2\text{H}$ was lower in the upper parts of profiles (shallower than about 0.2 m in the mound and 0.4 m in the depression). Below these depths, ratios fluctuated down the profile and the mean of the ratio in the depression was slightly higher than the mound (0.13 *cf* 0.12). Groundwater from the nearby bore (RN42220086) was sampled at the same time as the soil and yielded values of: $\delta^{18}\text{O}$ -3, $\delta^2\text{H}$ -27.6. The aquifer intercepted by the bore was at approximately 20 m depth and salinity was ~32 000 $\mu\text{S}/\text{cm}$, thus it was not surprising that the groundwater isotopic signature was very close to the deeper soil water signature – the dominant recharge process in the LBF is diffuse, with evaporative concentration, resulting in saline water and an enriched isotopic signature (Herczeg 2004).



a) $\delta^2\text{H}$

b) $\delta^{18}\text{O}$

Figure 43 Soil water isotope ($\delta^{18}\text{O}$) variation with depth (10cm intervals), November 2014 at Nelyambo

Vegetation sampled in November comprised seven trees (5 coolabah, 2 belah) of varying sizes. Two of these (one coolabah and one belah) were outside the plot, but directly adjacent to the bore. Given the dry antecedent conditions (approximately 268 mm in the previous 12 months and below-average rainfall for 2013-14), it was expected that there was a high likelihood of trees accessing groundwater (if possible) at the time of sampling. Tree isotopic values obtained plot very closely to the soil water line, but spanned a spectrum (Figure 44). On the basis of the soil values, it appeared that the two belah and two of the coolabah (trees C1 & C57) were accessing enriched soil water (typical of the upper soil profile), whereas the two other coolabah trees sampled within the plot and a coolabah tree adjacent to the bore were accessing subsoil water and/or groundwater. There was no relationship evident between tree height and $\delta^{18}\text{O}$ or $\delta^2\text{H}$.

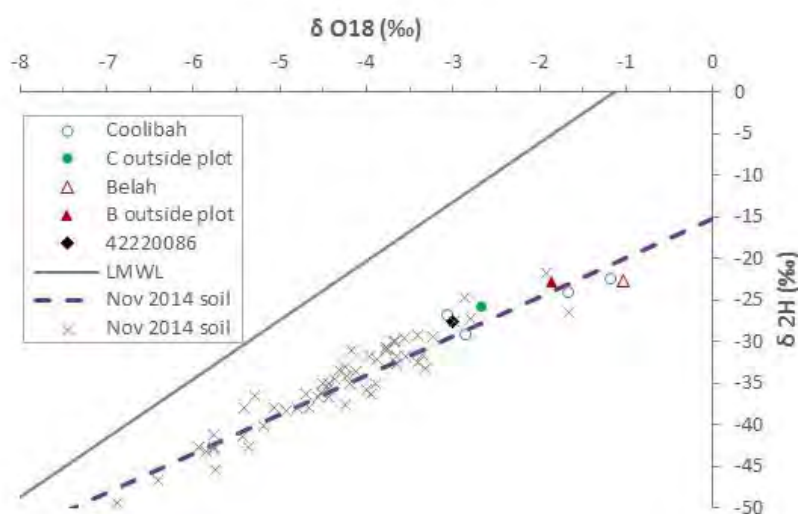
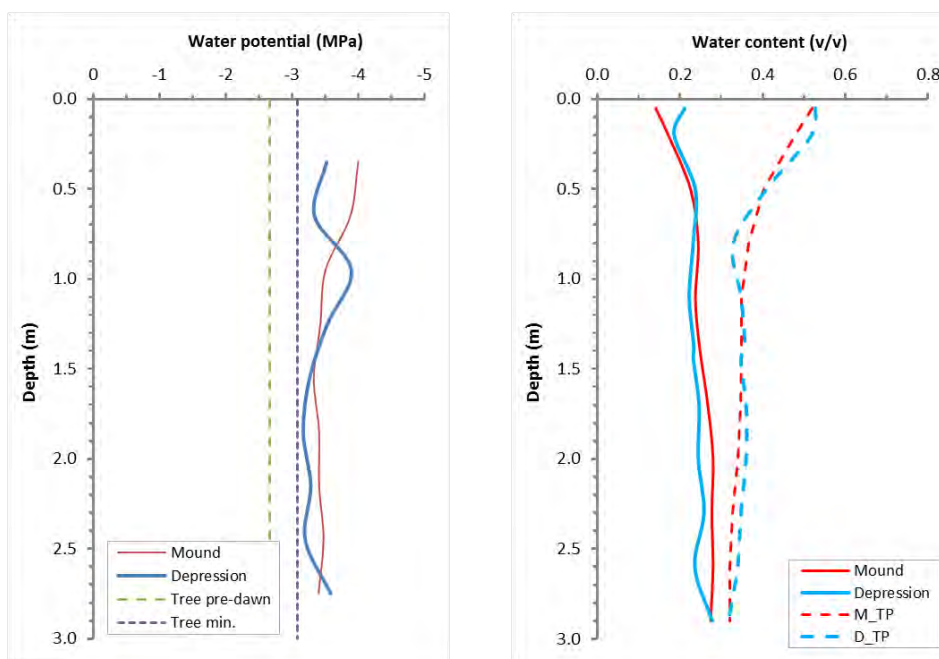


Figure 44 Vegetation, soil and groundwater stable isotopes, November 2014

Pre-dawn tree water potential data from the same sampling (Figure 45a) suggests that nowhere in the upper 1.5 m of the soil profile was the soil water potential less negative than the tree water potential i.e there was no moisture gradient from the soil to the tree. However, the difference between pre-dawn tree water potential and soil water potential was only in the order of 0.6-0.7 MPa for the majority of the soil profile. Minimum tree water potential, recorded about mid-afternoon, was only 0.1-0.3 MPa greater than soil water potential. Considering the error margins of both measurements, it is possible that trees may still be utilising subsoil water, particularly from 1.5-3.0 m depth in the depression profile.

As noted above, the majority of the soil isotopic data, particularly that from the subsoil, was more depleted than the tree isotopic values. However, while the isotopic data suggests that trees were utilising enriched upper profile water, the water potential data suggests this was unlikely to be the case at the time of sampling (Figure 45). The most probable explanation for this was local variation in soil water content. Only one soil core was utilised at this site (in the site centre), on the basis of detailed knowledge of low variability of soil water and stable isotopes in similar soils in the Border Rivers alluvia to the east of the LBF (Biggs in prep). Most trees sampled were within 20 m of the core but variations in surface water flow patterns were evident within the plot.

If it is assumed that all soil water was available to trees, a two source $\delta^{18}\text{O}$ mixing model using representative end-members for surface soil and subsoil suggests that all belah and all coolabah, with the exception of C57, could have been utilising >90% upper profile soil water. Interestingly, C57 was the largest of all coolabah in the plot. If $\delta^2\text{H}$ was utilised for the mixing model, trees were estimated to be accessing 30-40% surface soil water. The reasons for the difference in outcome with isotope used are not clear but differences in mixing model water source determination when using $\delta^{18}\text{O}$ vs $\delta^2\text{H}$ is a known issue and $\delta^2\text{H}$ often suggests a greater proportion of groundwater (Evaristo et al. 2017). The above calculations do not however resolve the issue of whether the trees were utilising groundwater, due to the similarity of the soil water and groundwater values.



a) Soil water potential

b) Volumetric water content

Figure 45 Soil profile water content and water potential at Nelyambo, November 2014

(D_TP = depression total porosity; M_TP = mound total porosity)

A subsequent sampling of a larger number of trees (3 belah, 11 coolabah) and shrubs (1 dogwood, 2 lignum) in April 2015 revealed a negative shift in the vegetation isotopic values (Figure 46). Most November tree $\delta^{18}\text{O}$ values were above the groundwater value (-3), but in April, many tree values were below the groundwater value. This shift was most likely the result of vegetation accessing replenished soil water in the upper 1.5 m. April vegetation values plot between the soil water values and the preceding rainfall values (Figure 47). In the soil profile, there was an observable reduction in enrichment in the upper 0.3 m in both mound and depression from November to April.

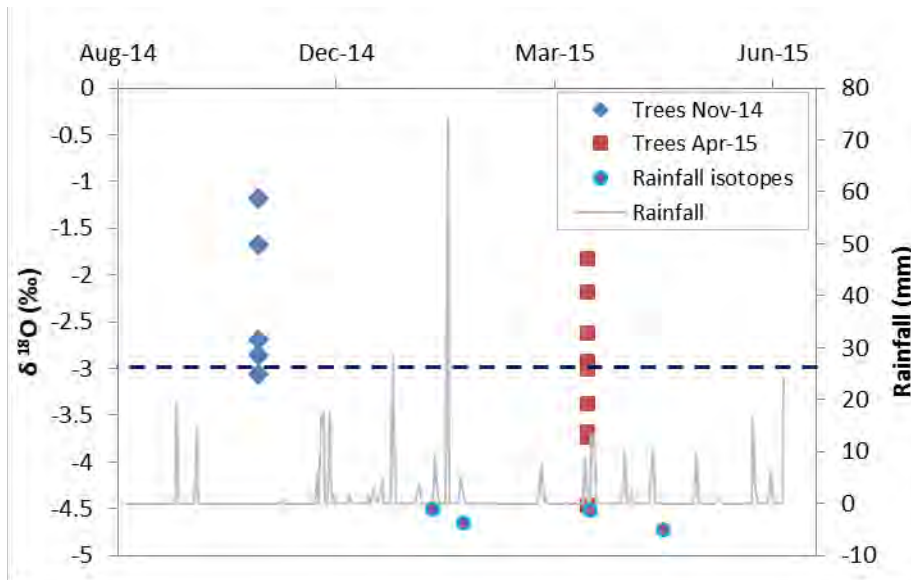


Figure 46 $\delta^{18}\text{O}$ over time in trees and rainfall at Nelyambo

(Dashed line is groundwater value)

In the April sampling, a number of shrubs were also sampled on the premise that these would be highly unlikely to be accessing groundwater, thus their isotopic values could be regarded as representative of an entirely soil water derived source. The dogwood and lignum did plot at the most enriched end of the vegetation spectrum (Figure 47), suggesting they were accessing near-surface soil water. Water potential data was not available for the same time as the isotope sampling, but data from two months previously (Figure 48) indicated that the upper portion of the depression soil profile was approaching potentials close to tree values. 23 mm of rain fell in scattered small events <8 mm in size between the February soil sampling and the April tree sampling. About half the rain fell in a four day period in mid-March. Such small falls are unlikely to have penetrated far into the soil profile but it is apparent that the vegetation was accessing this recent rainfall.

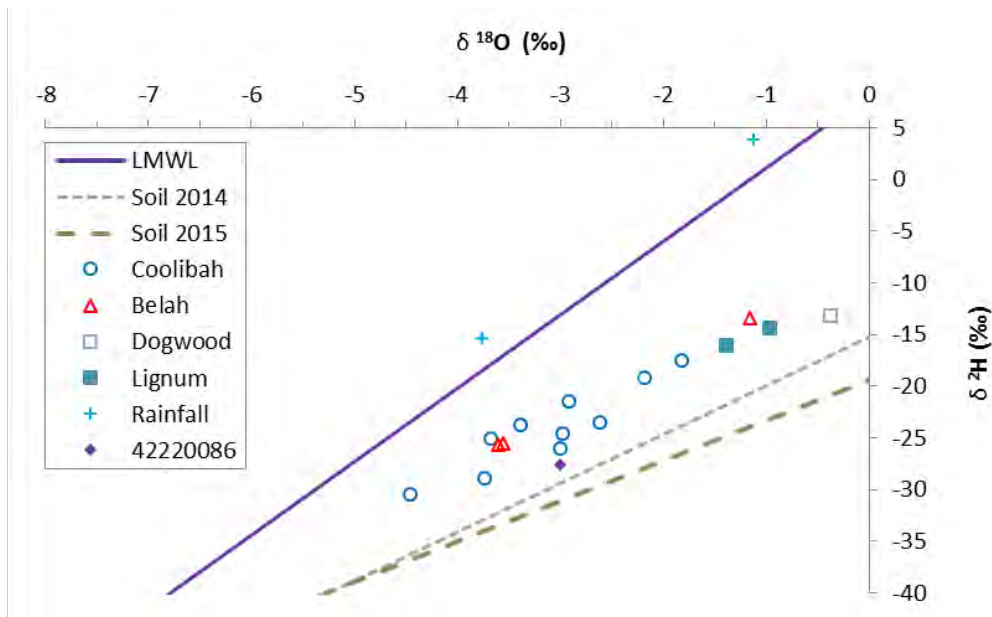
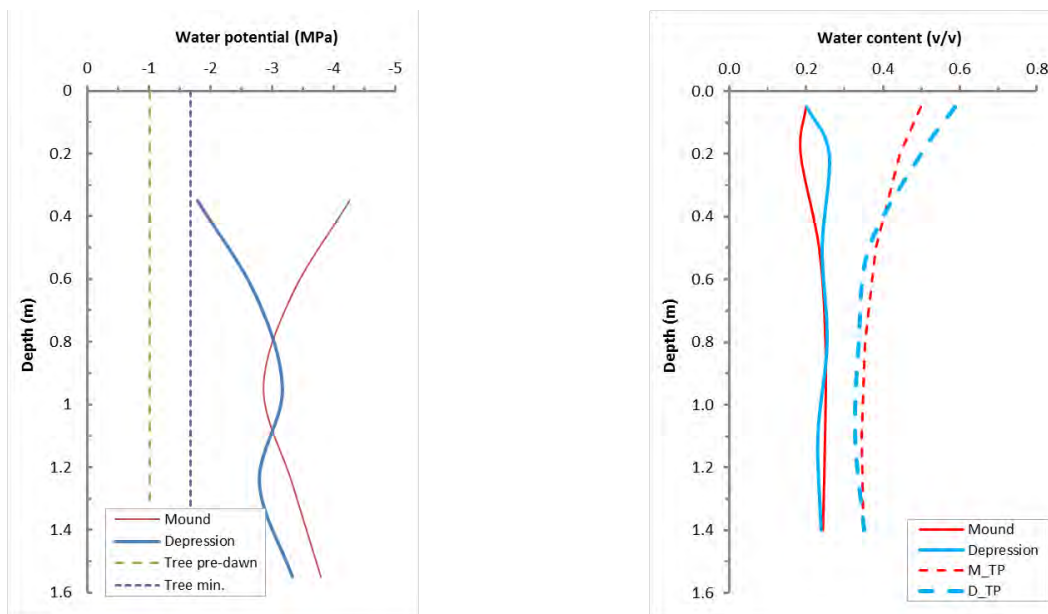


Figure 47 Vegetation stable isotope values, April 2015 at Nelyambo



a) Soil water potential

b) Volumetric water content

Figure 48 Soil profile water content and water potential at Nelyambo, February 2015

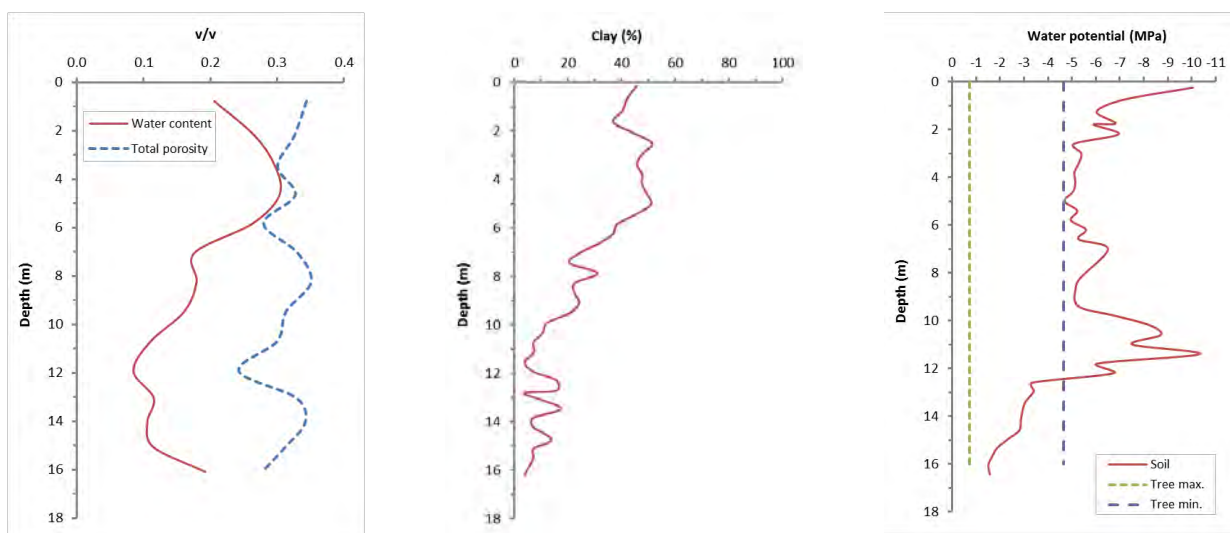
(D_TP = depression total porosity; M_TP = mound total porosity)

Data from a deeper soil core (Figure 49), and geophysical investigations (Figure 50) indicated that from 3-6 m depth the soil profile was clay rich and close to saturation. Below this was a sand-rich zone of much lower water content. The contrast in water content and water potential between 0-3 m and 3-6 m depth may be explained a number of ways. The 0-3 m zone may represent the depth of dynamic water content in relation to infiltration and subsequent water use by all vegetation. The deeper zone may represent a more stable water content that is beyond the water extraction depth of shrubs, grasses and other small plants and perhaps may not be utilised significantly by trees. Alternatively, the pattern could be explained by recharge events during the above average rainfall

years in 2010-11 refilling a water extraction zone that extended to depth – particularly given the drought decade from 2000-2010. The validity of either explanation could be determined via more detailed water balance calculations. The episodic nature of recharge in these landscapes is well known (Silburn et al. 2011), as is the inherently low hydraulic conductivity of sodic Vertosols, thus it is probable that the 3-6 m zone is not necessarily the result of only two years of recharge. Tree water use investigations in the Border Rivers alluvia (Biggs unpub) has shown that the water requirements of a brigalow/belah forest could be met by a soil depth of only 3 m. Such forests also occur in areas of soil as shallow as 1-2 m. This suggests that a deeper soil profile does not automatically confer a greater water supply to trees and that root architecture may be the limiting factor to water supply.

A third possible influence of the wetter zone from 3-6 m is hydraulic redistribution from areas of higher soil water potential to areas of lower soil water potential via tree roots. It is a documented process (Bleby et al. 2010) but it is unknown whether this was a factor at this site. Given the very negative water potential measured in the upper 1.5 m of the soil profile, upwards gradient flow via root pathways from the near-saturated zone at 3-6 m, or from closer to the aquifer was theoretically possible, particularly given roots were identified deep in the profile (9 m depth). Isotopic detection of this was however unlikely given the similarity of the soil and groundwater values.

Water potential data (Figure 49) indicated that the majority of the deep core profile was drier than the minimum recorded pre-dawn water potential, but close to the most negative water potential recorded during the experimental period. Below a depth of ~13 m, the soil water potential increased to values that were within the range that was observed in trees at the site, and more generally in the Lower Balonne, which may suggest that the trees were accessing water at this depth. The water potential data, coupled with the bore drilling data, confirmed interpretation of the geophysics, suggesting that the capillary fringe of the aquifer was likely to be ~17-18 m depth. Collectively the data suggests that the isotopic values recorded in some trees could have been the result of groundwater use but are most likely to be the result of soil water use. The lack of stable isotope data for below 3 m depth limits confirmation, but first principles (and the underlying groundwater isotopic values) suggest the values would be similar to those from 1.5 -3 m. Thus the mixing model determination of groundwater use may be valid.



a) Volumetric water content b) Clay content c) Soil water potential
Figure 49 Soil water content and water potential from a deep core at Nelyambo, Oct 2015

(Tree max. and tree min. represent least negative and most negative water potential measured during the period)

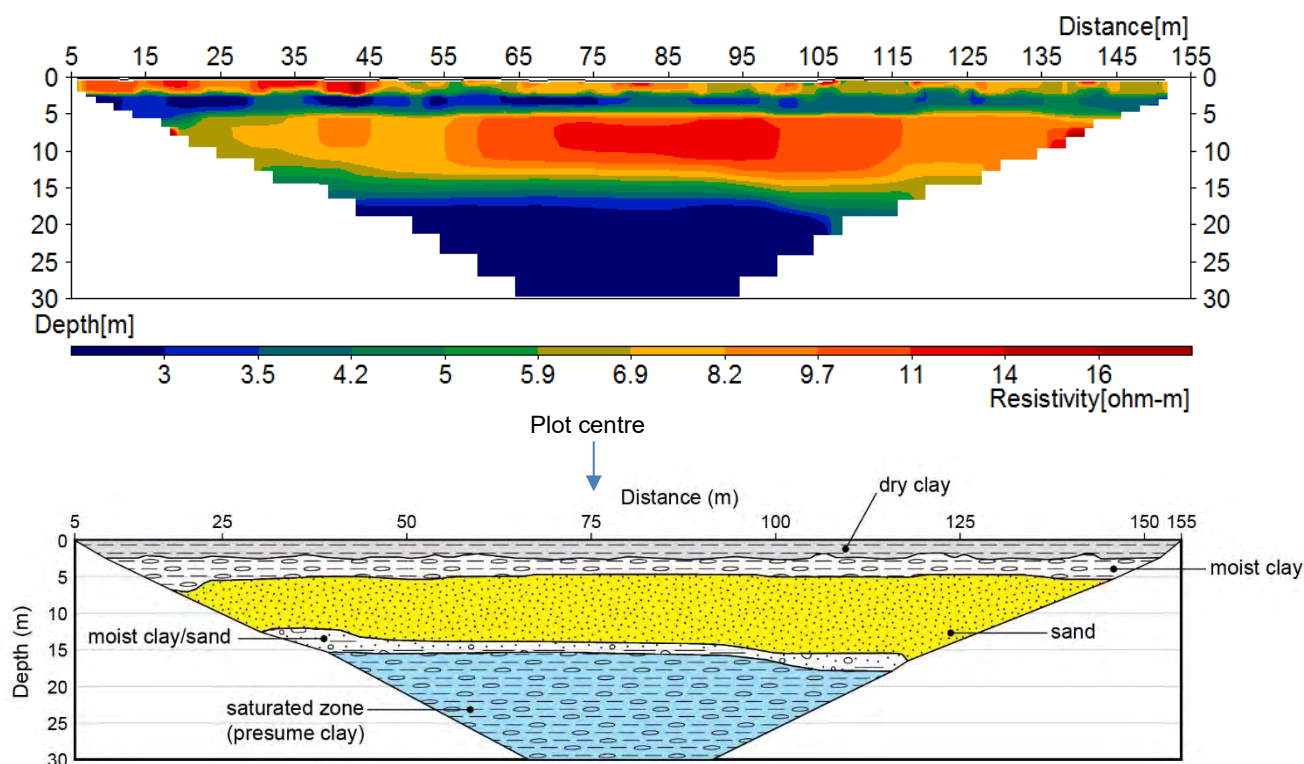
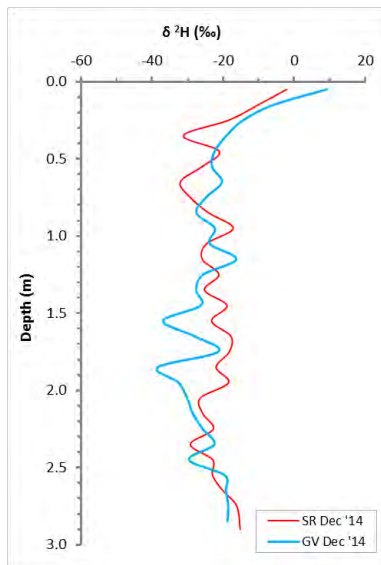


Figure 50 ERT image and associated interpretation at the Nelyambo site

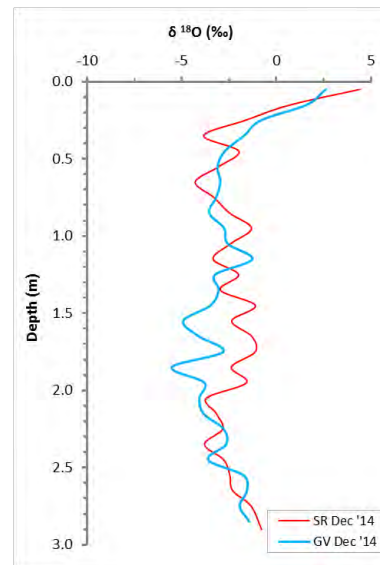
Overall, the isotopic data from the Nelyambo was not conclusive with respect to identifying groundwater use by trees. Sample variability was obviously a factor, but the most significant issue affecting interpretation of the data was the similarity of the groundwater and soil water isotopic values. On balance, it is likely that larger trees were accessing groundwater.

Euraba Rd

Soil profile stable isotope values for Euraba Rd in December 2014 were similar to those for Nelyambo – a surface enrichment zone was evident, driven by surface evaporation, below which values were relatively stable (Figure 51). There was surprisingly little difference between the GV and SR sites despite the large contrast in soil type (Tenosol vs Vertosol). Fluctuations at 1.5-2 m in the GV profile correspond to large changes in clay content.



a) $\delta^2\text{H}$



b) $\delta^{18}\text{O}$

Figure 51 Soil profile stable isotope trends at Euraba Rd, Dec 2014

At the initial sampling, two coolabah at the SR site and two at the GV site were sampled, as well as three small lignum at the GV site. Isotope results varied widely (Figure 52), more so than results from the same time at Nelyambo. Due to the absence of groundwater data for the site, values for 42220086 and 42220224 have been used on the basis that they represent end-members of slow recharge, saline groundwater and rapid recharge, low salinity groundwater respectively. Lignum values were all very enriched and close to the soil isotope values at 0-10 cm depth. Whether or not the plants could extract soil water from such shallow layers is not known – little data exists on the water extraction limits of lignum – but it seems unlikely given the very dry conditions at the time of sampling. The enriched values for lignum and two of the GV coolabah could also be the result of enrichment processes within the plant – particularly in the case of the lignum, given the material sampled was essentially a leaf and thus prone to enrichment (Thorburn et al. 1993b). The two enriched trees at the GV site were smaller trees and the whole size cohort displayed poor health and apparent moisture stress. The only coolabah at the GV site that possessed depleted delta values, similar to deeper soil water, was a large, old tree (C25).

Trees at the SR site were relatively depleted in comparison to the GV site, with the exception of C25 at the GV site. A regression through all vegetation data (Figure 52) plots very closely to the values for 4220086 and the soil water line generated from both sites. There was no relationship between stable isotope values and tree height at the SR site.

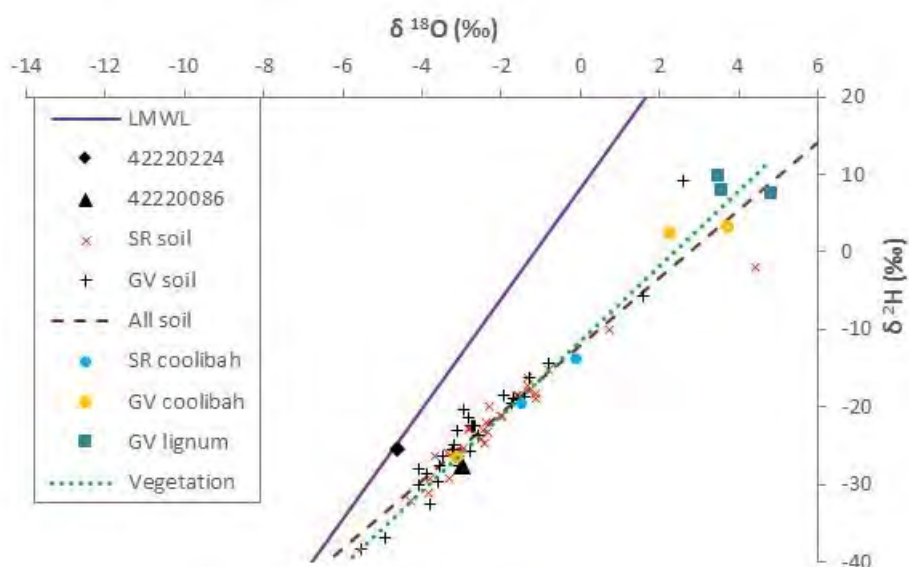
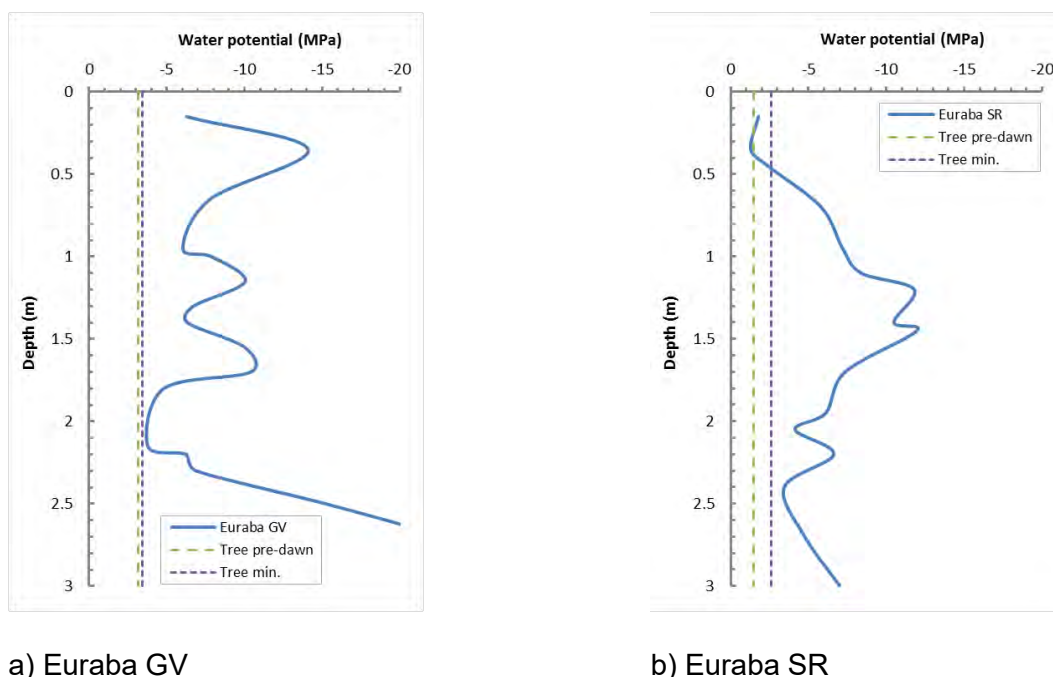


Figure 52 December 2014 stable isotope results in vegetation at Euraba Rd sites compared with regressions of soil water values and a regression of all vegetation values

Soil water potential trends at the two sites differed considerably (Figure 53). At the GV site, where the Vertosol overlay sand at about 1.1 m depth, soil water potential was very negative, particularly in the upper 0.5 m and below about 2.2 m depth, reaching -23 MPa at 2.7 m down the profile. The only part of the profile that was close to tree water potential was at ~2.15 m depth. In contrast, the most negative (driest) values in the SR profile were at ~1.5 m depth. Between 0.1-0.4 m depth, soil water potentials were less negative and within the potential range measured in trees, despite the dry conditions.



a) Euraba GV

b) Euraba SR

Figure 53 Soil and tree water potential at Euraba Rd sites, December 2014

If stable isotope values were selected in the portions of the profile where soil water and tree water potential were close to equivalent, the stable isotope value for SR trees plotted about mid-point in the soil water isotope range. There remained a large difference however between the Euraba GV soil and vegetation values, with the exception of C25. This further suggests that enrichment in the vegetation may be a factor.

The subsequent sampling in April 2015 revealed a shift in tree values towards the depleted end of the spectrum, despite only 70 mm of rain falling as small events within a period of very hot, dry weather. The largest rainfall event delivered 24 mm, 22 days prior to sampling of trees. The shift in tree values would be consistent with trees accessing depleted rainfall event water. This may have been assisted by the dry, cracked nature of the Vertisol at the GV site, enabling macropore flow and subsoil recharge.

Considering just coolabah, there was a general discrimination in stable isotope values between the two sites – the GV trees were generally more enriched than the SR trees – a not surprising outcome. Trees at the GV site were apparently drought affected and thus would potentially be extracting more enriched soil water – there may also have been enrichment effects within the trees. At the SR site, infiltration to the subsoil is more likely to be rapid, due to the sandy nature of the soils present, reducing the likelihood of enrichment related to surface evaporation. The vegetation values consequently are more likely to be depleted. As with the Nelyambo site, there was no apparent relationship between tree structural attributes such as height and stable isotope values.

While only a limited number of tree samples were collected in July 2015, the data from both sites shows a shift in tree isotopic values back towards the enriched end of the spectrum despite 119 mm of rainfall between April 2015 and July 2015. The largest event recorded in the period was 20 mm. The shift towards enriched values contrasts with the depleted trend from the April sampling, which was after a smaller quantity of rain. However, rainfall events for June and July were more enriched than the SR vegetation values from April, hence the shift in SR tree values towards more enriched values is consistent with the contributing source water.

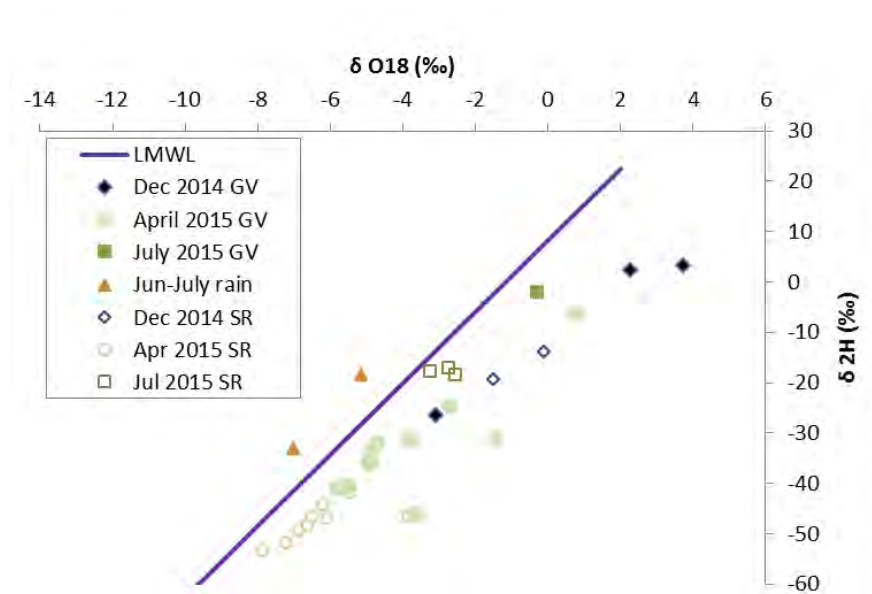


Figure 54 Stable isotopes in coolabah at the Euraba Rd sites, all samples

Soil coring found a good correlation between soil type and geophysical data across the transect. A considerable portion of it is underlain by sand at a relatively shallow depth with the exception of the relict backplain chenopod shrubland between the two plots. ERT data (Figure 55) suggests the sand ridge is underlain by clay at around 15-20 m depth. Drilling to 18m has validated this but found no aquifer present.

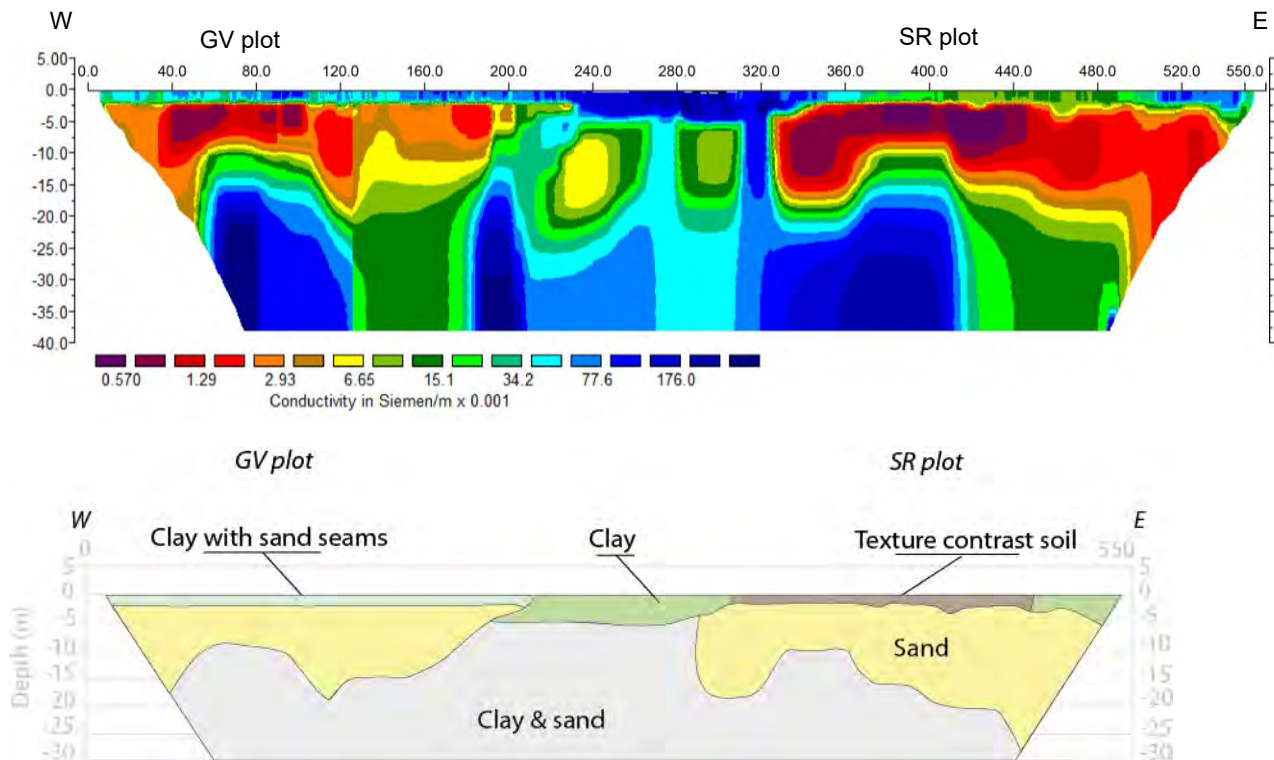


Figure 55 Euraba Rd ERT image showing extensive sand deposits (orange/red colours) and interpretation

Collectively, the data does suggest that trees at both sites were primarily using soil water, even during the driest times. The lack of groundwater use at the Euraba GV site is supported by the widespread mortality of trees at that site – recent rainfall has apparently been insufficient to support the collective water demand of the community. The comparatively high vigour stand of trees at the Euraba SR site can potentially be explained despite the apparent lack of groundwater. The sandy soils of that site enable greater water entry of rainfall events and of the water that enters, a high proportion is readily accessible to plants. This type of pattern, with more woody plants on sandy soils in arid biomes, is an established phenomenon labelled the inverse texture effect (Noy-Meir 1973). At the GV site, small rainfall events have little benefit to trees, particularly when antecedent conditions are dry because slow infiltration increases the proportion of water lost to evaporation and because the relatively high matric potential of clay soils restricts the portion of soil water that is extractable by plants (Fensham et al. 2015). Thus overall, a higher proportion of incident rainfall is accessible to vegetation at the SR site compared to the GV site. Further water balance calculations may validate this hypothesis. It is notable that at any given sampling, Euraba SR trees possessed a generally more depleted consistent isotope signature than the Euraba GV trees, which would be consistent with more rapid water entry and utilisation on the sand ridge.

Balonne-Minor

Sampling of soils, vegetation and groundwater for stable isotopes in the meander bend form of riparian zone at the Balonne-Minor transect occurred in July 2017 during an extended dry period. Sampling sites corresponded to the bore locations (Figure 38). Species sampled included river red gum, coolabah, whitewood, native sandalwood, dogwood, wilga (*Geijera parviflora*), river cooba, sally wattle and prickly wattle.

Soil data yielded similar values at the three treed sites closest to the river but the grassland site (42220085) was more enriched in both $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in the upper 1.5 m (Figure 56). Differences in soil isotope enrichment in relation to vegetative cover (and therefore evaporation) have been observed by other authors (Barnes et al. 1988). Greater enrichment in the grassland site is consistent with the greater evaporation expected there. Below 1.5 m, all sites approached similar values, again a trend consistent with historical theoretical and field data. A regression for all soil values (excluding the soil surface) was derived ($^2\text{H} = 6.2124^{18}\text{O} - 3.7788$; $R^2 = 0.86$).

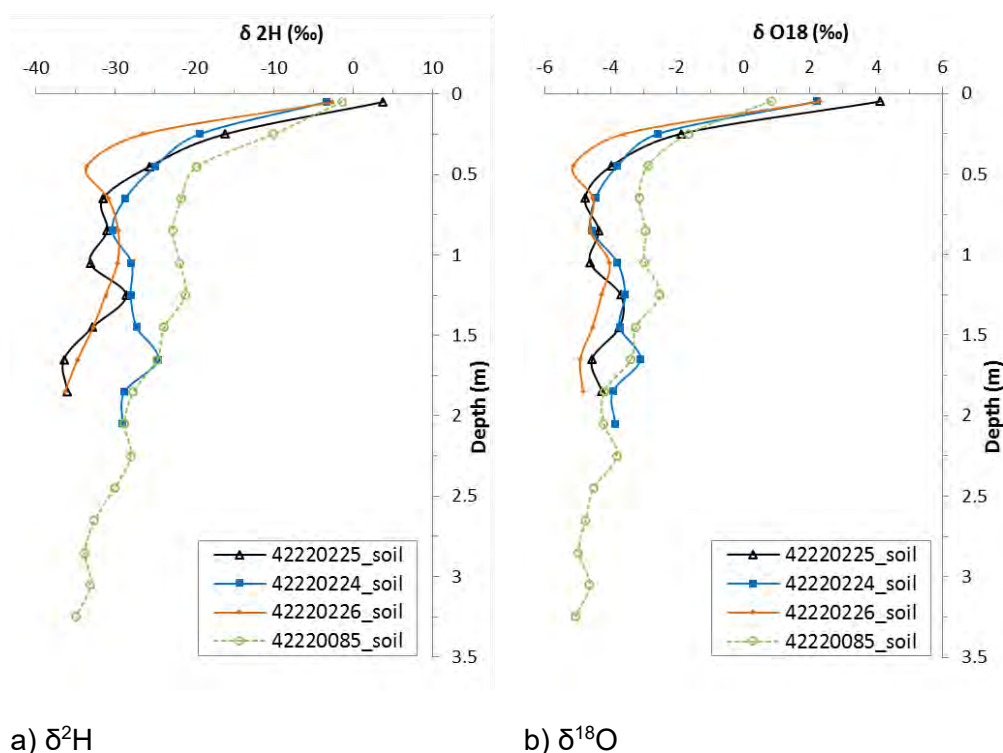


Figure 56 Stable isotopes in soil at Balonne-Minor, July 2017

Historical groundwater data for RN42220224 plotted on the LMWL (Figure 57), consistent with the hypothesis that the shallow groundwater at this site is recharged by high flow stream events rather than via deep drainage through the surficial Vertosol. The July samples for all bores plotted to the right of the LMWL and both RN42220085 and RN42220225 plotted on the soil water line but at either end of the spectrum. There was a general trend of depletion in groundwater stable isotope values with distance away from the river. Salinity on the other hand increased with distance from the river. Vegetation isotope data generally plotted parallel to the soil water line and spanned a wide range of values – greater than the groundwater values. There was no relationship between stable isotope values and tree height nor was there any discrimination between trees and shrubs.

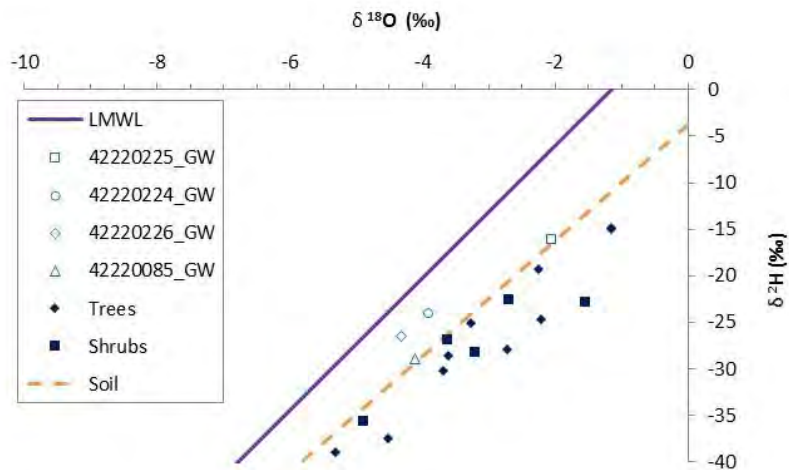


Figure 57 Comparison of stable isotopes for trees and shrubs at Balonne-Minor

At the bore closest to the river (RN42220225), the groundwater was enriched compared to most soil and vegetation samples, with the exception of surface soil, sally wattle and coolabah samples (Figure 58). Sandalwood, was only slightly depleted with respect to groundwater, whereas prickly wattle, wilga and whitewood were more depleted. The two species confirmed by DNA as having roots at the watertable (coolabah and sally wattle) possessed identical isotopic values at the enriched end of the spectrum, suggesting groundwater use. The value for sandalwood was also suggestive of groundwater use. The values for all trees and shrubs other than coolabah and sally wattle could be derived by proportional use of both soil water and groundwater. Water potential data indicated the soil profile water potential was only slightly more negative than tree water potential and may have been accessible to the species concerned.

At RN2220224, which was drilled in a drainage depression to the west of RN42220225, dogwood plotted closely amongst soil values (Figure 59), consistent with observations at Nelyambo and Euraba Rd, and suggesting that its sole water source was the soil. All other vegetation values were enriched in $\delta^{18}\text{O}$ relative to groundwater and soil water. The reason for this is unclear.

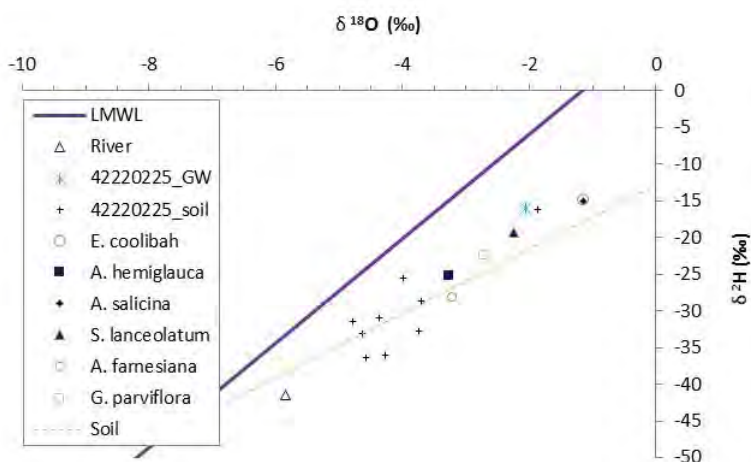


Figure 58 Stable isotopes in soil, vegetation and groundwater at RN42220225

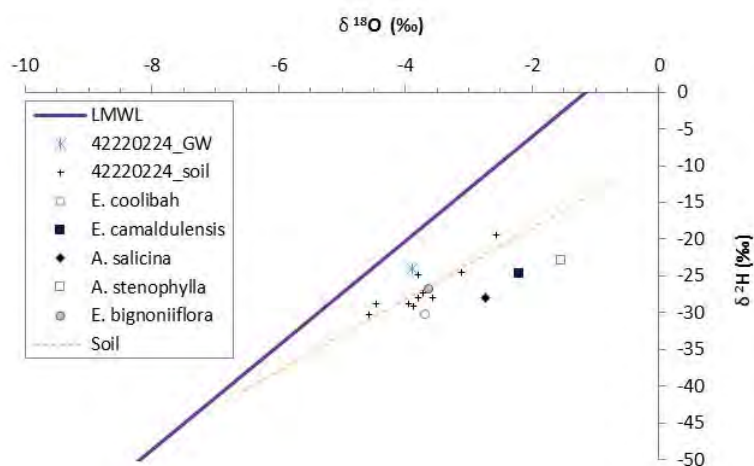


Figure 59 Stable isotopes in soil, vegetation and groundwater at RN4220224

RN4220226 was located towards the outer margin of the riparian zone where community structure had transitioned from forest to woodland. All vegetation values plotted towards the most depleted end of the soil values and were less enriched in $\delta^{18}\text{O}$ compared to vegetation within the forest area (Figure 60). The groundwater value was also less enriched than in the bores closer to the river, thus the shift in vegetation values was consistent with the shift in the groundwater values. The vegetation values could not however be obtained by mixing of groundwater and soil water, as they do not plot between the two water sources. Given the presence of roots at the aquifer interface in the bore, it can only be surmised that there is a question surrounding the isotopic representativeness of the groundwater samples (see below for further discussion).

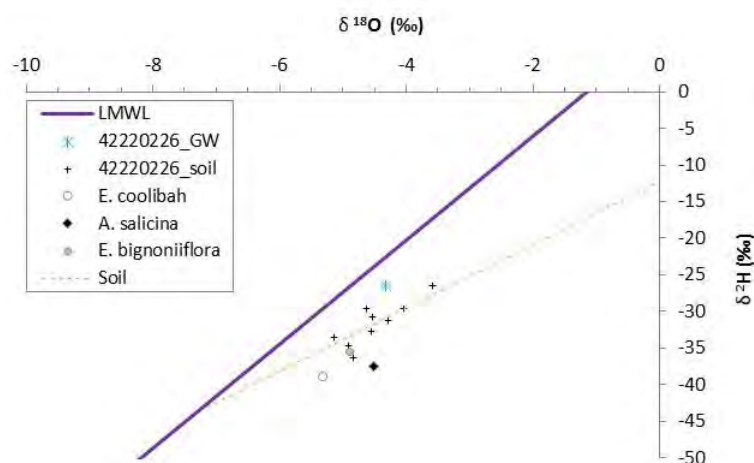


Figure 60 Stable isotopes in soil, vegetation and groundwater at RN4220226

There were no trees adjacent to the western-most bore (RN4220085). The coolabah sampled and plotted on Figure 61 was about 80 m east of the bore (towards the river). Geophysical imaging (Figure 62) and coring data suggests that the underlying sand aquifer extends to the location of the tree, thus the values from RN4220226 would be more representative of the aquifer available to the tree than the deep groundwater tapped by RN4220085. The coolabah sample value plotted about midway in the spectrum of soil water values. The only part of the soil profile with a water potential close to tree water potential was ~0.45m depth. If that value was used as one end-member and the groundwater from RN42200226 as the other end-member, a mixing

model based on $\delta^{18}\text{O}$ yielded approximately equivalent proportions of soil water and groundwater contribution.

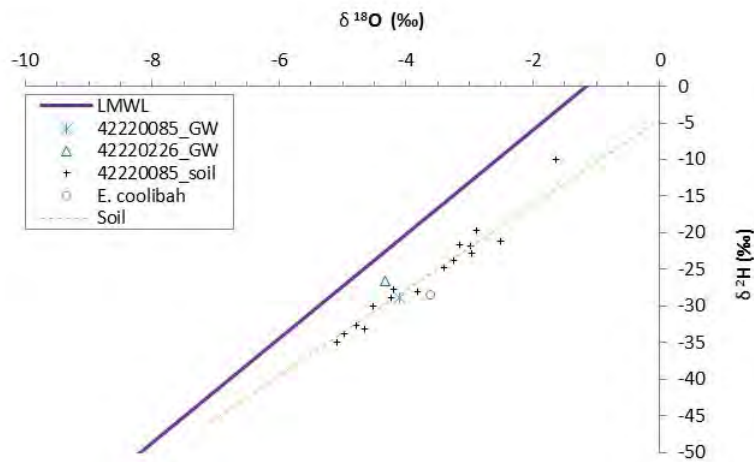


Figure 61 Stable isotopes in soil, vegetation and groundwater at RN42220085

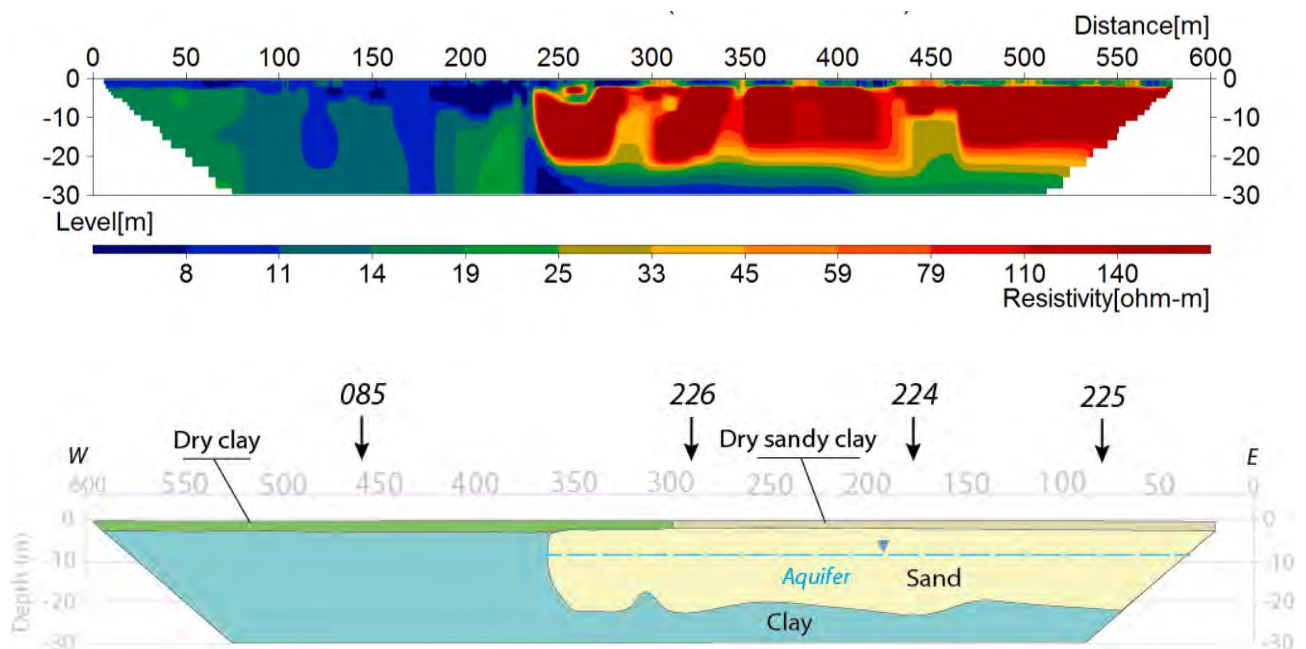


Figure 62 ERT image and interpretation for the Balonne-Minor transect

Unusually, the majority of trees at the Balonne-Minor transect plotted to the enriched side of the soil water line – their values did not lie between soil water and rainfall/groundwater as found at other sites and as would be expected from first principles. A possible explanation for this involves consideration of vapour phase processes at the capillary fringe, root architecture and sampling methods. Evidence from within the bores (Figure 42) suggests that the tree roots are primarily within the capillary fringe and perhaps the top 0.5 m of the saturated zone. The groundwater samples were collected after purging of the bores and thus represent the bulk aquifer isotopic value, which is influenced primarily by the water source – presumed to be river recharge. At the

capillary fringe however, water loss processes (diffusion, vapour loss) may be leading to enrichment of isotopes within the narrow zone that is being accessed by the tree roots. Thus the bulk aquifer sample may not necessarily be representative of the water from the capillary fringe being utilised by the trees. A similar trend in isotopic data (vegetation more enriched than source water) was observed by Jacobs Group (2015) in an ecohydrological study in Victoria. They did not reach a definitive conclusion for the trend but proposed similar possible causes. Further investigations are required to test this hypothesis.

While soil water potential data was not available all the way to the water table, a rapid increase in volumetric water content was evident from about 5.8 m depth (Figure 63) – an expected trend as the capillary fringe is approached. It also suggested that the zone of available water immediately above the aquifer may be thicker than would be anticipated for a sand aquifer. Night-time maximum water potential in coolabah reached values approaching zero while daytime minimum reached -1.95 MPa. The latter value was close to soil water values at all sites except for the grassland, which was more negative. A psychrometer was also installed in a whitewood tree near RN42220225. Maximum water potential achieved at night was -1.88 MPa and minimum during the day was -2.58 MPa. The more negative value at night in the whitewood compared to the coolabah suggests that the whitewood was not accessing groundwater – a hypothesis also supported by the isotopic data. Its roots were not detected in that bore via DNA analysis although this may have been a function of distance from the bore.

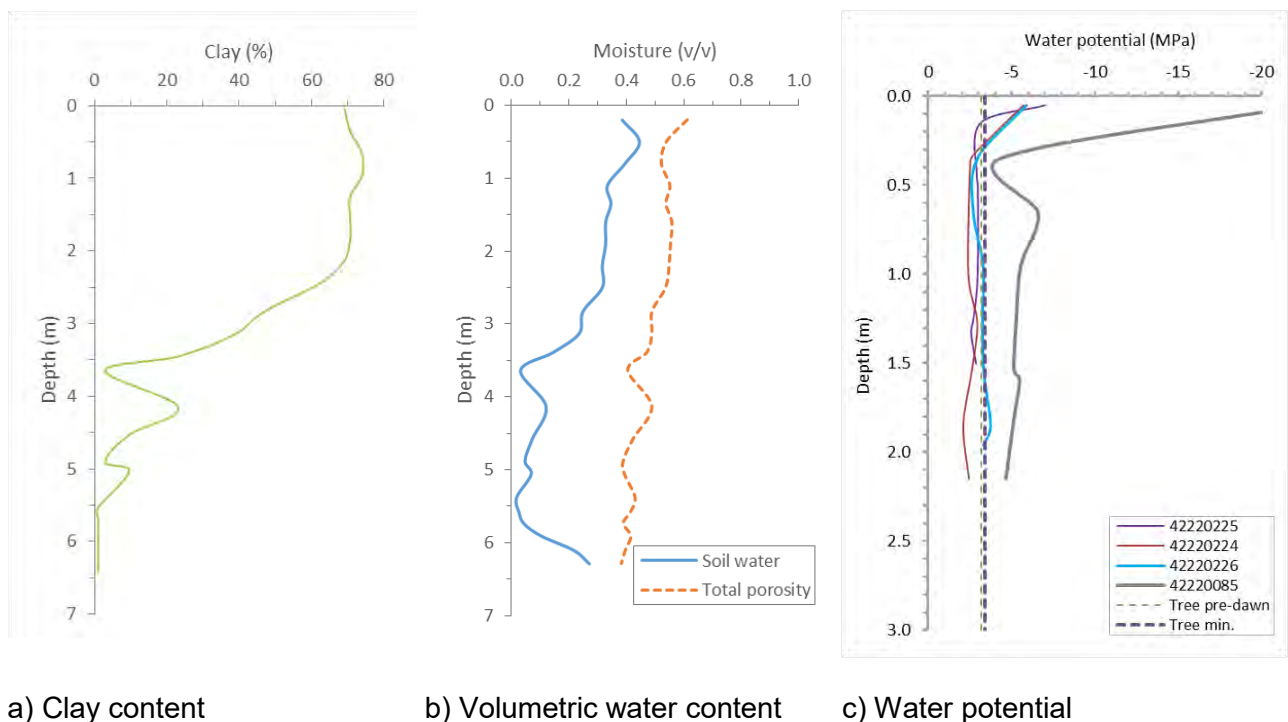


Figure 63 Soil profile clay content, water content at RN42220225 and water potential at all bores

The root analysis confirmed the presence of coolabah and sally wattle at the water table and the absence of confirmation for river red gum is more likely to be related to distance of the nearest example from the bore (sampling bias) rather than implying an absence of roots at the watertable, given it was the largest tree in the transect. Thus if analysis of the data is constrained to only those three species, it is notable that regression of the data plots towards values for soil surface

samples (Figure 64) i.e values that are driven by evaporative processes (vapour loss). This perhaps provides support to the idea that the tree values are indicative of a capillary fringe water source that has experienced vapour loss enrichment, rather than the bulk aquifer value.

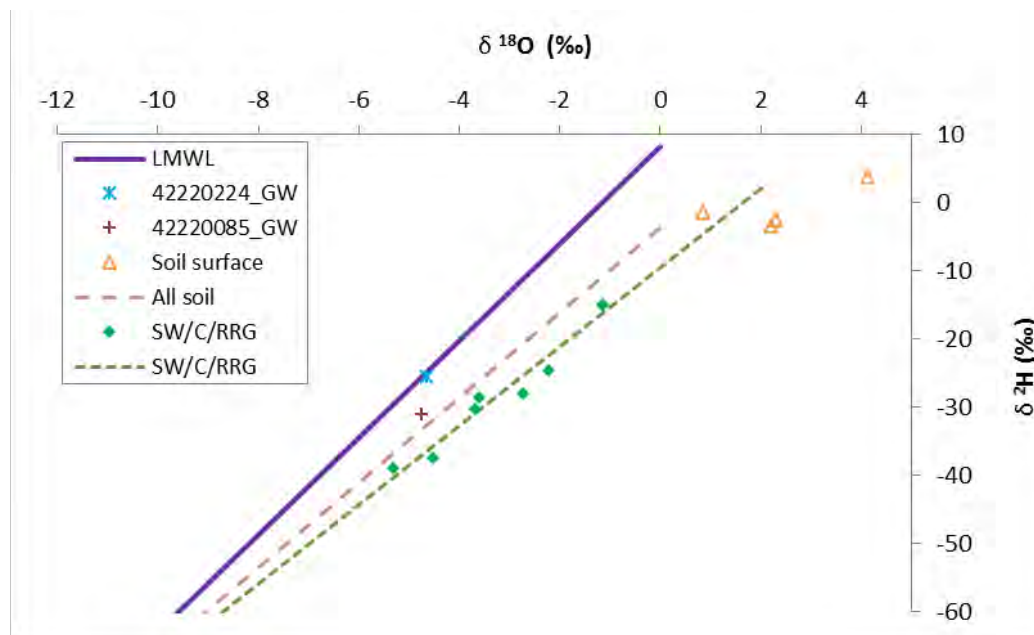


Figure 64 Selected vegetation and soil water stable isotope data for the Balonne-Minor transect

Conclusions from stable isotope investigations

Stable isotope investigations were conducted at four differing sites to determine source water(s) in vegetation. Isotopic data provided useful insight on recharge pathways in the sites, differentiating river recharge of the aquifer at the Balonne-Minor from the diffuse recharge of a saline water table at Nelyambo. However, the method did not provide conclusive evidence of whether trees were using groundwater at sites where groundwater was present. The data suggested that some tree species at Balonne Minor were utilising groundwater but determination of groundwater use by vegetation was not as conclusive as might be expected given the other evidence from that site. Larger trees at Nelyambo are likely to be utilising groundwater, but their isotopic values could also have been derived from soil water alone.

A number of issues concerning representativeness of isotope samples have been identified. Local variation due to gilgai and surface flow/recharge may be more significant to soil sampling than has been assumed from parallel studies in brigalow/belah communities. Similarly, evidence from the Balonne-Minor site suggested there may be an issue with representativeness of groundwater samples in relation to water accessed by trees at the capillary fringe. Further work is being undertaken to resolve interpretation at that site.

Sapflow

Sapflow investigations in coolabah were undertaken at Nelyambo and Euraba Rd in 2014/15, encompassing both detailed investigations of radial variability as well as measurements across a range of tree sizes. Sapwood dimensions were gathered at all instrumented trees and other trees

within the plots. Calculations of sap flux was undertaken in SapFlow Tool v1.4 software (ICT International). During the initial measurement period, 10 trees were instrumented at both Euraba Road sites, but only three were instrumented at Nelyambo – although the latter had 4 sensors in each tree and the mean of all 4 was taken as the value for each tree.

At all sites, sapwood thickness was relatively constant in relation to tree height (Figure 65). In larger trees, the bark was much thicker but the sapwood thickness did not necessarily increase proportionally – a relationship that would be expected in most trees due to the creation of heartwood as the tree grows. This is more evident when sapwood area is considered as a percentage of basal area and compared with tree height. Figure 66 suggests that the proportion of sapwood decreases as trees gets taller. For young trees, heartwood is absent – consequently the relationship between % sapwood and basal area should display a curvilinear shape rapidly approach 100% for low values of basal area.

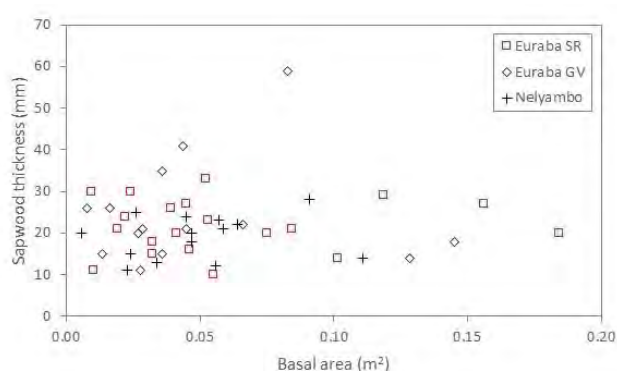


Figure 65 Constant relationship between sapwood thickness and basal area at Nelyambo and Euraba Rd

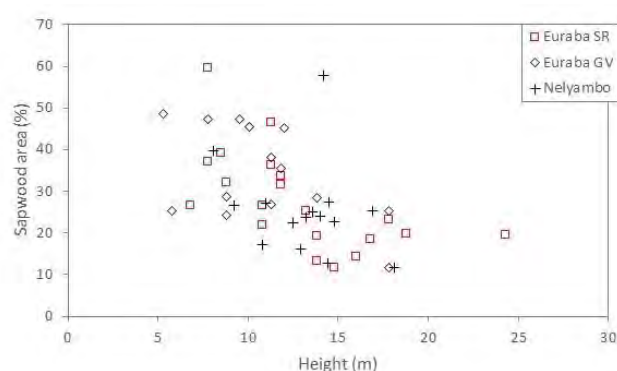


Figure 66 Decrease in percentage of sapwood area with increasing basal area at Nelyambo and Euraba Rd

Leaf area and leaf area index of trees harvested at Euraba GV were lower than trees at Euraba SR or Nelyambo – an expected outcome given the poor health of the trees at Euraba GV. The mean LAI at Euraba GV was 0.35 compared to 1.62 at Euraba SR and 1.88 at Nelyambo.

Sapflow at the sites was compared over the period Dec 2014 to May 2015 and expressed in terms of L/day for individual trees and mm/day for the plots. Trees in poor health at Euraba GV had the lowest water use (<10L/day). In comparison, trees at Euraba SR were in the order of 8-42 L/day and trees at Nelyambo used 11-65L/day. There was no relationship evident between water use and canopy area (Figure 67), which was not surprising for Euraba GV, due to the variable degree of defoliation of canopies. There was also little relationship between water use and tree height across the sites. Some trees at all sites, including Euraba GV were amongst those recording the highest water use – in the case of Euraba GV, these were typically trees in better health than those that achieved lower water use (Figure 68).

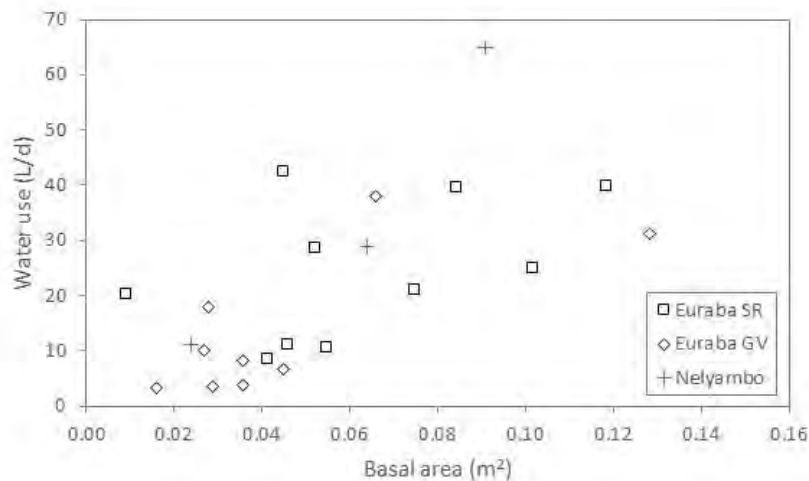


Figure 67 Tree water use in relation to basal area at Nelyambo and Euraba Rd for Dec 2014 to May 2015

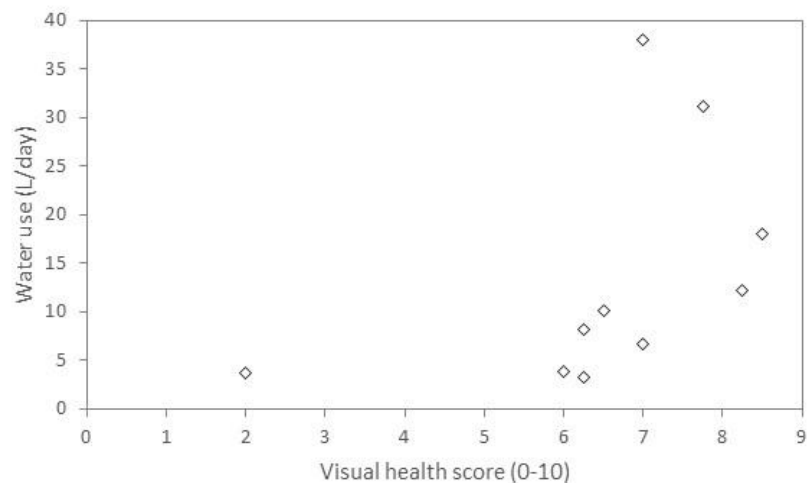


Figure 68 Tree water use in comparison to average visual health score at Euraba GV for Dec 2014 to May 2015

There was an increasing trend of water use in relation to measured and estimated leaf area but considerable variation was evident (Figure 69). This may in part be a function of the estimation of leaf area, given the small number of trees sampled to yield the LAI at each site. The use of an LAI approach to derive leaf area, combined with the poor vigour of trees at the Euraba GV site will have led to over-estimation of the leaf area for trees at that site. When the leaf area is adjusted using the visual health score, the relationship between leaf area and water use at Euraba GV improves considerably (Figure 70).

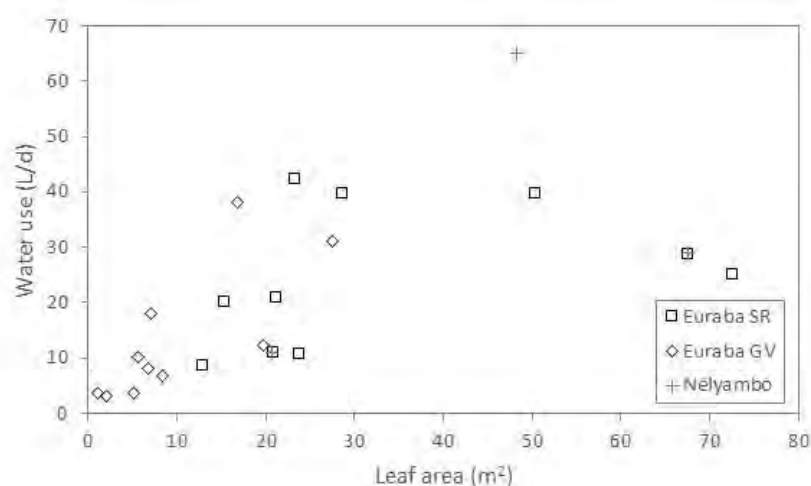


Figure 69 Water use in relation to leaf area at Nelyambo and Euraba Rd for Dec 2014 to May 2015

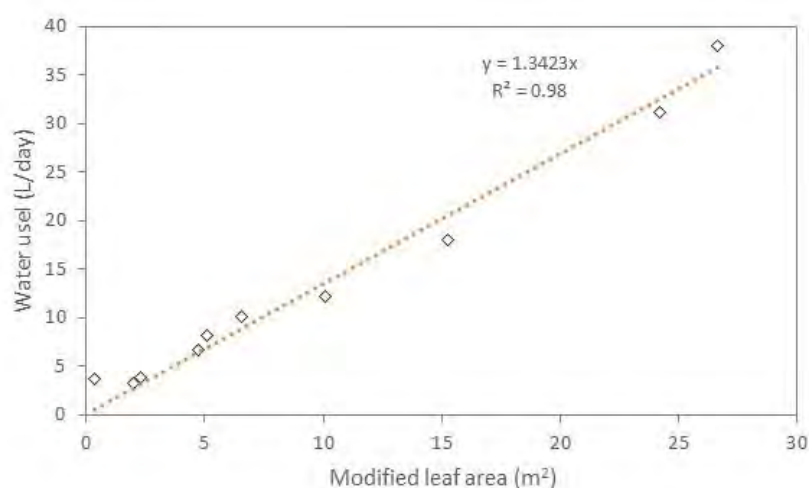


Figure 70 Water use in relation to modified leaf area at Euraba GV for Dec 2014 to May 2015

In order to scale up to plots, relationships were examined between tree water use and both sapwood area and basal area. The degree to which water use correlates to these or other attributes has varied amongst various studies and species (Hatton et al. 1995). Given the variability in the relationship between sapwood thickness and basal area, a relationship between water use and basal area was utilised for scaling up, avoiding the need for the intermediary calculation of sapwood area (and introduction of further error). The use of a relationship between basal area and water use will however generate an over-estimate for Euraba GV because trees were in poor health.

The resultant values across the three sites were in the order (lowest to highest) of Euraba GV (0.0697 mm/day), Nelyambo (0.385 mm/day) and Euraba SR (1.261 mm/day). The values from Euraba GV and Nelyambo are of a similar magnitude to values recorded by Doody et al. (2009) for black box and river redgum, but the numbers from Euraba SR are higher. The daily values equate to 25, 141 and 460 mm/yr respectively. A low value for Euraba GV was not surprising but the

value for Nelyambo was lower than might be expected, particularly if the trees were accessing groundwater or deeper soil water. This suggests that the high soil water content recorded at 3-6 m in the soil profile at that site was potentially the result of a lack of utilisation of that zone by the trees.

Over the 138 day period from Nov 2014 to end of March 2015, plot tree water use was 10 mm for Euraba GV, 53 mm for Nelyambo and 174 mm for Euraba SR. The rainfall during the same period was 153 mm at Euraba and 225 mm at Nelyambo. This suggests that trees at Euraba GV were not utilising all available rainfall whereas trees at Euraba SR were utilising rainfall plus stored soil water (deeper unsaturated zone). Trees at Nelyambo used less water than fell in rain. The period of measurement used in these calculations was during a very hot dry summer, consequently values recorded may be lower than in times of higher water rainfall. Overall, the sapflow measurements yielded results consistent with other data for the sites – least water use (and availability) at Euraba GV and the most at Euraba SR, with Nelyambo between.

Vegetation structural evidence

Structural data from the detailed plots, the ancillary plots and the riparian transects provided a large body of data (*E. coolabah* $n = 1382$) from which to evaluate the relationships between tree structural attributes in general and specifically in the context of the assumed water availability of the sites as a whole or elements within the sites.

Detailed plots

Considering the contrasting Euraba Rd sites first, the height statistics at the GV plot were skewed towards shorter trees – reflecting the knowledge that this site had thickened since 1950 (Figure 71). Despite the lower stem density at the SR plot (30 coolabah) compared with the GV plot (68 coolabah) the basal area of coolabah at the SR plot was 8.56 m²/ha – more than twice the value for the GV plot (3.41 m²/ha). Nelyambo had a coolabah basal area of 6.93 m²/ha. There was also a difference in the number of stems per tree at each site. At the GV site, 73% of trees were single stemmed compared with only 16% of trees at the SR and 25% at Nelyambo – a trend that matches anecdotal observations more generally across the LBF that larger trees tend to possess multiple stems. Historical anthropogenic and natural factors at each site would no doubt play a significant role in the population distribution. Multi-stemmed habit is potentially also the result of factors such as historical grazing pressure by sheep and/or the influence of fire, rather than being a function of age alone. This was evident in the seedlings observed at the Euraba SR site – nearly all had multiple stems despite being <0.3 m in height. The Euraba sites were only destocked in recent years and goats and sheep still occasionally graze the area.

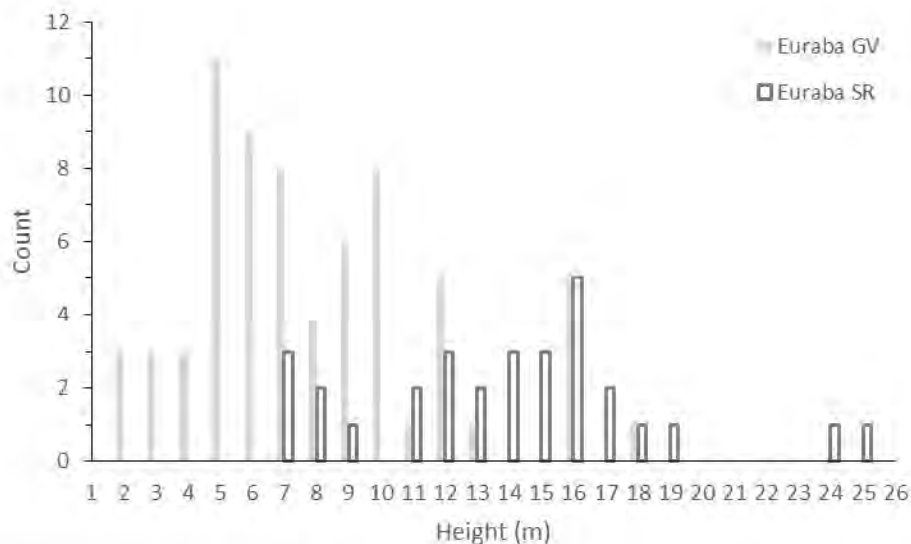


Figure 71 Height statistics for Euraba Rd detailed plots

Considering the three main metrics (height, basal area and canopy area) from all detailed plots, Figure 72 illustrates that the when height and canopy area are compared, there is an apparent upper boundary to the relationship – represented by the dashed line (drawn by eye) in the figure. The relationship would not be expected to be identical across all sites because there has been deliberate bias in the site selection on the basis of apparent water supply. Local factors such as fire and grazing history would also be important. An upper bounds to such a relationship would however be expected as a function of climatic and tree physiological attributes (Eamus *et al.* 2006). While all three sites contained a range of tree sizes, the Euraba sand ridge site contained a lower proportion of small trees (i.e few juveniles) and also contained the largest trees. Beyond a height of about 15 m, the apparent upper boundary to the relationship is less obvious due to a paucity of data. A similar relationship was observed between tree height and basal area (Figure 73), with an apparent maximum to the relationship again evident, along with outliers from the Euraba sand ridge site.

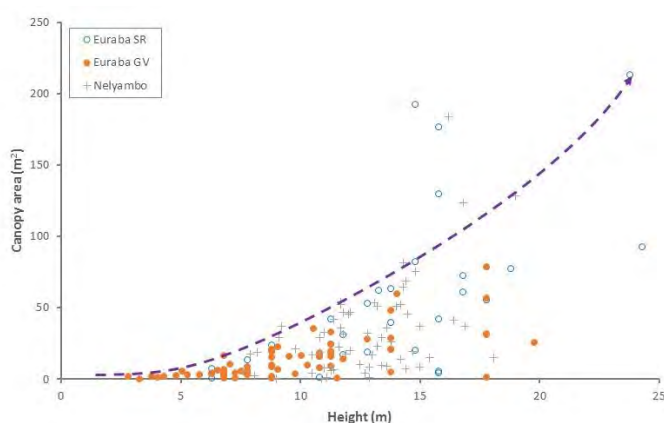


Figure 72 Relationship between tree height and canopy area for coolabah at the three detailed study plots

(Dashed line represents a possible upper bounds to the relationship)

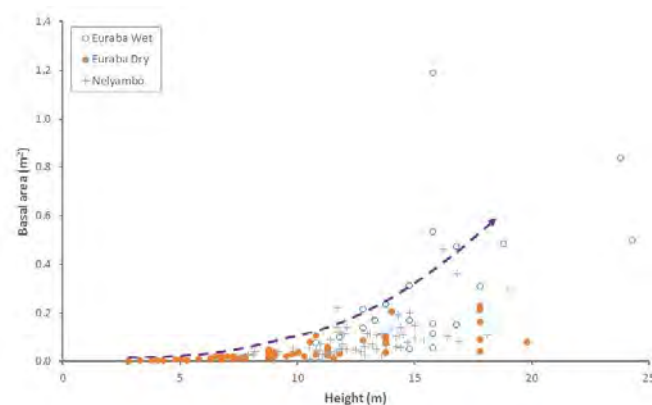


Figure 73 Relationship between tree height and basal area for coolabah at the three detailed study plots

(Dashed line represents a possible upper bounds to the relationship)

A log-log plot illustrates both upper and lower bounds to the data more clearly.

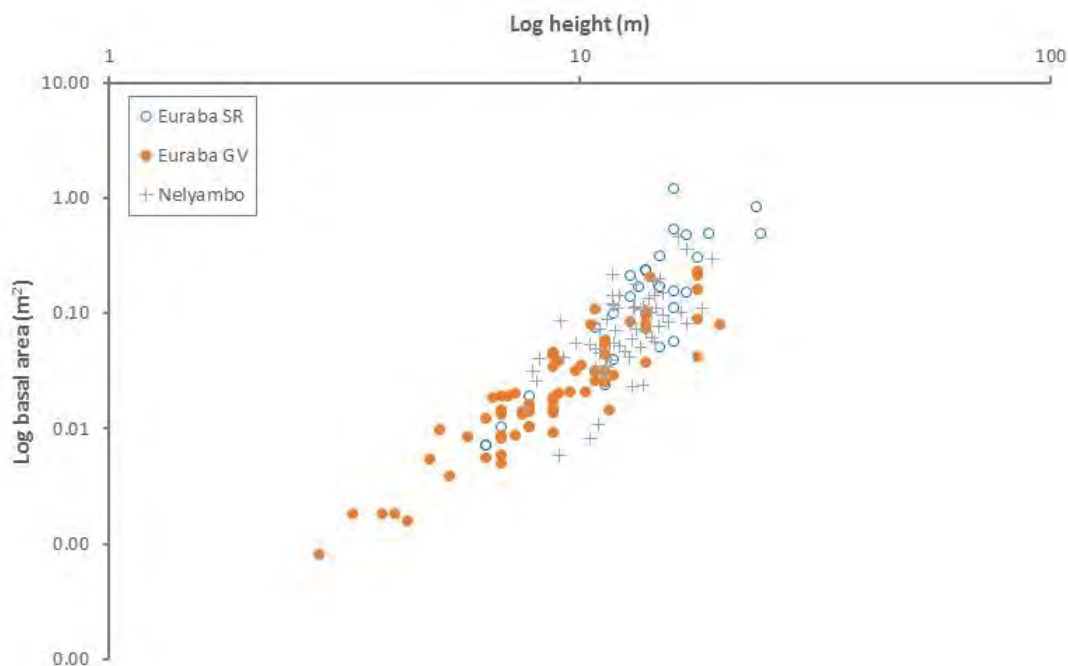


Figure 74 Relationship between tree height and basal area for the three detailed study plots (log-log plot of same data as in Figure 73)

A positive relationship between basal area and canopy area was evident (Figure 75), particularly for trees below a basal area of $\sim 0.3 \text{ m}^2$ ($\sim \text{DBH} = 0.6 \text{ m}$). There was some suggestion in the data that the largest trees may reach a maximum canopy area $\sim 200 \text{ m}^2$ – illustrated by the hand drawn line in the Figure. Again, a theoretical maximum is expected, likely to be a function of climatic and tree structural architecture factors.

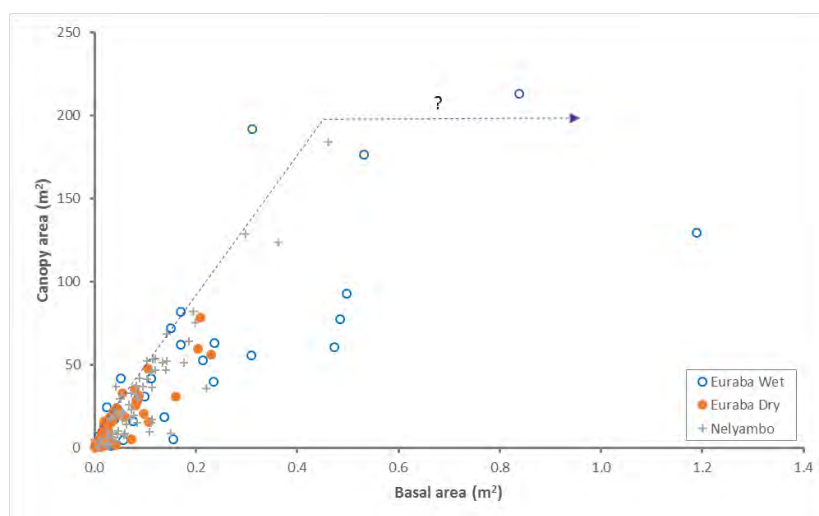


Figure 75 Relationship between basal area and canopy area for coolabah at the three detailed study plots

(Dashed line represents a possible upper bounds to the relationship)

Incorporation of the data from the Euraba ancillary sites (Figure 76, Figure 77) supported the general conclusions from the detailed plots, in particular that canopy area values plateau ~200 m² and that a generalised upper bounds to each relationship was evident. Nearly all of the largest trees, in terms of canopy area and height, were from sand ridge sites.

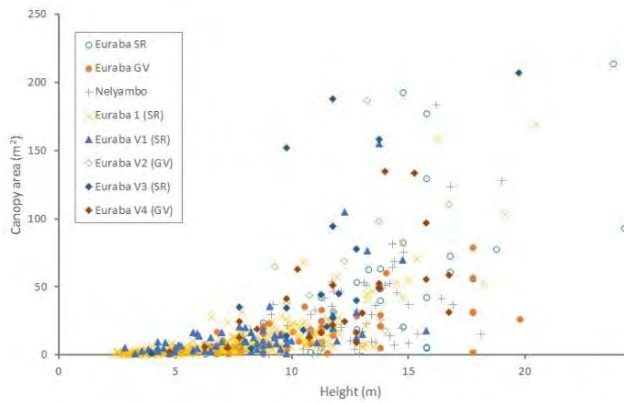


Figure 76 Relationship between tree height and canopy area for coolabah, all circular plots

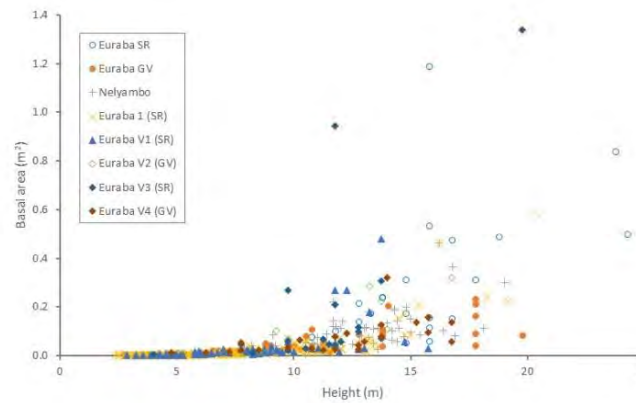


Figure 77 Relationship between tree height and basal area for coolabah, all circular plots

Given that groundwater use has not been proven at any of these sites, with the exception of possible use at Nelyambo, the relationships determined may be considered as primarily representative of non-groundwater dependent trees. Specifically, if only trees from backplain Vertosol sites are selected, there is a high probability that these trees are representative of non-groundwater dependent communities and their structural data may be used as a reference point in terms of water availability and use. The 95th percentile of basal area at the Vertosol sites was 0.207 m², height was 17.5 m and canopy area was 91.3 m².

When the SLATS plots were included, average height and basal area data (Figure 78) indicated that the detailed plots were towards the outer bounds of the pool of data. The Euraba SR site possessed the greatest average height for coolabah (13.6 m, median 13.8 m), followed by Nelyambo (12.6 m, median 12.6 m) and then Euraba GV (10.1 m, median 9.1 m). Trend in basal area was in the same order and a similar trend was observed at the ancillary sites nearby – plots on sand ridges possessed nearly double the basal area of plots on grey Vertosols.

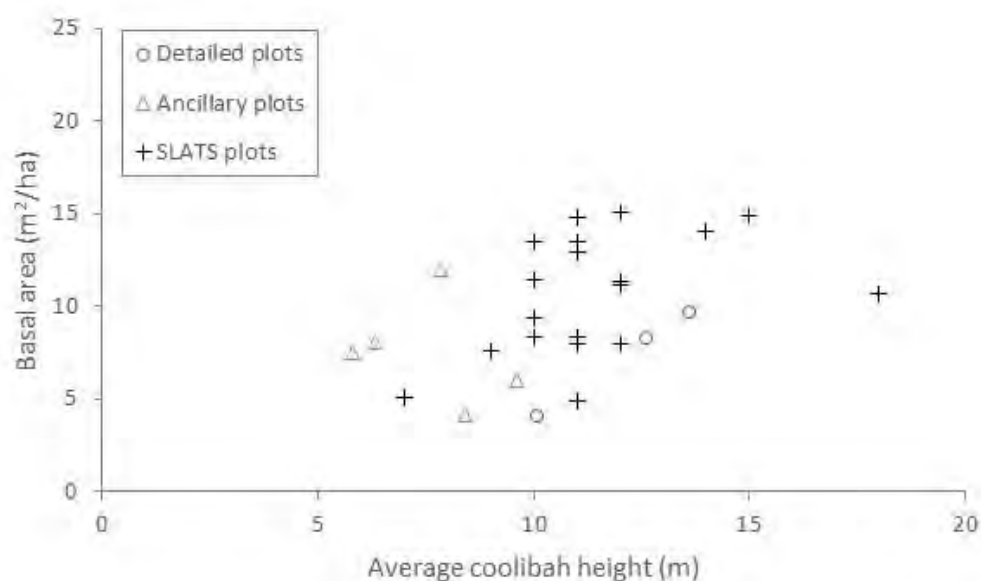


Figure 78 Height versus basal area for the three circular plot types (detailed, ancillary, SLATS)

Transects

The transect data provided an opportunity to evaluate the relationship between water availability and tree structural characteristics in a relative sense at the local scale. Across the 5 riparian transects, the Balonne-Minor represented the maximum available water – the presence of shallow groundwater has been proven, as has the presence of tree roots accessing that water. At the other end of the spectrum, the Briarie Creek transect represented an extremely dry site with no suggestion of groundwater availability to trees. Each transect can thus be placed conceptually on the spectrum of minimum to maximum water supply (Figure 79).

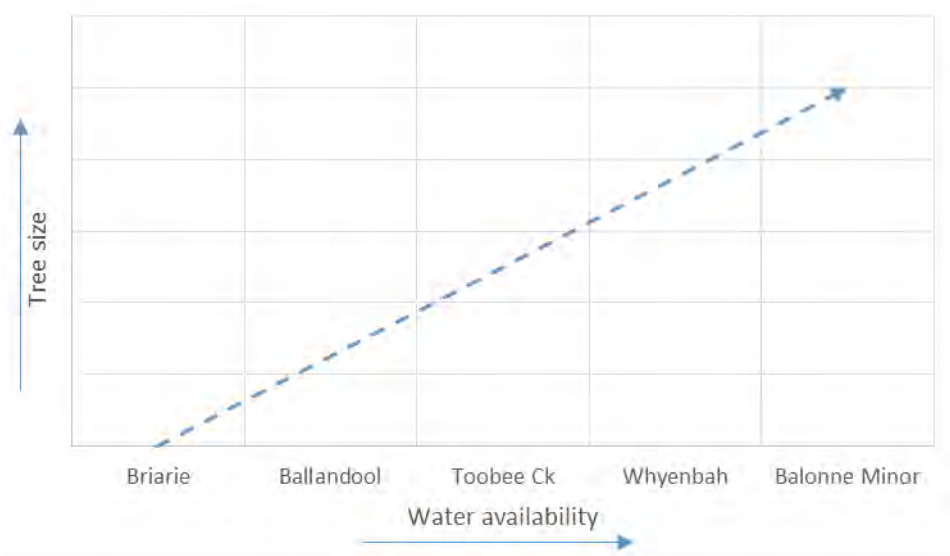


Figure 79 Conceptualisation of theoretical relationship between water supply and tree size for riparian transects in the study

Data from the transects indicated that the largest coolabah were found within close proximity of the river bank at sites such as Ballandool, Briarie and Toobee (Figure 80, Figure 81), which fits with an assumption that there is no groundwater accessible to vegetation at those sites and that the zone of greatest water availability is on the river bank. The decline in tree size with distance away from the riverbank is very rapid – maximum height, canopy area and basal area decline within 10 m, beyond which the decline is only minor. Away from the river bank, trend in tree size is influenced by local drainage. For example, at Briarie Creek, a drainage depression was present halfway along the transect – thus within the backplain component there was a localised area of increased water supply. Similar trends were apparent at Whyenbah and Balonne Minor, where larger trees were associated with the margins of drainage depressions between levees, but there was an overall asymptotic decline in tree size with distance away from the river.

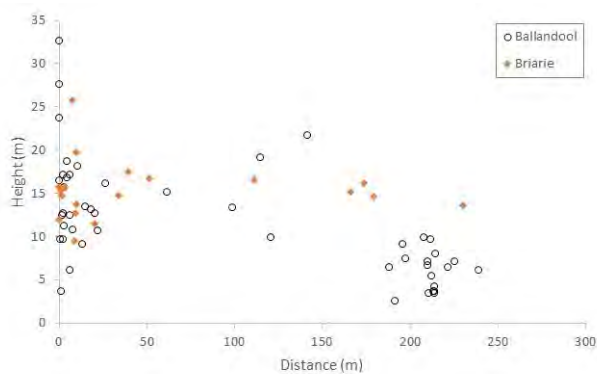


Figure 80 Trend in coolabah height with distance away from the riverbank at Ballandool River and Briarie Creek

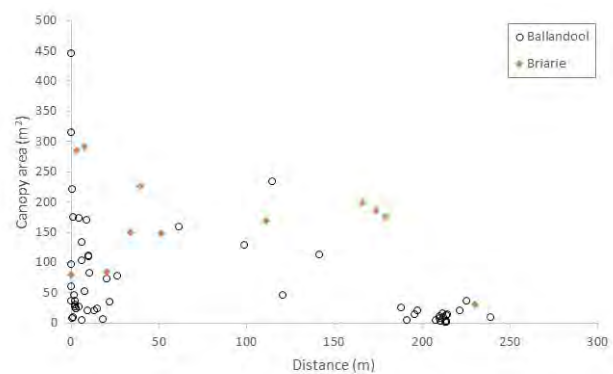


Figure 81 Trend in coolabah canopy area with distance away from the riverbank at Ballandool River and Briarie Creek

River red gum was generally only present within close proximity to riverbanks and was most evident at Balonne-Minor and Whyenbah. Occasional trees were present at Toobee Creek, Ballandool and Briarie Creek, although not always within the transects. The sparse nature of the river red gum and its spatial constraint close to river banks was consistent with historical mapping for the region. It is rare for river red gum to be found in non-riparian areas on the LBF. This suggests that it has a high water requirement and/or recruitment requirement that is only met in areas where bank wetting occurs and/or there is shallow groundwater. The latter example was evident at the Balonne-Minor, where the species was found up to 27 m away from the riverbank – compared with Ballandool River and Briarie Creek where it was only found on the riverbank or on scroll bars in the channel. Structural relationships for river red gum were more diverse than for coolabah in the same landscape position (data not shown) but the overall number sampled was low.

The Balonne Minor transect possessed the densest riparian forest of all transects evaluated. This coincided with the zone in which groundwater was present. Figure 82 illustrates the stem count in 10m intervals along the transect, showing both the overall decline with distance away from the river, as well as obvious peaks that correlate to the fringes of drainage depressions. Figure 83

illustrates basal area in the same manner. In both instances, the change from the riparian vegetation zone to the grassland corresponds with the visible topographic outer boundary of the meander bend.

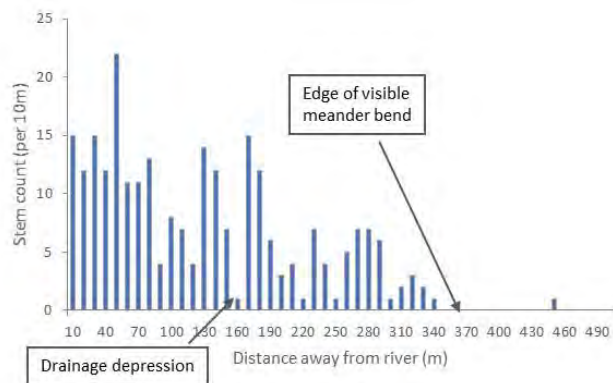


Figure 82 Stem count in 10 m intervals along the Balonne Minor riparian transect

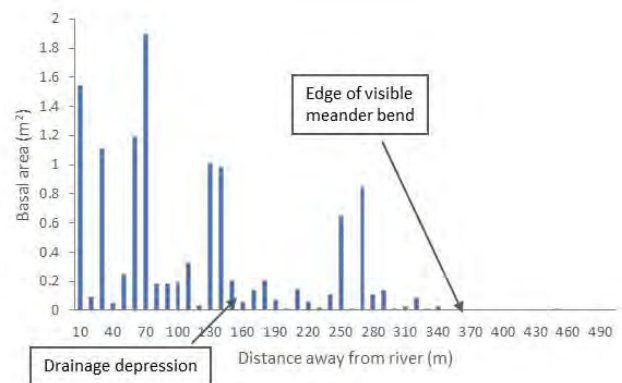


Figure 83 Basal area in 10 m intervals along the Balonne Minor riparian transect

Maximum coolabah height in the Balonne Minor transect decreased only slightly (23.5 to 18.2 m) with distance away from the river, suggesting that water availability is similar throughout the wooded zone – a feature confirmed by drilling and geophysical investigations. Beyond the boundary of the visible meander bend, no groundwater was present in the upper 12 m.

As with the Balonne Minor transect, stem density and basal area was influenced by the presence of drainage depressions and related topographic features.

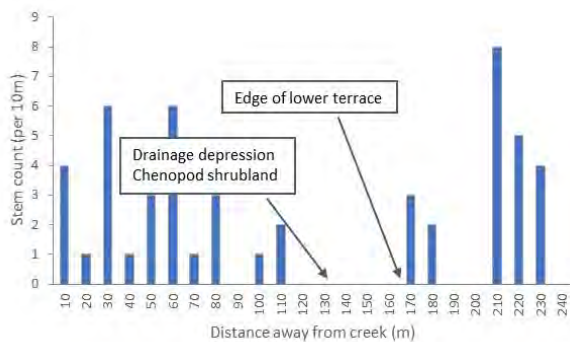


Figure 84 Stem count in 10 m intervals along the Briarie Creek riparian transect

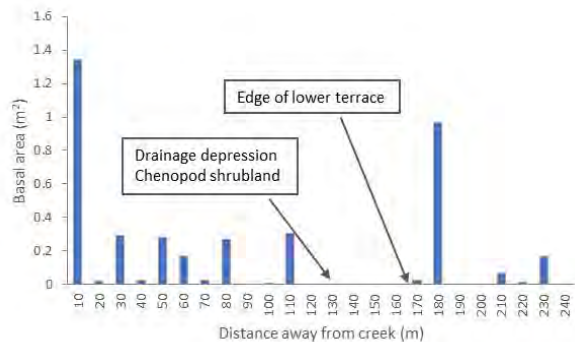


Figure 85 Basal area in 10 m intervals along the Briarie Creek riparian transect

The data from the riparian transects creates a reference for trees with a high water supply – specifically if trees close to the river bank are selected. The 95th percentile values for riverbank coolabah were: height 21.8 m; basal area 1.6 m² and canopy area 182 m². When these values are compared with those from the grey Vertosol plots, there is an obvious difference. Basal area was 8 times greater and canopy area was twice as large for trees on river banks than trees on Vertosol backplains. This comparison does not account for factors surrounding fire, disease, mortality and age, all of which may have a significant influence. If other factors are assumed to be constant across the floodplain, trees within backplain environments with similar or greater structural attribute values to those on river banks can be assumed to have a similar or greater water supply.

5.4 Discussion and conclusions

Establishing a greater understanding of the presence/absence of shallow groundwater accessible to vegetation was a key pre-requisite to answering the research questions posed. If shallow groundwater was absent, the answers to the questions are self-evident. The fieldwork, in particular geophysics and drilling, has provided new knowledge regarding the presence of shallow aquifers in close proximity to river channels in the LBF and some understanding of the probable recharge mechanisms of aquifers. Further work and long-term monitoring beyond the life of this project will refine that understanding. The data collected to date suggests a strong correlation between above ground features (vegetation, topography and geomorphology) and the presence/absence of riparian aquifers, specifically the presence of shallow aquifers in complex meander bends with riparian forests.

A greater understanding of sand ridge architecture has also been developed but it is clear that there are still many knowledge gaps from a spatial perspective. It was found that not all sand ridges contain shallow aquifers but they are a key recharge feature of the LBF, particularly in areas where floods inundate them. The improved knowledge regarding the presence/absence of shallow groundwater in the floodplain provides a partial answer to the research questions – there are areas within the LBF where trees apparently do not use groundwater, simply because no shallow groundwater is present. This appears to be the case for much of the the current and relict backplain environments as well as some sand ridges. Paucity of data however prevents spatial delineation of those areas with certainty – other than via inference using remote sensing of vegetation response, as explored in previous sections.

The first research question considers vegetation response to all water sources – in this case deemed to be flooding, rainfall and groundwater. The role of flooding could not be specifically investigated due to a lack of flood events during the life of the project. The influence of flooding on groundwater recharge has been inferred from soil water/recharge estimation (see Chapter 6) but the follow-on influence on vegetation response remains unclear at this point in time. Without pre-empting the findings of Chapter 6, it is important to consider that flood recharge may only lead to unsaturated zone recharge – inundation of the landscape does not necessarily lead to the presence of a shallow aquifer. Thus a vegetation response to flooding may be expressed in the long-term as increased resilience against drought periods – via increased water supply from an unsaturated or saturated zone. This was the hypothesis explored within the remote sensing component of this project. Definitive proof would however require further long-term monitoring of groundwater and vegetation responses.

Considering the question of whether specific trees species use groundwater, we have obtained clear visual evidence of roots at the capillary fringe of a shallow riparian aquifer on the Balonne Minor River. The growth of roots into the bores in the Balonne Minor transect provided an opportunity to use DNA to confirm the species with roots present at the aquifer interface in that riparian zone. Roots were evident within 2-3 months of construction of the bores. The bore construction method (full cementing) is such that growth of roots down the annulus of the bore is unlikely. Furthermore, the slotted section of the bores was sleeved with a fine nylon ‘stocking’ designed to prevent ingress of sand. This sleeve, while flexible, does not appear to have posed a barrier to root penetration. Slot size in the casing was 0.5 mm, thus all roots found in the bores must be narrower than this at the point of entry to the casing. Coolabah and sally wattle were

consistently present at the aquifer interface and the presence of other species such as river red gum could not be ruled out due to sample bias associated with bore locations.

This validated the conceptual model that the dense riparian forest evident at that site was likely to be a groundwater dependent ecosystem. While water use was not specifically measured, sufficient evidence exists to suggest that larger species at the site were accessing groundwater in conjunction with soil water. On-going investigations at this site will further confirm this.

Stable isotope and sapflow methods were found to be informative at the sites investigated but limitations to the methods meant that they were not entirely conclusive regarding the identification of trees or species accessing groundwater. The sampling of shrubs as part of stable isotope studies did appear to be a useful means of determining a soil water end-member but a greater sample size is recommended. Further application of these methods at sites such as Whyenbah and Balonne Minor may yield more conclusive results. Given the intensive/costly nature of sapflow and stable isotope measurements, and the size of the LBF, the future use of these methods should be strategic and informed by preliminary regolith investigations. Such investigations should encompass geophysical (ERT) imaging coupled with coring/drilling as these methods proved highly successful in a range of landscape types.

The final method used for estimating the impacts of differing water availability was analysis of vegetation structural data from differing components of the landscape – encompassing areas with a relatively high water availability (near channel) and those with a relatively low water availability (backplain, terrace environments). The intention of the approach was to validate what is obvious when traversing the LBF – larger trees are typically located adjacent to channels. The dominance of coolabah in the landscape coupled with the very sporadic extent of river red gum meant that a large data set was achieved for the former species but only a limited data set for the latter. This vegetation structure approach confirmed that the size of coolabah was influenced by proximity to a stream channel, thus an inference could be drawn regarding the impact of water availability. Whether this is a function of total water supply or reliability of supply could not be determined. Others have found similar trends – for example, Bacon et al. (1993) found the presence of shallow groundwater increased mean leaf area in river red gum and short-term flooding increased the species growth rate. Their study was undertaken in a channelized floodplain similar in geomorphology to the Whyenbah and Balonne Minor sites in our project.

The use of vegetation structural data to infer water availability could be further developed via more detailed LiDAR and remote sensing analysis to identify areas of the floodplain that have a greater water supply than typical for the backplain environment.

The presence of coolabah on low sand ridges such as at Euraba Road has not previously been described in the LBF. In southern inland Queensland, and in much of the MDB, the species is almost exclusively constrained to Vertosols. The larger size of coolabah and other species on such sand ridges may potentially be explained without the presence of accessible groundwater. Understanding this has considerable relevance to the conceptualisation of GDEs in the LBF and it highlights the significance of the soil profile in determining the type and vigour of the vegetation present. This is illustrated by considering three of the sites investigated (Nelyambo, Euraba GV and Dirranbandi Minor), which possessed similar regolith profiles (~2 m clay over sand). Despite the similar soils, the vegetation structure and health was clearly different between the sites. The primary reason appeared to be soil surface controls on infiltration. The Euraba GV site encompassed a shallow flowpath, but the vegetation at that site was suffering drought related

mortality in late 2014, despite flooding events in 2010-2012. It is apparent that 1-2 m of surface clay (Vertosol) was sufficient to impeded recharge and no shallow aquifer was present. In contrast, the Balonne Minor meander, which had a similar thickness of surface clay, possessed an aquifer at ~7 m depth, but the recharge mechanism is likely to be lateral rather than vertical. Collectively, the data from all sites suggest that the surface 2 m of soil has a very strong control over the vegetation species and structure present – more so than the presence/absence of floods. This is primarily due to the role of the soil type in governing infiltration and water availability. These relationships will be further evaluated in academic studies linked to this project.

6 Identifying the influence of flooding on water availability in shallow aquifers and unsaturated root zones

6.1 Research questions

Given there has been some evidence of trees accessing groundwater presented, further assessment of groundwater recharge mechanisms is essential to understanding the ecohydrology of the LBF. An important distinction with respect to this component of the project is the difference between inundation and over-bank flooding on the LBF. Inundation may be caused by overbank flooding, but in inland Queensland it also frequently results from large rainfall events. The size and nature of the LBF is such that rainfall ponds on parts of the land surface, causing localised inundation that may last for days to weeks. Similarly, the flow of water from the higher elements of the floodplain to the lower elements leads to localised inundation of low-lying areas. The discussion below does not specifically discriminate between surface water sources (rainfall or overbank) in relation to the origin of water that has caused inundation, consistent with the definition of flooding by the Queensland Government (www.chiefscientist.qld.gov.au/publications/understanding-floods/what-is-a-flood).

The key research questions posed were:

- Do floods recharge the unsaturated zone and shallow aquifers
- What is the potential rate of shallow groundwater recharge and root zone saturation from flooding in the LBF

These questions were investigated via conventional methods for determining the infiltration, deep drainage of soils and thus the potential recharge to aquifers. The approach built upon prior knowledge for the landscapes concerned. First principles dictate that the maximum groundwater recharge achievable is determined by the amount of water passing the root zone i.e deep drainage. Knowledge of deep drainage for different soils in the LBF and more generally in the region is comparatively good, compared to knowledge of the extent of shallow aquifers and their actual recharge rates. Deep drainage has been modelled, measured and estimated for a variety of soils and land uses/vegetation in the region (Robinson et al. 2010; Silburn et al. 2011; Tolmie et al. 2011; Yee Yet and Silburn 2003). The simplest field method for obtaining deep drainage rates and thus maximum potential groundwater recharge is the soil chloride method. A disadvantage of this method however is that it is representative of long-term processes and does not necessarily yield insight to short-term dynamic processes. In the event of a natural flood event within the project, targeted soil sampling was to be used to investigate the depth of wetting. The lack of natural flood events during the project necessitated the use of a small controlled experiment (wet-up plot – see below) to simulate the influence of inundation. This plot also served a role for a companion project investigating recruitment processes in coolabah (A. Prior, DNRM).

Recharge estimates have also been obtained historically in the LBF using hydrogeochemical approaches. Herczeg (2004) estimated median recharge to be 0.25 mm/yr (range of 0.05 – 4.5 mm/yr) for the upper alluvial aquifer. Kellet et al. (2004) suggested that floods would play a role in localised recharge via exposed sand ridges and that there was some evidence upstream of Whyenbah of bed recharge. Herczeg (2004) observed that lower salinity groundwater's (Cl <5000 mg/L) were the most depleted in $\delta^2\text{H}$ and $\delta^{18}\text{O}$ and may be indicative of flood recharge rather than diffuse recharge. Dating by Herczeg (2004) suggested a wide range in percentage modern carbon

for the upper aquifer and in general the shallowest waters had the greatest percentage of modern carbon. Overall, the existing data and knowledge suggests that apart from localised areas of more permeable soils, recharge (either from rain, in-channel flow or flood) on the LBF is limited, primarily by the low permeability of the clay soils that dominate the floodplain.

6.2 Methods

Field-based methods of investigation comprised a small simulated flood plot, coring of stream beds after a flow event, coupled with profile data obtained while investigating detailed plots and riparian transects. Modelling approaches were used to investigate the possible recharge behaviour of sand ridges. Spatial data concerning the spatial extent of a number of historical floods was then coupled with recharge estimates and a number of assumptions, to provide a spatial and volumetric estimate of recharge across the LBF.

Infiltration determination (wet-up plot)

A small wet-up plot was used to determine the depth of infiltration of water on a typical soil profile of the floodplain. The plot was the second used in the project – the first was at the Euraba GV site and used to wet a profile for sampling of cores used in a tree root growth experiment (Prior et al unpub). The area selected for this infiltration experiment was in an *Astrelia* spp. grassland between Dirranbandi and Hebel. A grassland site was chosen in order to avoid influences of tree water use. Vegetation in the plot was killed with herbicide and a wet-up installation created according to the methods of Dalglish and Foale (1998). In brief, water tanks were used to create a constant supply to drippers installed under hessian covered with plastic for a period of 40 days. Approximately 15 500 L was applied to the area (equivalent to 765 mm rainfall). The wetting process resulted in surface runoff from the plot. Interestingly, large cracks were still present after wetting, although they were full of water (Figure 86), which contrasts with the general theory that cracking clays fully swell and all cracks close upon saturation.

The site was sampled for standard soil chemistry (outside the plot). Soil moisture sampling commenced at day 0, which was about 1 day after the cessation of the water supply. The monitoring period spanned from April to December 2016, with more frequent sampling in the earlier part. Rainfall data was obtained from the nearby Euraba Rd weather station. Soil moisture monitoring comprised soil moisture sensors installed at three depths (0.05m, 0.2m, 0.3m), EM38 measurements and replicated cores. Cores were sampled for gravimetric water content, bulk density and water potential and all core holes were backfilled with bentonite to prevent preferential drying or water entry. All bulk density values over time were averaged to create a single bulk density profile for the site, which was used to calculate total porosity and volumetric water contents. Comparative cores were obtained outside the plot, particularly after a natural wetting event associated with heavy rainfall, approximately halfway through the monitoring period.



Figure 86 Soil surface of the wet-up plot at day zero of sampling, with open cracks still evident

River-beds and riparian zones

The knowledge gained from the artificial wet-up plot was supplemented by opportunistic sampling of river beds associated with the riparian zone vegetation transects. Coring to validate the geophysical data was timed to occur just after a bank full flow event (November 2016). Channels cored varied from clay rich ones at Ballandool River and Briarie Creek to sand rich ones at Toobee Creek and Balonne Minor. Physical properties, chemistry and water content data provided insights to the relative differences in recharge through the riverbeds.

Modelling sand ridges and spatial recharge estimates

Spatial estimation of recharge across the LBF was undertaken by application of long-term deep drainage values to the revised land system mapping for the Queensland section of the LBF (

Table 11). This approach did not explicitly consider inundation as the deep drainage values used were primarily rainfall derived, thus areas such as river channels may be under-estimated.

Table 11 Recharge rates used for each land system

Land-system	Description	Soil	Recharge rate (mm/yr)
28	Sand ridges	Sand (Tenosol)	5.0
29	Box mulga alluvial plains	Texture contrast (Sodosol)	0.2
30	Box/leopardwood	Texture contrast (Sodosol)	0.2
31	Coolabah open woodland	Moderately sodic cracking clay ('Good' grey Vertosol)	0.5
32	Black box	Very sodic cracking clay ('Bad' grey Vertosol)	0.1
33	Coolabah/lignum	Less sodic cracking clay (Black Vertosol)	1.0

At the landscape scale, the role of flooding in terms of shallow groundwater recharge is controlled by the nature of the soil and topography. While the majority of the floodplain is clay dominant, sand ridges (LS28) are a significant feature. It is known that in some areas, sand ridges may be partially or fully inundated by overbank floods, thus they may be a localised episodic source of a large amount of recharge. The potential for this was evaluated using Hydrus modelling of a 'typical' sand ridge (conducted by E. Dafny, USQ).

Three conceptualisations of sand ridges were utilised – a sand ridge overlying clay, a sand ridge that penetrates into the surficial clay a short distance (2m) or a larger distance (5 m). Four synthetic time series were used to simulate inundation depths of 0.25m to 3 m with durations of 3-16 days. Vegetation water use during model runs was set to zero.

The absence of a flood inundation model for the whole of the floodplain causes difficulty with determining the spatial extent of inundation of sand ridges. Consequently, an estimation of maximum potential groundwater recharge through sand ridges was obtained by assuming that all mapped sand ridges were of the 'deep' form and intersecting these with the mapped extent of a series of floods in the 1990s. A 0.25 m flood depth scenario was utilised. The full methodology is provided in Dafny (2016).

6.3 Results

The following provides a summary of results for each methodology. Discussion in the context of the research questions is provided in a subsequent section.

Wet-up plot

The soil profile at the wet-up plot was typical of Vertosol profiles in the semi-arid inland of Queensland, and consistent with existing data for Vertosols on the LBF. Clay content was 50-55% throughout the profile but declined with depth (Figure 87a). The soil displayed characteristic features of a pH inversion (Figure 87b) and a distinct salt bulge (Figure 87c) associated with both chloride and gypsum – attributes common to Vertosols in the region. Chloride peaked at 1880 mg/kg by a depth of 0.75 m (Figure 87d) and only displayed a slight decline with depth. Exchangeable sodium percentage (ESP) was 20-30% for the majority of the profile.

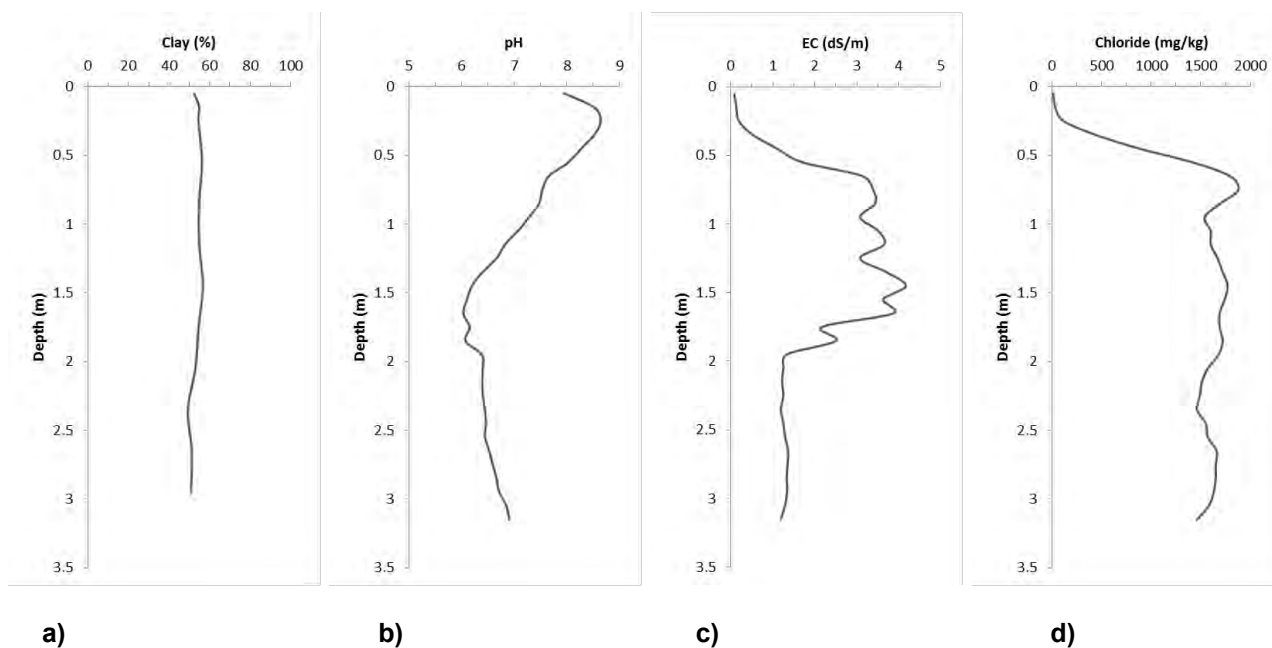


Figure 87 Clay content, pH, electrical conductivity and chloride in the wet-up plot profile

Steady state deep drainage calculation

The steady state deep drainage (USSSL 1954) rate at the site was calculated using the peak chloride value within the profile, the annual average rainfall for Hebel and a chloride concentration derived from the equations of Biggs (2013). The value derived was 0.16 mm/yr, consistent with the observations of other authors on similar soils in the region.

Soil water monitoring

Soil water monitoring of the wet-up plot produced results that confirmed historical field observations and pedological principles i.e water movement to depth was constrained and the initial wetting front correlated to the salt bulge in the profile. At commencement of the wetting up phase the soil was very dry (visibly cracked), and the soil outside the plot remained this way until after the cessation of wetting (little rainfall fell in this period). Water content at day 0 and day 8 outside the plot was very low and may be regarded as equivalent to a crop lower limit i.e grassland lower limit (Figure 88a).

The applied water was sufficient to raise the water content to visible saturation for the upper part of the profile and initial sampling revealed a very abrupt visible boundary (<5 cm) between near-saturated soil and dry soil at about 0.75 m. Water content data indicated that the upper 0.3 m of the profile was not at saturation (Figure 88a). This is most likely a result of drying down of the profile in the day between cessation of water application and sampling. The plot contained a slight

slope (~0.1%) resulting in surface water flowing out the southern side. Samples were taken from the upslope end of the plot.

Comparison with calculated total porosity suggests the profile was at or very near saturation between 0.3 and 0.5 m depth (making an allowance for non-water filled porosity and measurement error). The lower boundary of the wetting front did not extend beyond 1 m, which corresponds with the base of the uppermost chloride bulge. Subsequent samplings showed a general decline in water content in the profile (Figure 88b) until September.

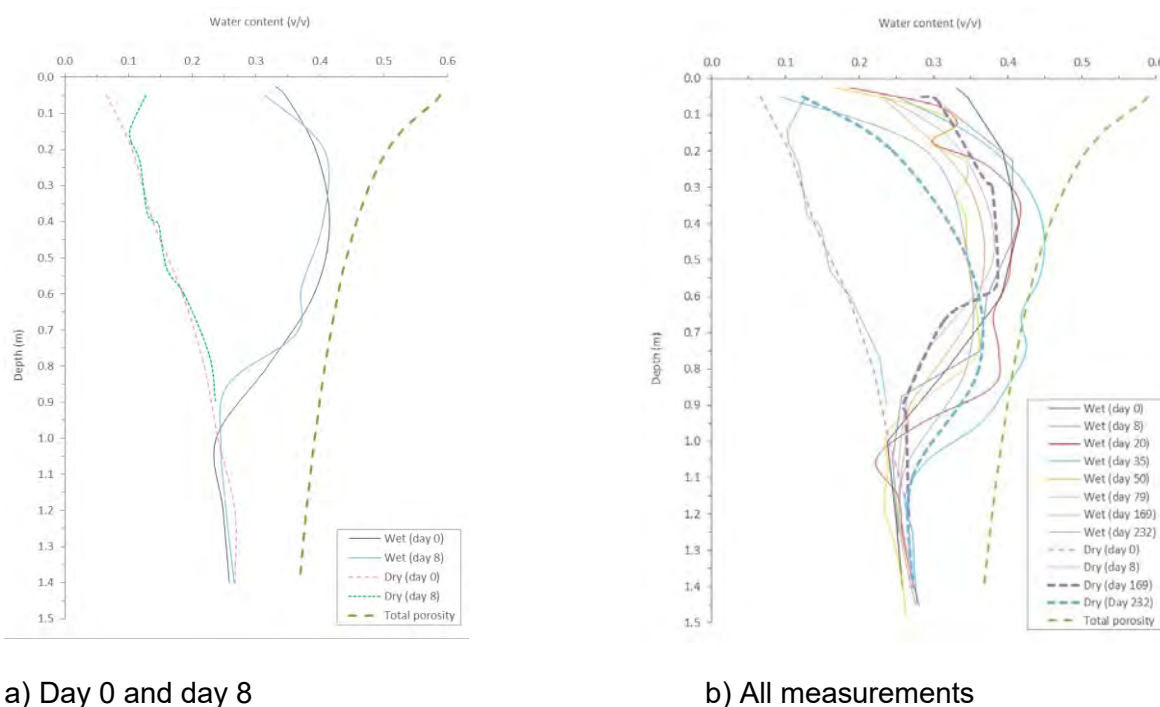


Figure 88 Soil water content over time inside (wet) and outside (dry) the wet-up plot

A large rainfall event occurred in September 2016 resulting in ponding of the surrounding landscape for a period of at least a week. This natural wetting event encompassed both the plot and the surrounding soil. The effect outside the plot was equivalent to that experienced in the wet-up plot. Despite the pre-wet status of the plot, the rainfall did not however contribute to a downwards shift in the wetting front within the plot. This suggests that water input is not the limiting factor to deep drainage (and thus recharge) – rather it is internal factors, most likely to be sodicity and porosity related. The base of the wetting front i.e the point at which the water content in the wet-up plot matched that in the dry zone, was between 1 m and 1.2 m in all cores over the whole sampling period. Overall, the data supported prior knowledge regarding the limited extent of infiltration in sodic Vertosols, even under ponded conditions.

River-channels and riparian zones

Cores were taken in the riverbeds of the Ballandool River, Briarie Creek and Toobee Creek transects. All were taken within 1 week of cessation of a flow event. Both the Ballandool River and Briarie Creek channels were dry, with the exception of the upper 1m. The Toobee Creek channel was however saturated to the depth of coring (12 m). The Ballandool River and Briarie Creek were generally clay rich (20-60%) whereas Toobee Creek was sandy (<20% clay). Chloride

profiles indicated leaching occurs in the channels, more so in Toobee Creek than in the other streams – consistent with the difference in clay content.

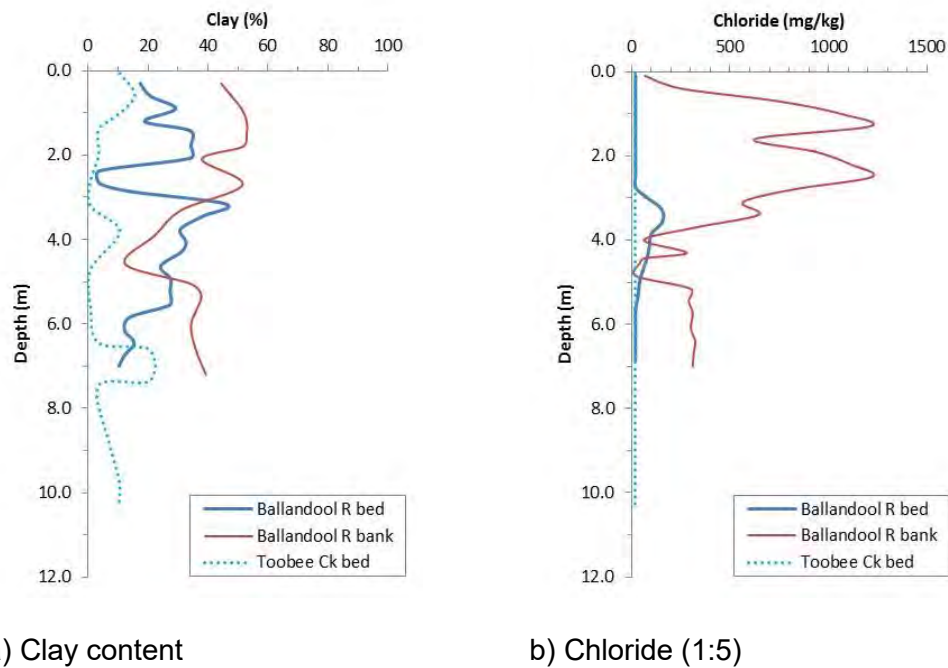


Figure 89 Clay content and chloride concentration in Ballandool River and Toobee Creek channels

Geophysical data and coring indicated that the Ballandool River (Figure 90) and Briarie Creek (Figure 91) overlay contiguous clay deposits to a depth of at least 25 m, thus any river bed recharge is unlikely to create a significant aquifer. Toobee Creek however overlies large semi-contiguous sand deposits, which would enable good recharge of groundwater. The depth to an aquifer is inferred to be 20-30 m, thus it may be beyond the extent of root penetration from trees.

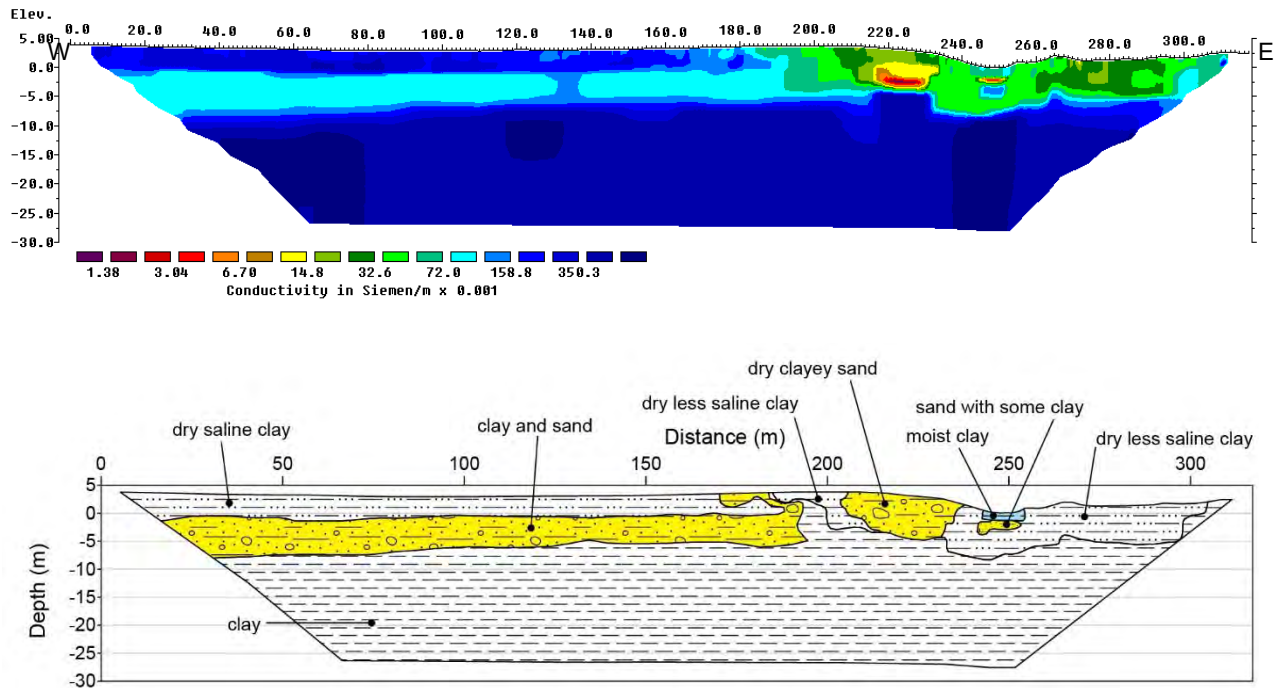


Figure 90 Briarie Creek ERT image and interpretation

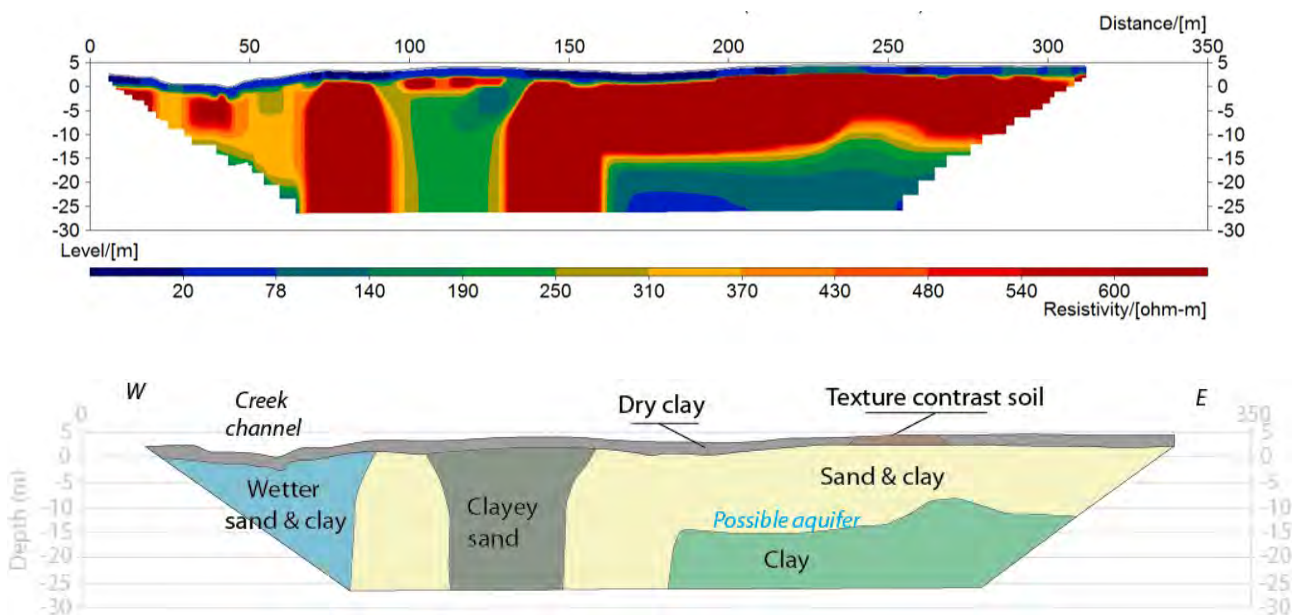
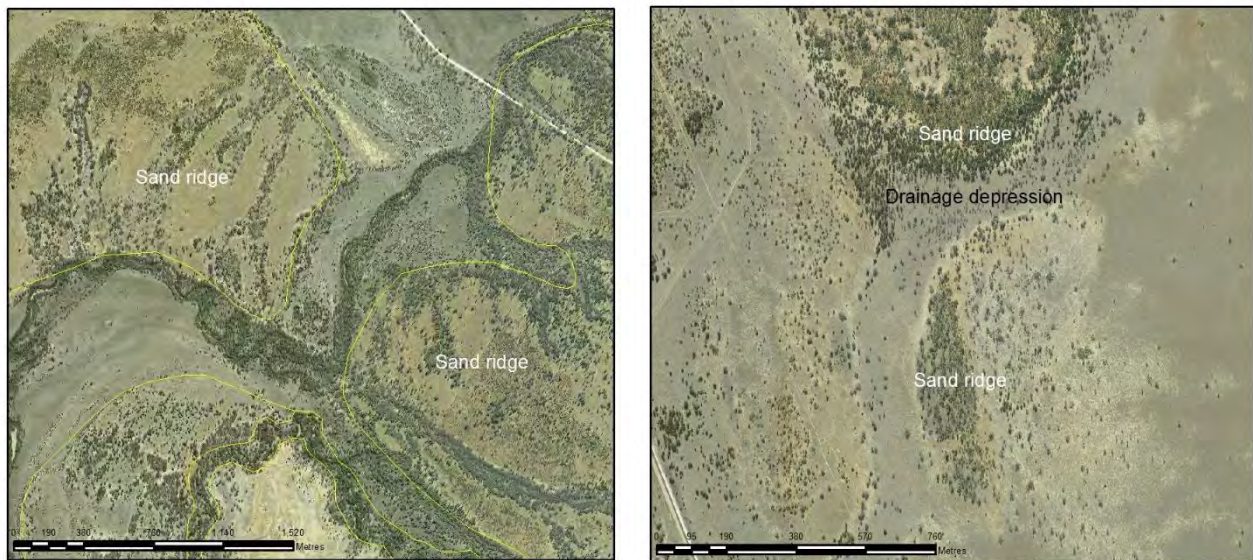


Figure 91 Toobee Creek ERT image and interpretation

The Toobee Creek transect and Balonne Minor transects were similar in that they both consist of extensive sand deposits under a surficial Vertosol, but they have quite different vegetation patterns. Despite the apparently good bed recharge at Toobee Creek, the riparian vegetation zone was very narrow. It may be the case that recharge is generally confined to the creek and the predominant direction of flow is vertical rather than lateral. At the Balonne-Minor, the topographic, regolith and vegetation patterns suggest that there is good connectivity of the sand lenses to the river channel at the upstream end of the meander bend. This connectivity appears to be lacking at

Toobee Creek. The only area where there may be a shallow aquifer present is under the sand ridge at the eastern end of the transect, where water may potentially perch on clay present at about 15 m depth. If present, this aquifer would most likely be recharged by rainfall and very large floods rather than from the riverbed.

It appears that lateral groundwater recharge in most parts of the LBF is limited by the high clay content of river banks e.g the Ballandool River and Briarie Creek. However, channels and drainage depressions cutting or adjacent to sand ridges are not uncommon in the LBF (Figure 92), particularly in the eastern third and the upper reaches. Areas such as this yield sand for re-deposition in meander bends as well as being local recharge points. Sand ridges on the backplains frequently have drainage depressions immediately adjacent (Figure 92b), which can lead to localised recharge on the margins of the sand ridges when the drainage depressions fill. Some low sand ridges, such as the Euraba SR site, can be fully inundated in very large flood events. It is evident that sand ridges may play an important role as local preferential recharge zones. The potential for this within the LBF has been further evaluated below.



a) Sand ridge cut by a major channel

b) Backplain sand ridge cut by a drainage depression

Figure 92 Examples of sand ridges that are likely to be partially inundated by floods

Modelling sand ridge recharge and spatial recharge estimates

Application of deep drainage values from

Table 11 to revised land systems mapping indicated that the majority of potential recharge across the LBF occurs in the sand rich areas of LS28, despite them occupying only 14% of the LBF area (Table 12). This estimate only accounts for rainfall recharge – the value may be greater where sand ridges are inundated by overbank flooding.

These estimates are highly sensitive to the recharge rates selected. For example, the upper aquifer recharge range determined by Herczeg (2004) was 0.05-5 mm/yr representing a range of

two orders of magnitude. Extrapolation of such magnitude across all land system units in the LB will result in recharge estimates of 450 ML to 44,920 ML/yr.

Table 12 Rainfall recharge estimation by land system

Land system	Area		Recharge	
	[Km ²]	%	[ML]	%
Sand ridges (28)	513.4	14.4%	2560	57.0%
Box mulga alluvial plains (29)	0.45	<0.1%	0.9	<0.1%
Box/leopardwood (30)	452.7	12.7%	90.5	2.0%
Coolabah open woodland (31)	1,342.3	37.7%	671	14.9%
Black box (32)	96.6	2.7%	9.6	0.2%
Coolabah/lignum (33)	1,160	32.5%	1160	25.8%
Other	22.6	<0.1%	***	***
Total:	3,588	100%	4492	100%

The Hydrus modelling revealed that the depth to the impeding clay layer is the key determinant of the quantity of recharge achieved. For a scenario of a thin surfaced sand ridge over clay, infiltrating water does not recharge aquifers as the constraint to recharge is the clay. Water is likely to perch on the clay and potentially be utilised by vegetation (although vegetation water use was not included in the model). In the case of the thickest sand ridge, recharge was only limited by the hydraulic conductivity of the sand. Sufficient recharge can occur to result in lateral flow of water and recharge of the surrounding regional aquifer.

An estimate of recharge through all sand ridges using the deep sand inundation scenario was obtained (Table 13) for the spatial intersection of 1990s mapped flood events and LS28. This estimate is of course sensitive to the assumption of flood depth and duration as well as the infiltration rate. It does reveal however that substantial recharge may potentially occur via flood inundation of sand ridges – values are equal to or greater than those derived from a rainfall source. These values do not of course represent actual recharge to an aquifer, as losses occur in the unsaturated zone. More accurate values could be obtained with an appropriate dynamic flood inundation model coupled with estimates of unsaturated zone losses.

Table 13 Estimated recharge through sand ridges from 1990's floods

Year	Inundated LS28 area [km ²]	Estimated deep infiltration [ML]
1994	29.25	2039
1996	218.64	15,243
1997	38.51	2685
1998	45.31	3159
1999	31.15	2172

6.4 Discussion

Data and modelling from this project confirms that groundwater recharge across the majority of the LBF is generally low – due to the dominance of sodic Vertosols in the landscape, and the limitation they impose to infiltration and deep drainage of water, whether it be from rainfall or flood sources. New knowledge has been generated however, regarding bed recharge and the presence/absence of shallow aquifers adjacent to rivers. On-going investigations at the Balonne-Minor and Whyenbah transects will further clarify recharge processes and surface water/groundwater interaction at those sites. Investigations at Euraba Rd and floodplain scale recharge estimates have also highlighted the relative importance of sand ridges as preferential recharge zones. The degree to which localised recharge spreads laterally to shallow aquifers underlying coolabah communities remains unknown and will only be clarified by extensive field investigations and long-term monitoring.

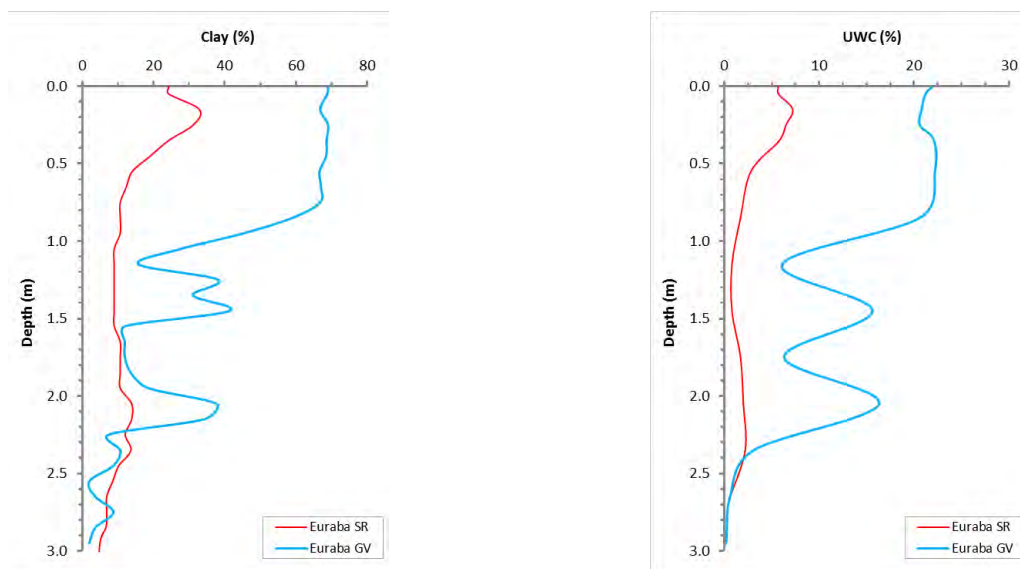
The difference between clay and sandy soils warrants further discussion as it relates to one of the underpinning GDE models for the LBF i.e that sand ridges are likely to possess groundwater accessible to trees. This was one of the reasons for selection of the Euraba pair of sites. The conceptual model was based on field evidence from historical and more recent drilling in sand ridges in the LBF. Shallow to moderately deep aquifers are known to sporadically exist in sand ridges and the hypothesis was that the vegetation (specifically the presence of large Moreton Bay ash) may be indicative of which sand ridges do or do not possess shallow aquifers. The Euraba SR site contained a grove of Moreton Bay ash on the western side – the coolabah inhabited the centre and eastern side of the ridge. Drilling found moist sand at depths to 17 m, overlying clay, but no aquifer was observed. This suggests that the conceptual model may not be entirely accurate. An alternate reason must be proposed therefore for the presence of large trees on the Euraba SR site and more generally on sand ridges. As alluded to earlier in this report, consideration of soil water entry and movement may propose an explanation. Sandy soils have a number of advantageous features in semi-arid environments where a large proportion of rainfall events are small and evaporation is high. These advantages are a function of high infiltration, high hydraulic conductivity to depth and a proportionally high water availability.

Starting at the soil surface, sandy soils have a high water entry rate compared to the Vertosols more common on the LBF. Vertosols do of course have a high propensity for macropore (crack) mediated water entry if the soil is dry and the rainfall event is of high intensity, but such high water entry rates are only a feature for a short period of time (Gardner *et al.* 1987). When rainfall events are small (<20 mm) and Vertosols are dry, the depth of infiltration is often limited to the upper 10-20 cm, which is likely to be shallower than the depth of most tree roots. While there is a general understanding that in drier environments trees and shrubs tend towards dimorphic root systems, the proportion of functional tree roots in the upper 10 cm of a cracked, dry Vertosol is likely to be low due to high soil surface temperatures and the presence of large voids. Jackson *et al.* (1996) observed that in drier environments, vegetation puts a greater proportion of roots below 30 cm depth. Hamer *et al.* (2016) noted differing root architecture in Eucalypts from sandy soils versus those from finer textured soils – this may also be a factor in the Lower Balonne. There is little knowledge regarding root depth for tree and shrub species in the LBF but it is reasonable to assume that most species are unlikely to have active roots in the upper 0.2 m of Vertosols during very dry periods and it is during such dry conditions that a greater proportion of incident rain is involved in re-hydration of swelling clays, and therefore not fully available to plants.

The long-term climate data (SILO 1889-2014) for the Euraba Rd site suggests that 74% of rainfall days recorded an amount less than or equal to the long-term daily evaporation value (6 mm).

About 96% of rainfall days recorded a value ≤ 25 mm. The data thus indicates that the majority of rainfall events are small, therefore the likelihood of the events being of little value to plants on Vertosols is high. This was observed at the Euraba Rd sites during 2015, when most rain in summer/autumn fell as events <25 mm. There was a large response in groundcover on sand ridges but little change on the surrounding Vertosol. Cumulative small rainfall events are also less likely to be functional on Vertosols as initial events lead to surface swelling/sealing and the infiltration of subsequent events is significantly reduced.

The accessibility of water once it enters a soil is of key importance. While cracking clays store more water than sands, a greater proportion of this is harder for plants to access due to the small pore size and consequential high matric potential in clays. This attribute is generally explained using the concept of the unavailable water content (UWC)³. The UWC is lower on sandy soils than clay soils, thus for smaller rainfall events, there is a greater proportion of rainfall available on sandy soils. This can be illustrated using the data from Euraba Rd (Figure 93) which shows a large difference in the unavailable water content between the Tenosol on the sand ridge and the adjacent Vertosol.



a) Clay content

b) Unavailable water content

Figure 93 Clay content and unavailable water content (UWC) at Euraba Rd sites

Once water enters the profile, the rate at which it moves downwards is important. The higher permeability of sands means that any given rainfall event infiltrates further into the soil compared with clay soils. This means that a greater proportion of incident rain infiltrates beyond the effects of evaporation and shallow roots. Overall, the result is that on sandy soils, a greater proportion of small event rainfall is accessible to plants. This concept is well known in cropping systems locally and more broadly (Noy-Meir 1973).

If the majority of roots associated with grasses, forbs, shrubs etc are in the upper few metres of the profile, then rapid downwards movement of water is potentially advantageous to vegetation with a deeper root system. The coring and geophysical investigations at Nelyambo suggested the primary zone of water extraction was the upper 3 m of the soil profile. Observations of roots >5 m depth and up to 12 m depth have been made in the LBF and the Border Rivers floodplain to the east. The saturated hydraulic conductivity of sands is typically estimated at one or more orders of

³ Difference between air dry moisture content and lower limit (represented in this case as the water content at -15 bars)

magnitude greater than in swelling clays, thus for the infrequent large rainfall or flood events that cause a deep drainage event beyond the upper soil profile, trees with deeper root systems will be able to exploit the downwards flux of water before it reaches an aquifer. Such deep drainage events are a more frequent occurrence on sands than on cracking clays in the region (Yee Yet and Silburn 2003).

The presence of shallow aquifers will also be governed by the depth to an aquitard. In areas such as Euraba SR, no aquitard was encountered until 17 m depth, providing a large distance over which trees can utilise any downward flux of water from a deep drainage event. At Balonne Minor, the aquitard was present at ~12 m depth and recharge rates were apparently higher, thus an aquifer was evident. For any given site, the shallower an aquitard, the more likely that deep drainage events are likely to accumulate and create a saturated zone. The discussion above highlights the considerable knowledge gaps that remain concerning deep drainage and the unsaturated/saturated zone and the associated implications for tree water use. Further water balance investigations/modelling should be undertaken to validate the concepts.

6.5 Conclusions

The research questions posed in relation to this section of the project were:

- Do floods recharge the unsaturated zone and shallow aquifers?
- What is the potential rate of shallow groundwater recharge and root zone saturation from flooding in the LBF?

Existing knowledge regarding soils, landscapes and hydrogeology for the LBF suggested that recharge through the majority of the clay rich landscape was likely to be limited by soil profile factors influencing saturated hydraulic conductivity. Consequently, inundation via floods or ponded rainfall was unlikely to cause significant groundwater recharge. Data collected and modelling undertaken further supports this paradigm and suggests that sand ridges are the primary location of recharge (flood or rainfall) in the LBF. While the species of interest (coolabah, RRG, lignum and black box) to this project are not commonly found on sand ridges, communities of these species may be accessing shallow aquifers recharged through sand ridges, particularly where channels cut sand ridges.

Thus the answers to the specific research questions are: yes, floods do recharge the soil water in the floodplain generally and in spatially restricted areas they are likely to recharge the deeper unsaturated zone and shallow aquifers. Recharge events are very episodic in the LBF – a function of the episodic nature of large rainfall events and floods.

The degree to which streambed and sand ridge recharge spreads laterally into intermediate to regional scale aquifers is still poorly understood. Investigation of riparian zone aquifers and surface water/groundwater interaction has validated initial conceptual models but many knowledge gaps still exist in terms of the spatial extent of these systems. The data collected to date does however suggest that vegetation and soil patterns correspond sufficiently to use them to infer the presence of shallow groundwater in riparian zones.

7 Identifying variation in water availability among vegetation communities

Earlier chapters considered vegetation water availability at discrete sites, either remote sensed pixel sites (chapter 4) or through field sites (chapters 5 and 6). The current chapter seeks to scale-up remote sensing data to a larger landscape view to determine if the concepts underpinning the conceptual models are supported at larger scales. This was done by comparing remote sensed data of vegetation characteristics of floodplain and riparian communities, including both greenness and structural characteristics (tree height).

7.1 How does vegetation greenness vary between different communities?

Using remote sensing techniques, we correlated vegetation response, as defined by the seasonal greenness metric (see section 4.2.1) with total rainfall within the season. The aim was to see whether it explained variation in vegetation response at the landscape scale. We also assessed variation between those communities based on their access to water (using the model zone classifications and also a tight riverine buffer used to define a 'fringing' zone) as a surrogate for potential accessibility to surface water sources.

As in chapter 4 (section 4.2.1), areas identified as potentially groundwater dependent (Appendix 1) were excluded from the analysis.

7.1.1 Methods

Defining landscape analysis units

We used the primary landscape classification within the project (as defined by vegetation and model zone mapping) to delineate specific landscape analysis units for the different vegetation communities across the study area. An additional 'fringing zone' was included as a specific landscape analysis unit as a subset of model zone 1 to include a single Landsat pixel width (i.e. 30m) either side of the watercourse. This spatial break was introduced to delineate 'one tree width' riparian vegetation communities which are considered to have their 'toes in the water' and are likely reliant on in-channel surface water. Twenty-eight asset combinations (landscape analysis units; see Table 14) were identified based on the asset/model zone/riverine across the study area (see Appendix 1).

The landscape analysis units were further refined by filtering using 'woody vegetation binary extent mapping' derived from the LiDAR data (Appendix 1). This process restricts the data set to only include areas within those polygons where a sufficient tree-canopy exists.

Landscape scale greenness and rainfall correlations

Using the same greenness and rainfall products as used in the pixel scale analysis (section 4.2.1) a zonal analysis was conducted to produce a time-series of mean greenness and total rainfall for each landscape analysis unit.

A linear regression was then applied to attempt to determine whether total seasonal rainfall did explain greenness at the landscape scale. In-season total rainfall was the only variable assessed at the landscape scale (as compared to lagged rainfall and other climate variables such as evaporation/deficits as were used within the pixel based analysis – section 4.2.1). This was due to

resource constraints to produce and summarise these data sets at the landscape analysis unit scales.

The outputs included the model co-efficient applied for each analysis unit, the best fitted values, the upper and lower 95th percentile confidence intervals, and the adjusted R^2 .

Statistical significance tests (including ANOVAs, F tests and student's t- tests) were also conducted (using the Microsoft excel data analysis package) to test for differences in average greenness values between landscape units grouped to model zones and also for grouped model zones excluding riverine units.

7.1.2 Results

Regression coefficients (R^2) are given for averaged seasonal greenness against averaged seasonal rainfall, and average seasonal greenness values for each landscape analysis unit are shown (Table 14). Averaged figures for each model zone (the mean of the mean greenness for landscape analysis units within each zone) are shown in Figure 94.

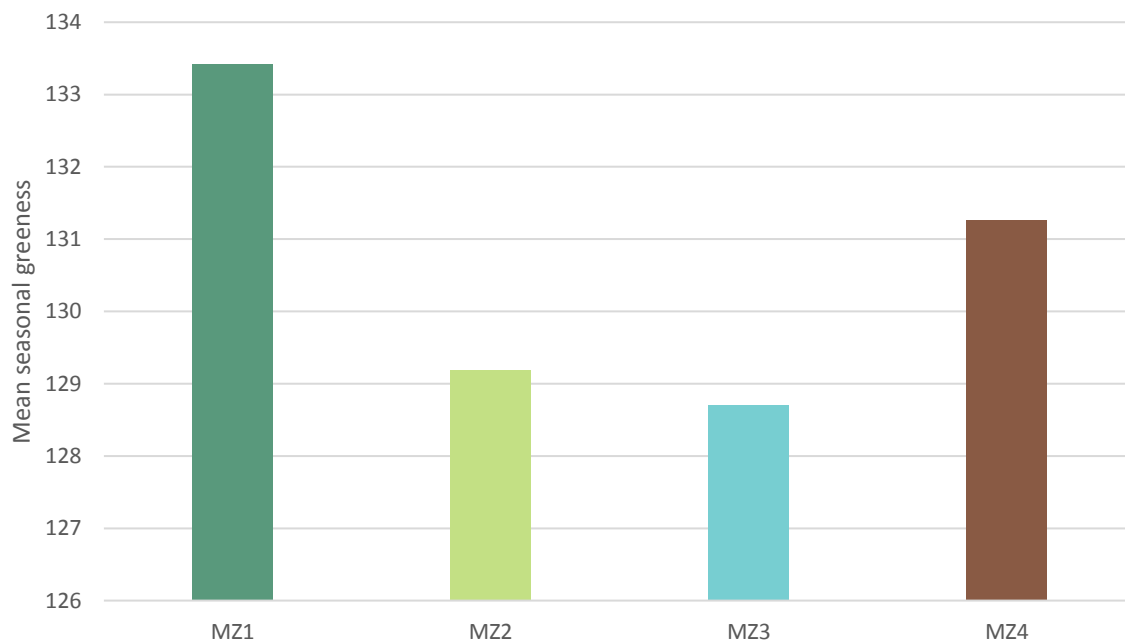


Figure 94 Mean greenness for each model zone, aggregated from landscape analysis units within each zone.

Results of the ANOVA show a slight statistical difference in mean greenness between different model zones ($p = 0.038$). When only the non-fringing floodplain landscape analysis units (i.e. those purely on the floodplain) are grouped to model zones and compared there was no statistical difference between the means ($p = 0.29$). Student's t-tests confirm that the greatest variation was explained by the difference between mean greenness of the fringing and non-fringing units within model zone 1.

Table 14 Landscape analysis unit attributes, area, average greenness value and regression coefficients between seasonal greenness and seasonal rainfall

Model zone	Vegetation species/combination	Fringing	Area HA	R ²	Average Greenness
1	coolabah	No	24,213	0.06	133.20
1	coolabah	Yes	4,587	0.02	135.54
1	coolabah and lignum	No	339,608	0.10	127.32
1	coolabah and lignum	Yes	24,791	0.04	132.14
1	coolabah and river red gum	No	13,697	0.03	135.70
1	coolabah and river red gum	Yes	4,600	0.02	140.88
1	coolabah, river red gum and lignum	No	1,523	0.02	132.52
1	coolabah, river red gum and lignum	Yes	508	0.01	134.83
1	lignum	No	1,974	0.06	129.05
1	lignum	Yes	1,418	0.05	128.37
1	river red gum	Yes	30,219	0.03	138.11
2	black box and lignum	No	56,625	0.04	126.49
2	coolabah	No	45,949	0.08	128.48
2	coolabah and lignum	No	704,589	0.11	125.98
2	coolabah and river red gum	No	10,318	0.06	130.57
2	coolabah, river red gum and lignum	No	1,033	0.03	133.75
2	lignum	No	1,628	0.07	126.50
2	river red gum	No	1,343	0.04	132.52
3	black box and lignum	No	6,408	0.05	126.99
3	coolabah	No	24,310	0.12	129.76
3	coolabah and lignum	No	159,027	0.16	127.48
3	coolabah and river red gum	No	4,871	0.07	130.02
3	lignum	No	170	0.01	129.25
4	coolabah	No	14,810	0.10	132.71
4	coolabah and lignum	No	30,957	0.07	130.68
4	coolabah and river red gum	No	3,634	0.04	134.60
4	lignum	No	71	0.05	126.47
4	river red gum	No	175	0.03	131.87

7.1.3 Discussion

The relationship between rainfall and greenness was not supported at the landscape scale based on the regression analyses undertaken. All the landscape analysis units had very low regression coefficients that suggest the rainfall metric used is not explaining the variation in greenness at this scale. This is thought to be a consequence of aggregating the data (both the rainfall and greenness of vegetation data sets) to the landscape scale. For instance, there will be significant temporal and spatial (e.g. latitudinal and longitudinal differences) variation in rainfall across the study area, and thus combining this into a single value for a landscape analysis unit (which is comprised of many polygons spatially spread across the study area), is likely to mask the variation in the data. The LBF is relatively large, with variation in rainfall between the north and south (Figure 25), and particularly between east and west (see 4.2.4), thus likely to exhibit significant variation at scales that are difficult to discern when amalgamated.

Similarly, the vegetation response, which is likely to respond to rainfall (as was supported by the more targeted pixel scale analysis), will vary significantly across the landscape, particularly for differing species. The aggregation of vegetation response data is likely to result in 'data smoothing' whereby variation which is likely to be present at a smaller scale is masked by averaging. For example, areas delineated as the same model zone in east and west may receive significantly different amounts of rainfall at the same time, introducing an enormous amount of noise into any tree response signal when aggregated.

Average greenness values between the landscape analysis units shows the highest values in model zone 1 (which is the nearest to the channel and a surface water source) and decreasing away from the channel across model zones 2 and 3 which might be expected due to distance from water sources and a clay dominated landscape limiting groundwater access. It is possible that the greenness signal is driven entirely by the true 'fringing' zone, which was found to be 'greener' than the rest of the floodplain, although this does not explain the relatively high greenness value for model zone 4. Model zone 4 displays the second highest overall greenness which could be as a consequence of access to groundwater through the sand ridge environment this model zone represents. This may align with the distribution and extent of GDEs across the area, although it is recognised that again the large scale aggregation of data is likely to lead to potential sources of error. However, an analysis of distributions of possible GDEs by model zone (Figure 30) shows a similar pattern to average greenness by model zone (Figure 94), suggesting a possible relationship.

7.2 Does variation in landscape unit explain differences in tree height?

We have addressed this question by using the tree height information from LiDAR capture across the study area in relation to distance to surface water sources (as defined by model zone) for all landscape analysis units. Our expectation is that a higher availability of water should allow for taller trees.

7.2.1 Methods

We compared tree height information from LiDAR capture using the defined landscape analysis units (see 7.1.1) across the model zones (which were taken as a surrogate for distance to surface water source).

The LiDAR-derived 5m (pixels size) Canopy Height Model (CHM) was filtered to 2m above ground where those pixels that contained maximum canopy heights below 2m were removed, and those pixels that contained maximum canopy heights above, or equal to, 2m remained. A spatial filter was applied to remove isolated pixels and pixel clusters representing less than 10m x 10m, as these canopies were too small for a Landsat pixel to represent its greenness. We used QGIS 2.8.9 for this process.

The outputs included the filtered CHM (with height assigned to every pixel) as well as a 'Woody Vegetation Extent' product whereby the filtered CHM was converted into a flat, binary (woody vegetation/no woody vegetation) extent layer (see Appendix 1).

The 95th percentile of all tree heights were identified and mapped across the study area. Data were aggregated to the landscape analysis units and frequency distributions of all tree heights above 2m were determined and evaluated. Maximum and average maximum height values were determined for each landscape analysis unit.

Histograms were produced to visualize the proposed relationship between vegetation height (structure) and water availability as defined by model zone/fringing classification for certain landscape analysis units and groupings (coolabah and fringing vs non-fringing are presented). Statistical significance tests (including ANOVAs, *F* tests and Student's *t*- tests) were also conducted (using the Microsoft excel data analysis package) to test for differences in average maximum height values between groups.

7.2.2 Results

There were detectable differences in tree heights (for all trees) between areas directly adjoining the river channel (as defined by the landscape analysis unit with a fringing classification (Figure 95) compared to those further away from the channel on the floodplain (Figure 96). The modal maximum mean height is 15.1m in floodplain trees compared to 20.3m for those classified as fringing. Results also suggest that nearly all the largest trees are present in the fringing zone. There are few trees over 30m present on the floodplain (Figure 96), whereas trees with heights of 30m to 40m are present in the fringing zone (Figure 95).

The 95th percentile of tree heights mapped across the landscape show an obvious association with river channels across the floodplain (Figure 97). This figure has been created using polygon based data set derived from the 5m x 5m LiDAR pixel locations (meaning that each polygon is larger than a 5m x 5m pixel and therefore extents on the map are exaggerated). This was necessary for the data to be viewed at this scale.

An analysis of coolabah tree heights using non-fringing landscape analysis units which consisted of coolabah and coolabah/lignum only (Figure 98) shows a comparable frequency distribution with a modal max height that is not significantly different between model zones. The 'shoulders' present on the left-hand side of the graphs potentially represent either the presence of a smaller tree species (possibly dogwood) or juvenile coolabah from a specific recruitment event (this is hypothesised as potentially extensive flooding that occurred in the area in 1996).

ANOVAs comparing tree height distributions between these groups, and also of all tree species, confirm that there is no statistically significant difference between average or maximum height between model zones away from the riverine zone.

A similar analysis based on coolabah mean height, but using tree height information derived from the individual sampled pixel locations (see Appendix 3), also showed no statistical difference in mean tree height for coolabah communities (Table 15) which were located on the floodplain. Within

the pixel scale analysis there were no defined fringing vs non fringing attribution so this could not be tested.

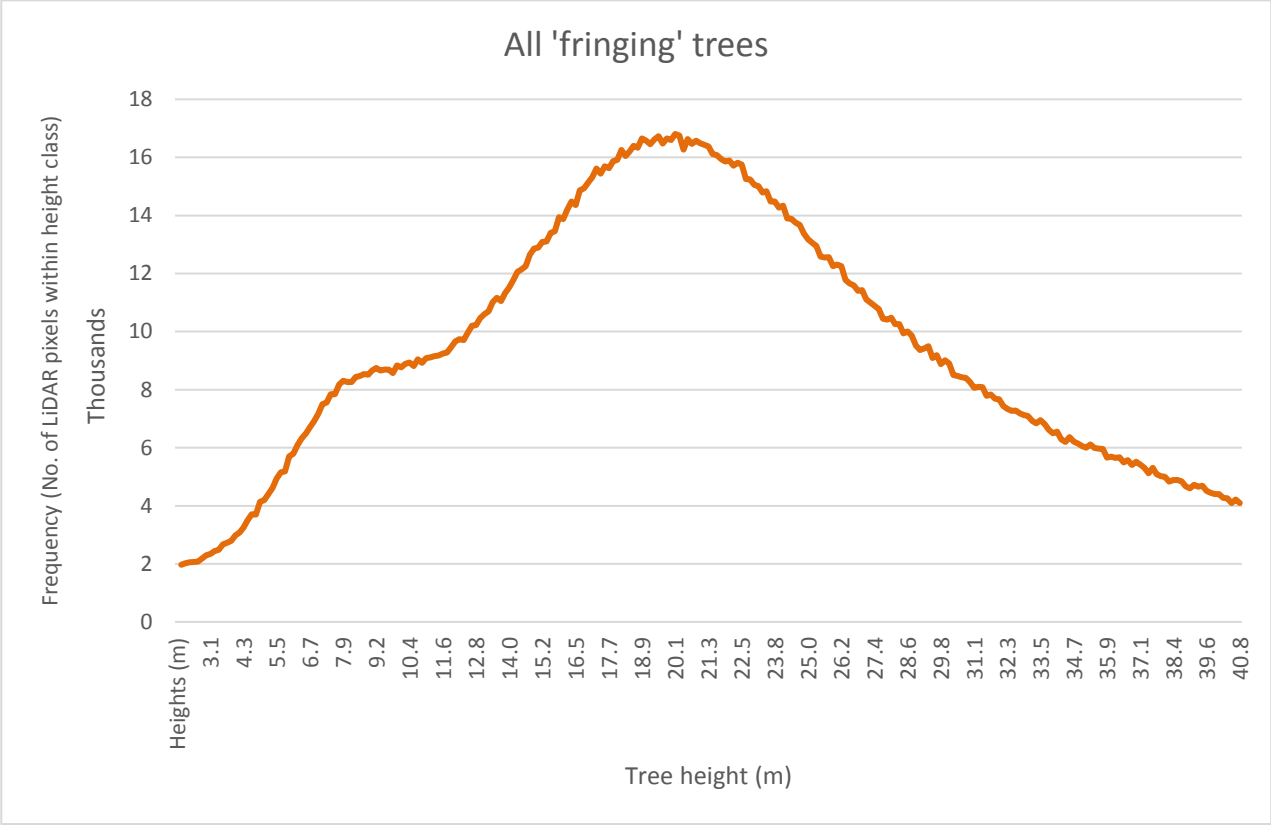


Figure 95 Frequency distribution of tree heights for all fringing areas

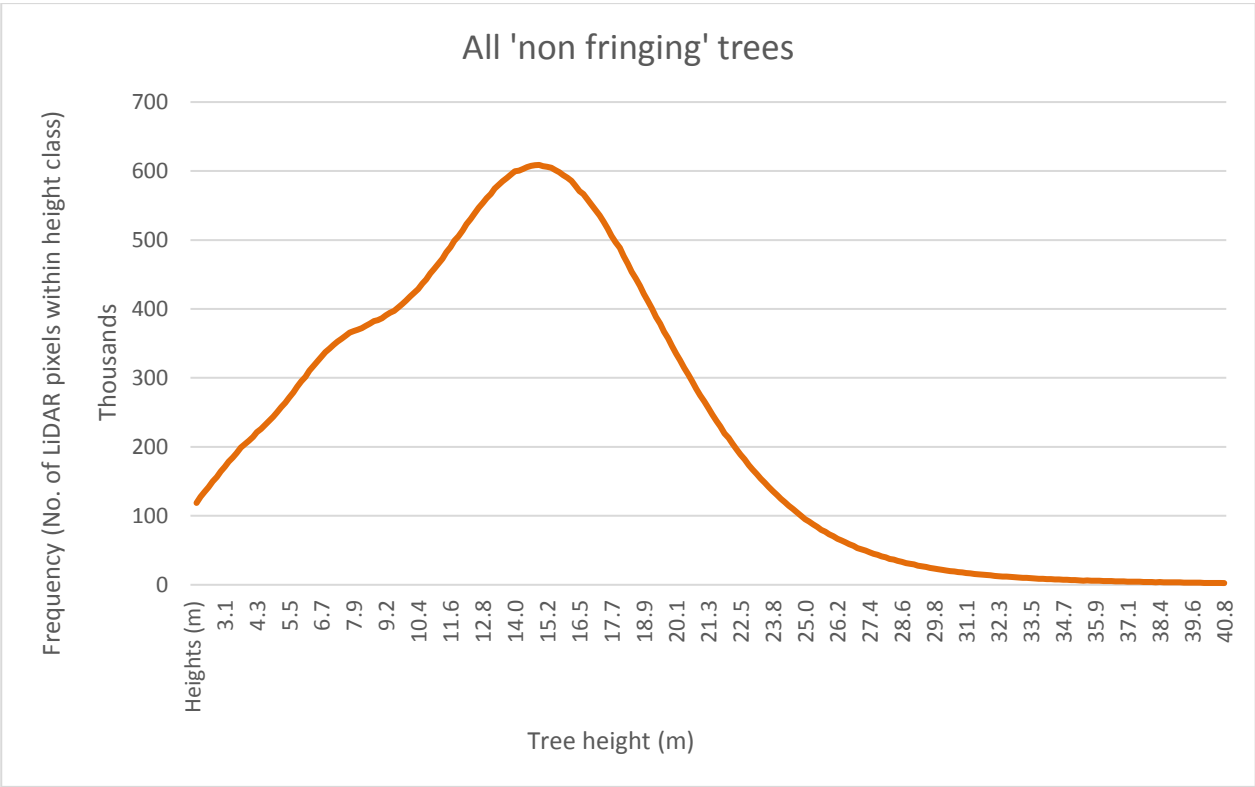


Figure 96 Frequency distribution of tree heights for all non-fringing areas

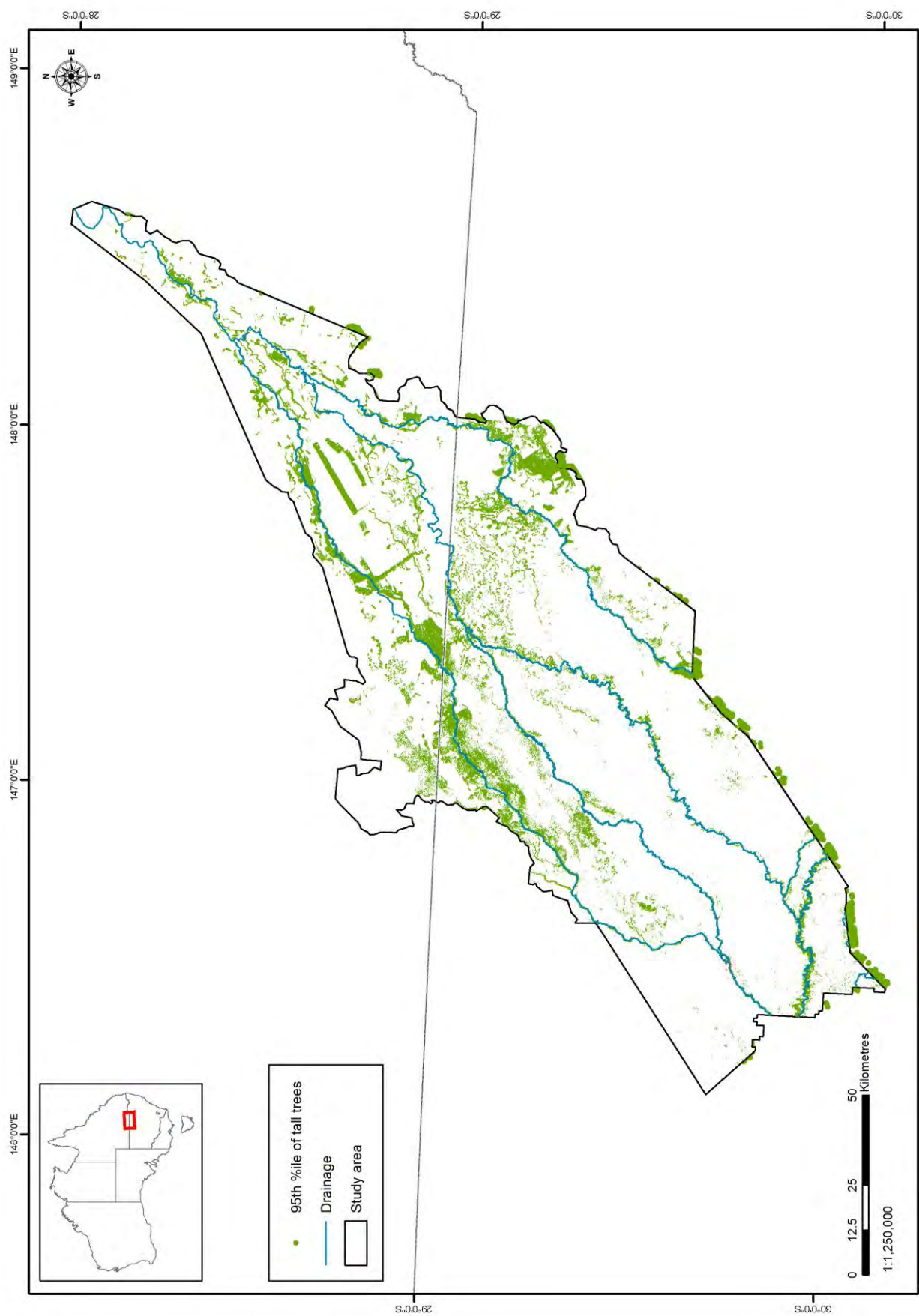


Figure 97 Distribution of tallest trees across the LBF (mapped 95th percentile of tree heights created using polygon data based on LiDAR pixel locations)

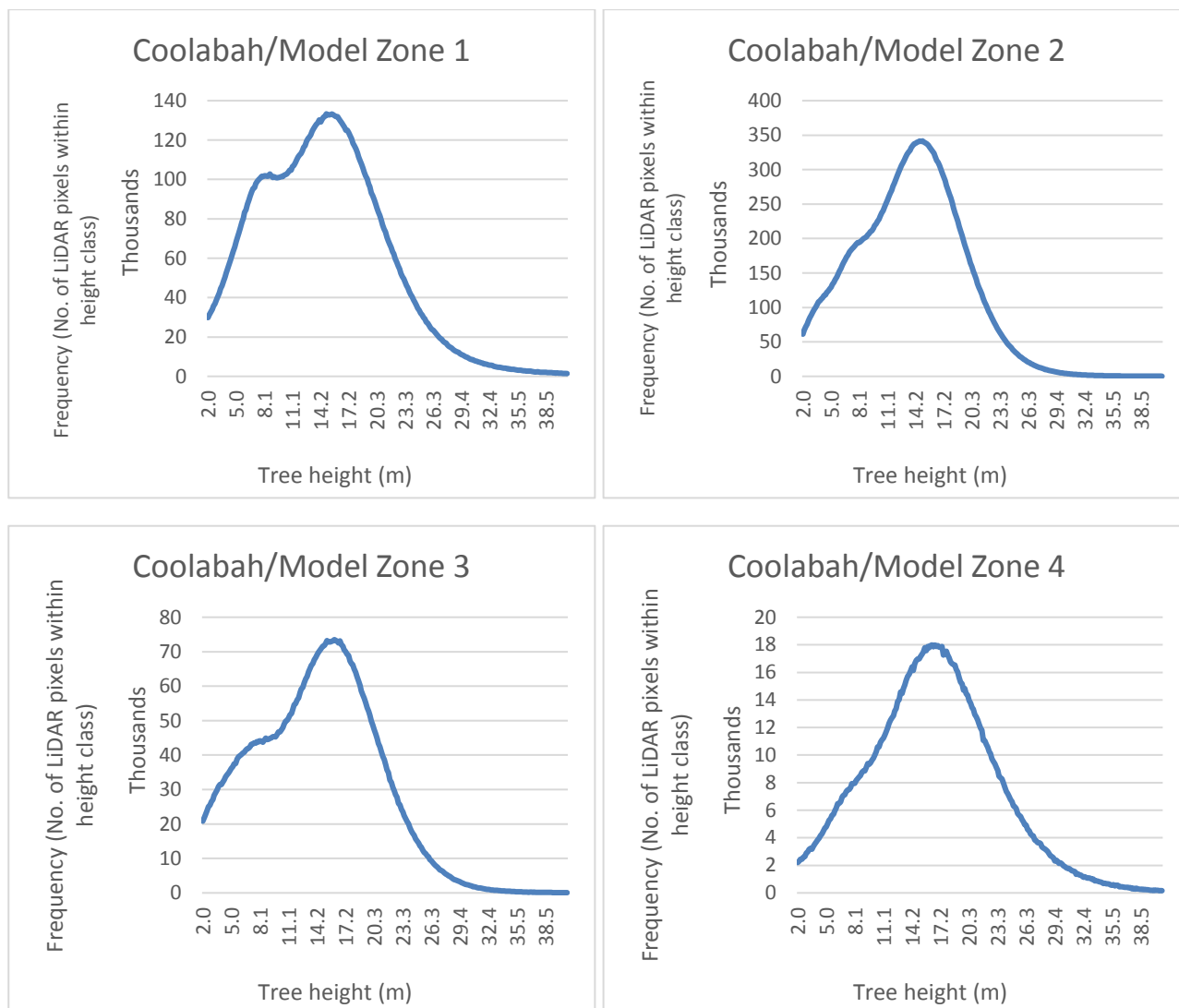


Figure 98 Comparison of coolabah tree height frequency distributions between model zones (for combined coolabah and coolabah/lignum landscape analysis units) showing similar modal maximum height values

Table 15 Mean tree height of coolabah within each model zone (as derived from individual pixel tree height information)

Groups	Count (number of pixels)	Mean height (m)
Model zone 1	74	9.66
Model zone 2	69	9.72
Model zone 3	48	9.54
Model zone 4	28	9.40

7.2.3 Discussion

Results show that the tallest trees are located within the 'fringing' zones and suggests, as expected, that access to a direct and persistent water source, provided by in channel flows, allows trees to grow taller. The maximum height of trees present on the LBF is a finding in itself as part of this analysis. Trees 30m to 40m tall were generally not thought to be present in this region, but the LiDAR interrogation and subsequent ground-truthing verifies the presence of some very large trees (both river red gum and coolabah). These were particularly prevalent in the riverine zone between St. George and Dirranbandi.

Further out on the floodplain there is no evidence for significant height differences between trees within the different model zones. This is supported for all tree species and also when coolabah was assessed independently. While the simplest explanation for this lack of height variation on the outer floodplain is a reduced availability to persistent water sources, an alternative explanation is that similar heights reflect similar responses to opportunistically available water i.e. rainfall. This would be surprising if overbank floods were the main source of water for vegetation in the long term, however results from chapter 4 suggests this may not be so. However, if the main water source was rainfall, then the fairly even spread of tree heights across the landscape would make sense, as this would not be related to relative distances to river channels.

8 Discussion

8.1 Addressing project objectives

We have structured this report around four project objectives (and associated research questions) as individual chapters. The key findings for each project objective are summarised below:

Identify eco-hydrological correlates of floodplain vegetation distribution and change in vegetation condition through time in the study area

- *How does asset species distribution relate to the flooding extent?*

Testing simple hypotheses for the distribution of coolabah, black box and river red gum, in relation to model zones as a surrogate for flood frequency, we found that asset species distribution was generally as expected, and fitted well with the conceptual model which was used to frame the project research.

- *Can changes in vegetation greenness be related to rainfall, flooding or groundwater availability?*

Based on correlations of remotely sensed tree greenness and rainfall data, our results suggest that that weather (rain and evaporation), rather than overbank flooding is driving the tree greenness response. There was no strong tree greenness signal for the influence of flood, as inferred by either simple landscape position (model zone) or flood frequency, suggesting that overbank floods may not be the keystone for these species.

A remote-sensing approach identified patches of vegetation across the entire floodplain that are greener than they should be, given their rainfall and flooding history. These areas of “High vegetation vigour” represent possible groundwater dependent ecosystems (GDE). Model Zone 1 had the highest percentage of possible GDE land area, which may represent the influence of in-channel water on nearby vegetation, as well as their association with meander bend zones (chapter 5). Model zone 4 had the next highest percentage, and this may represent GDEs associated with sand ridge environments of that zone.

Identifying and quantifying vegetation water use

- *Do tree species express visible and quantifiable responses to different sources of available water?*

Various geomorphological, hydrological, geochemical and plant physiological investigations conducted at selected field sites characterised patterns of variability in use of water by vegetation on the floodplain. These results complemented and vindicated results of remote spatial assessments described above.

The role of flooding in providing water to asset species could not be specifically investigated due to a lack of flood events during the life of the project.

- *Do trees use groundwater?*

Yes - in conjunction with other available water sources. Direct evidence of tree roots at the capillary fringe of a shallow riparian aquifer provided validation that the dense riparian forest evident at that site was likely to be a groundwater dependent ecosystem. Other evidence suggests

that larger species were accessing groundwater in conjunction with soil water. On-going investigations will be required to further confirm this.

- *Does groundwater use vary between tree species?*

Of the asset species, coolabah roots were consistently present at the aquifer interface suggesting groundwater use. Groundwater use of other species such as river red gum could not be ruled out.

The asset species (coolabah, river red gum, lignum and black box) are not commonly found on sand ridges; however communities of these species may be accessing shallow aquifers recharged through sand ridges, particularly where river channels cut through sand ridge environments.

Identify and quantify the influence of river flooding on water availability in shallow aquifers and unsaturated root zones

- *Do floods recharge the unsaturated zone and shallow aquifers?*

Yes, floods do recharge the soil water in the floodplain generally, and in spatially restricted areas they are likely to recharge the deeper unsaturated zone and shallow aquifers. Recharge events are very episodic in the LBF – a function of the episodic nature of both large rainfall events and floods.

Investigation of riparian zone aquifers has validated the conceptual understanding of surface water/groundwater interaction in these zones. Whilst many knowledge gaps still exist in terms of the spatial extent of these systems, results suggest that vegetation and soil patterns correspond sufficiently to use them to infer the presence of shallow groundwater in riparian zones.

- *What is the potential rate of shallow groundwater recharge and root zone saturation from flooding in the LBF?*

Based on existing knowledge regarding soils, landscapes and hydrogeology for the LBF, inundation via floods or ponded rainfall are unlikely to cause significant groundwater recharge. Data collected and modelling undertaken supports this and further suggests that sand ridges (model zone 4) are likely to be the primary location of recharge (from flood or rainfall) in the LBF. The degree to which streambed and sand ridge recharge spreads laterally, into intermediate to regional scale aquifers, is still poorly understood.

Identifying variation in water availability among vegetation communities

- *How does vegetation greenness vary between different communities?*

Average greenness values show a trend decreasing away from the channel across model zones 1, 2 and 3 which might be expected due to distance from water sources and a clay dominated landscape limiting groundwater access. Model zone 4 displays the second highest overall greenness which could be as a consequence of access to groundwater through the sand ridge environment this model zone represents.

The relationship between rainfall and greenness was not supported at the landscape scale based on the regression analyses undertaken. This was thought to be a consequence of aggregating the data (both the rainfall and greenness of vegetation data sets) to the landscape scale.

- *Does variation in landscape unit explain differences in tree height?*

Results show that the tallest trees are located within the ‘fringing’ zones and suggests, as expected, that access to a direct and persistent water source, provided by in channel flows, allows trees to grow taller. Further out on the floodplain there is no evidence for significant height differences between trees within the different model zones.

8.2 Summary of key learnings

The key focus of this project has been to improve understanding of the importance of different water sources to key floodplain vegetation species, in particular the influence of overbank floods and shallow groundwater on vegetation condition and structure. We also aimed to investigate shallow groundwater recharge processes.

We used multiple lines of evidence to provide a body of results that illuminate ecological relationships between different levels of flow, flood and groundwater dependence and vegetation communities across the landscape. These vegetation communities included:

- Fringing (dependent on access to river water)
- Meander bend/paleochannel dependent (in-channel flows are also important)
- Floodplain (where rainfall and/or flooding may sustain them)
- Groundwater dependent (GDEs) (those accessing true shallow aquifers)

Only in the fringing zone, where trees are likely to have their ‘toes in the water’, did we see clear and consistent evidence of an increased vegetation response indicative of regular supplementary water, beyond rainfall - with trees both persistently greener and taller than in other areas. These riverine trees can be considered highly reliant on persistent in-channel surface water and are therefore ‘flow dependent’.

The evidence gained from the project also highlights groundwater/surface water connectivity in the wider riparian zones within meander bends (Figure 100). The shallow aquifers within these zones, formed from paleo-channels through the meander bends, are connected to the river through bank recharge which is likely to be facilitated through high flow scouring events. Whilst the recharge mechanisms of the aquifers still need further clarification, these specific meander bend communities can also be considered flow dependent.

On the floodplain beyond the riparian zone, the situation is less clear cut. Remote sensing analysis indicated that vegetation response to flooding was not pronounced, but was more influenced by climate factors, notably rainfall and evaporation. An additional influence of flood on either vegetation greenness or tree height was not demonstrated. Traditionally floodplain vegetation has been considered flood dependent, requiring a given overbank flood return frequency to maintain condition. However, within the Northern Basin the reality is more complex with non-flood water sources playing a larger role through time and across the wider landscape. These findings are of particular importance given that the southern MBD has equitable evidence of flood dependency for the floodplain asset species, suggesting that management of floodplain species in a large basin needs to allow for variation in management approaches. The analysis here has focussed on tree health, but there are other processes such as reproduction and recruitment that may show clearer effects of flooding across the floodplain.

As in other environments, trees in the LBF will use any water source available to them including floods, rainfall or groundwater. Direct evidence supports that trees are using groundwater in some locations, both from direct observation at the site scale and also indirect evidence from the remote sensing analyses. Based on our results it is most likely that river red gum and coolabah (and potentially also other floodplain tree species) are using groundwater.

Groundwater use by terrestrial vegetation appears widespread, but patchy across the floodplain with the highest potential groundwater use being found within the inner floodplain (model zone 1) and decreasing further out onto the floodplain (model zones 2 and 3) where restricted recharge means that accessible groundwater may not exist. On the sand ridges (model zone 4), which occupy the highest and therefore least inundated parts of the floodplain there was some evidence of higher groundwater use in model zone 4, with a relatively high proportion of possible GDEs identified via remote sensing. Field based measurements have not definitively demonstrated groundwater use in sand ridges although aquifers are known to exist in them and more research is required.

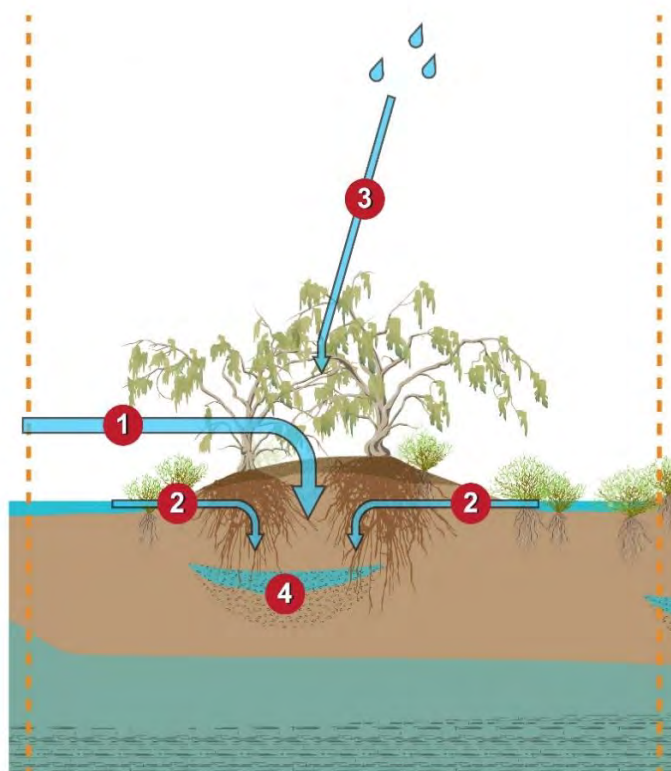
The recharge processes of shallow aquifers were also a key research topic. It was shown that there is a fundamental difference between clay and sandy soils in terms of their potential to facilitate groundwater recharge processes. As would be expected, sand ridges provide an important groundwater recharge conduit via both rainfall and flooding with considerable spatial variability in the latter according to local topography.

8.3 Improved conceptual understanding

The overall conceptual model used within the project (Figure 7) has served as a framework for the research undertaken. As part of this project, validation of some of the concepts, such as the distribution of floodplain species in relation to the model zones, has been provided. In the course of the project, two further elements were identified as being potentially important in representing the landscape.

8.3.1 Conceptual model of shallow aquifers on floodplain – groundwater dependent terrestrial vegetation

A conceptual model based on the observed vegetation communities, topography and soil profiles seen at the Euraba Road SR site was developed and is shown in Figure 99. This model represents the presence, and mechanisms of groundwater recharge, for sand ridges on the LBF. These systems have also been documented within the Gwydir floodplain system of northern New South Wales to the east of the Lower-Balonne, and referred to as ‘sand monkey’ communities by Bowen *et al* (2012).



- 1 Large scale flood events can inundate less elevated sand ridges. Direct infiltration is limited by physical soil characteristics (in particular the thickness of the clay layer).
- 2 Overland flow from flooding or heavy rainfall can wet edges of sand ridges. As for direct inundation this will be limited by physical soil characteristics.
- 3 Rainfall can also directly recharge groundwater.
- 4 Shallow fresh perched aquifers sporadically exist in this landscape and are likely to be tapped by vegetation.

Figure 99 Conceptual model of a ‘sand monkey’ community (*sensu* Bowen et al 2012))

Historical data and drilling/geophysical investigations in the project suggest there is considerable variability in this conceptual model – water may be perched on clay bands or reside on bedrock under the sand ridges. It is apparent that the depth to an aquitard governs the likelihood of the presence of an aquifer as much as recharge – for sand ridges without a significant aquitard in the upper 15 m, there is little likelihood of an aquifer developing and trees utilise recharge water from the unsaturated zone. The validity of this model is discussed in more detail in chapter 5, however it is recommended that further work be undertaken to validate some of the findings.

8.3.2 Conceptual model of surface/groundwater connectivity in riparian zones with complex vegetation communities

This model conceptualises the surface to groundwater interaction in meander bend zones and the soils and vegetation communities associated with them (in particular as at the Balonne Minor transect). The variability of the bank recharge is likely to depend on in channel flow velocities and the potential for scouring to expose sand dominated sediments on the bank, allowing ingress of surface flows to recharge the shallow aquifers that are connected within the meander bend zone. Low in- channel velocities are likely to lead to increased deposits of finer clay based sediment and smothering of banks that ‘seal off’ the shallow aquifer recharge pathways.

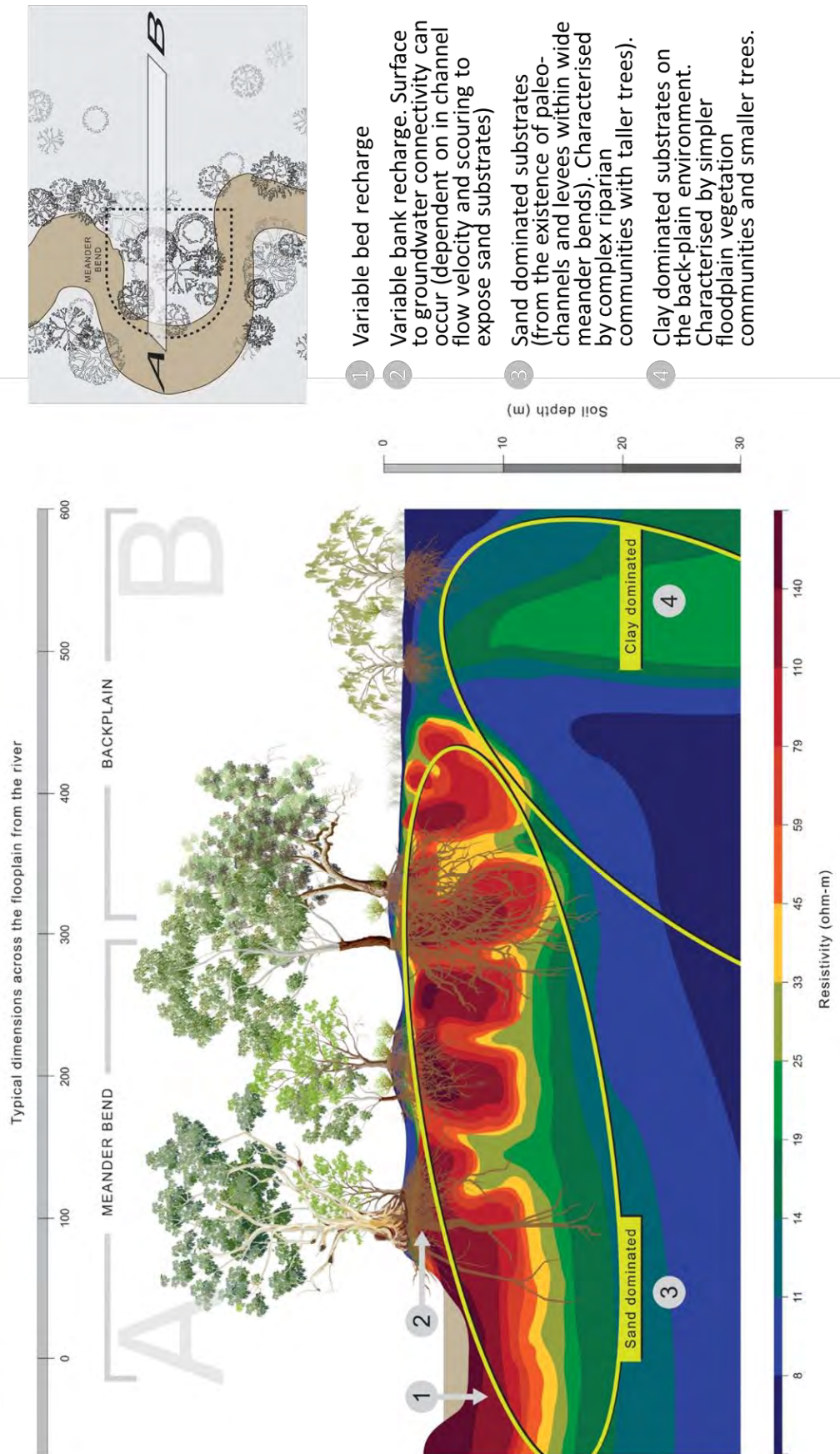


Figure 100 Conceptual model of surface/groundwater connectivity in meander bend riparian zones

8.4 Applying ecohydrological understanding

One of the original objectives of the project was to provide knowledge that could be utilised within an ecohydrological modelling context (*sensu* McGregor et al. 2017) to assess the potential risks to floodplain vegetation asset species from different water management regimes. Whilst the modelling itself was not able to be undertaken as part of this project (see section 1.3.1), evidence gathered within this project may be utilised within a water management context.

The project has found no direct evidence to suggest that overbank flood events maintain the condition of the floodplain vegetation asset species considered. This suggests that survival of existing populations may be independent of overbank flooding, and therefore this information has modified our understanding of the assumed dependencies of these vegetation communities on overbank flow events. As a result, while flooding may sometimes provide an opportunistic source of water to these floodplain vegetation species, either directly or via groundwater recharge, a regimented “critical link” to the flow regime may not be required. It is therefore proposed that, within the context of the LBF at least, floodplain vegetation condition is not a suitable indicator for ecological risk modelling based around frequency/duration of overbank flow events.

While this work did not detect a strong relationship between floodplain vegetation responses and overbank flooding, the correlation between flooding and tree recruitment processes was not studied (this was outside the scope of work based on the project proposal). It may be that overbank flooding is not necessarily always important in maintaining the long-term condition of individual mature floodplain trees. However, flooding could be vital to multiple stages of the tree recruitment process, which maintains whole communities of vegetation through time.

Other aspects of the project findings that may inform improved environmental watering actions include;

- Recognition of the potential for groundwater use as a significant mechanism for maintaining the condition of floodplain vegetation populations across the LBF and potentially more broadly in the Northern Murray-Darling Basin.
- The potential for aquifer recharge through sand ridges should be considered in managing rules around overbank flow events.
- Lignum’s response to water stress was consistent across a number of study sites, suggesting possible thresholds for an ecohydrological modelling application.
- The new understanding of surface/groundwater connectivity in meander bends (Figure 100) suggests that high in-channel flows are a mechanism for bank scouring to facilitate surface water/groundwater connectivity within complex riparian zone meander bends. Ensuring high in-channel flows are maintained will support hydrological connectivity. This process is thought to be more relevant to the upper reaches of the LBF than in the southern parts where the channel morphology is different with naturally lower channel velocities.

Within the northern basin, and particularly within the LBF, there may be limited opportunities for the direct delivery of environmental water (as is the case in many parts of the southern Murray-Darling Basin) due to the lack of infrastructure present in the area. Therefore, delivery of bankfull and overbank flows is far more constrained. Event management strategies which target these flow bands may be considered as options.

These findings provide a guide to be used by others, rather than providing specific recommendations regarding environmental watering or water recovery actions, which are considered outside the scope of this report.

8.5 Identified knowledge gaps

There are a number of knowledge gaps that have been identified in the course of completing this project. If these gaps were to be properly addressed, it would significantly increase the overall understanding of water availability to floodplain vegetation, and may inform related management strategies.

1. Current estimate of flood inundation are coarse and inadequate. Consequently, accurately judging the water balance for floodplain vegetation was difficult because the quality and quantity of data for flood was low compared to other potential water sources, for example rain. The CSIRO flood inundation model (Dutta et al 2016) did not satisfy the criteria of being able to accurately predict flooding extent in the study area. Reliable estimates of flooding are a key input to estimating floodplain vegetation water use.
2. While there are location specific rainfall and climate data across the study area, these are limited in number. Interpolated data sets allowed us to provide location specific rainfall and climate estimates, however small-scale variation will have been lost. Finer scale climate data would be required to examine more fully the effects of climate on vegetation condition.
3. The scale of vegetation mapping, particularly in the Queensland part of the study area, constrains detailed analysis of species distributions. This project's focus was on four asset species, however vegetation mapping in both Queensland and New South Wales is based around ecosystems and communities, not individual species. This means that large-scale studies that focus on particular species need to infer distributions from community information, which will always be at best an estimate, or else it will require remapping the whole area. For example, identifying black box and lignum distributions across the LBF was challenging. Development of species specific flow management rules will always be limited while vegetation mapping is of insufficient scale.
4. There is a lack of baseline information on groundwater depth and quality across the study area, given the small number of existing monitoring bores. This was identified as a particular knowledge gap in the report commissioned as part of this project (Dafny 2016).
5. Knowledge about the distribution of shallow groundwater and its interaction with surface water remains poor across the area, despite its demonstrated importance to floodplain vegetation in this project. This is recognised as a significant limitation to the spatial depiction of floodplain vegetation GDEs. Whilst a GDE aquifer mapping layer has been developed (Queensland GDE mapping version 1.5, Queensland Herbarium 2017) in most cases this has not been validated by direct measurement. The effort expended here to detail groundwater resources in a handful of locations suggests that the prospects of field-validating such mapping at regional scales are poor.
6. Recharge of sand ridges associated with vegetation water use – the project has identified that large trees on sand ridges may be supported without the presence of permanent aquifers. Further water balance modelling/ecohydrology investigations should be

undertaken to validate this and consequently improve the rules underpinning GDE mapping for the LBF.

7. The influence of other factors on vegetation condition in the LBF, other than water availability, is not well understood. Extensive land clearing, grazing, spray drift and other human landscape change will have had multiple and not easily quantifiable effects. For example, the specific hydrology of many areas may well have changed numerous times, making modelling, both forward and backward in time, problematic. Improved information on these other stressors will assist in resolving the relative contribution of water stress to these floodplain vegetation communities.
8. Tree recruitment and population regeneration dynamics remain poorly understood, particularly within the northern basin. Regardless of water availability, an improved understanding of these dynamics is required for any water management activities to successfully sustain tree populations and communities.
9. This research applies only to the LBF part of the Northern Basin of the Murray-Darling. However, there are many other adjacent catchment areas, such as Maranoa, Nebine, and Moonie. It is not clear how applicable the conclusions of this project will be in other areas and more research would be required.

8.6 Recommendations

8.6.1 Addressing knowledge gaps

One of the key recommendations of this project is that further work be undertaken to specifically address the identified knowledge gaps. This could include improving knowledge of a number of specific topics;

- Flood inundation mapping
- Vegetation mapping
- Groundwater monitoring and assessment
- Surface/groundwater connectivity

Improved flood inundation mapping (knowledge gap 1)

It is acknowledged that building a flood inundation model is particularly challenging in an area such as the LBF. Factors such as the very low gradients, complexity of channels and floodplain features, infrastructure that influences the movement of water on the floodplain, the influence of inundation from rainfall and the effects antecedent soil conditions make it very hard to accurately predict floodplain inundation extent. It is however vital that accurate models for depicting extent and duration of flood inundation be developed if quantitative modelling of risk to floodplain assets is to be viable.

Improved vegetation mapping (knowledge gap 3)

There is need to improve mapping of vegetation across the study area (particularly the Regional Ecosystem mapping in the Queensland section of the LBF). This applies to all of the asset species (as some errors were noted in RE classifications), however it is particularly the case for distribution

of black box and lignum. Any new vegetation mapping of the area would include further validation of the revised land system line work that was conducted as part of the present project.

For lignum in particular it is suggested that a more species-specific mapping approach be used. This could entail overlaying RE/PCT mapping with a GIS rule set approach (e.g. using information such as the LiDAR generated DEM that could identify drainage lines), that may highlight specific areas where dense lignum monocultures (that potentially have a high ecological value as habitat for other species) may exist.

Groundwater monitoring and assessment (knowledge gaps 4 - 6)

There needs to be focussed and improved monitoring of groundwater bores throughout the study area to provide more consistent baseline information. Given the probable importance of groundwater to floodplain vegetation, this water source needs to have data quality at least as good as that associated with climate and flood.

Surface/groundwater connectivity (knowledge gap 5)

There is a need to further understand the interaction of surface water and groundwater in both the riparian zone and backplain environments. In particular, the residence time of groundwater within paleo-channels may be a key factor. The monitoring bore network established along the riparian transects at the Balonne Minor near Dirranbandi and at Whyenbah provide the only existing monitoring infrastructure in this location. This provides a unique opportunity to study the long-term dynamics of surface water/groundwater interactions at established research locations.

8.6.2 Continued research opportunities

This project collected and generated a large volume of data, only some of which was directly required to address the research questions. This legacy data provides a unique resource to further investigate priority environmental watering issues in the Northern Murray-Darling Basin surrounding plant water use, surface water/groundwater interactions and fluvial geomorphological processes at a range of spatial and temporal scales. In particular, through peer-reviewed scientific publication in collaboration with multiple stakeholders.

8.6.3 Project communication

It is highly recommended that there be continued engagement between the project team and the wider EWKR project team to allow the integrated communication of project findings via communication pathways already identified as part of the EWKR. This could include in conjunction with the MDB EWKR project outputs. This would include provision of project communication material such as short videos and participation in stakeholder workshops to communicate project findings to water managers.

9 References

- Akaike, H 1974, A new look at the statistical model identification. *IEEE Transactions on Automatic Control* **19**(6), 716–723.
- Akeroyd, MD, Tyerman, SD, Walker, GR & Jolly, ID 1998, Impact of flooding on the water use of semi-arid riparian eucalypts. *Journal of Hydrology* **206**(1-2), 104-117.
- Bacon, PE, Stone, C, Binns, DL, Leslie, DJ, Edwards, DW 1993, 'Relationships between water availability and Eucalyptus camaldulensis growth in a riparian forest', *Journal of Hydrology* **150**(2-4), 541-561.
- Barnes, CJ & Allison, GB 1988, Tracing of water movement in the unsaturated zone using stable isotopes of hydrogen and oxygen. *Journal of Hydrology* **100**(1-3), 143-176.
- Biggs, AJW 2013, *The distribution and mobilisation of salts in the Queensland Murray-Darling Basin*. University of Queensland.
- Bleby, TM, McElrone, AJ & Jackson, RB 2010, Water uptake and hydraulic redistribution across large woody root systems to 20 m depth. *Plant, Cell and Environment* **33**(12), 2132-2148.
- Bowen, S, Simpson, S, Thomas, R & Spencer, J 2012, *Defining ecological assets of the Gwydir Wetlands*. Report for the Healthy Floodplains Project. Rivers and Wetlands Unit, New South Wales Office of Environment and Heritage.
- Burgess, SSO, Adams, MA, Turner, NC, Beverly, CR, Ong, CK, Khan, AAH & Bleby, TM 2001, 'An improved heat pulse method to measure low and reverse rates of sap flow in woody plants', *Tree Physiology* **21**(9), 589-598.
- Campbell GS, Smith DM, Teare, BL 2007, 'Application of a Dew Point Method to Obtain the Soil Water Characteristic'. In: Schanz T. (eds) *Experimental Unsaturated Soil Mechanics*. Springer Proceedings in Physics, vol 112. Springer, Berlin, Heidelberg.
- Casanova, MT 2015, *Review of Water Requirements for Key Floodplain Vegetation for the Northern Basin: Literature review and expert knowledge assessment*, The Murray-Darling Basin Authority, Commonwealth of Australia, Canberra.
- Commonwealth of Australia 2012, *Basin Plan 2012*, Prepared by the Murray-Darling Basin Authority for subparagraph 44(2) © (ii) of the *Water Act 2007*, <https://www.comlaw.gov.au/Details/F2012L02240>

Dafny, E 2015, *Analysis of groundwater levels and chemistry to detect streambed recharge in the Lower Balonne and Lower Moonie catchments*, The University of Southern Queensland, Toowoomba, Australia.

Dafny, E 2017, *Recharge and infiltration assessment across the Lower Balonne floodplain, Queensland*. The University of Southern Queensland, Toowoomba, Australia.

Dalgliesh, NP & Foale, MA 1998, *Soil matters. Monitoring soil water and nutrients in dryland farming*. (Agricultural Production Systems Research Unit/ CSIRO: Toowoomba, Queensland).

Danaher, T & Collett, L 2006, 'Development, Optimisation and Multi-temporal Application of a Simple Landsat Based Water Index', *Proceedings of the 13th Australasian Remote Sensing and Photogrammetry Conference*, Canberra, Australia, November 2006.

Doody, TM, Holland, KL, Benyon, RG and Jolly ID 2009, 'Effect of groundwater freshening on riparian vegetation water balance'. *Hydrological Processes* **23**(24), 3485-3499.

DSITIA 2014, *Western Cape York groundwater study 2. Groundwater dependent ecosystems supporting the assessment of groundwater sustainability in the Great Artesian Basin of Cape York. Attachment 1: Spatial analysis technical description and maps of potential groundwater dependent ecosystems*, Department of Science, Information Technology, Innovations and the Arts, Brisbane.

Dutta, D, Vaze, J, Karim, F, Kim, S, Mateo, C, Ticehurst, C, Teng, J, Marvanek, S, Gallant, J & Austin, J, 2016, *Floodplain inundation mapping and modelling in the northern regions, the Murray Darling Basin*. Canberra: CSIRO; 2016. csiro:EP165465.
<https://doi.org/10.4225/08/58542df21051c>

Eamus, D, Hatton T, Cook, P & Colvin, C 2006, *Ecohydrology: vegetation function, water and resource management*. (CSIRO Publishing: Collingwood, Victoria)

Eco Logical Australia 2015, *Vegetation of the Barwon-Darling and Condamine-Balonne floodplain systems of New South Wales: Mapping and survey of plant community types*. Report prepared for the Murray-Darling Basin Authority.

Evaristo, J, McDonnell, JJ & Clemens, J 2017, 'Plant source water apportionment using stable isotopes: A comparison of simple linear, two-compartment mixing model approaches'. *Hydrological Processes* **31**(21), 3750-3758.

Fensham, RJ, Butler, DW, Foley, J 2015, 'How does clay constrain woody biomass in drylands?'. *Global Ecology and Biogeography* **24**(8), 950-958.

Flood, N 2013, 'Seasonal Composite Landsat TM/ETM+ Images Using the Medoid (a Multi-dimensional Median)'. *Remote Sensing* **5**, 6481-6500.

Foley, JL 2017, *Rapid field and laboratory methods for measuring plant available water capacity and water retention curves*, Department of Natural Resources and Mines, Queensland.

Ford, CR, Goranson, CE, Mitchell, RJ, Will, RE & Teskey, RO 2004, 'Diurnal and seasonal variability in the radial distribution of sap flow: Predicting total stem flow in Pinus taeda trees', *Tree Physiology* 24(9), 941-950.

Freestone, FL, Brown, P, Campbell, CJ, Wood, DB, Nielsen, DL & Hendersen, MW 2016, 'Return of the Lignum dead: Resilience of an arid floodplain shrub to drought', *Journal of Arid Environments* 138, 9-17.

Galloway, RW, Gunn, RH, Pedley, L, Cocks, KD & Kalma, JD 1974, *Lands of the Balonne-Maranoa Area, Queensland*. Land Research Series No. 34, CSIRO, Canberra.

Gardner, EA, Coughlan, KJ & Silburn, DM 1987, 'Soil water measurement and management on Vertisols in Queensland, Australia', In *'Management of Vertisols in sub-Saharan Africa; Proceedings of a Conference held at ILCA, Addis Ababa, Ethiopia, 31 August-4 September 1987.'* (Eds SC Jutzi, I Haque, J McIntire and JES Stares), International Livestock Centre for Africa.

Glanville, K, Ryan, T, Tomlinson, M, Muriuki, G, Ronan, M & Pollett, A 2015, 'A Method for Catchment Scale Mapping of Groundwater-Dependent Ecosystems to Support Natural Resource Management (Queensland, Australia)', *Environmental Management*, DOI10.1007/s00267-015-0612-z.

Hale, J, Sheldon, F, Balcombe, S & Capon, S 2014, *Reviewing the scientific basis of environmental water requirements in the Condamine-Balonne and Barwon-Darling*, Murray Darling Basin Authority Technical Report, MDBA, Canberra.

Hamer, JJ, Veneklaas, EJ, Renton, M & Poot, P 2016, 'Links between soil texture and root architecture of Eucalyptus species may limit distribution ranges under future climates'. *Plant and Soil* **403**(1-2), 217-229.

Hatton, TJ, Moore, SJ & Reece, PH 1995, 'Estimating stand transpiration in a Eucalyptus populnea woodland with the heat pulse method: measurement errors and sampling strategies', *Tree Physiology* 15(4), 219-227.

Herczeg, AL 2004, *Groundwater ages, sources of salt and recharge mechanisms in the Lower Balonne area, southern Queensland, Australia: isotope and geochemical data*. CRC LEME/CSIRO Open File Report 164.

Holland, KL, Tyerman, SD, Mensforth, LJ & Walker, GR 2006, 'Tree water sources over shallow, saline groundwater in the lower River Murray, south-eastern Australia: implications for groundwater recharge mechanisms', *Australian Journal of Botany* 54(2), 193-205.

Holloway, D, Biggs, A, Marshall, JC & McGregor, GB 2013, *Watering requirements of floodplain vegetation asset species of the Lower Balonne River Floodplain: Review of scientific understanding and identification of knowledge gaps for asset species of the northern Murray–Darling Basin*, Department of Science, Information Technology, Innovation and the Arts, Brisbane.

Isbell, R 2002, *The Australian Soil Classification: Revised Edition*, Australian Soil and Land Survey Handbooks Series 4, CSIRO Publishing.

Jackson, RB, Canadell, J, Ehleringer, JR, Mooney, HA, Sala, OE & Schulze, ED 1996, 'A global analysis of root distributions for terrestrial biomes', *Oecologia* **108**(3), 389–411.

Jacobs Group (Australia) 2015, *Barwon Downs Groundwater Dependent Terrestrial Vegetation Investigations*, Newcastle, NSW.

Jolly, ID, Walker, GR 1996, 'Is the field water use of *Eucalyptus largiflorens* F. Muell. affected by short-term flooding?' *Australian Journal of Ecology* **21**(2), 173–183.

Jolly, I, Walker, G & Narayan, K 1994, 'Floodwater recharge processes in the Chowilla Anabranch system, South Australia', *Soil Research*, vol. 32, pp. 417–435.

Kellet, J, Pearce, B, Coram, JE, Herczeg, AL & Wilkinson, K 2004, '5. Groundwater', In '*Salinity investigations using airborne geophysics in the Lower Balonne area, southern Queensland*.' (Eds K Wilkinson and T Chamberlain), Natural Resources and Mines; Bureau of Rural Sciences; CRC Landscapes, Environment and Mineral Exploration; National Action Plan for Salinity and Water Quality.

Klein, T, Randin, C & Körner, C 2015, Water availability predicts forest canopy height at the global scale. *Ecology Letters* **18**(12), 1311–1320.

Liu, J, Fu, G, Song, X, Charles, SP, Zhang, Y, Han, D & Wang, S 2010, Stable isotopic compositions in Australian precipitation. *Journal of Geophysical Research Atmospheres* **115**(23).

Marshall, J, McGregor, G, Lobegeiger, J, Fawcett, J, Dent, C & Harding, P 2011, *Murray–Darling Basin Plan: Assessment of flow scenario implications for ecological assets of the upper Murray–Darling Basin*, Environment and Resource Sciences, Department of Environment and Resource Management, Brisbane, Queensland.

McGregor, GB, Marshall, JC, Lobegeiger, JS, Holloway, D, Menke, N & Coysh, J 2017, 'A risk-based ecohydrological approach to assessing environmental flow regimes', *Environmental Management*, (online first), doi:10.1007/s00267-017-0850-3.

Mensforth, LJ, Thorburn, PJ, Tyerman, SD & Walker, GR 1994, 'Sources of water used by riparian *Eucalyptus camaldulensis* overlying highly saline groundwater', *Oecologia* **100**(1-2), 21–28.

Murray-Darling Basin Authority 2011, *The proposed “environmentally sustainable level of take” for surface water of the Murray-Darling Basin: methods and outcomes*, MDBA Publication no: 226/11, Murray-Darling Basin Authority, Commonwealth of Australia, Canberra.

Murray-Darling Basin Authority 2012a, *Assessment of environmental water requirements for the proposed Basin Plan: Lower Balonne Floodplain*, MDBA publication no: 24/12, Murray-Darling Basin Authority, Commonwealth of Australia, Canberra.

Murray-Darling Basin Authority 2012b, *Assessment of environmental water requirements for the proposed Basin Plan: Macquarie Marshes*, MDBA publication no: 28/12, Murray-Darling Basin Authority, Commonwealth of Australia, Canberra.

Murray-Darling Basin Authority 2013, *New LiDAR for the MDB and Flood inundation models* (fact sheet), publication number 26/13, Murray-Darling Basin Authority, Commonwealth of Australia, Canberra.

Murray-Darling Basin Authority 2014, *Basin-wide environmental watering strategy*, Murray-Darling Basin Authority, Commonwealth of Australia, Canberra.

Murray-Darling Basin Authority 2016, *Assessment of environmental water requirements for the Northern Basin review: Condamine-Balonne river system*, Murray-Darling Basin Authority, Commonwealth of Australia, Canberra.

NCST 2009, *Australian Soil and Land Survey Field Handbook: Third Edition*, Australian Soil and Land Survey Handbooks Series 1, CSIRO Publishing.

Noy-Meir, I 1973. Desert ecosystems. I. Environment and producers. *Annual Review of Ecology & Systematics* 4, 25-52.

Penman, HL 1948, *Natural evaporation from open water, bare soil and grass*. *Proc. Roy. Soc. London A*(194), S. 120-145.

Poff, NL, Allan, JD, Bain, MB, Karr, JR, Prestegard, KL, Richter, BD, Sparks, RE, Stromberg, JC 1997, 'The natural flow regime: A paradigm for river conservation and restoration', *BioScience*, **47**(11), 769-784.

Queensland Herbarium 2017, *Surface Expression Groundwater Dependent Ecosystems - Polygon Features V1.5*, Queensland Department of Science, Information Technology and Innovation, Brisbane.

Queensland Herbarium 2015, *Regional Ecosystem Description Database (REDD)*, Version 9.0, April 2015, Queensland Department of Science, Information Technology and Innovation, Brisbane.

R Development Core Team 2008, *R: A language and environment for statistical computing. R Foundation for Statistical Computing*, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org>

Rayment, GE & Lyons, DJ 2011, *Soil chemical methods: Australasia*, CSIRO Publishing: Collingwood, Victoria.

Richardson, E, Irvine, E, Froend, R, Book, P, Barber, S & Bonneville, B 2011, *Australian groundwater dependent ecosystems toolbox part 1: assessment framework*, National Water Commission, Canberra.

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

Robinson, JB, Silburn, DM, Rattray, D, Freebairn, DM, Biggs, A, McClymont, D & Christodoulou, N 2010, 'Modelling shows that the high rates of deep drainage in parts of the Goondoola Basin in semi-arid Queensland can be reduced with changes to the farming systems', *Australian Journal of Soil Research* **48**(1), 58-68.

Sattler, P & Williams, R 1999, *The conservation status of Queensland's bioregional ecosystems*, Environmental Protection Agency, Brisbane.

Scarth, P, Röder, A & Schmidt, M 2010, 'Tracking grazing pressure and climate interaction - the role of Landsat fractional cover in time series analysis', In: *Proceedings of the 15th Australasian Remote Sensing and Photogrammetry Conference (ARSPC)*, 13-17 September, Alice Springs, Australia. Alice Springs, NT.

Senior, EW, Biggs, A, Marshall, JC, Page, TJ, McGregor, GB & Starkey, A 2016. *Watering requirements of floodplain vegetation asset species of the northern Murray-Darling Basin: Interim technical report*. Department of Science, Information Technology and Innovation, Brisbane, and Department of Natural Resources and Mines, Toowoomba.

Silburn, DM, Tolmie, PE, Biggs, AJW, Whish, JPM & French, V 2011, 'Deep drainage rates of Grey Vertosols depend on land use in semi-arid subtropical regions of Queensland, Australia', *Soil Research* **49**(5), 424-438.

Specht, RL & Specht, A 1999, *Australian plant communities - Dynamics of structure, growth and biodiversity.* (Oxford University Press: Victoria, Australia).

Steppe, K, De Pauw, DJW, Doody, TM & Teskey, RO 2010, 'A comparison of sap flux density using thermal dissipation, heat pulse velocity and heat field deformation methods', *Agricultural and Forest Meteorology* **150**(7-8), 1046-1056.

Thorburn, PJ, Walker, GR & Brunel, JP 1993a, 'Extraction of water from Eucalyptus trees for analysis of deuterium and oxygen-18: laboratory and field techniques', *Plant, Cell & Environment* **16**(3), 269-277.

Thorburn, PJ, Hatton, TJ, & Walker, GR 1993b, 'Combining measurements of transpiration and stable isotopes of water to determine groundwater discharge from forests', *Journal of Hydrology*, vol. 150, pp. 563–587.

Tolmie, PE, Silburn, DM & Biggs, AJW 2011, 'Deep drainage and soil salt loads in the Queensland Murray-Darling Basin using soil chloride: comparison of land uses', *Soil Research* **49**(5), 408-423.

Tucker, P 2004, '*Your wetland monitoring manual: Data collection*'. River Murray Catchment Management Board, Berri and Australian Landscape Trust, Renmark.

Vertessy, RA, Benyon, RG, O'Sullivan, SK & Gribben, PR 1995, 'Relationships between stem diameter, sapwood area, leaf area and transpiration in a young mountain ash forest', *Tree Physiology* **15**(9), 559-567.

Walker, PJ 1991, *Land systems of Western New South Wales*, Soil Conservation Service of New South Wales, Technical Report No. 25.

Yee Yet, JS & Silburn, DM 2003, *Deep drainage estimates under a range of land uses in the QMDB using water balance modelling*, Queensland Department of Natural Resources and Mines, No. QNRM03021.

Appendix 1 Remote sensing/Geographical Information System (GIS) methods

Vegetation mapping

Regional Ecosystem (RE) definitions, as provided by the Queensland Herbarium, were assessed to identify all potential RE types likely to support asset species. A full list of all potential REs was produced, in which any of the asset species could occur in any combination, (Table 16). To compile the list of RE's, a search of the full RE descriptions within the database (REDD version 9; Queensland Herbarium 2015) was conducted and constrained geographically by intersection with the relevant bioregions within the LBF.

The RE list was subsequently refined to produce a list for each asset species which included only the REs where the asset species were considered a 'dominant' component of the flora community. This RE assessment process was based on consideration of the full RE descriptions and included input and advice from the Queensland Herbarium (D. Butler, pers. comm.). These RE lists were compiled for each asset species in (Table 17 to Table 20) and form the basis for mapping the distribution of the asset species across the study area. There were some cases where a key asset species (such as river red gum) was identified as part of a RE sub-type. In these cases, the broader RE category was included to ensure all asset species were represented inclusively despite sub-type composition and mapping.

A spatial layer describing the distribution of each asset species was then produced by selecting individual mapped polygons that contained a majority (greater than or equal to 50 per cent in area) of one or a combination of these asset RE types.

Within New South Wales the equivalence table produced by Eco-Logical 2015 was used to directly equate identified asset REs to the PCT classes (Table 17 to Table 20).

Table 16 All Regional Ecosystems (within the Brigalow belt (6) and Mulga lands (11) bioregions) potentially containing asset species (Black box: BB, Coolabah: CLB, Lignum: LIG, River red gum: RRG)

Regional Ecosystem ID	Asset species	Regional Ecosystem ID	Asset species
6.3.1	CLB, RRG	11.3.1	BB, CLB, LIG
6.3.2	CLB, LIG, RRG	11.3.2	RRG
6.3.3	CLB, RRG	11.3.3	CLB, LIG
6.3.4	LIG	11.3.4	CLB
6.3.5	CLB, LIG	11.3.5	BB, CLB
6.3.7	CLB, LIG	11.3.15	CLB, LIG
6.3.8	BB, CLB, LIG	11.3.16	BB, CLB, LIG
6.3.9	CLB, LIG	11.3.21	CLB
6.3.11	BB, CLB, LIG	11.3.24	LIG
6.3.12	CLB, LIG	11.3.25	CLB, RRG
6.3.13	CLB, LIG	11.3.27	BB, CLB, LIG, RRG
6.3.24	CLB	11.3.28	CLB, LIG
6.3.25	BB, CLB	11.3.37	CLB, RRG
6.4.1	BB, CLB	11.4.11	CLB
		11.5.14	RRG

Table 17 Regional Ecosystems and equivalent Plant Community Types used to map distribution of Black Box

RE ID	RE description	PCT ID	PCT description
6.3.8	<i>Eucalyptus largiflorens</i> ± <i>Acacia cambagei</i> woodland on alluvium	38	Black Box low woodland wetland lining ephemeral watercourses or fringing lakes and clay pans of semi-arid (hot) and arid zones
11.3.16	<i>Eucalyptus largiflorens</i> ± <i>Acacia cambagei</i> ± <i>A. harpophylla</i> woodland to low open woodland on alluvial plains	37	Black Box woodland wetland on New South Wales central and northern floodplains including the Darling Riverine Plains Bioregion and Brigalow Belt South Bioregion
		197	Black Box - Gidgee - chenopod low open woodland wetland on alluvial clay soils in the Culgoa River region of the Darling Riverine Plains Bioregion and Mulga Lands Bioregion

Table 18 Regional Ecosystems and equivalent Plant Community Types used to map distribution of river red gum

RE ID	RE description	PCT ID	PCT description
6.3.1	<i>Eucalyptus camaldulensis</i> woodland on alluvium within <i>Acacia aneura</i> associations	No direct equivalent	N/A
6.3.2	<i>Eucalyptus camaldulensis</i> ± <i>E. coolabah</i> ± <i>Acacia cambagei</i> woodland on major drainage lines or rivers	No direct equivalent	N/A
6.3.3	<i>Eucalyptus camaldulensis</i> ± <i>E. coolabah</i> ± <i>E. populnea</i> , <i>Acacia stenophylla</i> woodland on alluvium	No direct equivalent	N/A
11.3.25	Freshwater wetlands.	36	river red gum tall to very tall open forest / woodland wetland on rivers on floodplains mainly in the Darling Riverine Plains Bioregion
11.3.27	Freshwater wetlands.	181	Common Reed - Bushy Groundsel aquatic tall reedland grassland wetland of inland river systems
11.3.37	<i>Eucalyptus coolabah</i> fringing woodland on alluvial plains	40a	Coolabah closed woodland wetland with chenopod/grassy ground cover on grey and brown clay inner floodplains adjacent to major inland rivers

Table 19 Regional Ecosystems and equivalent Plant Community Types used to map distribution of Coolabah

RE ID	RE description	PCT ID	PCT description
6.3.7	<i>Eucalyptus coolabah</i> , <i>Acacia stenophylla</i> low open woodland on alluvium	No direct equivalent	N/A
6.3.9	<i>Eucalyptus coolabah</i> , <i>E. populnea</i> open woodland on alluvium	No direct equivalent	N/A
6.3.12	<i>Acacia omalophylla</i> ± <i>A. microsperma</i> ± <i>Eucalyptus coolabah</i> tall open shrubland on alluvium	No direct equivalent	N/A
6.3.24	<i>Eucalyptus coolabah</i> or <i>E. populnea</i> woodland on alluvial plains	No direct equivalent	N/A
11.3.3	<i>Eucalyptus coolabah</i> woodland on alluvial plains	40a	Coolabah closed woodland wetland with chenopod/grassy ground cover on grey and brown clay inner floodplains adjacent to major inland rivers
11.3.15	<i>Eucalyptus coolabah</i> , <i>Acacia stenophylla</i> , <i>Duma florulenta</i> fringing woodland on alluvial plains	39	Coolabah - River Cooba - Lignum woodland wetland of frequently flooded floodplains mainly in the Darling Riverine Plains Bioregion
11.3.27	Freshwater wetlands.	181	Common Reed - Bushy Groundsel aquatic tall reed-land grassland wetland of inland river systems

Table 20 Regional Ecosystems and equivalent Plant Community Types used to map distribution of Lignum

RE ID	RE description	PCT ID	PCT description
6.3.2	<i>Eucalyptus camaldulensis</i> ± <i>E. coolabah</i> ± <i>Acacia cambagei</i> woodland on major drainage lines or rivers	No direct equivalent	
6.3.5	<i>Eucalyptus ochrophloia</i> ± <i>Acacia cambagei</i> ± <i>E. coolabah</i> woodland on alluvium	No direct equivalent	
6.3.7	<i>Eucalyptus coolabah</i> , <i>Acacia stenophylla</i> low open woodland on alluvium	No direct equivalent	
6.3.8	<i>Eucalyptus largiflorens</i> ± <i>Acacia cambagei</i> woodland on alluvium	38	Black Box low woodland wetland lining ephemeral watercourses or fringing lakes and clay pans of semi-arid (hot) and arid zones
6.3.9	<i>Eucalyptus coolabah</i> , <i>E. populnea</i> open woodland on alluvium	No direct equivalent	
6.3.11	<i>Eleocharis pallens</i> ± short grasses ± <i>Eragrostis australasica</i> open herbland on clays, associated with ephemeral lakes, billabongs and permanent waterholes	24	Canegrass swamp tall grassland wetland of drainage depressions, lakes and pans of the inland plains
6.3.12	<i>Acacia omalophylla</i> ± <i>A. microsperma</i> ± <i>Eucalyptus coolabah</i> tall open shrubland on alluvium	No direct equivalent	
11.3.3	<i>Eucalyptus coolabah</i> woodland on alluvial plains	40	
11.3.15	<i>Eucalyptus coolabah</i> , <i>Acacia stenophylla</i> , <i>Duma florulenta</i> fringing woodland on alluvial plains	39	
11.3.16	<i>Eucalyptus largiflorens</i> ± <i>Acacia cambagei</i> ± <i>A. harpophylla</i> woodland to low open woodland on alluvial plains	37	Black Box woodland wetland on New South Wales central and northern floodplains including the Darling Riverine Plains Bioregion and Brigalow Belt South Bioregion
		197	Black Box - Gidgee - chenopod low open woodland wetland on alluvial clay soils in the Culgoa River region of the Darling Riverine Plains Bioregion and Mulga Lands Bioregion
11.3.27	Freshwater wetlands.	181	Common Reed - Bushy Groundsel aquatic tall reed-land grassland wetland of inland river systems

Identifying potential groundwater dependent ecosystems

GDEs require access to groundwater on a permanent or intermittent basis to meet some or all of their water requirements in order to maintain their communities, ecological processes and function (DSITIA 2014; Richardson et al. 2011). Within the LBF there are likely to be patches of terrestrial vegetation (including those of our asset species) that could be classified as GDEs. The level of dependence on groundwater is likely to vary across the floodplain, as indicated in the conceptual models utilised within this project. It is important to know the location of GDEs since their associated vegetation may not rely directly on floodwaters for their watering needs to the same extent as other areas of the floodplain.

We aimed to map groundwater dependent vegetation patches within the identified asset vegetation across the study area. Identification of the location of potential groundwater dependent vegetation patches was then used to understand their extent, distribution and context on the floodplain and also in turn to exclude sites selected within the pixel scale analysis from the multiple stepwise regression analysis.

In this study, potential GDEs were identified using remote sensing spatial analysis by accumulation of multiple lines of evidence, as observed by satellite imagery, as described in DSITIA (2014) and comparing them to existing regional-scale rulesets (in Queensland portion only), as described in Glanville et al. (2015).

A GDE spatial likelihood product was developed for all asset RE patches to determine whether they were potentially accessing groundwater. We utilised a variety of products derived from Landsat satellite imagery across the floodplain:

- Seasonal green fraction mean and coefficient of variation (years 1988–1994; 1995–2000; 2001–2005; 2006–2010; 2011–2015) (known as the dib stage)
- 2006 (dry dates) Normalised Difference Vegetation Index (NDVI) maintaining high vigour (known as df3 stage)
- 2006 water indices (Danaher & Collett 2006) (known as the dd6 stage).

The products were derived from USGS Landsat imagery at DSITI's Remote Sensing Centre facility. Thresholds as described in DSITIA (2014) were applied to each of the inputs. Where pixels met the thresholds applied, they were assigned a value '1', where pixels did not meet the thresholds they were assigned a value of 0.

Four Landsat scenes were analysed to cover the study area (p092r080; p092r081; p093r080; p093r081) as constrained by the LBF and the pre-defined FAAs. For each Landsat scene, the input derivatives were classified in criteria such as vegetation vigour, green signal persistence and variability, and moisture content of vegetation patches.

Outputs from this analysis were combined, using defined thresholds, into a 'GDE spatial likelihood product'. In addition to the spatial analysis, the potential GDEs were then intersected with the Queensland GDE mapping (for the Queensland region only), which was derived using a rule-set based GDE mapping and assessment methodology built primarily off Queensland's regional ecosystem and wetland mapping data (Glanville et al. 2015). Potential GDEs that were detected in both the remote-sensing based analysis and the Queensland GDE rule-set based approach were then checked for agreement across the study area. Potential GDEs agreed with four out of seven criteria; likely GDEs agreed with five out of seven criteria and highly likely GDEs agrees with greater than or equal to six out of seven criteria (Table 21 GDE likelihood values used for mapping potential GDE patches).

Table 21 GDE likelihood values used for mapping potential GDE patches

Value	Class	Description
7	Highly Likely GDE	Pixels greater than 4 contiguous pixels and meet either 6 or 7 of the GDE criteria and are inside the Queensland regional GDE mapping
5	Likely GDE	Pixels greater than 4 contiguous pixels and meet either 4 or 5 of the GDE criteria and are inside the Queensland regional GDE mapping
4	Possible GDE	Pixels that meet greater than 4 criteria but are outside of the Queensland regional GDE mapping
0	No Data	Pixels were outside Asset Species or did not meet any minimum criteria for GDE likelihood.

The Potential GDE mapping was also compared with field site locations at Euraba Road (wet and dry) and Nelyambo.

Statistical methods for correlating vegetation response to climate variables

A multiple stepwise regression analysis using in- season greenness (as specified in Chapter 4) and nine climate variables was performed over the data. The variables are outlined in Table 22 and a pictorial representation of the variables in relation to each season is shown in Figure 101.

Table 22 Variables used in the multiple stepwise regression analysis on pixel scale data

Code	Name	Description
GSL0	Greenness – in-season	Autumn, Winter, Spring, Summer for each year.
RSL0	Rainfall – in-season	Total daily rainfall summed for each Season.
RSL1	Rainfall – one-season lag	Total daily rainfall summed for each Season, lagged by one season.
RYL1	Rainfall – one-year lag	Total daily rainfall summed for preceding four seasons, lagged by one season
ESL0	Evaporation – in-season	Total monthly evaporation summed for each season.
ESL1	Evaporation - one-season lag	Total monthly evaporation summed for each season, lagged by one season.
EYL1	Evaporation - one-year lag	Total monthly evaporation summed for preceding four seasons, lagged by one season
DS0	Deficit – in season	RSL0 minus ESL0
DSL1	Deficit – one-season lag	RSL1 minus ESL1
DYL1	Deficit – one-year lag	RYL1 minus EYL1

For each stepwise regression (forward and backward), an AIC function was applied to test for the model with the best fit. The best-fit model was then applied to predict greenness to determine whether the model explained the variability.

The outputs included the model applied for each site, the best fitted values, the upper and lower 95th percentile confidence intervals, and the adjusted r^2 .

This analysis was conducted for all individually selected pixels and also on data summarised to the landscape analysis unit scale.

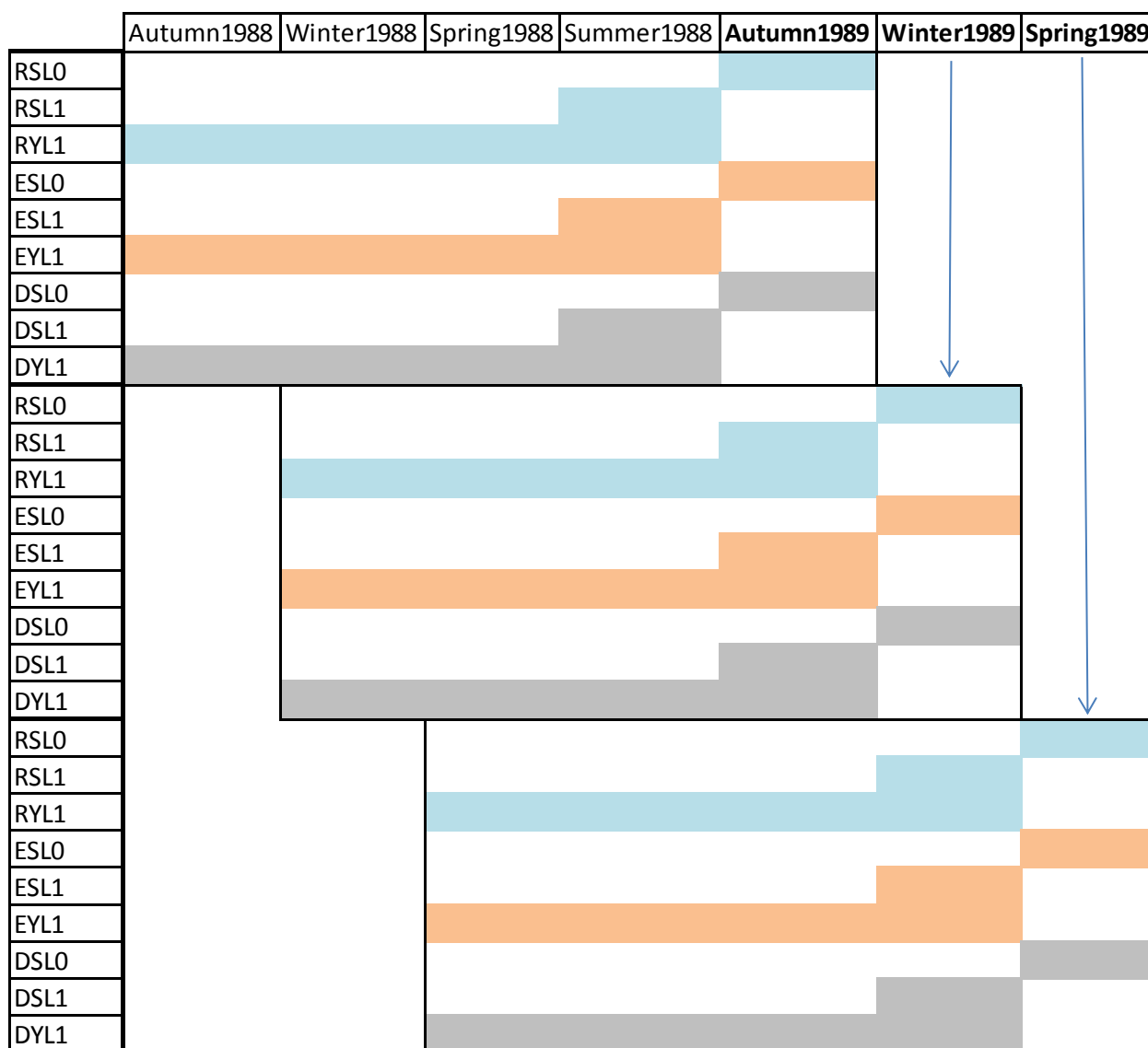


Figure 101 Pictorial representation of climate variables used in the stepwise multiple regression analysis for three example seasons

LiDAR data processing and analysis

LiDAR was sourced from the MDBA via Geoscience Australia. The '.las' files were supplied to the DSITI Remote Sensing Centre for standardised processing.

A LiDAR-derived 5m (pixels size) Canopy Height Model (CHM) was filtered to remove pixels that contained maximum Canopy heights below 2m. A spatial filter was applied to the remaining pixels, with maximum Canopy heights of at least 2m, to remove isolated pixels and pixel clusters representing less than 10m x 10m. Small canopy patches such as these are too small for a 30m x 30m Landsat pixel to represent adequately. We used QGIS 2.8.9 for this process.

The outputs included the filtered CHM (with height assigned to every pixels) as well as a 'Woody Vegetation Extent' product whereby the filtered CHM was converted into a flat, binary (woody vegetation/no woody vegetation) extent layer.

Frequency distributions of tree heights for all landscape Histograms were calculated by Ozius and supplied for further analysis by the DSITI team to consider relationships between vegetation structure (height) and water availability.

Landscape scale analysis

The landscape analysis units were defined using the asset patch data (intersection of Land-systems and vegetation mapping for each asset species) and also a riverine zone (as a subset of model zone 1 only) was defined using one pixel width (30m) buffer around the stream layer. The data set was then further filtered using the Woody Vegetation binary extent mapping (derived from the LiDAR data set) to reduce the polygons to only areas where a tree-canopy exists. Twenty-eight asset combinations were identified.

Zonal analysis was then conducted to produce mean greenness and rainfall for each season for each landscape zone. A linear regression was used to model greenness at the landscape scale as a function of in-season rainfall.

The outputs included the model co-efficients applied for each site, the best fitted values, the upper and lower 95th percentile confidence intervals, and the adjusted r^2 .

Table 23 Landscape analysis units attributed by asset vegetation species, model zone, area and whether they intersect with the riverine buffer

Model zone	ID	Vegetation species/combination	Riverine	Area HA
4	CLASS1_RIV0	lignum	No	71
4	CLASS2_RIV0	river red gum	No	175
4	CLASS3_RIV0	coolabah	No	14,810
4	CLASS4_RIV0	coolabah and lignum	No	30,957
4	CLASS5_RIV0	coolabah and river red gum	No	3,634
3	CLASS6_RIV0	lignum	No	170
3	CLASS7_RIV0	black box and lignum	No	6,408
3	CLASS9_RIV0	coolabah	No	24,310
3	CLASS10_RIV0	coolabah and lignum	No	159,027
3	CLASS11_RIV0	coolabah and river red gum	No	4,871
2	CLASS12_RIV0	lignum	No	1,628
2	CLASS13_RIV0	black box and lignum	No	56,625
2	CLASS14_RIV0	river red gum	No	1,343
2	CLASS15_RIV0	coolabah	No	45,949
2	CLASS16_RIV0	coolabah and lignum	No	704,589
2	CLASS17_RIV0	coolabah and river red gum	No	10,318
2	CLASS18_RIV0	coolabah, river red gum and lignum	No	1,033
1	CLASS25_RIV0	lignum	No	1,974
1	CLASS25_RIV1	lignum	Yes	1,418
1	CLASS26_RIV1	river red gum	Yes	30,219
1	CLASS27_RIV0	coolabah	No	24,213
1	CLASS27_RIV1	coolabah	Yes	4,587
1	CLASS28_RIV0	coolabah and lignum	No	339,608
1	CLASS28_RIV1	coolabah and lignum	Yes	24,791
1	CLASS29_RIV0	coolabah and river red gum	No	13,697
1	CLASS29_RIV1	coolabah and river red gum	Yes	4,600
1	CLASS30_RIV0	coolabah, river red gum and lignum	No	1,523
1	CLASS30_RIV1	coolabah, river red gum and lignum	Yes	508

Appendix 2 Field methods

Site selection and establishment

The key criteria for selecting the long term vegetation monitoring sites and riparian transect locations were primarily the health and representativeness of the vegetation community (as assessed through examination of historical and contemporary aerial photography and on ground observations). Other considerations included vehicle access, landholder permissions, equipment security and preferably the presence of a shallow aquifer bore to enable groundwater sampling.

Three detailed field sites were established in coolabah communities. The first coolabah site (Nelyambo) was established in land-system 31, just south of Dirranbandi in November 2014. A pair of coolabah sites was also established in December 2014, approximately 15 kilometres north of Hebel at Euraba Road. One of the pair of Euraba Road sites lies on a grey Vertosol (GV) while the other was located approximately 400 metres east on a sand ridge (SR); both within a mapped area of land-system 33. Records were collected continuously from the three detailed sites for just over one year to December 2015 (site location details are given in Table 24 below).

Five riparian transect sites to investigate river red gum/coolabah communities were also surveyed (Table 24).

Table 24 Vegetation monitoring site locations and surveys undertaken at each

Site	latitude	longitude	DVM	Riparian Transect	SLATS ⁺	Rapid veg. assess.
Whyenbah 2	-28.24571	148.46017			y	y
Whyenbah/FVP 02	-28.24707	148.46058		y	y	y
fvp	-28.51758	148.11125			y	
Pixel 17	-28.52120	148.10377			y	y
FVP pixel 21	-28.52770	148.08696				y
FVP near pixel 21	-28.52829	148.08695			y	y
FVP 16	-28.54227	148.12241			y	y
FVP sliver	-28.55310	148.13462			y	y
Toobee Creek 2	-28.56850	148.15135			y	y
Toobee Creek FVP	-28.56970	148.15107		y	y	y
fvp	-28.59512	148.18383			y	

Site	latitude	longitude	DVM	Riparian Transect	SLATS ⁺	Rapid veg. assess.
Balonne Minor at Dirranbandi	-28.60030	148.20689		y	y	y
fvp15	-28.66493	147.77521			y	
Nelyambo	-28.69218	148.17869	y		y+	y
fvpb	-28.69693	147.70637			y	y
FVP 81,82,83,84,85,86,87	-28.83079	147.86186				y
Euraba Rd GV	-28.83390	147.87170	y		y +(x2)	y
Euraba Rd SR	-28.83626	147.87435	y		y+ (x2)	y
Euraba Rd Extra Dry 2 GV	-28.83924	147.88014			y+	
Euraba Rd Extra Wet 2 SR	-28.83932	147.87872			y+	
Lignum A	-28.84171	148.05198				y
Euraba Rd Extra Dry 1 GV	-28.84297	147.88484			y+	
Lignum B	-28.84355	148.04859				y
Euraba Rd Extra Wet 1 SR	-28.84367	147.88647			y+	
Euraba Rd Extra 1 SR	-28.84531	147.88862			y+	
Euraba Rd wet up plot	-28.84920	147.92276				Wet up only
Briarie creek/fvp05	-28.90501	147.69021		y	y	
Balandool river/fvp06	-28.93984	147.75115		y	y	
BB16	-28.99307	147.12279				y
BB15	-28.99530	147.11829				y
Birrie River at Goodooga	-29.10186	147.42775				y
Birrie River at Goodooga (gauging station)	-29.10188	147.42784				y
Bokhara at Goodooga	-29.11122	147.44780				y
FVP pixel 128	-29.11913	147.01603			y	y
Bokhara River anabranh (Goodooga - Brewarrina Rd)	-29.26636	147.42748				y
Muckerwaw Creek	-29.29232	147.42431				y
Wilby Wilby (D/S)	-29.42293	147.55539				y

y+ - More detailed SLATS surveys undertaken at these locations (x2) – SLATS surveys repeated

Climate

Climatic variables were measured via a weather station at each detailed monitoring site. In each case the station was located within the site in a naturally clear area. Rainfall was measured in a Campbell Scientific CS700 Hydrological Services TB3 Tipping Bucket pluviometer measuring 0.2 millimetres per tip. At the wet plot, bulk monthly rainfall samples were collected by plumbing the pluviometer into a 4 litre dark glass Winchester bottle. Radiation was measured with a Middleton EP08 Pyranometer or a Li-Cor Li200x Pyranometer programmed to measure flux density as an average in W/m^2 on the 30 minutes collection and to give the total flux in MJ/m^2 for each 30 minutes. A daily total of the MJ/m^2 were also tallied. Relative humidity and temperature were collected with a Vaisala HMP45C or Vaisala HMP35C sensor with average temperature recorded every 30 minutes along with minimum, maximum and average percentage relative humidity.

Climate monitoring was used to interpret vegetation water use data and vegetation condition indices derived from remote sensing.

Vegetation community structure and allometric methods

At each detailed monitoring plot, a 40 metre or 50 metre radius circle was delineated and all trees >2 metre height were given a unique identifier. Dominant tree, shrub and ground cover species were identified. Vegetation structural parameters were recorded using the Auscover SLATS methods:

(<http://www.auscover.org.au/xwiki/bin/view/Field+Sites/Data+Collection+Resources>).

In brief, all live trees >2 metres height in the plot were measured for: tree height, height to first branch, girth at 0.3 metres from ground, girth at 1.3 metres from the ground (DBH), major and minor canopy axis dimensions. Girth measurements were taken for all stems in multi-stemmed trees. Heights were derived using clinometer and tape measure and canopy dimensions were derived with a tape measure and densitometer. Six radial axes (0–180°, 60–240°, 120–300°) from a centre peg were delineated and ground cover and canopy intercepts recorded at metre intervals on each using a densitometer and laser pointer mounted on a staff. Leaf area index was measured using imagery captured with a hemispherical camera.

Following completion of the major ecophysiological measurement phase at Nelyambo and Euraba Road sites, at least three trees at each site were cut down and harvested. For these trees, LAI was derived manually (by picking all individual leaves from harvested trees and passing through a leaf scanner) and above ground biomass of the whole tree and leaf, branch and trunk components were also measured.

Tree eco-physiology

Tree water use and water potential within trees at the detailed study sites was measured using sap flow meters and stem psychrometers.

Sap flow

Sapflow was measured using the heat ratio method via SFM1 sensors (ICT International). Full specifications of the sensors are available from the manufacturer:

(<http://au.ictinternational.com/products/sfm1/sfm1-sap-flow-meter/?from=/products/plants/sap-flow/>).

In brief, each sensor consists of three probes, 1.3 millimetres diameter and 35 millimetres in length. The upper and lower probes contain thermistors at 7.5 millimetres and 22.5 millimetres from the probe tip. The central probe contains the heater element. All probes were installed parallel and 5 millimetres apart using a Dremel® drill, drill bit and a drill guide as per the ICT instrument installation guide. Instruments logged on half hourly intervals and used a 20 joule heat pulse. Initially, three trees that spanned the size range within the site (T1, T10, T15) were selected and four sensors were installed in each (one at each compass axis) to investigate within-tree variability. Sensors were installed at approximately 1.3 metres above ground. The depth of installation was initially estimated via bark/sapwood thickness measurements, but was adjusted over a period of weeks to ensure consistency in measurements – specifically the sap velocity of the outer thermistor must be greater than the inner. After a period of days, the sensors were re-deployed to 12 trees (one per tree, installed on the south side) including the original three trees.

Stem psychrometer

A single ICT stem psychrometer was installed in one tree as per manufacturer's instructions. It was installed on the first branch (< 50 millimetres in diameter) above ground. Outer bark was removed with a sharp blade to create a flat installation surface on the sapwood. The calibrated psychrometer chamber was clamped to the branch and silicon vacuum grease applied around the outside and over the wound. The installation was wrapped in an R1.5 commercial polyester insulation batt which was then covered in a silver reflective plastic sheet. The insulation was installed in such a manner to allow drainage of any condensation. The instruments logged on half hourly interval.

At the end of a measurement period for any sapflow instrument, zero flow conditions were created by drilling a 25 millimetres diameter hole into the heartwood above and below each sensor. These were used for obtaining wood samples and verifying the thickness of bark and sapwood.

Moisture content and density of sapwood was determined using two different approaches. Sapwood cores were obtained from the south side of the studied trees by using a 20 millimetres hole saw at low speed with a power drill. Samples were obtained from immediately above the sapflow instruments. These were taken at the time of establishment of zero flow conditions and all cores were taken within 2 hours of dawn. Large irregular samples were also taken from trees cut down. All samples were wrapped in Parafilm® and stored in sealed jars at the time of sampling. In the laboratory, they were unwrapped, weighed wet, dried at 60° C for three days and weighed again. Volume of large samples was then determined by displacement and the volume of small cores by measurement with calipers.

Thickness of bark and sapwood was characterised in trees using a depth gauge in a 12 millimetres hole drilled at 1.3 metres above ground in each of the four primary compass axes. Sapwood samples were taken for moisture content and density determination using a 20 millimetres hole saw in a drill at low speed. Samples were taken progressively during the study period.

Sapwood thickness was also determined for all other trees in each plot. Branch samples were collected for analysis of stable isotope ($\delta^2\text{H}$ & $\delta^{18}\text{O}$) signatures from trees in various size categories at each plot.

Soil

Sampling of soils was undertaken via coring to characterise physical, chemical and morphological properties at each site. At the commencement of each detailed study site, the soil profile was described and sampled for a full analytical suite: pH, electrical conductivity (EC) and chloride (Cl),

particle size, cation exchange capacity, exchangeable cations, moisture content and soil water potential. A core was also taken for measurement of stable isotopes from soils ($\delta^2\text{H}$ & $\delta^{18}\text{O}$) to be used for comparison to isotope signatures from surface water, groundwater and vegetation.

Sampling for stable isotopes ($\delta^2\text{H}$ & $\delta^{18}\text{O}$) was conducted at site establishment, towards the end of the experimental period and also after a significant rainfall event. Stable isotope cores were to a maximum of three metres. Deeper cores (up to 12 metres) were taken in the centre of the Nelyambo site, in a transect across the Euraba Road sites and at the riparian transect locations to investigate regolith materials and soil water potential for validation and calibration of ground-based geophysics.

At the Nelyambo site, gilgai were present, thus all soil sampling was undertaken separately for both mound and depressions. Sampling of soils was undertaken to characterise physical, chemical and morphological properties. Morphology of each profile was described as per NCST (2009) and the soils classified according to Isbell (2002). Data was recorded in the Queensland Government soil database (SALI) which is accessible online via the Queensland Globe within Google Earth. All cores were 1.5–2 inch in diameter and taken with a vehicle-mounted hydraulic corer to a depth of approximately 3 metres. At commencement of the study, a single mound/depression pair was sampled and described. At each sampling point, three cores were taken close together (within 0.4 metres lateral distance) and corresponding 0.1 metre intervals were bulked for chemical analysis. Methods and corresponding method codes from Rayment & Lyons (2011) are summarised as follows: pH, electrical conductivity and chloride were measured on a 1:5 solution (methods 4A1, 3A1, 5A2 respectively). Selected samples were analysed for particle size using the hydrometer method and cations. A single core was taken in each mound and depression for measurement of stable isotopes ($\delta^2\text{H}$ & $\delta^{18}\text{O}$) using a modification of the method of Thorburn et al. (1993a). All analytical chemistry and particle size analysis was undertaken at the DSITI Chemical Centre, Dutton Park.

Three replicated cores in each mound and depression were taken for soil moisture (gravimetric and water potential) and bulk density determination. Each core was cut into sections approximately 0.3 metres long. From this, a 0.2 metre section was taken for bulk density and gravimetric water content determination and a 0.1 metre section taken for water potential determination. Internal diameter of the core tube and the length of the core sections (three measurements) were determined with calipers. Core sections were bagged and wet and dry (105°C) weights obtained. Water potential samples were wrapped in plastic film and placed in sealed jars. They were equilibrated in a controlled temperature room (20°C) for 14 days prior to measurement with Decagon WP4C and WP4-T Dewpoint Potentiometers.

Towards the end of the experimental period and after a significant rainfall event, the original soil sampling sites were re-sampled using the same sampling protocol as the initial sampling for isotope and soil water cores. At this time, a further two mounds and depressions were sampled at each plot – consisting of one core for stable isotopes, one core for soil moisture, and two closely spaced cores bulked for limited soil chemistry. The reduction in the number of soil moisture cores was on the basis of the low variability between cores observed in previous samplings.

Ground-based geophysics

Ground based geophysical surveys were carried out at detailed plots and riparian transects. At all sites, electrical resistivity tomography (ERT) was carried out. Electromagnetic induction (EMI) surveys were also conducted at the three detailed plots. Both these geophysical techniques aim to

characterise the soils, identify the presence of shallow aquifers and explain recharge processes of soil water and groundwater at the field sites.

ERT (an earth resistance technique) utilises an electrical current applied to a series of probes laid out across a site to produce a two dimensional cross-section along the transect line indicating the broad stratigraphy and deeper soil features. The ERT was combined with topographical data and validation from soil cores along the transect to provide an accurate representation of the underlying materials.

Lower Balonne ERT transects:

1. Nelyambo – 160m (additional 96m section with 1m spacing done over the centre of the veg plot)
2. Euraba Road – 650m
3. Balonne Minor River - 585m
4. Whyenbah – Balonne River- 650m
5. Toobee Creek – 320m (additional 160m section done on the other side of the creek)
6. Briarie Creek – 320m
7. Ballandool River – 320m (additional 160m section done over sand ridge)

The ERT surveys were carried out along the transects using an ABEM Terrameter LS resistivity meter in a range of differing configurations. Transects 1, 5, 6 and 7 used a 2x32 (set of 2 electrode cables with 32 take-outs each) increasing spread with the Gradient8 protocol all with a pin spacing of 2.5m. Transects 2, 3 and 4 used a 4x21 (set of 4 electrode cables with 21 take-outs each) spread with the GradientPlus protocol and a pin spacing of 2.5m. The overall length of each transects was achieved by using the roll-along data acquisition technique. All data has been processed to produce the associated 2D inversion models and transect pseudosections using the RES2DINV software package

EM38 surveys were undertaken over the three detailed research plots with the EM38-MK2 (Geonics Ltd, Ontario, Canada) instrument to generate the apparent soil electrical conductivity (ECa) maps. The major influences on the ECa response are clay content, salts and moisture. The EM38-MK2 is configured with two different coil arrangements (1m and 0.5m) so that two different depth responses of approximately 1.5m and 0.75m can be collected in a single pass in vertical dipole mode. The ECa value recorded is a depth-weighted average for each coil arrangement and is recorded as a weighted average for the given depth of response of the instrument for a given configuration. ECa data is collected and stored on a portable, handheld, field computer (Archer) that has GPS capabilities and is able to associate a given ECa reading with a set of GPS coordinates that can be related back to the surveyed area. At the Nelyambo plot a 100 x 100 meter survey area was traversed at 1 meter grid intervals to encapsulate the circular vegetation research plot area. At the Euraba Rd research plots two EM surveys were carried out. The first survey was conducted over an area of 700 x 155 meters that was traversed at 10 meter grid intervals and encapsulated both the wet and dry sites as well as the area in between the sites. A more detailed survey was then conducted at the dry site and was a 100 x 100 meter survey area that was traversed at 1 meter grid intervals to encapsulate the circular vegetation research plot area. Once the data was collected it was then interpolated in Surfer© using nearest neighbour to convert point data files to a 1 meter grid file. This technique was chosen because it does not extrapolate ECa grid values beyond the range of data.

Hydrogeology and groundwater monitoring

The groundwater bore network for the Lower Balonne was reviewed and a list of useful bores determined (bores with aquifer depth < 30 metres). During reconnaissance trips in 2014 and 2015, all bores were been dipped and their condition evaluated – many had been inundated during the floods of 2010 and 2012. Bores closest to the study sites were cleaned and the bore at Nelyambo (RN42220086) was sampled for ionic chemistry and stable isotopes ($\delta^2\text{H}$ & $\delta^{18}\text{O}$).

Groundwater monitoring contributes to the identification of shallow aquifers and the hydrogeological mapping of the landscape. Groundwater chemistry will help explain recharge processes of soil water and groundwater at the field sites. Stable isotope analysis of groundwater was considered in conjunction with that taken from surface water, vegetation and soils.

Surface water sampling

Surface water sampling comprised monthly rainfall samples at Nelyambo and Euraba Road and opportunistic samples from streams. All have been analysed for ionic chemistry and stable isotopes at the DSITI Chemistry Centre, Dutton Park (all vegetation and soil samples were also analysed at the Centre).

Stable isotope analysis of surface water ($\delta^2\text{H}$ & $\delta^{18}\text{O}$) was considered in conjunction with isotope data from ground water, vegetation and soils.

Rapid vegetation condition assessment

A method for the rapid field assessment of condition of Coolabah trees was developed based on the work of Tucker (2004). The protocol was developed using the assessment criteria for individual trees (using the guidelines given in Table 25) and through comparison with the photo standards for tree condition shown in Figure 102 below. These photo standards were based on observed and photographed individual trees surveyed during project fieldwork (November 2016) which were later compiled.

This assessment was then applied to an area of approximately 100m x 100m using the guidelines in Table 26. At each site a GPS location was recorded for the centre of the site and a photograph taken of the general environs. This was recorded using a ‘snap and go’ form within the Open Data Kit (ODK) platform.

The rapid vegetation assessment sites were primarily used to ground truth selected pixel site locations to ensure they were the specific vegetation communities of interest. A comparison of observed vegetation condition with remote sensing assessment was not undertaken as dates were not directly comparable.

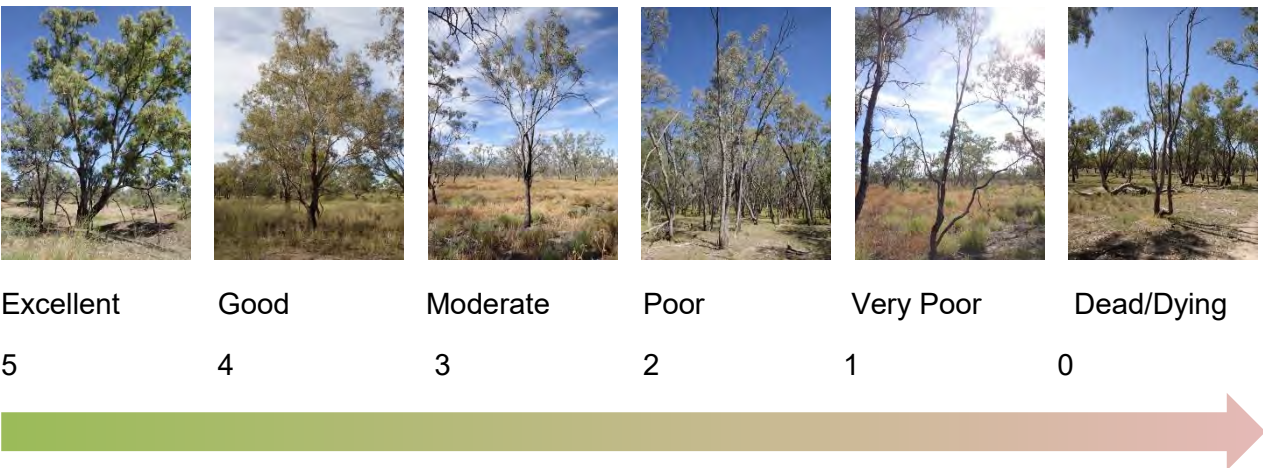


Figure 102 Pictorial photo standard of Coolabah tree condition

Table 25 Individual tree condition rating descriptions for coolabah

Condition Rating	Tree condition Rating Description
5 - Excellent	Tree with >75 % of original canopy. Less than 5 % epicormic growth. May include some dead branchlets and leaves.
4 - Good	Tree with 50 - 75 % of original canopy present. Epicormic growth less than 10 % of remaining canopy. Some dead branchlets (<50 % of remaining canopy).
3 - Moderate	Tree with 25 - 49 % of original canopy present. Some epicormic growth (<50 % of remaining canopy). Some small dead branchlets (<50 % canopy).
2 - Poor	Tree with <25 % of original canopy present. Predominantly epicormic growth (>50 % of remaining canopy). Some main branches dead (<50 % canopy).
1 – Very Poor	Unhealthy tree with no original canopy. All epicormic growth. Most main branches dead (>50 % canopy).
0 - Dead	Dead tree.

Table 26 Vegetation patch condition rating (description and guidelines) for coolabah

Condition Rating	Vegetation patch - general description	Vegetation patch rating – guidelines
5 - Excellent	Nearly all trees healthy	>75 % of living trees in excellent condition Any dead trees appear to be old
4 - Good	The majority of trees healthy	>50 % of living trees in good or better condition Some dead trees (< 5%) may be present
3 - Moderate	Some healthy trees but as many in moderate or poor condition	>50% of living trees in moderate or better condition Living trees in a range of condition classes Up to 10% dead trees may be present
2 - Poor	The majority of trees unhealthy	>50 % of living trees in poor or very poor condition Greater than 10% dead trees may be present
1 – Very Poor	Nearly all trees unhealthy	>75 % of living trees in poor condition or very poor condition Up to 25 % dead trees may be present
0 – Dead/Dying	Nearly all trees dead	>50 % of trees dead Any living trees in poor or very poor condition

Appendix 3 Pixel analysis site details

The following table provides site attribute including location, species selection, associated gauging station, associated Landsat tile, model zone, flood frequency classification, GDE classification and also the R^2 value for correlation of pixel greenness with climate variables.

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9280001	Pixel	CLB	147.6051	-29.4288	422016	3	0	N/A	p092r080	0.485146
9280002	Pixel	CLB	147.6093	-29.4298	422016	3	2	N/A	p092r080	0.487927
9280003	Pixel	CLB	147.6101	-29.4288	422016	3	1	N/A	p092r080	0.440702
9280004	Pixel	CLB	147.6064	-29.4249	422016	3	0	Highly Likely	p092r080	0.537058
9280005	Pixel	CLB	147.6086	-29.427	422016	3	0	N/A	p092r080	0.534198
9280006	Pixel	CLB	147.606	-29.4305	422016	3	0	Potential	p092r080	0.643888
9280007	Pixel	CLB	148.0795	-28.5243	422204	3	0	N/A	p092r080	0.322863
9280008	Pixel	CLB	148.0733	-28.5211	422204	3	0	N/A	p092r080	0.457653
9280009	Pixel	CLB	148.0811	-28.5287	422204	3	3	N/A	p092r080	0.385557
9280010	Pixel	CLB	148.0978	-28.5168	422204	3	2	N/A	p092r080	0.41264
9280011	Pixel	CLB	148.1021	-28.5174	422204	1	2	N/A	p092r080	0.410451
9280012	Pixel	CLB	148.1069	-28.5247	422204	3	3	N/A	p092r080	0.39985
9280013	Pixel	CLB	148.0793	-28.5234	422204	3	0	N/A	p092r080	0.390142
9280014	Pixel	CLB	148.083	-28.5256	422204	3	0	N/A	p092r080	0.407417
9280015	Pixel	CLB	148.0947	-28.5196	422204	3	0	N/A	p092r080	0.287041
9280016	Pixel	CLB	148.1075	-28.526	422204	1	4	N/A	p092r080	0.426008
9280017	Pixel	CLB	148.1038	-28.5212	422204	3	1	N/A	p092r080	0.369903
9280019	Pixel	CLB	148.0787	-28.5305	422204	3	1	N/A	p092r080	0.441367
9280020	Pixel	CLB	148.0795	-28.5291	422204	3	2	N/A	p092r080	0.412634
9280021	Pixel	CLB	148.087	-28.5276	422204	3	0	N/A	p092r080	0.40881

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9280022	Pixel	CLB	148.0851	-28.5235	422204	3	0	N/A	p092r080	0.35421
9280023	Pixel	CLB	148.1075	-28.5276	422204	1	4	N/A	p092r080	0.454737
9280024	Pixel	CLB	147.6065	-29.4292	422016	3	0	N/A	p092r080	0.575141
9280025	Pixel	CLB	147.6085	-29.4231	422016	3	1	N/A	p092r080	0.51167
9280026	Pixel	CLB	147.6096	-29.4291	422016	3	2	N/A	p092r080	0.465577
9280027	Pixel	CLB	147.8192	-29.2037	422030	3	0	N/A	p092r080	0.62649
9280028	Pixel	CLB	147.8133	-29.2064	422030	3	0	Potential	p092r080	0.576182
9280029	Pixel	CLB	147.8246	-29.1959	422030	3	0	Potential	p092r080	0.581595
9280030	Pixel	CLB	147.8232	-29.2072	422030	3	0	N/A	p092r080	0.595823
9280031	Pixel	CLB	147.8147	-29.2115	422030	3	1	N/A	p092r080	0.648619
9280032	Pixel	CLB	147.8171	-29.2104	422030	3	2	N/A	p092r080	0.652863
9280033	Pixel	CLB	147.8248	-29.2012	422030	3	2	N/A	p092r080	0.623697
9280034	Pixel	CLB	147.8246	-29.203	422030	3	1	N/A	p092r080	0.605084
9280035	Pixel	CLB	147.8191	-29.2066	422030	3	0	N/A	p092r080	0.647977
9280036	Pixel	CLB	147.8043	-29.2073	422030	3	6	N/A	p092r080	0.472762
9280037	Pixel	CLB	147.6595	-28.7792	422208	3	2	Potential	p092r080	0.468152
9280038	Pixel	CLB	147.6582	-28.7809	422208	3	2	N/A	p092r080	0.501382
9280039	Pixel	CLB	147.654	-28.79	422208	3	2	N/A	p092r080	0.502819
9280040	Pixel	CLB	147.6546	-28.7903	422208	3	2	N/A	p092r080	0.484696
9280041	Pixel	CLB	147.6535	-28.7907	422208	3	1	N/A	p092r080	0.496204

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9280042	Pixel	CLB	147.654	-28.7882	422208	3	3	N/A	p092r080	0.486676
9280043	Pixel	CLB	147.6563	-28.7869	422208	3	3	N/A	p092r080	0.450103
9280044	Pixel	CLB	147.8454	-28.8633	422207	3	0	Likely	p092r080	0.427582
9280045	Pixel	CLB	147.8481	-28.8643	422207	3	0	N/A	p092r080	0.41495
9280046	Pixel	CLB	147.8318	-28.8848	422207	3	1	N/A	p092r080	0.425571
9280047	Pixel	CLB	147.8365	-28.8786	422207	3	3	N/A	p092r080	0.425441
9280048	Pixel	CLB	147.8485	-28.8653	422207	3	0	N/A	p092r080	0.557195
9280049	Pixel	CLB	148.2187	-28.5585	422205	3	7	N/A	p092r080	0.486444
9280050	Pixel	CLB	148.2186	-28.5595	422205	3	0	N/A	p092r080	0.376806
9280051	Pixel	CLB	148.2256	-28.5611	422205	2	0	N/A	p092r080	0.50294
9280052	Pixel	CLB	148.2206	-28.5615	422205	3	2	N/A	p092r080	0.428855
9280053	Pixel	CLB	148.2284	-28.5484	422205	2	0	N/A	p092r080	0.319333
9280054	Pixel	CLB	148.2311	-28.5468	422205	2	0	N/A	p092r080	0.354154
9280055	Pixel	CLB	148.2338	-28.5489	422205	2	0	N/A	p092r080	0.401033
9280056	Pixel	CLB	148.2325	-28.5518	422205	3	0	N/A	p092r080	0.471817
9280057	Pixel	CLB	148.0829	-28.5288	422204	3	2	N/A	p092r080	0.39712
9280058	Pixel	CLB	148.0782	-28.5195	422204	3	4	N/A	p092r080	0.353515
9280059	Pixel	CLB	148.2253	-28.552	422205	2	0	N/A	p092r080	0.49885
9280072	Pixel	CLB	148.0327	-29.103	422030	1	6	N/A	p092r080	0.486242
9280073	Pixel	CLB	148.0311	-29.1053	422030	1	0	N/A	p092r080	0.546205

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9280074	Pixel	CLB	148.0272	-29.1144	422030	1	0	Potential	p092r080	0.54987
9280075	Pixel	CLB	148.0297	-29.1125	422030	1	0	N/A	p092r080	0.414179
9280076	Pixel	CLB	148.0277	-29.1153	422030	1	6	N/A	p092r080	0.461446
9280077	Pixel	CLB	148.0259	-29.1191	422030	1	2	N/A	p092r080	0.536896
9280078	Pixel	CLB	148.0314	-29.1031	422030	1	2	N/A	p092r080	0.415647
9280079	Pixel	CLB	148.0343	-29.1064	422030	1	4	N/A	p092r080	0.540463
9280080	Pixel	CLB	148.0262	-29.1171	422030	1	1	N/A	p092r080	0.513025
9280081	Pixel	CLB	147.865	-28.8237	422207	1	2	N/A	p092r080	0.523539
9280082	Pixel	CLB	147.8652	-28.8226	422207	1	1	N/A	p092r080	0.453973
9280083	Pixel	CLB	147.8643	-28.8215	422207	1	2	N/A	p092r080	0.474251
9280084	Pixel	CLB	147.8626	-28.8256	422207	1	1	N/A	p092r080	0.481366
9280085	Pixel	CLB	147.863	-28.8295	422207	1	0	N/A	p092r080	0.375669
9280086	Pixel	CLB	147.8666	-28.8197	422207	1	1	N/A	p092r080	0.492382
9280087	Pixel	CLB	147.8626	-28.828	422207	1	0	N/A	p092r080	0.42522
9280153	Pixel	CLB	147.6202	-28.7686	422208	2	5	N/A	p092r080	0.545912
9280154	Pixel	CLB	147.6154	-28.7675	422208	2	5	N/A	p092r080	0.499914
9280155	Pixel	CLB	147.6213	-28.767	422208	2	4	N/A	p092r080	0.57373
9280156	Pixel	CLB	147.6269	-28.7658	422208	2	3	N/A	p092r080	0.650426
9280157	Pixel	CLB	147.6264	-28.763	422208	2	2	N/A	p092r080	0.572728
9280158	Pixel	CLB	147.6178	-28.7665	422208	2	4	N/A	p092r080	0.605372

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9280159	Pixel	CLB	147.6146	-28.7656	422208	2	2	N/A	p092r080	0.549764
9280160	Pixel	CLB	147.6145	-28.7773	422208	2	5	N/A	p092r080	0.493758
9280161	Pixel	CLB	147.6186	-28.7605	422208	2	7	N/A	p092r080	0.538904
9280162	Pixel	CLB	147.6279	-28.7579	422208	2	1	N/A	p092r080	0.609487
9280163	Pixel	CLB	147.6401	-28.7637	422208	2	0	N/A	p092r080	0.570433
9280164	Pixel	CLB	147.6349	-28.7633	422208	2	3	N/A	p092r080	0.592397
9280165	Pixel	CLB	147.6158	-28.7801	422208	2	3	N/A	p092r080	0.496015
9280166	Pixel	CLB	148.0295	-29.1326	422030	2	3	N/A	p092r080	0.414164
9280167	Pixel	CLB	148.0342	-29.1227	422030	2	1	Likely	p092r080	0.492438
9280168	Pixel	CLB	148.048	-29.1036	422030	2	0	N/A	p092r080	0.596517
9280169	Pixel	CLB	148.0384	-29.1051	422030	2	2	Potential	p092r080	0.425754
9280170	Pixel	CLB	148.0419	-29.1129	422030	2	0	Potential	p092r080	0.561729
9280171	Pixel	CLB	148.0395	-29.1153	422030	2	1	Potential	p092r080	0.583358
9280172	Pixel	CLB	148.0445	-29.1101	422030	2	0	Potential	p092r080	0.57346
9280173	Pixel	CLB	148.0413	-29.1074	422030	2	0	Potential	p092r080	0.587896
9280175	Pixel	CLB	148.0373	-29.1338	422030	2	1	N/A	p092r080	0.586316
9280176	Pixel	CLB	147.6339	-28.7768	422208	2	0	N/A	p092r080	0.58892
9280177	Pixel	CLB	148.0338	-29.1336	422030	2	0	Potential	p092r080	0.483299
9280178	Pixel	CLB	147.6225	-28.7563	422208	2	0	N/A	p092r080	0.574696
9280197	DVM	CLB	147.8716	-28.8337	N/A	1	N/A	N/A	p092r080	0.600224

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9280198	DVM	CLB	147.8749	-28.8364	N/A	4	N/A	N/A	p092r080	0.438434
9280199	Pixel	CLB	148.1113	-28.5176	N/A	1	N/A	N/A	p092r080	0.339396
9280200	Pixel	CLB	148.1227	-28.5424	N/A	1	N/A	N/A	p092r080	0.438784
9280201	Pixel	CLB	148.1838	-28.5951	N/A	2	N/A	N/A	p092r080	0.446198
9280202	Pixel	CLB	148.4606	-28.247	N/A	4	N/A	N/A	p092r080	0.397304
9280203	Pixel	CLB	147.7752	-28.6649	N/A	1	N/A	N/A	p092r080	0.507346
9280204	DVM	CLB	148.1787	-28.6921	N/A	1	N/A	N/A	p092r080	0.476493
9280205	Pixel	CLB	147.7064	-28.6969	N/A	2	N/A	N/A	p092r080	0.507442
9280206	Pixel	CLB	147.6894	-28.9048	N/A	1	N/A	N/A	p092r080	0.306325
9280207	Pixel	CLB	147.7502	-28.9399	N/A	1	N/A	N/A	p092r080	0.500379
9280208	Pixel	CLB	147.8485	-28.8653	422207	3	0	N/A	p092r080	0.557195
9280209	Pixel	CLB	148.032	-29.1042	422030	1	2	N/A	p092r080	0.458185
9280210	Pixel	CLB	148.0336	-29.1081	422030	1	0	N/A	p092r080	0.545133
9280211	Pixel	CLB	148.032	-29.1111	422030	1	1	N/A	p092r080	0.547467
9280215	Pixel	CLB	148.0295	-29.1326	422030	2	0	N/A	p092r080	0.414164
9280217	Pixel	CLB	148.0474	-29.1078	422030	2	0	Potential	p092r080	0.61144
9280300	Rip. Tran	CLB	148.4602	-28.2447	N/A	1	N/A	N/A	p092r080	0.489654
9280301	Rip. Tran	CLB	148.4609	-28.2483	N/A	1	N/A	N/A	p092r080	0.573252
9280302	Rip. Tran	CLB	148.4607	-28.2475	N/A	1	N/A	N/A	p092r080	0.54794
9280333	Rip. Tran	CLB	148.4604	-28.2459	N/A	1	N/A	N/A	p092r080	0.470302

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9280334	Rip. Tran	CLB	148.4604	-28.2455	N/A	1	N/A	N/A	p092r080	0.504679
9280335	Rip. Tran	CLB	148.4601	-28.2438	N/A	1	N/A	N/A	p092r080	0.524564
9280336	Rip. Tran	CLB	148.461	-28.2488	N/A	1	N/A	N/A	p092r080	0.535157
9280337	Rip. Tran	CLB	148.4611	-28.25	N/A	1	N/A	N/A	p092r080	0.294804
9280338	Rip. Tran	CLB	148.1501	-28.5687	N/A	1	N/A	N/A	p092r080	0.500816
9280339	Rip. Tran	CLB	148.1503	-28.5689	N/A	1	N/A	N/A	p092r080	0.537909
9280340	Rip. Tran	CLB	148.151	-28.5694	N/A	1	N/A	N/A	p092r080	0.527376
9280341	Rip. Tran	CLB	148.1513	-28.5696	N/A	1	N/A	Potential	p092r080	0.551592
9280342	Rip. Tran	CLB	148.1518	-28.57	N/A	1	N/A	N/A	p092r080	0.441504
9280343	Rip. Tran	CLB	148.1528	-28.5707	N/A	1	N/A	N/A	p092r080	0.465316
9280344	Rip. Tran	CLB	148.2088	-28.6005	N/A	1	N/A	N/A	p092r080	0.396496
9280345	Rip. Tran	CLB	148.208	-28.6004	N/A	1	N/A	N/A	p092r080	0.255854
9280346	Rip. Tran	CLB	148.2076	-28.6003	N/A	1	N/A	N/A	p092r080	0.42349
9280347	Rip. Tran	CLB	148.2073	-28.6003	N/A	1	N/A	N/A	p092r080	0.638613
9280348	Rip. Tran	CLB	148.2068	-28.6002	N/A	1	N/A	N/A	p092r080	0.533255
9280349	Rip. Tran	CLB	148.2062	-28.6001	N/A	1	N/A	N/A	p092r080	0.549063
9280350	Rip. Tran	CLB	148.2059	-28.6001	N/A	1	N/A	N/A	p092r080	0.530968
9280351	Rip. Tran	CLB	148.2056	-28.6001	N/A	1	N/A	N/A	p092r080	0.535887
9280359	Pixel	LIG	148.4143	-28.2823	422201	4	6	N/A	p092r080	0.395194
9280360	Pixel	LIG	148.4182	-28.2854	422201	4	3	N/A	p092r080	0.578133

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9280361	Pixel	CLB	148.4839	-28.249	422201	1	0	Likely	p092r080	0.398766
9280362	Pixel	CLB	148.4827	-28.2482	422201	1	0	Highly Likely	p092r080	0.498154
9280363	Pixel	LIG	148.3152	-28.4476	422201	2	1	N/A	p092r080	0.362257
9280364	Pixel	LIG	148.3202	-28.4478	422201	2	0	N/A	p092r080	0.471433
9280365	Pixel	CLB	148.1652	-28.7089	422206	4	0	Highly Likely	p092r080	0.445707
9280366	Pixel	LIG	148.0487	-28.8437	422206	1	1	N/A	p092r080	0.380425
9280367	Pixel	LIG	148.0519	-28.8417	422206	1	0	N/A	p092r080	0.393664
9280368	Pixel	CLB	148.2664	-28.4826	422205	2	2	N/A	p092r080	0.450157
9280389	Pixel	LIG	147.646	-29.2332	422016	2	0	N/A	p092r080	0.322533
9280390	Pixel	LIG	147.7264	-29.3097	N/A	2	0	N/A	p092r080	0.267205
9281061	Pixel	CLB	147.4547	-29.5834	422016	1	9	N/A	p92r081	0.417299
9281062	Pixel	CLB	147.4518	-29.5864	422016	1	5	N/A	p92r081	0.468476
9281063	Pixel	CLB	147.4477	-29.5882	422016	1	2	N/A	p92r081	0.526662
9281064	Pixel	CLB	147.457	-29.5802	422016	1	5	N/A	p92r081	0.347061
9281065	Pixel	CLB	147.4564	-29.5841	422016	1	4	N/A	p92r081	0.5392
9281066	Pixel	CLB	147.4509	-29.585	422016	1	3	N/A	p92r081	0.468097
9281067	Pixel	CLB	147.4605	-29.5877	422016	1	2	N/A	p92r081	0.55424
9281068	Pixel	CLB	147.4622	-29.5825	422016	1	2	N/A	p92r081	0.57099
9281069	Pixel	CLB	147.4541	-29.5815	422016	1	2	N/A	p92r081	0.45936
9281070	Pixel	CLB	147.4537	-29.5851	422016	1	0	N/A	p92r081	0.504008

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9281071	Pixel	CLB	147.4535	-29.5864	422016	1	0	N/A	p92r081	0.562048
9281391	Pixel	LIG	147.3895	-29.5449	422016	2	4	N/A	p92r081	0.421111
9281392	Pixel	LIG	147.3867	-29.5433	422016	2	5	N/A	p92r081	0.42265
9281393	Pixel	LIG	147.3127	-29.6376	422016	2	0	N/A	p92r081	0.483617
9380087	Pixel	CLB	146.81	-29.3456	422017	1	4	Likely	p093r080	0.562533
9380088	Pixel	CLB	147.4116	-28.9849	422015	1	4	N/A	p093r080	0.507064
9380089	Pixel	CLB	147.4104	-28.9871	422015	1	6	N/A	p093r080	0.462515
9380090	Pixel	CLB	147.4126	-28.9811	422015	1	3	N/A	p093r080	0.488725
9380091	Pixel	CLB	147.4097	-28.9883	422015	1	8	N/A	p093r080	0.409071
9380092	Pixel	CLB	147.4127	-28.9868	422015	1	4	N/A	p093r080	0.542131
9380093	Pixel	CLB	147.4168	-28.9789	422015	1	3	N/A	p093r080	0.553246
9380094	Pixel	CLB	147.4171	-28.9859	422015	1	4	N/A	p093r080	0.51615
9380095	Pixel	CLB	147.4091	-28.9925	422015	1	0	N/A	p093r080	0.520298
9380096	Pixel	CLB	147.4097	-28.994	422015	1	0	N/A	p093r080	0.517243
9380097	Pixel	CLB	147.4169	-28.9825	422015	1	3	N/A	p093r080	0.563113
9380098	Pixel	CLB	147.4191	-28.9806	422015	1	5	N/A	p093r080	0.500946
9380099	Pixel	CLB	147.4074	-28.994	422015	1	0	N/A	p093r080	0.600146
9380100	Pixel	CLB	146.8046	-29.3585	422017	1	0	N/A	p093r080	0.247504
9380101	Pixel	CLB	146.8051	-29.3489	422017	1	0	N/A	p093r080	0.463839
9380102	Pixel	CLB	146.805	-29.3569	422017	1	0	N/A	p093r080	0.297059

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9380103	Pixel	CLB	146.8071	-29.3469	422017	1	0	N/A	p093r080	0.39734
9380104	Pixel	CLB	146.8048	-29.3606	422017	1	4	Likely	p093r080	0.40593
9380105	Pixel	CLB	146.8007	-29.3613	422017	1	4	N/A	p093r080	0.303193
9380106	Pixel	CLB	146.8059	-29.3503	422017	1	4	N/A	p093r080	0.369607
9380107	Pixel	CLB	146.8067	-29.3519	422017	1	5	Potential	p093r080	0.467158
9380108	Pixel	CLB	146.8082	-29.3459	422017	1	5	N/A	p093r080	0.448851
9380109	Pixel	CLB	146.81	-29.3456	422017	1	4	Likely	p093r080	0.578899
9380121	Pixel	CLB	147.0185	-29.1214	422017	4	2	Potential	p093r080	0.460001
9380122	Pixel	CLB	147.0267	-29.1236	422017	4	0	Potential	p093r080	0.439698
9380123	Pixel	CLB	147.0345	-29.1184	422017	4	0	N/A	p093r080	0.362739
9380124	Pixel	CLB	147.0233	-29.1172	422017	4	1	N/A	p093r080	0.395782
9380125	Pixel	CLB	147.0112	-29.1356	422017	4	1	N/A	p093r080	0.466076
9380126	Pixel	CLB	147.0338	-29.123	422017	4	1	Potential	p093r080	0.544805
9380127	Pixel	CLB	147.0349	-29.1208	422017	4	0	N/A	p093r080	0.401841
9380128	Pixel	CLB	147.0158	-29.1188	422017	4	0	N/A	p093r080	0.51492
9380129	Pixel	CLB	147.0324	-29.1124	422017	4	2	N/A	p093r080	0.490687
9380130	Pixel	CLB	147.0333	-29.1118	422017	4	0	N/A	p093r080	0.512982
9380131	Pixel	CLB	147.0117	-29.1343	422017	4	0	N/A	p093r080	0.495069
9380132	Pixel	CLB	147.0278	-29.1299	422017	4	4	N/A	p093r080	0.42902
9380133	Pixel	CLB	147.4738	-28.9061	422015	2	0	Highly Likely	p093r080	0.62024

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9380134	Pixel	CLB	147.474	-28.903	422015	2	0	Likely	p093r080	0.588591
9380135	Pixel	CLB	147.4688	-28.9052	422015	2	3	Potential	p093r080	0.476281
9380137	Pixel	CLB	147.474	-28.9049	422015	2	0	Likely	p093r080	0.646697
9380138	Pixel	CLB	147.475	-28.9073	422015	2	0	N/A	p093r080	0.469061
9380139	Pixel	CLB	147.4766	-28.9067	422015	2	0	N/A	p093r080	0.472347
9380140	Pixel	CLB	147.4751	-28.9037	422015	2	0	Highly Likely	p093r080	0.458885
9380141	Pixel	CLB	147.4758	-28.9055	422015	2	0	Potential	p093r080	0.451695
9380142	Pixel	CLB	147.4731	-28.9035	422015	2	0	Highly Likely	p093r080	0.570764
9380143	Pixel	CLB	146.8829	-29.2554	422017	4	1	N/A	p093r080	0.524512
9380144	Pixel	CLB	146.8907	-29.2549	422017	4	0	N/A	p093r080	0.643936
9380145	Pixel	CLB	146.8903	-29.2529	422017	4	0	N/A	p093r080	0.478729
9380146	Pixel	CLB	146.8822	-29.2558	422017	4	0	N/A	p093r080	0.364388
9380147	Pixel	CLB	146.8938	-29.2548	422017	4	0	N/A	p093r080	0.537044
9380148	Pixel	CLB	146.9014	-29.2521	422017	4	0	N/A	p093r080	0.562734
9380149	Pixel	CLB	146.899	-29.2523	422017	4	0	N/A	p093r080	0.566358
9380150	Pixel	CLB	146.9023	-29.2521	422017	4	0	N/A	p093r080	0.539442
9380151	Pixel	CLB	146.8946	-29.2526	422017	4	0	N/A	p093r080	0.550489
9380152	Pixel	CLB	146.8877	-29.2559	422017	4	0	N/A	p093r080	0.629373
9380172	Pixel	CLB	147.447	-28.9642	422015	2	0	N/A	p093r080	0.533342
9380174	Pixel	CLB	147.4596	-28.9648	422015	2	4	N/A	p093r080	0.409103

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9380175	Pixel	CLB	147.447	-28.9642	422015	2	3	N/A	p093r080	0.542073
9380176	Pixel	CLB	147.4518	-28.9819	422015	2	4	N/A	p093r080	0.487173
9380177	Pixel	CLB	147.4486	-28.9834	422015	2	4	N/A	p093r080	0.416662
9380178	Pixel	CLB	147.4479	-28.9883	422015	2	0	N/A	p093r080	0.58694
9380179	Pixel	CLB	147.4388	-28.98	422015	2	4	N/A	p093r080	0.485342
9380180	Pixel	CLB	147.4466	-28.9778	422015	2	3	N/A	p093r080	0.470365
9380181	Pixel	CLB	147.4517	-28.9665	422015	2	4	N/A	p093r080	0.473717
9380182	Pixel	CLB	147.465	-28.9605	422015	2	5	N/A	p093r080	0.438344
9380183	Pixel	CLB	147.4596	-28.9604	422015	2	2	N/A	p093r080	0.552429
9380184	Pixel	CLB	147.4587	-28.9583	422015	2	0	N/A	p093r080	0.552208
9380185	Pixel	CLB	147.4559	-28.9595	422015	2	0	N/A	p093r080	0.459344
9380186	Pixel	CLB	147.434	-28.9943	422015	2	8	Potential	p093r080	0.406674
9380187	Pixel	CLB	147.4576	-28.9604	422015	2	1	N/A	p093r080	0.43853
9380188	Pixel	CLB	147.4447	-28.9623	422015	2	2	Likely	p093r080	0.402369
9380189	Pixel	CLB	147.4543	-28.9625	422015	2	0	N/A	p093r080	0.545224
9380190	Pixel	CLB	146.9764	-29.1762	422017	2	2	N/A	p093r080	0.491442
9380191	Pixel	CLB	146.977	-29.1702	422017	2	3	Potential	p093r080	0.595391
9380192	Pixel	CLB	146.9798	-29.1787	422017	2	2	N/A	p093r080	0.44812
9380193	Pixel	CLB	146.9828	-29.1817	422017	2	1	N/A	p093r080	0.504174
9380194	Pixel	CLB	146.9839	-29.1778	422017	2	4	N/A	p093r080	0.540794

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9380195	Pixel	CLB	146.982	-29.1697	422017	2	2	N/A	p093r080	0.632665
9380196	Pixel	CLB	146.9594	-29.1882	422017	2	3	N/A	p093r080	0.47423
9380197	Pixel	CLB	146.975	-29.1704	422017	2	4	N/A	p093r080	0.514238
9380355	Pixel	CLB	147.0205	-29.1227	422017	4	0	Highly Likely	p093r080	0.448701
9380356	Pixel	CLB	147.0247	-29.1209	422017	4	1	Highly Likely	p093r080	0.388408
9380357	Pixel	CLB	146.9022	-29.2607	422017	4	0	Highly Likely	p093r080	0.443116
9380358	Pixel	CLB	146.9035	-29.2603	422017	4	0	Likely	p093r080	0.495925
9380359	Pixel	CLB	147.4702	-28.906	422015	2	3	N/A	p093r080	0.498125
9380369	Pixel	BB	147.2332	-28.8211	N/A	2	N/A	N/A	p093r080	0.489696
9380370	Pixel	BB	147.2216	-28.8099	N/A	2	N/A	N/A	p093r080	0.543101
9380371	Pixel	BB	147.2665	-28.8059	N/A	2	N/A	N/A	p093r080	0.487471
9380372	Pixel	BB	147.2404	-28.7774	N/A	2	N/A	N/A	p093r080	0.527343
9380373	Pixel	BB	147.0389	-28.9533	N/A	2	N/A	N/A	p093r080	0.575389
9380374	Pixel	BB	147.0755	-28.9361	N/A	2	N/A	N/A	p093r080	0.559081
9380375	Pixel	BB	147.1674	-28.8867	N/A	2	N/A	Potential	p093r080	0.550622
9380376	Pixel	BB	147.1696	-28.8875	N/A	2	N/A	N/A	p093r080	0.582731
9380377	Pixel	BB	146.951	-28.8734	N/A	N/A	N/A	N/A	p093r080	0.555632
9380378	Pixel	BB	146.9522	-28.8707	N/A	N/A	N/A	N/A	p093r080	0.622549
9380379	Pixel	BB	147.0265	-28.839	N/A	N/A	N/A	N/A	p093r080	0.629438
9380380	Pixel	BB	147.022	-28.8431	N/A	N/A	N/A	N/A	p093r080	0.585391

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9380381	Pixel	BB	147.0559	-28.8557	N/A	N/A	N/A	N/A	p093r080	0.687348
9380382	Pixel	BB	147.0526	-28.9638	N/A	2	N/A	N/A	p093r080	0.492106
9380383	Pixel	BB	147.1184	-28.9954	N/A	3	N/A	N/A	p093r080	0.489805
9380384	Pixel	BB	147.123	-28.9931	N/A	3	N/A	N/A	p093r080	0.502716
9380385	Pixel	BB	147.2179	-28.9278	N/A	3	N/A	N/A	p093r080	0.477348
9380386	Pixel	BB	147.2146	-28.9225	N/A	3	N/A	N/A	p093r080	0.560276
9380387	Pixel	BB	147.2629	-28.7645	N/A	2	N/A	N/A	p093r080	0.572189
9380388	Pixel	BB	147.2687	-28.7605	N/A	2	N/A	N/A	p093r080	0.466858
9381110	Pixel	CLB	146.4843	-29.8128	422006	1	7	N/A	p093r081	0.66466
9381111	Pixel	CLB	146.4852	-29.8117	422006	1	5	N/A	p093r081	0.671312
9381112	Pixel	CLB	146.4831	-29.8091	422006	1	5	N/A	p093r081	0.546221
9381113	Pixel	CLB	146.4818	-29.8121	422006	1	7	N/A	p093r081	0.532293
9381114	Pixel	CLB	146.4805	-29.805	422006	1	6	N/A	p093r081	0.403496
9381115	Pixel	CLB	146.481	-29.804	422006	1	5	N/A	p093r081	0.579299
9381116	Pixel	CLB	146.4819	-29.801	422006	1	7	N/A	p093r081	0.493711
9381117	Pixel	CLB	146.4809	-29.8073	422006	1	5	N/A	p093r081	0.642372
9381118	Pixel	CLB	146.4836	-29.8081	422006	1	5	N/A	p093r081	0.638732
9381119	Pixel	CLB	146.4799	-29.8046	422006	1	0	N/A	p093r081	0.336983
9381120	Pixel	CLB	146.4838	-29.8107	422006	1	5	N/A	p093r081	0.515194
9381208	Pixel	CLB	146.568	-29.7399	422006	2	0	N/A	p093r081	0.502148

SITE ID	Site type	Spp.	Long.	Lat.	Gauging station	Model Zone	Flood Freq.	GDE class	Landsat tile	R ² (variance explained by climate)
9381209	Pixel	CLB	146.4816	-29.7814	422006	0	0	N/A	p093r081	0.424692
9381210	Pixel	CLB	146.6089	-29.6738	422006	0	4	N/A	p093r081	0.696226
9381211	Pixel	CLB	146.6436	-29.6735	422006	0	4	N/A	p093r081	0.518818

CLB = Coolabah, LIG = Lignum, BB = Black box

Pixel = Site selected by stratification within vegetation and model zone classification, Rip. Tran.= Site selected along riparian transect location,
DVM = Detailed vegetation monitoring site

Appendix 4 Project data inventory – remote sensing

Table 27 Inventory of data sets used in remote sensing and spatial analysis (includes data type, format, spatial extent, reference to where used in the report, data storage location and access arrangements).

Data group	Data Code	ID	How measured/ collected	Data Source	Spatial extent	Format	Report Section	Database Storage	Access arrangements
Climate	CL01	Rainfall	Existing datasets	SILO (DSITI)	LBF	raster	4.2, 7.1	Online	www.longpaddock.qld.gov.au/silo
Climate	CL02	Evaporation	Existing datasets	CSIRO	LBF	raster	4.2	Online	registry.it.csiro.au/sandbox/csiro/oznome/A/WRA-L/potential-evapotranspiration
GIS/RS	GR01	Regional Ecosystems	Existing datasets	Herbarium (QLD Government)	LBF (QLD)	Shape file	4.1	Online	qldglobe.information.qld.gov.au/
GIS/RS	GR02	Plant Community Types	Existing datasets	NSW Government	LBF (NSW)	Shape file	4.1	Online	www.environment.nsw.gov.au/research/Visclassification.htm
GIS/RS	GR03	LBF Vegetation Mapping	Manipulation of datasets	GR01, GR02	LBF	Shape file	4.1, 4.2, 7.1	WPE (DSITI)	By arrangement
GIS/RS	GR04a	Land Systems (QLD)	Existing datasets	QLD Government	LBF (QLD)	Shape file	4.1	Online	data.qld.gov.au/dataset/land-systems-series/resource/c059dd3d-dc0d-42b9-bd26-02b8fc6e72c2
GIS/RS	GR04b	updated Land Systems (QLD)	Existing datasets	QLD Government	LBF (QLD)	Shape file	4.1	DNRM	By arrangement
GIS/RS	GR05	Land Systems (NSW)	Existing datasets	NSW Government	LBF (NSW)	Shape file	4.1	Online	data.environment.nsw.gov.au/dataset/land-systems-of-western-new-south-wales0f783

Data group	Data Code	ID	How measured/ collected	Data Source	Spatial extent	Format	Report Section	Database Storage	Access arrangements
GIS/RS	GR06	Modelling Zones	Manipulation of datasets	GR04a, GR04b, GR05	LBF	Shape file	4.1, 4.2, 7.1	WPE (DSITI)	By arrangement
GIS/RS	GR07	Black Box Distribution	Manipulation of datasets	GR03, GR06	LBF	Shape file	4.1, 4.3	WPE (DSITI)	By arrangement
GIS/RS	GR08	Coolabah Distribution	Manipulation of datasets	GR03, GR06	LBF	Shape file	4.1	WPE (DSITI)	By arrangement
GIS/RS	GR09	Lignum Distribution	Manipulation of datasets	GR03, GR06	LBF	Shape file	4.1, 4.3	WPE (DSITI)	By arrangement
GIS/RS	GR10	Red Gum Distribution	Manipulation of datasets	GR03, GR06	LBF	Shape file	4.1	WPE (DSITI)	By arrangement
GIS/RS	GR11	GDE Distribution	Manipulation of datasets	GR15a, GR15b, GR15c	LBF	Shape file	4.2, 4.3, 7.1	WPE (DSITI)	By arrangement
GIS/RS	GR12	Pixel Sites	Selected points	DSITI	283 sites	Shape file	4.2	WPE (DSITI)	By arrangement
GIS/RS	GR13	Floodplain Assessment Areas	Existing datasets	DSITI/DNRM	LBF	Shape file	4.2	DNRM/DSITI	By arrangement
GIS/RS	GR14	Flood Frequency Value	Manipulation of datasets	GR13, SF01, SF02, GR15c	Pixel sites	Shape file	4.2	WPE (DSITI)	By arrangement
GIS/RS	GR15a	Landsat Seasonal Greenness	Existing datasets	Landsat	LBF (4 tiles)	Various	4.2, 7.1	RS Centre	By arrangement

Data group	Data Code	ID	How measured/ collected	Data Source	Spatial extent	Format	Report Section	Database Storage	Access arrangements
GIS/RS	GR15b	Landsat NDVI	Existing datasets	Landsat	LBF (4 tiles)	Various	4.2	RS Centre	By arrangement
GIS/RS	GR15c	Landsat water indices	Existing datasets	Landsat	LBF (4 tiles)	Various	4.2	RS Centre	By arrangement
GIS/RS	GR16	GFC Black Box	Manipulated existing datasets	GR12, GR15a	20 sites	Excel	4.2	WPE (DSITI)	By arrangement
GIS/RS	GR17	GFC Coolabah	Manipulated existing datasets	GR12, GR15a	236 sites	Excel	4.2	WPE (DSITI)	By arrangement
GIS/RS	GR18	GFC Lignum	Manipulated existing datasets	GR12, GR15a	11 sites	Excel	4.2	WPE (DSITI)	By arrangement
GIS/RS	GR19	GFC GDE	Manipulated existing datasets	GR11, GR15a	40 sites	Excel	4.3	WPE (DSITI)	By arrangement
GIS/RS	GR20	Climate vs GFC Black Box	Manipulated existing datasets	GR16, CL1, CL2	20 sites	Excel	4.3	WPE (DSITI)	By arrangement
GIS/RS	GR21	Climate vs GFC Coolabah by model zone (not GDE)	Manipulated existing datasets	GR17, CL1, CL2, GR06	209 sites	Excel	4.2	WPE (DSITI)	By arrangement

Data group	Data Code	ID	How measured/ collected	Data Source	Spatial extent	Format	Report Section	Database Storage	Access arrangements
GIS/RS	GR21	Climate vs GFC Coolabah by flood frequency (not GDE)	Manipulated existing datasets	GR17, CL1, CL2, GR14	180 sites	Excel	4.2	WPE (DSITI)	By arrangement
GIS/RS	GR22	Climate vs GFC Coolabah (GDE)	Manipulated existing datasets	GR19, CL1, CL2	40 sites	Excel	4.3	WPE (DSITI)	By arrangement
GIS/RS	GR23	Climate vs GFC Lignum	Manipulated existing datasets	GR18, CL1, CL2	11 sites	Excel	4.3	WPE (DSITI)	By arrangement
GIS/RS	GR24	Riverine zone	Manipulation of datasets	GR06	LBF	Shape file	7.1, 7.2	WPE (DSITI)	By arrangement
GIS/RS	GR25	LiDAR 5m	Existing datasets	Geoscience Australia	LBF	.las	7.1, 7.2	Online	http://www.ga.gov.au/scientific-topics/national-location-information/digital-elevation-data
GIS/RS	GR26	Woody vegetation binary extent mapping	Manipulation of datasets	GR25	LBF	Shape file	7.1, 7.2	WPE (DSITI)	By arrangement
GIS/RS	GR27	Canopy Height Model	Manipulation of datasets	GR25	LBF	Shape file	7.2	WPE (DSITI)	By arrangement
GIS/RS	GR28	Landscape analysis units	Manipulation of datasets	GR03, GR06, GR24, GR26	LBF	Shape file	7.1, 7.2	WPE (DSITI)	By arrangement
GIS/RS	GR29	Rainfall vs GFC by Landscape unit	Manipulation of datasets	CL01, GR15a, GR28	LBF	Shape file	7.1	WPE (DSITI)	By arrangement

Data group	Data Code	ID	How measured/ collected	Data Source	Spatial extent	Format	Report Section	Database Storage	Access arrangements
GIS/RS	GR30	Tree height by Landscape unit	Manipulation of datasets	GR28, GR26, GR27	LBF	Shape file	7.2	WPE (DSITI)	By arrangement
GIS/RS	GR31	Tree height by Coolabah pixel	Manipulation of datasets	GR08, GR12, GR27	236 sites	Shape file	7.2	WPE (DSITI)	By arrangement
Stream flow	SF01	QLD River gauges	Existing datasets	QLD Government	LBF (QLD)	Excel	4.2	Online	water-monitoring.information.qld.gov.au/
Stream flow	SF02	NSW River gauges	Existing datasets	NSW Government	LBF (NSW)	Excel	4.2	Online	realtimedata.water.nsw.gov.au/water.stm

Appendix 5 Project data inventory – field data

Table 28 Inventory of data sets collected at field sites (includes data type, format, spatial extent, reference to where used in the report, data storage location and access arrangements)

Data group	Data Code	ID	How measured/ collected	Spatial extent	Format	Report Section	Database Storage	Access arrangements
Climate	CL03	Radiation	Pyranometer	Veg monitor (3 sites)	Excel	5	HYDSTRA	By arrangement
Climate	CL04	Rainfall	Pluviometer	Veg monitor (3 sites)	Excel	5, 6	HYDSTRA	By arrangement
Climate	CL05	Relative humidity	Vaisala HMP35C sensor	Veg monitor (3 sites)	Excel	5	HYDSTRA	By arrangement
Climate	CL06	Temperature	Vaisala HMP35C sensor	Veg monitor (3 sites)	Excel	5	HYDSTRA	By arrangement
Geophysics	GP01	EM38	Area based survey	Veg monitor (1 site)	Raster	6	DNRM	By arrangement
Geophysics	GP02	ERT	Transect	Veg monitor, Riparian (8 sites tot)	Raster	5, 6	DNRM	By arrangement
Soil	SO1	Chemistry	Soil cores	Veg monitor/ Riparian, wet up plot, ancillary plots (92 sites tot)	Raw data	5, 6	DNRM (SALI)	Qld Globe, by arrangement
Soil	SO2	Morphology	Soil cores	Veg monitor/ Riparian, wet up plot, ancillary plots (92 sites tot)	Raw data	5, 6	DNRM (SALI)	Qld Globe, by arrangement

Data group	Data Code	ID	How measured/ collected	Spatial extent	Format	Report Section	Database Storage	Access arrangements
Soil	SO3	Soil water	Soil cores	Veg monitor/ Riparian, wet up plot (7 sites tot)	Raw data	5, 6	DNRM	By arrangement
Soil	SO04	Stable isotopes (² H, ¹⁸ O)	Soil cores	Veg monitor/ Riparian (4 sites tot)	Raw data	5	DNRM (SALI)	Qld Globe, by arrangement
Vegetation	VE01	Community/ floristics	Quadrats, transects	Veg monitor/ Riparian (8 sites tot)	Excel	5	DNRM	By arrangement
Vegetation	VE02	in Tree water potential	Stem psychrometer	Veg monitor and Riparian (4 sites tot)	Excel	5	DNRM	By arrangement
Vegetation	VE03	Leaf area	Manual leaf area (lab analysis)	Veg monitor (3 sites)	Excel	5	DNRM	By arrangement
Vegetation	VE04	Rapid assessment of Veg condition	Plots	Various (20+ sites)		5	DNRM	By arrangement
Vegetation	VE05	Sap flow	ICT sap flow meter	Veg monitor (3 sites)	Excel	5	DNRM	By arrangement
Vegetation	VE06	Sapwood density	Tree sample (lab analysis)	Veg monitor (3 sites)	Excel	5	DNRM	By arrangement
Vegetation	VE07	Sapwood moisture content	Tree sample (lab analysis)	Veg monitor (3 sites)	Excel	5	DNRM	By arrangement
Vegetation	VE08	Sapwood thickness	During sap flow meter installation	Veg monitor (3 sites)	Excel	5	DNRM	By arrangement

Data group	Data Code	ID	How measured/ collected	Spatial extent	Format	Report Section	Database Storage	Access arrangements
Vegetation	VE09	SLATS veg structural survey	Transects	SLATS (18 sites)	Excel	5	DNRM / RSC	RSC website
Vegetation	VE10	Stable isotopes (² H, ¹⁸ O)	Vegetation sample	Veg monitor/ Riparian (4 sites tot)	Excel	5	DNRM	By arrangement
Vegetation	VE11	Terrestrial laser scanning	Terrestrial laser scanner (desktop analysis)	Veg monitor (3 sites)	Raw data	5	DSITI Remote sensing centre	By arrangement
Vegetation	VE12	Tree Biomass	Harvest and weigh	Veg monitor (3 sites)	Excel	5	DNRM	By arrangement
Vegetation	VE13	Vegetation structure	Transects	Veg monitor, Riparian, ancillary (3 sites tot)	Excel	5	DNRM	By arrangement
Water sampling	WS01	Groundwater - stable isotopes	Groundwater sample	Various	csv	5	Groundwater database	DNRM / QLD Globe
Water sampling	WS02	Groundwater - unstable isotopes	Groundwater sample	Riparian (1 site)	Excel	5	Groundwater database	DNRM / QLD Globe
Water sampling	WS03	Groundwater - ionic chemistry	Groundwater sample	Various	csv	5	Groundwater database	DNRM / QLD Globe
Water sampling	WS04	Rainfall - ionic chemistry	Bulk monthly sample from pluvio	Veg monitor (2 sites)	Excel	5	HYDSTRA	Water portal/by arrangement
Water sampling	WS05	Rainfall - stable isotopes	Bulk monthly sample from pluvio	Veg monitor (2 sites)	Excel	5	HYDSTRA	Water portal/by arrangement

Data group	Data Code	ID	How measured/ collected	Spatial extent	Format	Report Section	Database Storage	Access arrangements
Water sampling	WS06	Surface water - ionic chemistry	Surface water sample	Various	csv	5	HYDSTRA	Water portal/by arrangement
Water sampling	WS07	Surface water - stable isotopes	Surface water sample	Various	csv	5	HYDSTRA	Water portal/by arrangement

Appendix 6 Glossary

Term	Description
Anthropogenic	Relating to, or resulting from, the influence of humans on nature.
Aquatic ecosystems	Are those that depend on flows, or periodic or sustained inundation/waterlogging for their ecological integrity (e.g. lakes, wetlands, rivers, aquifers, saltmarshes and estuaries) but do not generally include marine waters.
Aquifer	Rock or sediment in formation, group of formations or part of a formation, that is saturated and sufficiently permeable to transmit quantities of water to wells and springs.
Baseflow	The portion of streamflow not directly influenced by precipitation or overland flow but emanating from deep subsurface flow paths and delayed shallow subsurface flow.
Biodiversity	Variation of life at all levels of biological organisation (molecular, genetic, species, and ecosystems) within a given area.
Biogeochemistry	The chemical, physical, geological, and biological processes and reactions that shape the composition of the natural environment (in this report mainly referring to the hydrosphere).
Black box	Tree species <i>Eucalyptus largiflorens</i>
Canopy cover	The proportion of the forest floor covered by the vertical projection of the tree crowns from the trees in upper vegetation layer within a forest or woodland.
Capillary fringe	Part of the unsaturated zone where groundwater is rising up from the water table by capillary forces.
Chlorophyll a	A green pigment, present in all green plants and in cyanobacteria, which is responsible for the absorption of light to provide energy for photosynthesis.
Condition	The condition of woody vegetation. Within this project this has been assessed by a measure of seasonal greenness derived from Landsat imagery.
Coolabah	Tree species <i>Eucalyptus coolabah</i> .
Diameter at breast height	The diameter of the trunk(s) or bole(s) of a standing shrub or tree 1.3m above the ground.
Diel	Of or relating to a 24-hour period, especially a regular daily cycle, as of the physiology or behaviour of an organism.
Eco-hydrology	Study of the availability and movement of water through the environment and ecosystems. The scientific overlap between the fields of hydrology and ecology and/or the impact of hydrology on ecosystems or vice versa.
Ecology	The branch of biology that deals with the relations of organisms to one another and to their physical surroundings.
Ecosystem functions	The biological, geochemical and physical processes that take place within an ecosystem.

Term	Description
Ecosystem services	Are the 'services' provided by natural (and semi-natural) ecosystems - 'ecosystem service providers' - that benefit, sustain and support the well-being of people.
Electrical resistivity tomography	Electrical resistivity tomography (ERT) is a geophysical technique for imaging sub-surface structures from electrical resistivity measurements made at the surface by a series of ground penetrating electrodes.
Flooding	A flood is an overflow of water that submerges land that is usually dry and can occur in rivers when the flow rate exceeds the capacity of the river channel causing overbank flow or can occur due to an accumulation of rainwater on saturated ground.
Floodplain	The area of flat land adjacent to a stream or river that floods during periods of high river overbank flows.
Floodplain assessment Area	Areas of floodplain and the length of river channel that can be reasonably represented by a stream gauging station, based on local topography, geomorphology, and river network features
Floristics	The branch of phytogeography concerned with the study of plant species present in an area.
Flow path	The route that water passes through in surface (including organic soil horizons) and subsurface environments.
Flow regime	The flow regime of flowing water systems has five components: magnitude, frequency, duration, timing and rate of change. Modification of flow has cascading effects on the ecological integrity of streams (Poff et al. 1997).
Geophysics	Study of the physical processes and physical properties of the earth and the use of quantitative methods for their analysis
Geomorphology	The study of the physical features of the surface of the earth and their relation to its geological structures.
Groundwater	Water occurring naturally below ground level (whether in an aquifer or other low-permeability material), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage. It does not include water held in underground tanks, pipes or other works.
Habitat	An ecological or environmental area that is inhabited by a particular species. It is the natural environment in which an organism lives, or the physical environment that surrounds (influences and is utilized by) a species population.
Hydrochemistry	Refers to the resulting chemical composition of water due to chemical, physical, and biological processes (often used interchangeably with 'water quality').
Hydrogeology	The branch of geology dealing with the waters below the earth's surface and with the geological aspects of surface waters
Hydrology	The study of the movement, distribution and quality of water on Earth and other planets, including the hydrologic cycle, water resources and environmental water allocations.
Hydrotype	Functionally similar plant species with shared requirements for and adaptations to specific hydrological conditions.
Landsat	Satellite based sensors, which record reflected and emitted energy from Earth in various wavelengths of the electromagnetic spectrum. The Landsat program has been operating from 1972 and the current Landsat satellite is the 8 th generation.
Lignum	Shrub species <i>Duma florulenta</i>

Term	Description
Mixing model	Mathematical models with fixed and random effects to determine the proportions of various sources in a mixture. Commonly used in stable isotope analysis.
Morphology	The physical form and structure of an organism or one of its parts.
Phreatophyte	Plants that habitually obtain water from groundwater, via the zone of saturation, either directly or through the capillary fringe above the water table.
Riparian	From the Latin word meaning of or belonging to the bank of the river, and refers to the biotic communities living along streams. The riparian zone can be thought of as the interface or ecotone between terrestrial and aquatic systems.
River red gum	Tree species <i>Eucalyptus camaldulensis</i>
Sclerophyll	Plants with hard, leathery, evergreen foliage that is specially adapted to prevent moisture loss and cope with low soil fertility (e.g. Eucalyptus).
Soil structure	The arrangement of the solid parts of the soil and of the pore space located between them. It is determined by how individual soil granules clump, bind together and aggregate.
Soil texture	The relative proportion by weight of the mineral soil (% sand, silt, and clay) for soil particles <2mm.
Species	A taxonomic rank that is the basic rank of biological classification. Commonly, a group of organisms capable of interbreeding and producing fertile offspring.
Sap flow	Movement of sap (fluid transported in xylem cells) through a tree.
Sap wood	Sapwood is the living, outermost portion of a woody stem or branch.
Stable isotope	An isotope that does not decay into other elements. Different isotopes of an element have the same number of protons as one another, but different numbers of neutrons. Stable isotope analysis can be used in ecological studies to trace chemical movement through the environment.
Stem psychrometer	An instrument for the measurement of stem water potential. It can continuously log changes in plant water status/potential, which directly reflect the energy required to access water or the stress the plant is under.
Tree above ground total biomass	The combined dry mass of all parts of tree (including leaves, stems and branches) above ground level.
Tree basal area	For a stand of vegetation, the cross-sectional area of tree trunks per unit of land area (typically expressed as m ² /ha).
Typology	A scheme for categorising entities into distinct groups such that those entities belonging to a type share common attributes, but in combinations that differ from other types.
Vertosols	Clay-rich soils that shrink and swell with changes in moisture content. During dry periods, the soil volume shrinks, and deep wide cracks form. The soil volume then expands as it wets.
Water availability	The type/source and amount of water accessible by the plant

Term	Description
Water quality	The physical, chemical and biological attributes of water that affect its ability to sustain environmental values.
Water use	Actual water use by plant from that which is available (i.e. a physiological parameter in mm per day)
Water use efficiency	A measure of a plant's capacity to convert water into biomass that includes the use of water stored in the soil, groundwater and rainfall during the growing season.
Water requirements	The water plants and their populations need to maintain all facets of their lifecycle (this includes maintenance of their current condition and recruitment). In the Basin Plan, water requirements have been expressed in terms of the magnitude and frequency of flood events and, to a lesser extent, the duration and depth of inundation needed to maintain key plants species and vegetation in good condition.
Water-table	The upper surface of a body of groundwater occurring in an unconfined aquifer. At the water-table, pore water pressure equals atmospheric pressure.
Xylem	Specialized plants cells that transport water and dissolved minerals from the roots to the leaves.