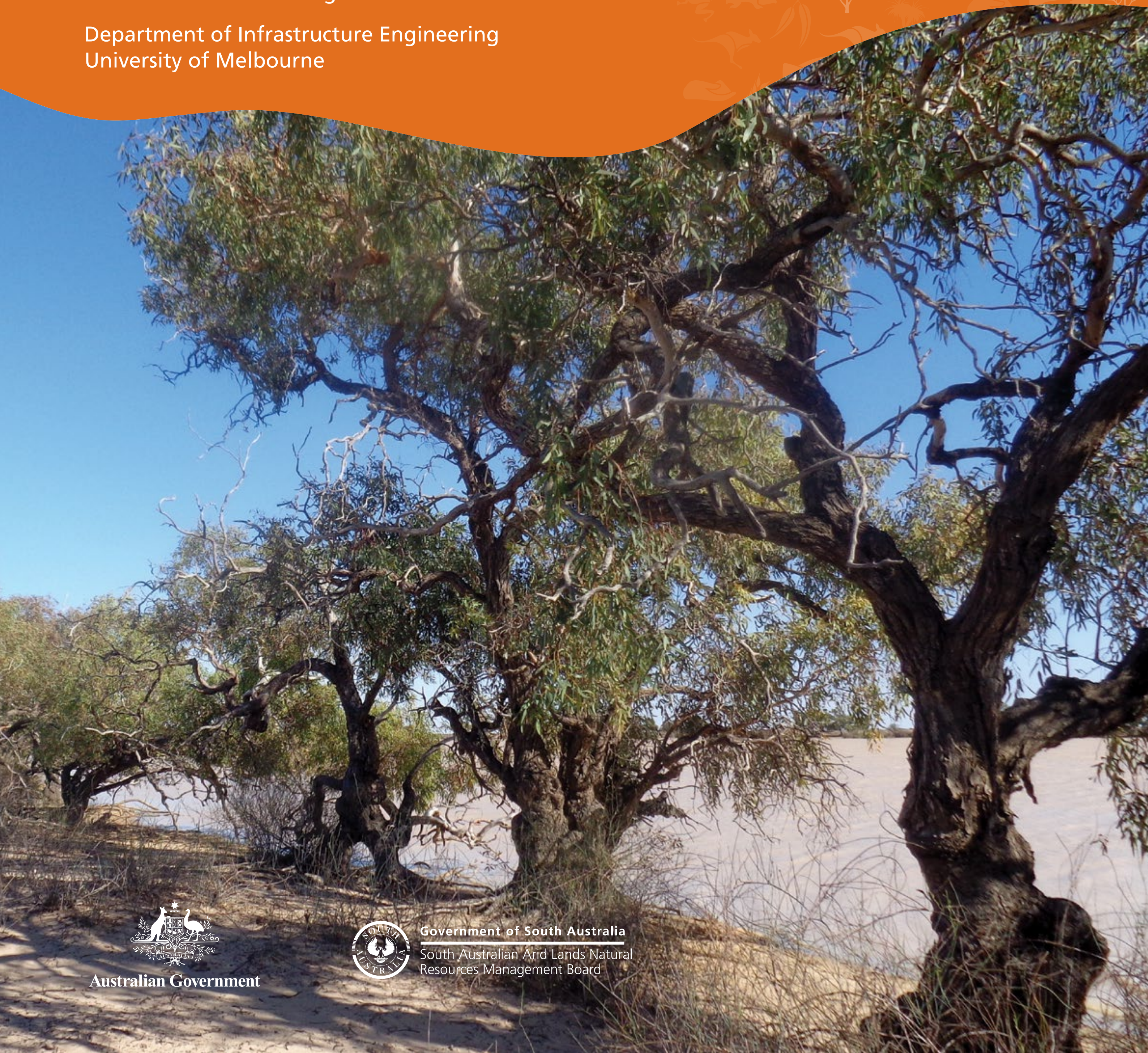
Natural Resources
SA Arid Lands

Hydrological Assessment and Analysis of the Diamantina River Catchment, South Australia

Justin F. Costelloe
July 2017

Report to the South Australian Arid Lands Natural Resources Management Board

Department of Infrastructure Engineering
University of Melbourne



Australian Government

Government of South Australia
South Australian Arid Lands Natural Resources Management Board

Disclaimer

This report may be cited as:

Costelloe, J.F 2017 Hydrological assessment and analysis of the Diamantina River catchment, South Australia. Report by the University of Melbourne to the South Australian Arid Lands Natural Resources Management Board, Pt Augusta.

Cover images:

Coolibahs Goyder Lagoon waterhole May 2015; Diamantina channel May 2014

Copies of the report can be obtained from:

Natural Resources Centre, Port Augusta
T: +61 (8) 8648 5300
E: saaridlands@sa.gov.au

Acknowledgements

This study was supported by Australian Commonwealth Government funding and was part of a larger project managed by the South Australian Arid Lands Natural Resource Management Board. The project team of Henry Mancini, Jake Gillen, Julian Reid, David Schmarr, Gresley Wakelin-King, Joc Schmiechen, Rupert Mathwin, Dave Cheshire, and Nerissa Haby greatly assisted this work and particular thanks to Henry Mancini for the initiation and management of the project. The fieldwork would not have been possible without the tireless assistance of Graeme Tomlinson. Thanks also to Don Rowlands for assistance in negotiating wet conditions back to Birdsville in May 2016. We thank the following landholders for allowing fieldwork on their properties.:

Sharon Oldfield, Craig Oldfield, (Cowarie Station); Peter Nunn (Manager) (Clifton Hills Station); Tess and Mark McLaren (Kalamurina Wildlife Sanctuary); Peter and Kylie Morton (Pandie Pandie Station) and Don Raymond (Alton Downs Station).

Contents

List of Tables

List of Figures

Executive Summary

The Diamantina River is renowned for its unregulated and extremely variable hydrology and these features underpin the very high ecological value of the river and its major environmental assets. This report describes important aspects of the hydrology, such as flow patterns and distribution of aquatic refugia, which can be used to better manage and model this system. In addition, the report provides baseline data and analysis on the drivers of successful recruitment of *Eucalyptus coolabah*, the keystone riparian tree species of the Diamantina River.

The distribution of flow and aquatic refugia in the South Australian reaches of the Diamantina River provide a framework for dividing the Diamantina into management reaches.

1) **Diamantina main channel**: Birdsville to Goyder Lagoon. This reach contains the most important fluvial refuges in the Diamantina River, Andrewilla and Yammakira Waterholes. The constriction of flow through these waterholes means they have excellent connectivity with upstream and downstream parts of the catchment and receives flow every year. This reach will provide the initial pathway for alien species (e.g. cane toads) into South Australia and has the potential for introduction of translocated species (e.g. freshwater crocodile found near Birdsville in 2013 and turtles found in Yammakira and Andrewilla Waterholes may also be translocated).

2) **Goyder Lagoon**: Distributary channels from Yammakira and Andrewilla Waterholes to the commencement of the Warburton River channel. This reach receives inflow every year but the smaller annual flows terminate in Goyder Lagoon. It does not have any long-term refugia waterholes but the large area of floodplain acting as a 'floodout' from the Diamantina flow means it has very high environmental value as a waterbird habitat.

3) **Warburton River**: Commencement of Warburton channel (approximately at the Warburton Crossing to the Simpson Desert National Park) through to Lake Eyre and including the Kallakoopah Creek flowpath. This reach receives flow approximately every 1.5-2.0 years and links with the Macumba River near the outflow into Lake Eyre North. Waterholes in this reach commonly receive saline groundwater discharge which increases their persistence despite relatively shallow depths, but also results in these potential refuge pools becoming highly saline within 6-12 months of streamflow cessation. As a result, they are important refuges for highly salt-tolerant aquatic species such as Lake Eyre hardyhead and desert gobies.

4) **Eyre Creek**: South Australian border to Goyder Lagoon. This reach does not contain any significant ark refugia and receives flow approximately every 5 years. Tepamimi Waterhole occurs near the junction of Eyre Creek with Goyder Lagoon and is currently receiving artesian bore discharge which is keeping the waterhole permanently at its cease-to-flow depth. This is the most radical change to the natural water regime of any of the waterbodies in the SA reaches of the Diamantina River and results in adverse ecological outcomes for the waterhole and, potentially for the downstream system. These include; the waterhole becoming a refuge for the alien fish species *Gambusia holbrooki*, increased grazing pressure on the riparian zone, and risk of increased water table and salinization around the waterhole.

The hydrology of the South Australian reaches of the Diamantina-Georgina catchments remains unregulated and unimpeded and water extraction from the catchment is at very low levels.

The hydrological monitoring capacity of Diamantina River has improved since 2011 with the installation of the Poothapoota permanent monitoring site on the Warburton by DEWNR and additional monitoring by LEBRA. The additional monitoring from the current project and the collection of discharge data at key distributary points along the Diamantina has assisted in better understanding flow patterns through the Diamantina River in South Australia. The long-term monitoring and management of Diamantina River has been enhanced by the construction of a new-generation hydrological model (Osti, 2015) capable of simulating the complex flow patterns of this system.

Water quality and groundwater interactions also vary between the management reaches. No groundwater data are available for the Diamantina main channel reach but its waterholes remain fresh at all times and this implies that the near channel groundwater is likely to be relatively fresh or the water table is too deep to intersect the main channels. In the Goyder Lagoon and Warburton reaches, the groundwater is saline (typically >30,000 mg L^{-1}) and relatively shallow (3-6 m below the floodplain surface). As a result, the ephemeral Warburton channel frequently intersects the saline water table and this results in saline groundwater discharge into the channel between flow events and results in this reach becoming saline to hypersaline during these periods. Recharge to the saline groundwater is minimised by the high water table and so the riparian vegetation must contend with shallow, highly saline groundwater away from the channel. As a consequence, the riparian zone can be quite narrow around the Warburton channel and floodplain trees are likely to be more reliant on soil water resources rather than tapping into the highly saline groundwater. No information is available on the unconfined groundwater in the Eyre Creek reach but it is likely to be saline and relatively shallow.

Extensive surveys of *Eucalyptus coolabah* distribution and characteristics has provided insights into preferable zones of recruitment and establishment and complements the riparian zone studies described in Gillen (2017). *E. coolabah* were found to occur in a wide variety of geomorphic positions and soil types and had low transpiration rates to cope with dry conditions. These characteristics, along with a high tolerance of salinity, illustrate how this species is able to dominate the riparian zone in the harsh, arid and saline conditions found along much of the Diamantina River in South Australia. The main finding of the coolibah component of the work was the scarcity of young *E. coolabah* recruits that could confidently be considered to have germinated during the 2009-2011 wet period. Our initial hypothesis was that this wet period would result in a boom in riparian vegetation recruitment that may only happen during these multi-annual wet periods that occur every 20-30 years. Only 38 of 1592 trees (2.4%) surveyed in 2014 and 2015 were considered as recent recruits. Most of the small coolibahs (<1 m in height) that appear as apparent recruits showed thicker woody, multiple stems that were consistent with resprouting following initial germination and were likely germinated years prior to the 2009-2011 period.. It appears that total grazing pressure (evidence was observed for cattle, camel and rabbit grazing of small coolibahs) and dry conditions in 2013-2014 had a role in limiting the number of successful recruits from the 2009-2011 wet period. The limited regeneration of the key riparian tree species, *E. coolabah*, along most of the SA reaches of the Diamantina may be of concern to the long-term productivity of the riparian zone. Further monitoring of key locations showing some recruitment would assist in better understanding the sustainable management of the area (e.g. identifying whether protecting key regeneration – recruitment locations from grazing is required).

1 Introduction

The Diamantina River is the third largest catchment of the Lake Eyre Basin (excluding the Georgina River catchment contribution) and the South Australian (SA) reaches are characterised by iconic sites and wetlands, such as Goyder Lagoon (Sheldon and Puckridge, 1998; Costelloe et al., 2004; Reid et al., 2010) and the Warburton River. Diamantina River has an unregulated flow regime with very little water extraction and forms one of the type examples of low gradient, intermittent, dryland rivers in the world. However, the Diamantina has received much less research activity in comparison to Cooper Creek (e.g. Knighton and Nanson, 1994a, b; 2000; 2001). As the catchment is unregulated, natural associations between ecology and flow patterns are largely intact (Costelloe et al., 2004) and are characterised by the 'boom and bust' dynamics that are the hallmark of Australian arid and semi-arid environments (e.g. Bunn et al., 2006). The boom-bust sequence is driven by the inter-annual variability in flow, with Diamantina River having one of the most variable flow regimes in the world (Puckridge et al., 1998; McMahon et al., 2008).

The SA reaches of the Diamantina River have very high environmental value, with the Goyder Lagoon area often being the focus of large waterbird congregations (Costelloe et al., 2004; Reid et al., 2010). The SA reaches of the Diamantina River are the centre of a robust cattle grazing industry, with a number of the Stations being run as organic beef properties. The Birdsville Track is a focus for outback tourism but there is relatively little tourism interaction with the Diamantina due to few access points from the Birdsville Track (Schmiechen 2017). In contrast to Cooper Creek, there are no extractive (oil and gas) industries currently operating in the catchment. Diamantina River, with its unregulated flow regime and relatively intact environmental assets, has a low level of information on its flow regime and general hydrological behaviour, particularly for a catchment of this size, although this has improved over the past 15 years (Costelloe et al., 2003; 2006; Jarihani et al., 2015; Osti 2015). This limits the capacity of water resource managers to identify and manage key aquatic refugia in the catchment and to monitor hydrological change that could occur from quick response anthropogenic changes (i.e. upstream water extraction, land use changes, infrastructure affecting flooding patterns) or climate change.

1.1 Objectives

The objective of this study is two-fold:

- To provide on-ground assessment and analysis of the hydrology of the study area, including site monitoring and delivery of nominated site survey hydrological data in the form of technical reports and workshops,
- To gain a greater understanding of the dominant riparian tree species, *Eucalyptus coolabah* (commonly called 'coolibah'), and its regeneration, recruitment and persistence in the landscape relating to the hydrological regime.

The fieldwork conducted over three years (2014-16) of this project provided an opportunity to gather data on the flow patterns of the Diamantina River, along with the bathymetry of the key waterbodies. Flow data in the SA reaches of the Diamantina River are very rare with the exception of the Birdsville gauging station record. Water level loggers were installed in the Diamantina during the ARIDFLO project (Costelloe et al., 2004) but gauging of flow in the complex network of distributary channels in the Diamantina is uncommon.

The delineation of flow patterns is a key obstacle in improving our capacity to hydrologically model the Diamantina. Basic information, such as the split in flow between the main distributaries over a range of discharges, is lacking and this affects the modelling or assessment of how any flow regime changes may affect key environmental assets. Therefore, the identification of key aquatic refugia and an improved understanding of flow behaviour and patterns in the Diamantina will greatly assist the protection and management of this unique river system.

E. coolabah is the keystone riparian tree species in the Lake Eyre Basin, particularly in the arid South Australian reaches, and is an iconic and dominant riparian species in many arid and semi-arid zone river systems of Australia (e.g. Good et al., 2012). The successful germination and growth (i.e. recruitment) of these trees, which occurs in response to floods (Roberts, 1993; Good et al., 2012), is critical to the ecology of these dryland rivers. Understanding the drivers of recruitment success is vital to determining how these systems respond to current and future pressures driven by grazing, flow regulation and climate change. Previous work has examined regeneration characteristics of *E. coolabah* on the regulated rivers of the Darling River catchment, where clearing of this species has commonly occurred (Good et al., 2012). The unregulated rivers and the largely natural vegetation communities of the LEB provide an excellent system for analysis of natural patterns of tree distribution.

1.2 Hydrological context of study period

The hydrological context for the Diamantina River project was for dry years in the first two years of the project (2014-2015) followed by quite wet conditions in 2016 (Figure 1 for streamflow and Figure 2 for rainfall). Another feature of the study period was that it was characterised by significant rainfall and local runoff events in the Warburton reach in 2015 and 2016 but which did not generate as much runoff higher in the catchment, particularly in 2015. This is illustrated in Figure 1b by the stage record at Poothapoota on the upper Warburton. The local rainfall and runoff is important in decreasing the saline conditions typical of the Warburton River and in providing soil moisture for vegetation. The 2013 year, preceding the study period, was a particularly dry year in terms of streamflow and rainfall (Figure 2), with the total volume passing Birdsville in that year being below the 10th percentile of the long-term record.

The ten years prior to the project period were characterised by a mix of dry years and floods, and a wet four year period (2009-2012) driven by a La Niña episode. During the Millennium Drought (1998-2009) that strongly affected rainfall and streamflow in south-eastern Australia (LeBlanc et al., 2009), the Diamantina experienced a large range in annual floods, with significant floods in 2000, 2004 and 2007 (these three floods had annual flood recurrence (ARI) intervals of 4-15 years) and relatively dry years in between with total annual flows less than the long-term median. The La Niña episode commenced with a major flood in 2009 and the subsequent large flood years of 2010 and 2011 had annual totals and peak discharges above the 90th percentile, ARIs of 9-15 years, and above average rainfall in the South Australian reaches (Figures 1 and 2). The 2009-2012 period represents a 'flood cluster' and these typically occur in response to significant La Niña episodes and occur on a 20-40 year return period (e.g. 1974-1977 and 1989-1991 in Figure 1). Puckridge et al. (2000) recognised that flood clusters allow for significant ramping up of recruitment, particularly of fish, and are likely critical for the long-term health of the Diamantina River. The effects of the flood cluster on vegetation recruitment has received less attention and a focus of this project is to examine the recruitment of *E. coolabah* in response to the 2009-2012 flood cluster.

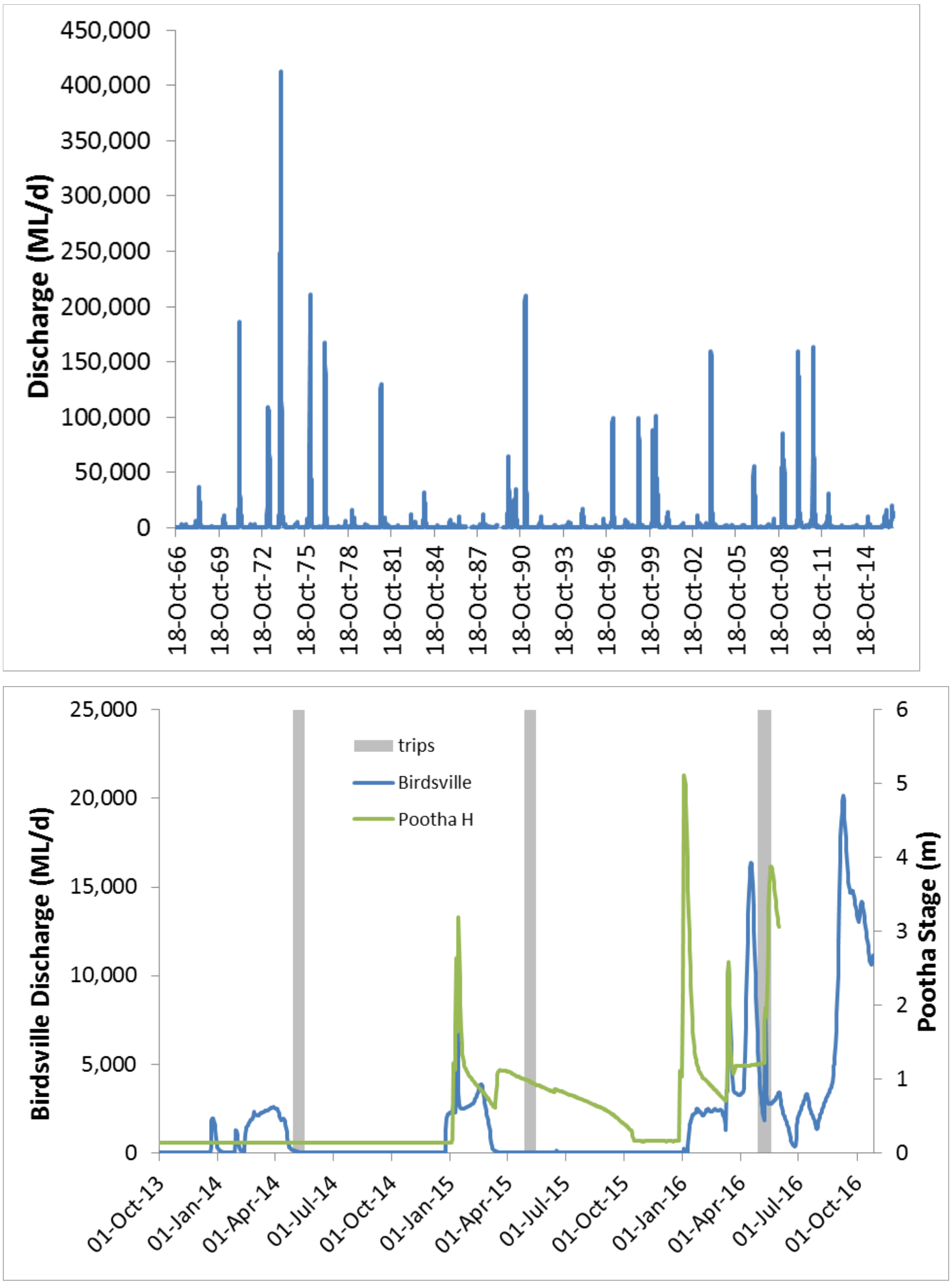


Figure 1. Hydrograph of Birdsville gauging station record for Diamantina River for the period 1966-2016 (top panel). The lower panel shows the Birdsville discharge hydrograph (blue) and the Poothapoota (Warburton River) stage hydrograph (green) for the flood years of 2014 – 2016. The periods of Diamantina River fieldwork are shown by the grey columns.

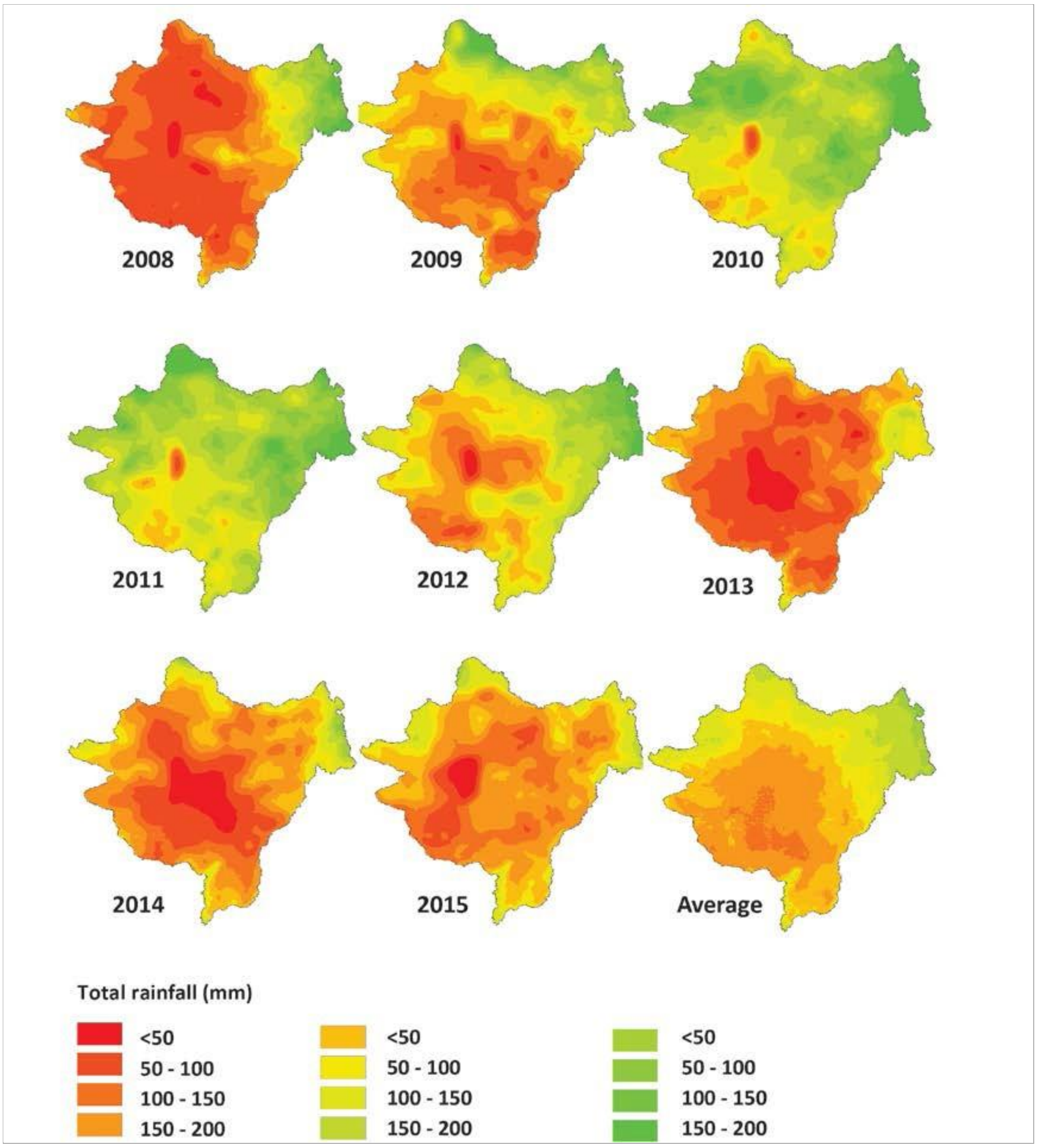


Figure 2. Total rainfall across the LEB in each 'water year' (i.e. 1st October to 30th September) from 2008 to 2015. Mean annual rainfall across the basin ('Average') is also shown illustrating that 2010 and 2011 were much wetter than average while 2008 and 2013-2014 were much drier than average. (Source: Australian Water Availability project, Bureau of Meteorology: http://www.csiro.au/awap)

1.3 Diamantina River

The Diamantina River is an intermittent river that forms the third largest catchment of the Lake Eyre Basin (LEB) with a catchment area of 160,000 km^2 and a river length of 1000 km from its upper reaches to Kati Thanda - Lake Eyre North (Kotwicki, 1986). This catchment area excludes that of the Georgina River, which is the major tributary of the Diamantina River and flows into Goyder Lagoon via Eyre Creek. The Diamantina has a remarkably low mean gradient of only 2.7×10^{-4} m/m (Kotwicki, 1986) and is characterised by reaches with dramatic widening of the river system to up to 50 km wide, known as the 'Channel Country'. A complex, anastomosing channel system is characteristic of the Channel Country (Knighton and Nanson, 1994a). While the hydrological characteristics of the Channel Country in the neighbouring catchment of Cooper Creek have been well described in a sequence of papers by Knighton and Nanson (1994a, b; 2000; 2001) much less work has been done on similar reaches in the Diamantina River (but see Costelloe et al., 2003; 2006; Jarihani et al., 2015).

In south-western Queensland, the Diamantina changes from a broad Channel Country reach to a single primary channel morphology as it approaches Birdsville. This primary channel morphology continues into South Australia and the river direction is constrained by the NNW trending regional dune systems. This reach is characterised by a single dominant channel with minor sinuosity and high flow parallel channel systems fed by break-out channels, mostly on the western side of the river (the Eleanor Creek flowpath). Once the Diamantina hits the uplifted area of Sturts Stony Desert, it emerges into the very low gradient and broad floodplain of Goyder Lagoon. The Goyder Lagoon reach forms a kind of Channel Country but has less channelization than the more typical Channel Country reaches of the middle Diamantina and Cooper catchments, and is more similar to a 'floodout' zone. The smallest annual flows in the Diamantina terminate in the broad, flat expanses of Goyder Lagoon and only every second year, on average, do flows extend into the Warburton River (Kotwicki, 1986). Goyder Lagoon also forms the junction between the Diamantina and Georgina catchments. Eyre Creek brings streamflow from the Georgina approximately every five years (Costelloe et al., 2004) into the northwestern side of Goyder Lagoon. The Eyre Creek inflow typically coincides with above average flows in the Diamantina River.

The Warburton comprises the lower reaches of the Diamantina-Georgina catchment and is characterised by a single primary channel system with low-moderate sinuosity and a number of anabranches and high flow channels occurring on the floodplain. Its course runs from the southern end of Goyder Lagoon to Lake Eyre North and has a major anabranch, Kallakoopah Creek that diverges and then rejoins the Warburton. The Macumba River also forms a junction with the Warburton close to the inflow point to Lake Eyre.

The study area includes the South Australian reaches of Diamantina River from Birdsville to within 80 km of the Diamantina's inlet to Lake Eyre North (see individual site locations in Figure 3). The South Australian reaches of Diamantina River are located in the arid core of Australia. The closest Australian Bureau of Meteorology climate station (Birdsville police station, 038002), has a mean annual rainfall of 165 mm, a mean maximum daily temperature of 30.5ºC and a mean annual Class A pan evaporation rate of 3358 mm.

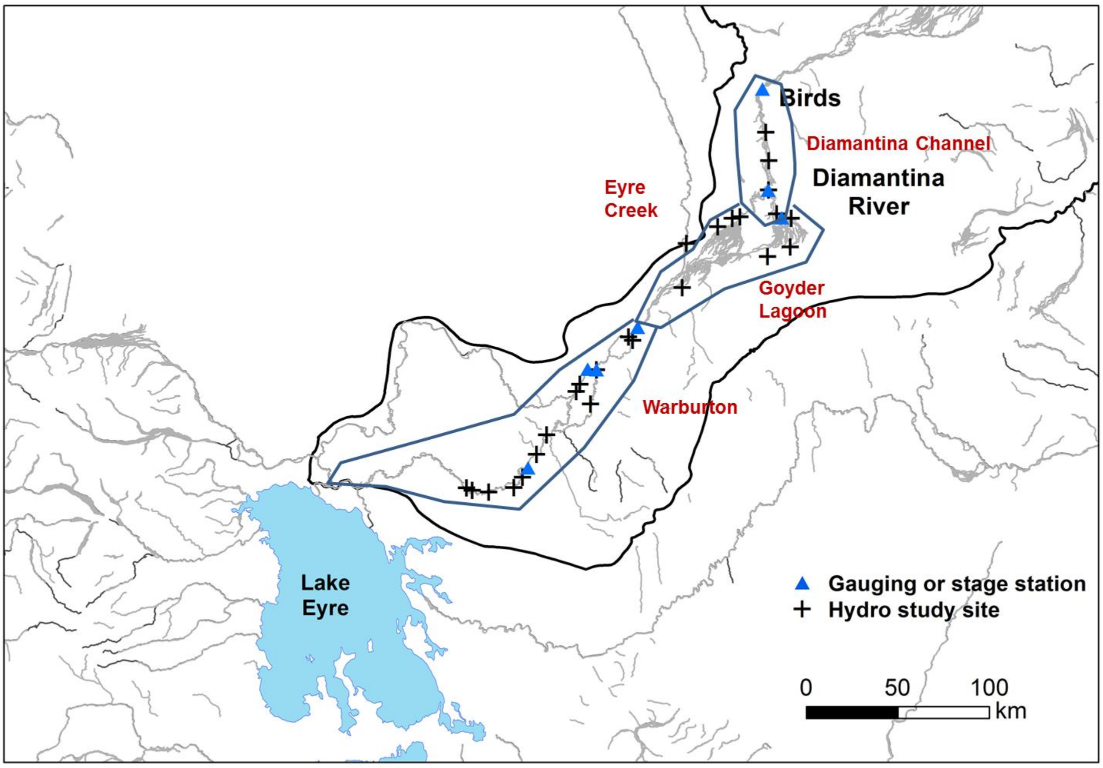


Figure 3. Location diagram of the study reaches of the Diamantina River investigated during this project. The management zones (or reaches) are shown by blue polygons. The Warburton zone can also incorporate all of Kallakoopah Creek. Note that no polygon is shown around the Eyre Creek zone.

2 Methods

This report draws upon hydrologic and geomorphic monitoring data collected over four periods. The first phase of data collection occurred from April 2000 to February 2003 as part of the ARIDFLO project (Costelloe et al., 2004). The second phase occurred during the period 2004-2006 as part of a University of Melbourne research project that examined salinity processes in the Diamantina River. The third phase occurred over 2007-2008 and involved maintenance of the water level logger network installed as part of the ARIDFLO project (Costelloe 2008). This phase was supported by the Lake Eyre Basin River Assessment (LEBRA), (then) Department for Water, Land and Biodiversity Conservation (DWLBC) and University of Melbourne. The fourth phase occurred from April 2014 to May 2016 as part of the current Diamantina River project.

2.1 Flow monitoring

The Diamantina River has been monitored by a gauging station at Birdsville (1949-2016, location changed in 1966) operated by DEWNR and a gauging station at Diamantina Lakes (1967-1988, 2011-2016) but very limited information has been collected in the South Australian reaches.

As part of the ARIDFLO project, water level loggers were installed at three locations in 2000 (Koonchera Waterhole, Goyder Lagoon Waterhole, Ultoomurra Waterhole – Warburton River) and recorded data until 2008. These loggers recorded water level variations each hour and provided the first recorded time-series data of flow events in the lower Diamantina. The history and analysis of this dataset over the 2000-2008 period is described in Costelloe (2008). As part of the Lake Eyre Basin Rivers Assessment (LEBRA) monitoring, SARDI have maintained a pressure-temperature logger at Stony Crossing (Kalamurina Wildlife Sanctuary) on the Warburton River since 2012.

As part of the current project, several pressure-temperature loggers were installed in key distributaries in the system (Andrewilla flow path split and the Warburton – Kallakoopah split). The occurrence of significant flows during the study period provided the opportunity to collect discharge data and better characterise flow distribution. This was done using a Sontek S5 acoustic Doppler current profiler (ADCP) which collected discharge and bathymetric data from a number of locations (see Figure 4).

2.2 Waterbody surveying

The maximum depth of a waterhole when flow ceases (cease-to-flow depth; CTFD) has been found to be an important measure of how long water will persist in the waterhole (Costelloe et al., 2007), and hence if the waterhole is capable of being a critical refugia in the catchment. As part of this project, key waterholes were identified from local knowledge, 1:250,000 scale topographical maps, Google Earth and previous work (ARIDFLO). In conjunction with SARDI, the dimensions of these waterholes were measured using the acoustic Doppler current profiler (ADCP) to characterise the dimensions of the waterhole. Water quality measurements for particular waterholes were also used to establish if salinity variations constrained the capacity of a waterhole to act as a refuge for most aquatic fauna.

Figure 4. Flow gauging using the ADCP at the outflow channels of Andrewilla Waterhole.

2.3 Water quality measurements

Water quality data were collected (particularly salinity) to identify waterholes that may be subject to groundwater inflow. The water quality data were collected with a Horiba multi-parameter probe and this measured temperature, pH, electro-conductivity (EC), salinity, turbidity and dissolved oxygen (DO). In addition, water quality measurements collected by SARDI (Schmarr et al., 2017) are included in the analysis and these were also collected using a Horiba probe. Earlier water quality measurements collected during previous projects (e.g. ARIDFLO and the University of Melbourne 'Salinity drivers in the Lake Eyre Basin Rivers') were also included in the analysis, where appropriate. These data included major ion analysis of selected surface water and groundwater samples.

2.4 *Eucalyptus coolabah* distribution surveys

Field data were collected on the distribution of *E. coolabah* during all three field trips. The aim of this data collection phase was to obtain insights into the main drivers of coolibah distribution and recruitment success. Data on the distribution of *E. coolabah* trees were collected from 19 belt transects on the Diamantina floodplain in May 2014, 19 in May 2015 and 14 in May 2016. Transects typically began at the main channel and were directed approximately perpendicular to the channel direction and were of varying length (200-1200 m). Some transects in 2016 were run parallel to channels to obtain more detailed information on the riparian bank zone. All *E. coolabah* trees located within the 10 m width of the transect were measured for their location and elevation (by differential GPS), number of stems, circumference of the largest stem above ground level, maximum height of tree canopy, maximum width of tree canopy and reproductive status (i.e. fruiting or not fruiting). In addition, between 2-6 soil profiles where drilled using a hand auger on each transect (Figure 5), totalling 54 soil profiles in 2014, 49 in 2015 and 12 in 2016. Profiles were between 0.3-0.5 m deep with soil samples collected every 0.1 m. The soil profile locations were chosen to characterize soil conditions where *E. coolabah* trees were relatively abundant and where they were absent (i.e. no *E. coolabah* within 30 m radius of the soil profile). The Geoscience Australia Water Observations from Space (WOfS) dataset provided a measure of the frequency of inundation over the study area using the Landsat record. This dataset has a 25 m spatial resolution and was used to assign mean frequency of inundation values to individual tree locations in each transect.

Laboratory analysis was subsequently completed on the soil samples and included: gravimetric water content of a 100 g sample dried at 100°C for 24 hours; electro-conductivity (EC) and pH measurements taken from a 1:5 mix of dried soil sample (10 g) and deionized water (50 ml); plasticity measurements using a 'roll-test' method. A small amount of the soil was mixed with a few drops of water until soil moisture content reached field texture (i.e. just below sticky point). The resulting mix was rolled into a cylinder by hand to a length of at least 40 mm. The cylinder was then held by the end to determine if it can support its own weight. The degree of plasticity categorizes the soil samples, where a diameter of 2 mm gives a very plastic soil (scored 5) and a diameter of 6 mm is non plastic (scored 1).

Two different methods were used to analyse the 2014 dataset; principal component analysis (PCA) and the Kolmogorov-Smirnov (KS) test. A PCA was initially performed on each of the three dependent tree measurement variables (diameter, crown and height) and 16 independent variables (soil characteristics including salinity, pH, plasticity, soil water content; inundation frequency; elevation above local channel thalweg; distance to other trees). Outliers were removed from the dataset manually, and the variables were standardised to remove noise in the data, constrain the dataset and remove any scaling influences. The results of the covariance matrix were used to identify poorly correlated variables; which were subsequently removed from the data in an attempt to increase the variability captured by the first three PCAs. A PCA was then re-performed on the reduced dataset.

Two sample non-parametric Kolmogorov-Smirnoff (KS) tests were performed to further analyse the soil data. Two populations of soil data were tested for significance between variables; 'soil samples with trees' and 'soil samples without trees'.

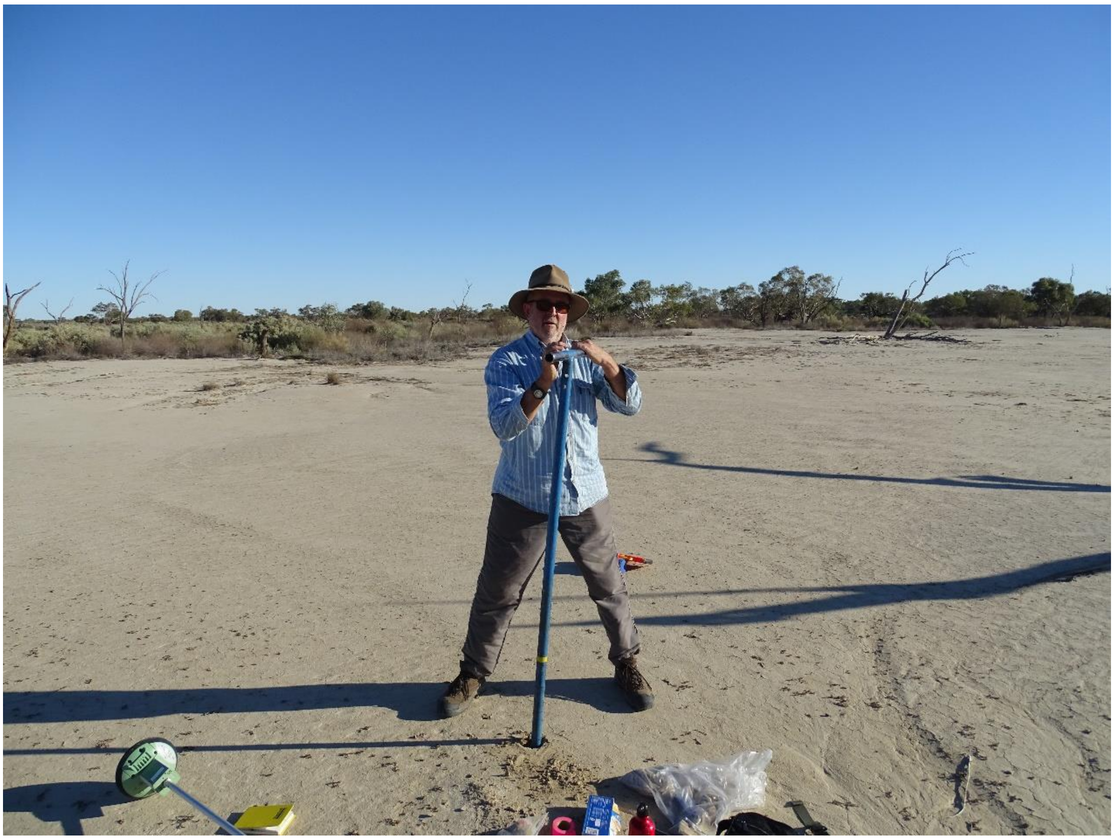


Figure 5. Graeme Tomlinson collecting soil profile samples using an auger in an area without any nearby coolibah trees (see dead trees around the edge of this scalded high floodplain area). The differential GPS unit used to record location and elevation is lying on the ground in the left foreground. Cliff Camp floodplain, May 2015.

2.5 *Eucalyptus coolabah* water use

Heat pulse sap flow meters (SFM1, ICT International) were installed into four locations (Andrewilla floodplain and riparian zone, Double Bluff floodplain and Pandie Pandie floodplain) between May 2014 and May 2016 with varying length of record (Table 1). The sap flow meters were installed into *E. coolabah* trees in relatively good health (Figure 6), i.e. with typical canopy cover and amount of dead branches for riparian trees in the field area. The trees ranged from very mature, single trunk riparian trees (e.g. Andrewilla) to younger and multi-stemmed trees on floodplain sites. Raw temperature data were recorded at a 10 min time-step and converted to daily sap flow velocities using ICT proprietary software (Sap Flow Tool) and information from 1-4 cores collected per tree to determine sapwood characteristics. The key measurements of each instrumented trees (Table 1) were used to determine sapwood dimensions (e.g. circumference at the sap flow logger, bark thickness, sapwood thickness) and thermal diffusivity (e.g. sapwood wet and dry core weight and dimensions).

The sap flow meters were installed at riparian - floodplain sites within 200 m (e.g. Pandie, Double Bluff and Andrewilla floodplain) and 20 m (Andrewilla riparian) of a large primary channel with consistently low salinity (i.e. $<0.5\ gL^{-1}$) permanent standing water. The depth to groundwater was not known but the approximate cease-to-flow water level in the channel was 9 m at Pandie floodplain site and 3.0 - 4.5 m below the floodplain surface at the Andrewilla riparian site. These characteristics are considered to be consistent with unconfined groundwater having depths of <10 m below the floodplain surface and relatively low salinity. The occurrence of flow events in the Diamantina was determined from a gauging station at Birdsville and a water level logger installed at the distributary connecting the main Diamantina channel to the Andrewilla flowpath.

Table 1. Characteristics of coolibahs monitored for tree water use.

Location	Period	Circum. (m)	Height (m)	Crown width (m)	Lat	Long
Pandie floodplain	May 14 – May 15	0.41	7.8	5.6	-26.1197	139.3857
Double Bluff floodplain	May 15 – May 16	0.60	6.0	5.2		
Double Bluff floodplain	May 15 – May 16	1.08	8.0	10.6		
Andrewilla riparian	May 14 – May 15	1.55	8.5	9.5	-26.5377	139.2564
Andrewilla flood runner	May 15 – May 16	0.51	6.0	3.3		
Andrewilla floodplain	May 14 – May 15	1.35	6.0	9.2	-26.5393	139.2512

Figure 6. Sap flow logger (covered by a half piece of PVC pipe to provide protection from animals) installed into a coolibah on the floodplain at the Double Bluff site. The sap flow logger only records from one stem and the whole of tree response requires that the circumferences of all stems are measured for the instrumented tree.

2.6 Algae measurements

Open water phytoplankton sampling was done with a plankton net using three 5 m tows at many of the waterbodies that were visited. The samples were examined by Joan Powling of the University of Melbourne on a voluntary basis. The algal sampling and examination was not a formal part of this project but gives important insights into the algal assemblage which forms an important part of the base of the food chain and provides the basis for future research in this area.

3 Results and Discussion

3.1 Distribution of refugial waterbodies

Bathymetric surveys of 28 waterbodies (Table 2) were conducted to identify their refugia potential and the distribution of these waterbodies is shown in Figure 7. As a result of the distributary splits and geomorphology of the study area, the distribution of the refugial waterbodies needs to be considered in terms of the following separate reaches (locations shown in Figure 3):

1. Diamantina main channel – Birdsville to Yammakira and Andrewilla waterholes,
2. Goyder Lagoon,
3. Eyre Creek,
4. Warburton - Kallakoopah.

The distribution of refugial waterholes in the Diamantina shows a clear clustering of the most important ark refugia in the Diamantina channel reach (Figure 7). Here, the waterholes show the deepest cease-to-flow depths (CTFD), greatest depths and widths, and also maintain low salinity levels over the full range of water depths. This reach also has excellent connectivity and experiences flow every year. As shown in Figure 8, the Diamantina main channel waterholes all have maximum CTFDs that exceed the approximate evaporation losses following two years without flow.

The CTFDs of the refugial waterholes generally decrease moving downstream and this pattern is in response to the decrease in mean annual flow (and event flow) moving downstream, particularly as flow splits into the different distributary systems and transmission losses decrease flow volumes.

The observations from this study are consistent with previous work that identified that most waterholes on Cooper Creek and the Diamantina River have CTFDs of 4-9 m (Costelloe 2013; Costelloe et al., 2004; McMahon et al., 2005; Bunn et al., 2006), with the exception of Cullyamurra Waterhole (23 m) on Cooper Creek. The ark refuge waterholes in the SA reaches of the Diamantina River are not exceptional at the basin scale but are highly significant at the catchment scale. In terms of the persistence of the Diamantina waterholes, the longest reported no-flow interval at Birdsville for the period 1966-2015 was 306 days. Therefore, periods of no flow greater than one year would appear to be quite rare and the deep waterholes in the Diamantina channel reach are essentially permanent. The importance of the Diamantina channel reach in the context of the catchment and the LEB is also suggested by the capture of turtles in Yammakira and Andrewilla Waterholes (Costelloe et al., 2004; Schmarr et al., 2017). These are the only observed turtle populations in the Diamantina and it is uncertain if they are the result of translocation or natural migration during interannual wet periods (e.g. 1973-1977). However, the Diamantina channel reach waterholes provide the first ark refuge environments that fauna would encounter if naturally migrating from the Cooper or Georgina catchments to the Diamantina catchment.

Table 2. Waterbodies surveyed in Diamantina reaches. Waterholes considered to have the highest refugial values in the four identified management reaches are highlighted. The maximum EC data comes from SARDI (Schmarr et al., 2017), ARIDFLO (Costelloe et al., 2004) and University of Melbourne (this project). Waterholes with maximum recorded EC values above approximately 3-5 mS/cm are highly likely to receive saline groundwater discharge.

Waterbody	Reach	Flow frequency (years)	Cease to flow depth (m)	Max EC (mS/cm)
Pandie (Windmill)	Diamantina channel	Annual	2.98	0.25
Double Bluff	Diamantina channel	Annual	1.35	0.27
Diamantina Split	Diamantina channel	Annual	7.35	0.21
Yammakira	Diamantina channel	Annual	5.95	0.19

Waterbody	Reach	Flow frequency (years)	Cease to flow depth (m)	Max EC (mS/cm)
Andrewilla	Diamantina channel	Annual	5.97	0.19
Andrewilla flow path	Diamantina channel	Annual	2.45	0.21
Peraka Channel	Goyder Lagoon	Annual	1.50	-
Bobbiemoonga	Goyder Lagoon	Annual	1.60	1.19
Pelican	Goyder Lagoon	1.75	2.58	0.13
Burt	Goyder Lagoon	Annual	0.80	0.34
Koonchera	Goyder Lagoon	Annual	1.74	0.33
Pandiburra dune	Goyder Lagoon	Annual	1.10	0.36
Goyder Lagoon Waterhole	Goyder Lagoon	Annual	2.10	0.36
Yelpawaralinna	Goyder Lagoon	1.75	2.41	1.13
Tepamimi	Eyre Creek	5.0	2.09	1.8
Ultoomurra	Warburton	1.5	2.21	85
Pirricoogoomoo	Warburton	1.5	1.40	95
Warburton @ Kalamunkinna	Warburton	1.75	1.00	148
Stony Point	Warburton	1.75	2.40	133
Kuncherinna	Warburton	1.75	2.60	0.18
Mona Downs	Warburton	1.75	2.15	0.18
Cowarie Crossing	Warburton	1.75	1.97	257
Yellow Hole	Warburton	1.75	0.50	144
Mia Mia	Warburton	1.75	0.50	8.3
Tinnie Landing	Warburton	1.75	2.25	26
Wadlarkaninna	Warburton	1.75	1,50	0.62
Cliff Camp	Warburton	1.75	0.80	35

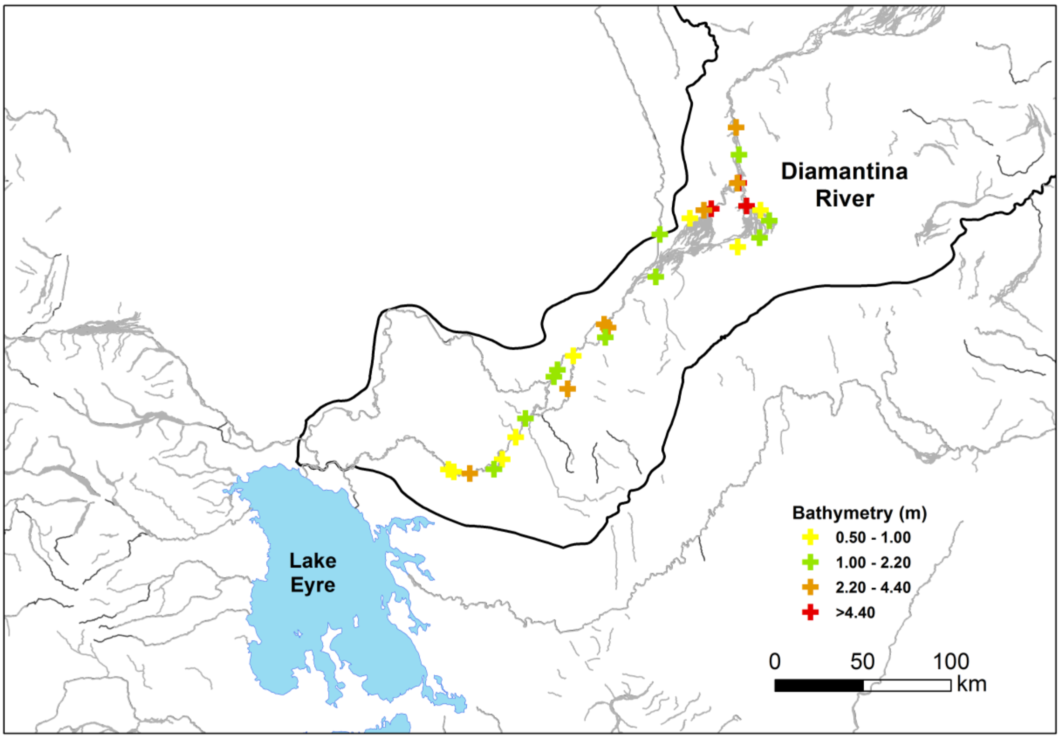
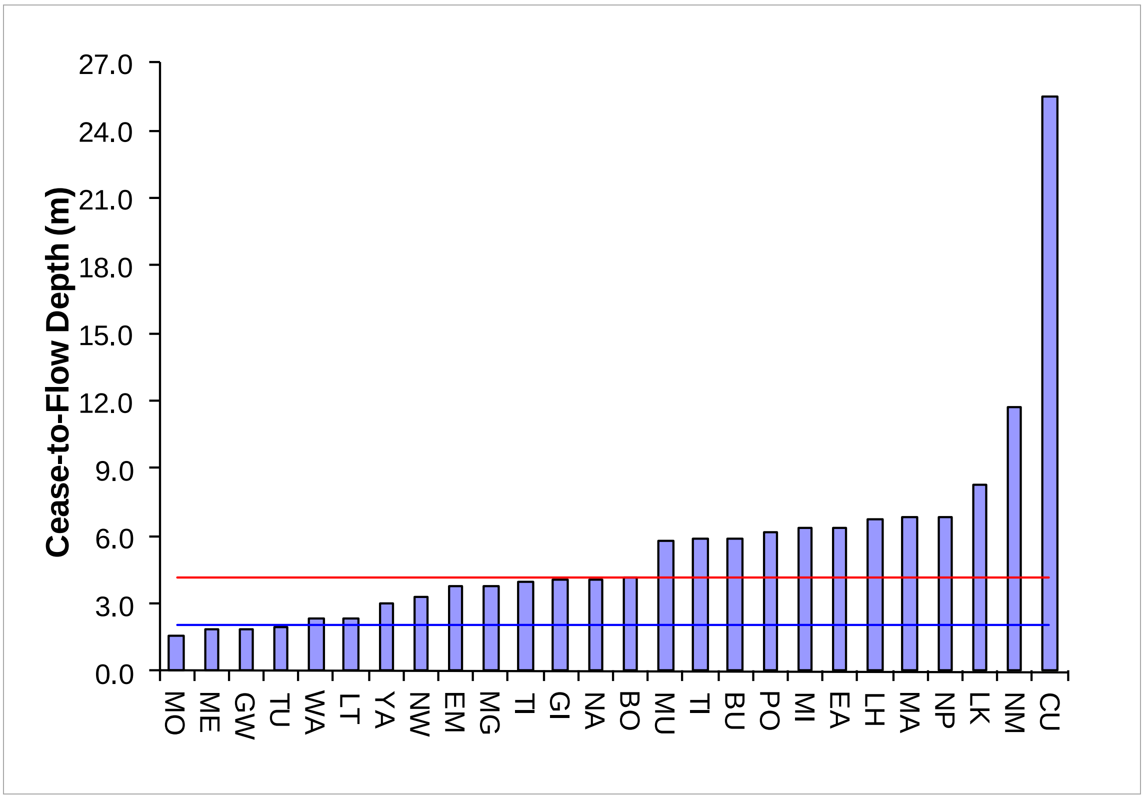


Figure 7.Distribution of waterbodies on Diamantina River with bathymetric measurements collected during 2014-2016. The legend shows the ranges for the observed maximum cease-to-flow depth. One year's evaporative loss (assuming no inflow) is approximately 2.2 m.



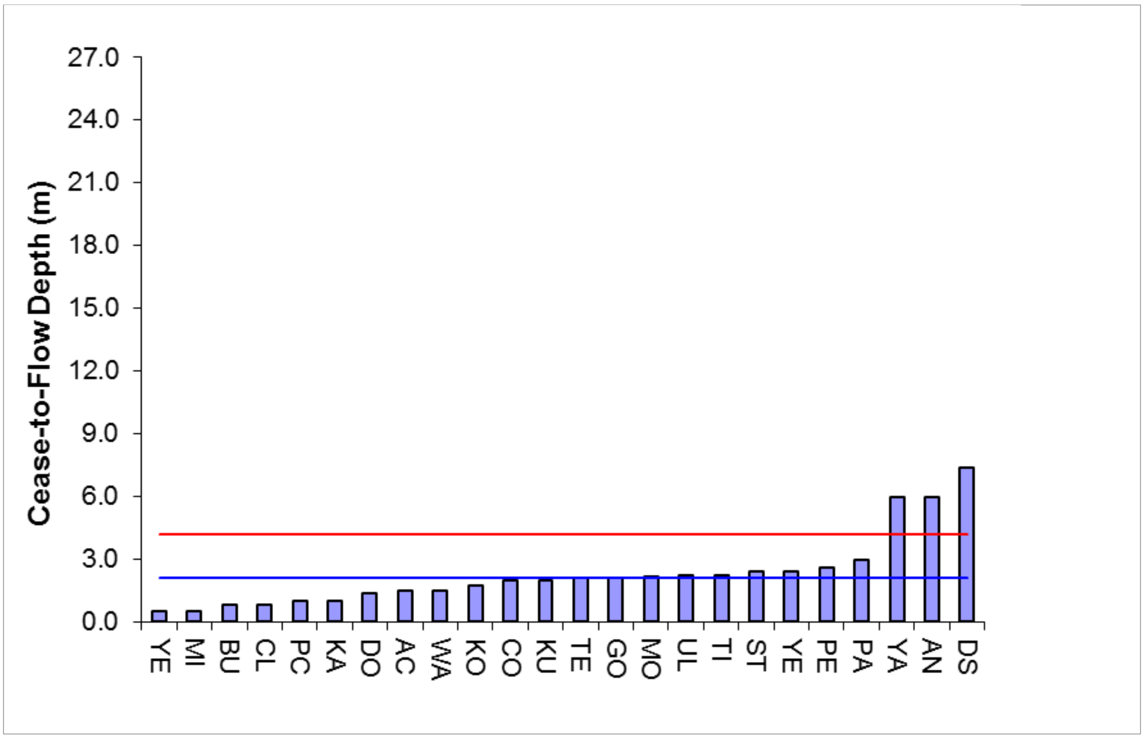


Figure 8. Maximum Cease-to-Flow Depths measured for Cooper Creek waterbodies (top panel) and Diamantina River waterbodies (bottom panel). The blue and red lines show the one-year and two-year open water evaporation loss rate, respectively.

The key refugial waterholes in each of the four recommended management reaches (see Figure 3) are the following.

Diamantina main channel (in SA) – Yammakira and Andrewilla are generally the deepest and longest although the ADCP survey at Diamantina Split indicates that deep holes can occur elsewhere along the main Diamantina channel. The high degree of upstream and downstream connectivity and focusing of flow through these waterholes enhances their value as refugia, in addition to their considerable persistence in the absence of flow. The focusing of flow also means these waterholes will be the likely conduits for weeds and alien fauna (e.g. cane toads) moving into the South Australian reaches of Diamantina River, or potentially up into Queensland if the pathway is from connection with Cooper Creek through Lake Eyre (Kati Thanda).

Goyder Lagoon – The Goyder Lagoon floodplain does not contain any deep waterholes (i.e. >4 m) that act as significant refugia. There are only three significant waterholes on Goyder Lagoon (Koonchera, Goyder Lagoon WH and Yelpawaralinna). Koonchera and Goyder Lagoon WH receive inflow in most years but there relatively shallow depths mean they will dry within 12 months if receiving no inflow. Yelpawaralinna has a longer persistence time but a lower frequency of inundation. It is likely that Goyder Lagoon WH could be an important 'staging post' for movement of fish from Goyder Lagoon to the Warburton during local flow events.

Eyre Creek – Only one waterhole on Eyre Creek was measured, Tepamimi, and this waterhole is quite important as it is located close to Goyder Lagoon. Its role as a refuge was limited by its natural frequency of inundation being approximately 1 in 5 years and its persistence time of approximately 12 months. However, its natural hydrological characteristics have been significantly altered by its use as a storage for bore drain flow from an artesian bore. As a result, the waterhole remains permanently full and acts as an ark refuge for its aquatic fauna.

Warburton and Kallakoopah – Waterholes on the Warburton and Kallakoopah have only relatively shallow depths and those on the Warburton become hypersaline during no flow conditions as a result of groundwater discharge and evapo-concentration. As a result, the refuge capacity of these waterholes is limited to the small-bodied, highly saline-tolerant fish species (e.g. Lake Eyre hardyhead and desert gobies). Some waterholes on the upper Kallakoopah (e.g. Mona Downs) were observed to remain fresh but would only last approximately one year without inflow.

3.2 Streamflow distribution

An important recent development for the management of Diamantina River and our capacity to detect adverse change was the development of a Source hydrological model for the Diamantina downstream of Birdsville (Osti, 2015). This model was developed by DEWNR and utilised advice by Justin Costelloe on the hydrology of the Diamantina but could not utilise the full range of data collected during the current project as the model was developed in 2014. The information collected during 2014-16 is currently being used to improve the Source hydrological model as part of a University of Melbourne student project. Previously, splits in flow percentages at major disjunctions ('splits') were based on best guesses but the field data collected in this project will provide additional confidence in the model's capacity to simulate flow through the Diamantina. The only previous hydrological models of the South Australian reaches of Diamantina River are; (1) A whole of basin RORB model including a very coarse representation of Diamantina River (Kotwicki, 1987), and (2) A grid-based conceptual model from the ARIDFLO project that modelled from Birdsville to the upper Warburton (Costelloe et al., 2004).

In this section, information collected during the current project is presented that advances our understanding of flow distribution during sub-bankfull flood events. Firstly, the conditions experienced during the three field trips are described and then the information learnt on the key distributary and flow constriction locations are presented in their downstream order. Finally, the ecological and management implications of changes in the flow regime are briefly discussed.

Conditions during the field trips

Flow gauging collected during the three hydrological field trips are shown in Appendix 1. As shown in Figure 1, the May 2014 field trip coincided with a small regional flow event in the Diamantina but dry conditions in the Warburton. During May 2015, little streamflow was encountered as the field trip occurred after the small regional event of 2015 had ceased.

The May 2016 field trip coincided with recession flows in the Diamantina (regional flood pulse) and lower Warburton (local flood event) but with near peak flows in the upper Warburton (regional flood pulse) following a significant local rainfall event during the field trip that boosted the first regional flood peak of 2016.

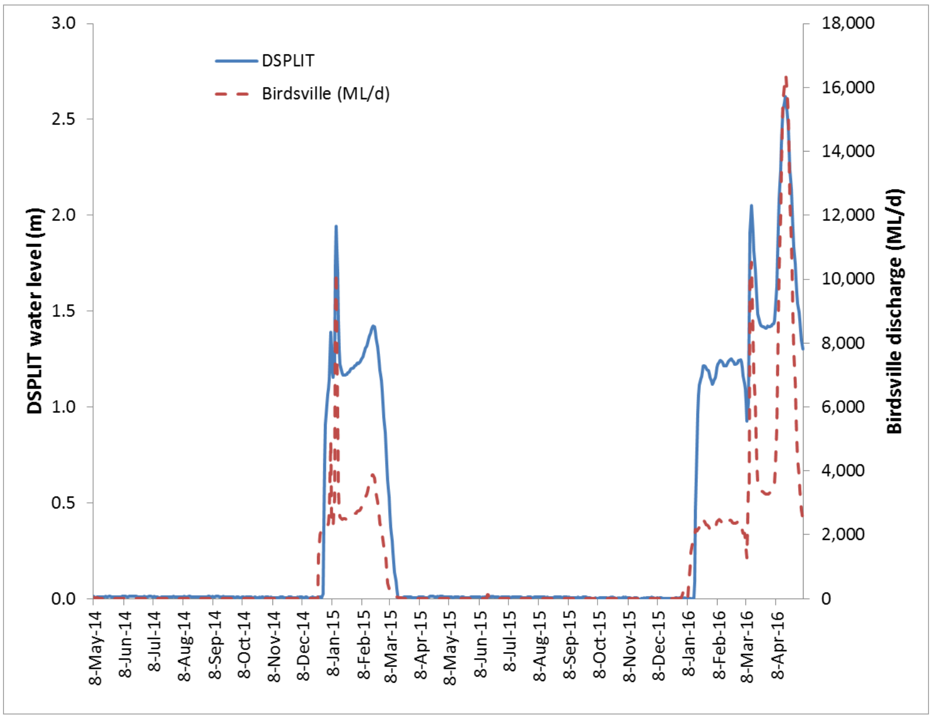
Distributaries from Diamantina main channel (Andrewilla and Yammakira flow paths)

Water level loggers were installed around the distributary junction of the Diamantina main channel and the Andrewilla low flow channel (Figure 9, see locations in Figure 3). One logger was installed in the Andrewilla channel (DSPLIT site) and the second was installed at Yammakira Waterhole.

The Andrewilla low flow channel was found to be flowing in May 2014 and again in May 2016, with approximately 50% of the total Diamantina flow entering the Andrewilla flow path during these periods of flow recession. The onset of flow in 2016 suggests an approximate threshold of 1500 ML/d at Birdsville and a six day lag before flow commences into the Andrewilla flowpath. Note that the 2016 local and regional peaks at Birdsville coincided with the DSPLIT peaks. The data also indicate that during flow recessions (e.g. in May 2014), when river levels remain relatively high,, flow continues into the Andrewilla flowpath for approximately the same time period as it continues down the main channel towards Yammakira.

The flood peak in the Diamantina in mid-April 2016 (16,362 ML/d measured at Birdsville) did not result in any significant flow into the Eleanor Creek flow path to the west of the Diamantina main channel. Landsat satellite images suggest that inflow into Lake Uloowaranie (a large storage to the east of the Diamantina channel) occurs between 16,000 – 20,000 ML/d. The Diamantina Source model uses a threshold of 40,000 ML/d for flow to occur into the Eleanor Creek flowpath and this is based on Landsat observations (described in Osti, 2015). For example, the 2007 flood with a peak discharge of 52,000 ML/d flowed into the Eleanor Ck flow path but the 2012 flood with a peak discharge of 31,000 ML/d did not.

The Andrewilla low flow channel at DSPLIT is a relatively small channel where it comes off at a bend in the main Diamantina channel (Figure 9). Its geomorphic stability is uncertain and it could be conceivably blocked by tree fall and bank erosion that could lead to variations in the percentage of flow that it receives from the Diamantina channel. The occurrence of other channels upstream of DSPLIT that lead into the Andrewilla flow path mean that changes in the DSPLIT distributary would not affect the amount of streamflow entering the Andrewilla flowpath during medium-large floods. However, geomorphic change around DSPLIT could affect the distribution of flow between the two major distributaries (Andrewilla and Yammakira) during smaller flow events.



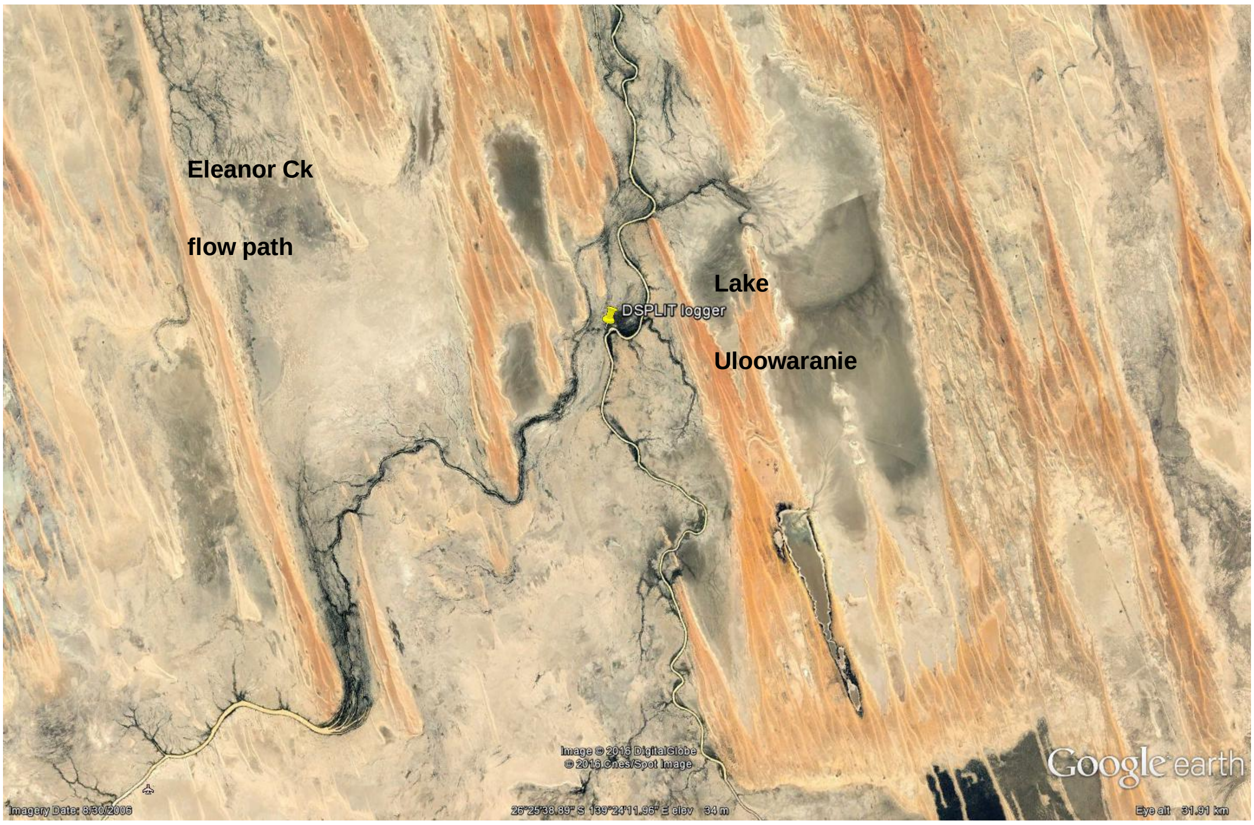


Figure 9. Hydrograph of Birdsville discharge compared to water level data recorded at channel leading to Andrewilla flow path at Diamantina Split (DSPLIT) location. Google Earth image shows location of logger at Diamantina Split. Bottom photo shows the Andrewilla flow path channel at its junction with the Diamantina main channel in May 2014. Note the green algal bloom occurring at this time.

Warburton – Kallakoopah Junction

Water level loggers were placed on the Kallakoopah and Warburton channels near the junction at Kalamunkinna Waterhole. The Kallakoopah logger was installed in May 2014 and the Warburton logger in May 2015. The data from these loggers are also compared to the DEWNR water level logger located at Poothapoota Waterhole, near the commencement of the Warburton River with Goyder Lagoon (Figure 10).

The data demonstrate that relatively small flows in the Warburton will not generate flow into the Kallakoopah. For example, a flow event generated by local rainfall occurred in January 2015 in both the Warburton and Kallakoopah. This event had a peak stage at Poothapoota of 3.19 m on the 14/01/15. The Kallakoopah stage peaked at 0.90 m on 10/01/15 and this timing, in conjunction with remnant pools having very high turbidity and low salinities (<0.5 mS/cm EC) and no fish being measured in the full Mona Downs Waterhole in May 2015, indicate that the Kallakoopah flow was in response to very local rainfall and did not connect with the Warburton flow event. Similarly, a small flow peak in the Warburton in March 2016 (peak of 2.58 m at Poothapoota and 1.35 m downstream of the Kallakoopah-Warburton junction) did not result in flow into Kallakoopah Creek.

Whilst the Warburton-Kallakoopah disjunction was not accessible during mid-May 2016, observations from Cowarie Station indicate that the Kallakoopah commenced flowing from Warburton inflow in this period. This equates to water levels at Poothapoota of <3.88 m and discharges of 3000-3500 ML/d (as measured in the Warburton at Ultoomurra Waterhole).

The large flood event in the Warburton generated by heavy local rainfall in January 2016 resulted in flow peaks on the same day (3/01/16) at Poothapoota, Warburton junction and Kallakoopah Creek. This reflects the influence of local runoff generated by the heavy rainfall dominating the peak discharge and there was no sign of secondary peaks related to the arrival of upstream flow at the Warburton junction and Kallakoopah loggers, although flow connectivity occurred between the Warburton and Kallakoopah.

In general, flow into the Kallakoopah would be in response to large regional floods and the 2016 data show that floods with annual recurrence intervals at Birdsville of 2 years generate flow into the Kallakoopah. In addition, events during the study period show the importance of local rainfall generating streamflow in the Warburton and Kallakoopah. These events are likely to be highly important in refreshing both volumes and salinities in waterholes along these distributaries.

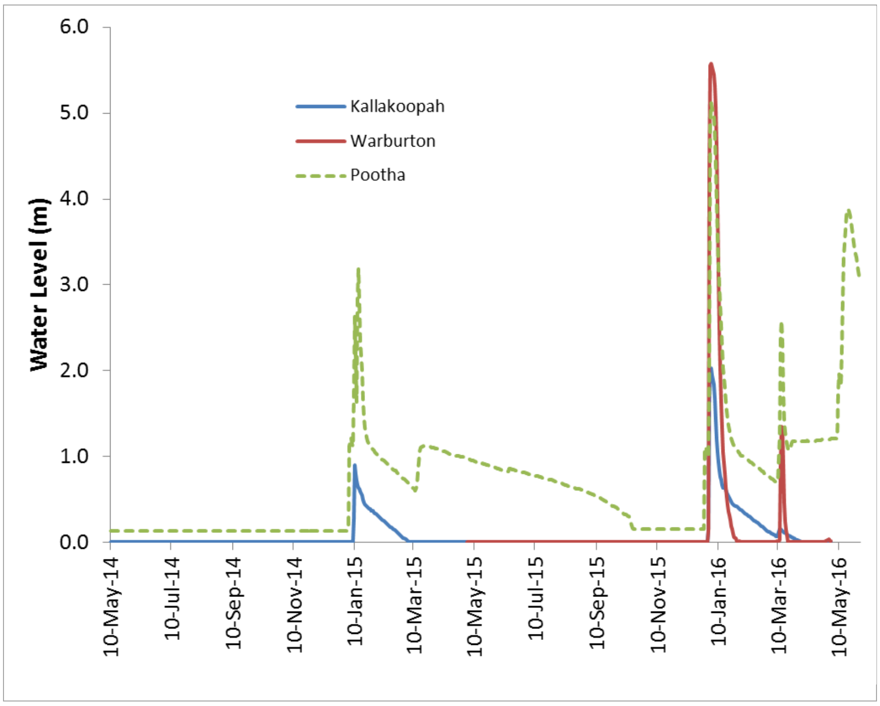


Figure 10. Top- Distribution of flow between Warburton River and Kallakoopah Creek during flow events in 2015 and 2016. Satellite image courtesy of Google Earth shows locations of the water level loggers at this site.

Inflow to Goyder Lagoon

Flow gaugings collected from outflow channels from Andrewilla and Yammakira Waterholes, and from channels within Goyder Lagoon, provides insights into the distribution of flow into Goyder Lagoon.

Yammakira Waterhole divides into two main distributary flow paths (Figure 11). The right (looking downstream) distributary feeds a dense network of channels in Goyder Lagoon that produces a strong vegetation response when flooded, while the left distributary feeds the flowpath that leads to the Peraka swamps and Bobbiemoonga and Koonchera Waterholes. Gaugings in May 2016 showed that in the recession flow (1301 ML/d), 34% flowed into the right distributary and 66% into the left distributary. Only 10% of the left distributary flow in May 2016 entered the channel that feeds the Peraka Swamps. Observations in May 2014 showed that the relatively small 2014 flood (<20th percentile of annual flows) generated a small amount of flow into the first two (western) swamp 'panels'. These swamps have been identified as important waterbird breeding areas (Julian Reid, pers. comm.). The flow from the two Yammakira flowpaths appears to coalesce in the vicinity of Pandiburra dune and flow was observed in the minor floodplain channels near Pandiburra in May 2014 and significant flow around the Pandiburra dune in May 2016.

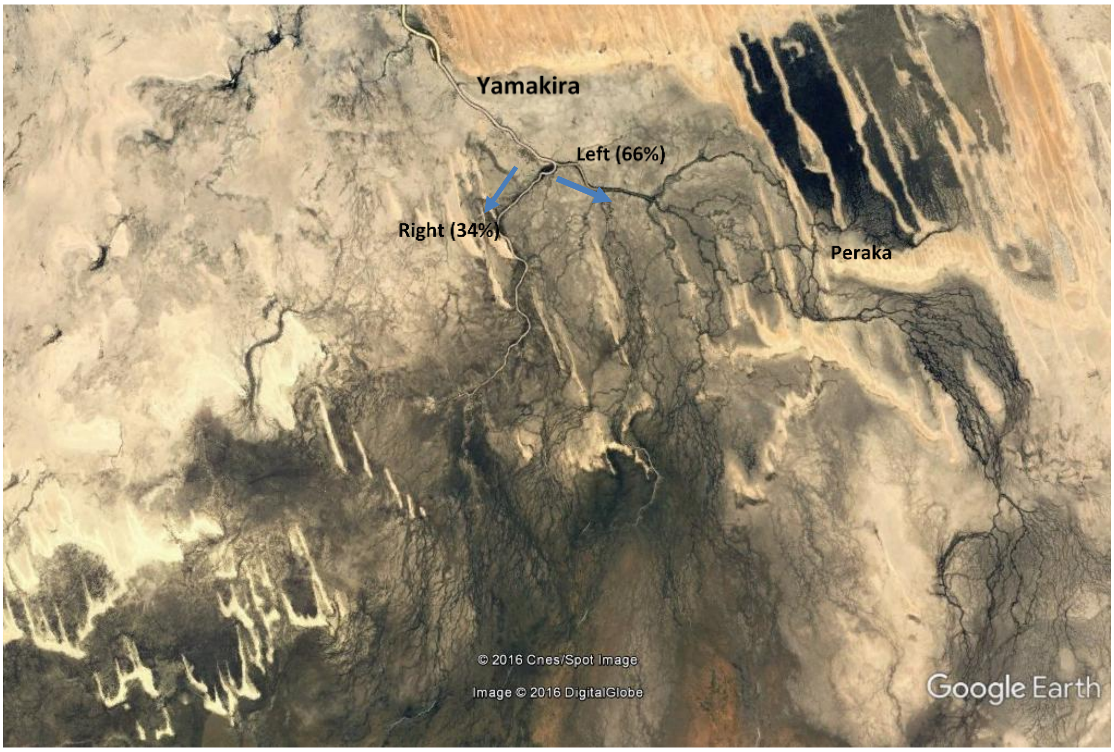


Figure 11. Flow distribution downstream of Yammakira Waterhole shown for May 2016. The left flow path feeds Bobbiemoonga and Koonchera Waterholes and the right distributary feeds into a dense area of vegetation.

Andrewilla Waterhole also divides into two main distributary flowpaths (Figure 12). The right distributary feeds the most prominent channel complex that leads to Burt Waterhole and towards Goyder Lagoon Waterhole. The left distributary feeds a less prominent channel network with uncertain downstream connectivity. The gaugings in May 2016 showed that during the recession flow through Andrewilla (1492 ML/d) the vast majority of the flow (86%) entered the right distributary. The right distributary also feeds flow into a series of floodplain waterholes northwest of Andrewilla that include Pelican Waterhole.

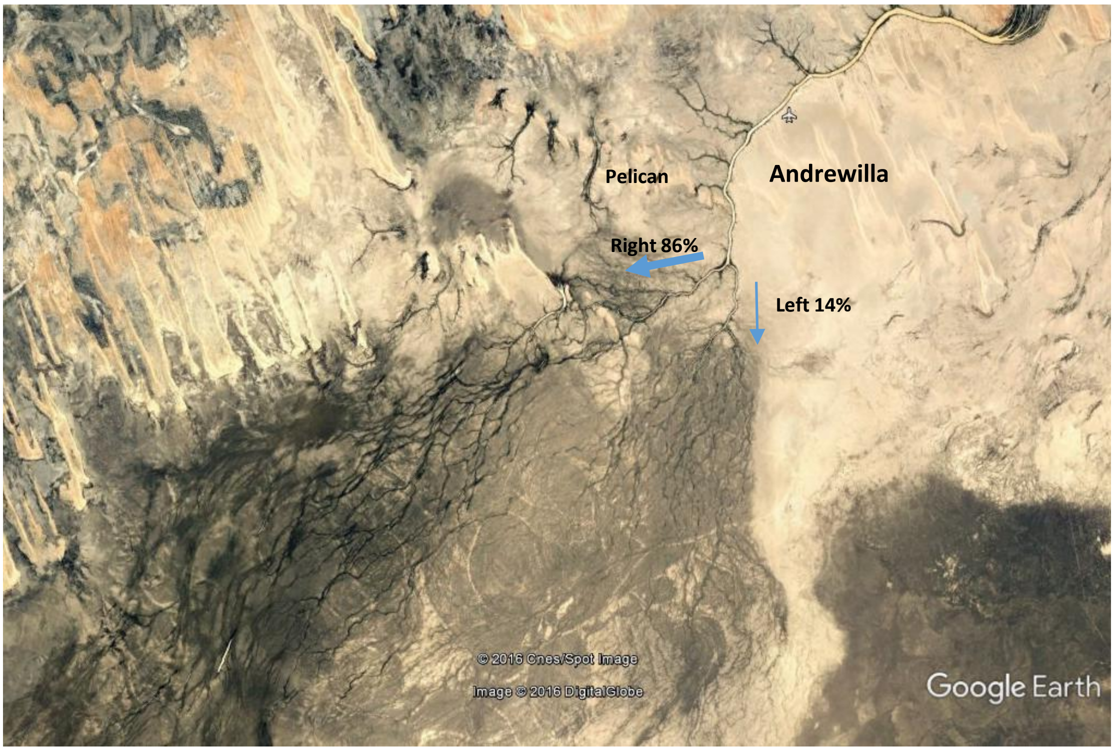


Figure 12. Flow distribution downstream of Andrewilla Waterhole shown for May 2016. The left flow path feeds a poorly developed channel network and the right distributary feeds the main flow path towards Goyder Lagoon Waterhole.

The Andrewilla and Yammakira flowpaths come together upstream of the Birdsville Inner Track (Figure 13). Observations during the low flow conditions of May 2014 suggest that the Andrewilla flowpath may have been the dominant contributor to inflows to Goyder Lagoon Waterhole at the forefront of the regional flood within the Lagoon but the source of the flowpath feeding channels along the Inner Track is uncertain. In May 2014, 58 ML/d was measured entering Goyder Lagoon Waterhole, which was filling from a dry state. Flow in the two most southern channels crossing the Inner Track was of the order of 1-7 ML/d and this suggests that most flow through the middle section of Goyder Lagoon is focused through the flow path that feeds Goyder Lagoon Waterhole, particularly during the smaller events. The 2014 flood had an annual volume around the 20th percentile of the long-term Birdsville record and an annual recurrence interval. This sized flood does not generate any flow into the Warburton River.

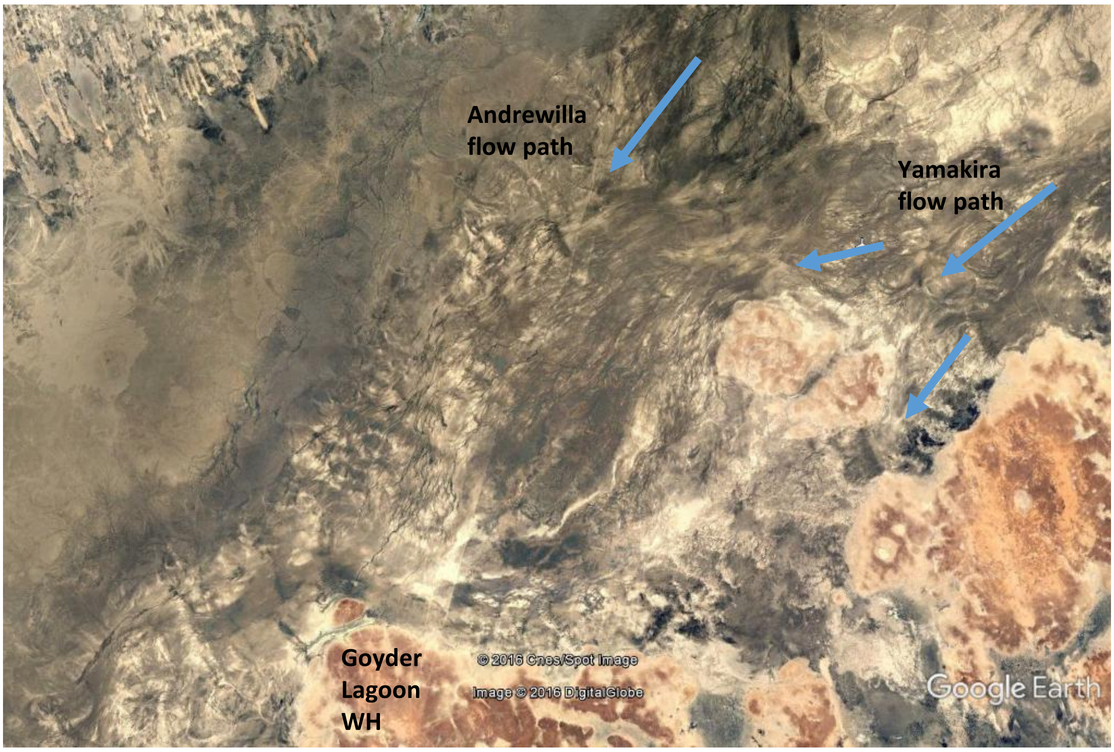


Figure 13. The Andrewilla and Yammakira flow paths merge upstream of the Birdsville Inner Track and flow is focused towards Goyder Lagoon Waterhole. The 2014 flow event terminated downstream of Goyder Lagoon WH but did not flow into the Warburton.

Table 3. Flow gaugings at the Yammakira and Andrewilla distributaries in May 2016.

Location	Date	Discharge (MLd[1])	Percentage flow
Yammakira Waterhole	16/05/16	1301	100
Yammakira right distributary	16/05/16	459	34
Yammakira left distributary	16/05/16	875	66
Yammakira-Peraka distributary	16/05/16	85	7
Andrewilla Waterhole	11/05/16	1492	100
Andrewilla right distributary	11/05/16	1191	86
Andrewilla left distributary	11/05/16	193	14

Flows into the Warburton River

The Poothapoota monitoring station on the upper Warburton indicated that the 2015 regional flood was of sufficient magnitude (approximately annual recurrence with a peak discharge of 3882 ML/d, total annual volume of 208,000 ML) to result in minor inflow into the Warburton. This was consistent with minor, turbid and lower salinity flow observed in the Warburton at Ultoomurra Waterhole in May 2015. The 2015 regional flood probably represents the smallest flood that would reach the Warburton and corresponds to a peak discharge with approximately annual recurrence interval and a total volume around the 35th percentile. The 2015 inflow may have been facilitated by the local runoff generated from the January 2015 rainfall that caused a local streamflow event in the Warburton.

Flow into Yelpawaralinna Waterhole occurs firstly from the Warburton channel and also by floodplain flow during large flood events. On 17/05/16, close to the peak of the 2016 regional flood in the Warburton, the Yelpawaralinna inflow channel was active at a Warburton discharge of 3562 ML/d but only received 3% of the Warburton flow.

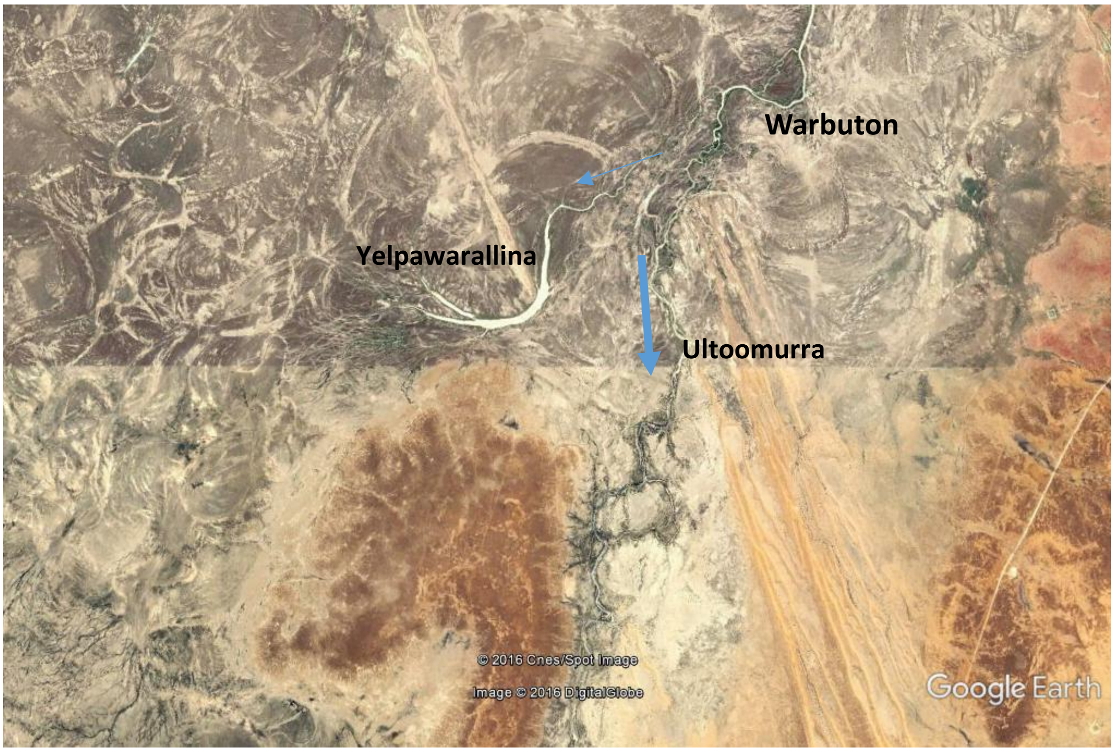


Figure 14. Flow distribution in the upper Warburton in May 2016 near the peak of the first 2016 regional flow peak in the Warburton. Only 3% of the Warburton flow entered the Yelpawaralinna channel. Larger flood events results in floodplain flow into Yelpawaralinna too.

Inputs into the Diamantina Source hydrological model

The hydrological observations obtained during the 2014-2016 period can be used to further calibrate the Diamantina Source hydrological model developed by DEWNR (Osti 2015). Discharge measurements at key distributary points can be used to refine the distribution of flow through the link-node network (e.g. see Figure 15) and the extent of flows in the study period can be used to calibrate the loss rate required for flow through the Diamantina channel and Goyder Lagoon reaches. These refinements to the Source model will be undertaken as a University of Melbourne student research project in 2017.

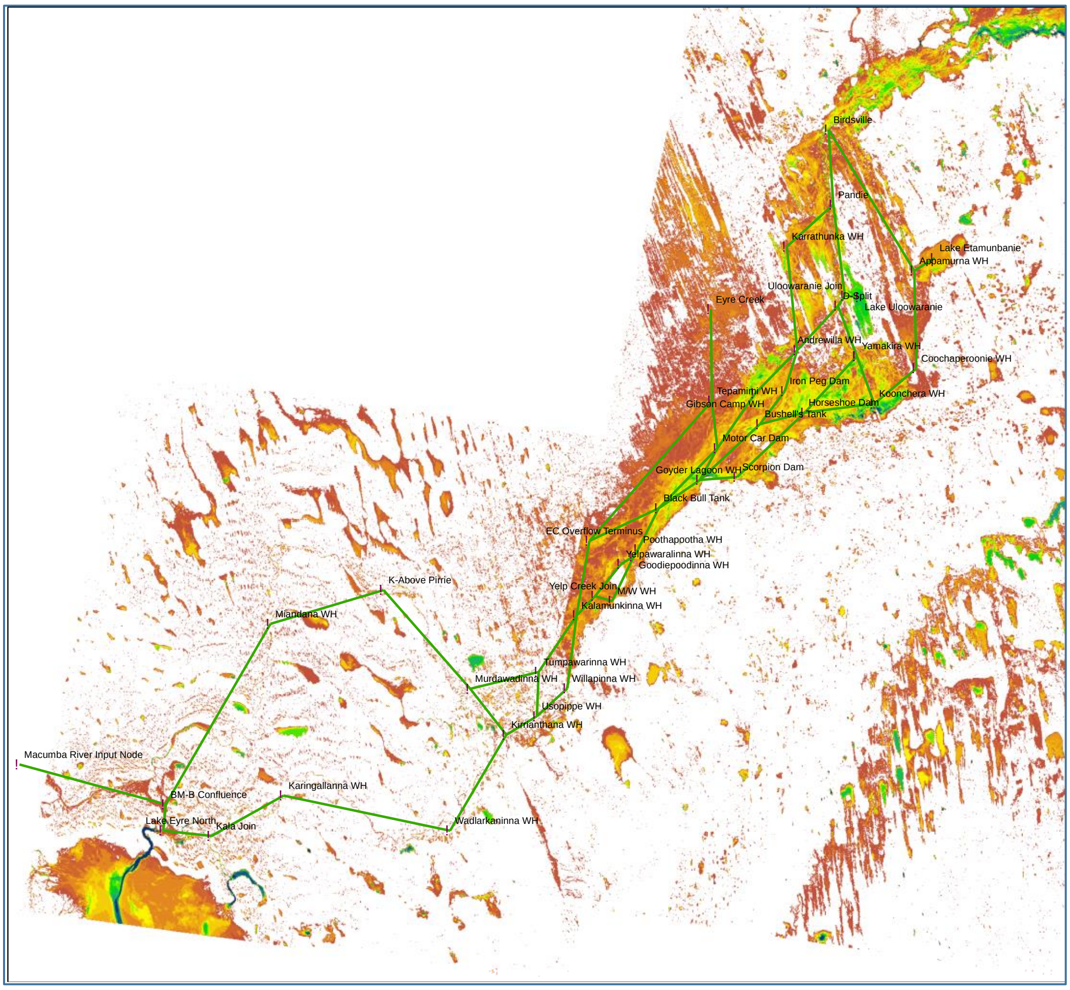


Figure 15. Link-node network for the Source model of the SA Diamantina reaches (Osti 2015) superimposed on Geoscience Australia's Water Observations from Space (WOfS) frequency of inundation map.

Ecological and management implications of changes in flow regime

Changes in the flow regime of a particular reach or wetland are likely to have significant long-term consequences for their ecology. The cause of changes, particularly the reduction in flow to a given reach, could be a result of natural changes (e.g. climate variability and climate change, geomorphic processes) or anthropogenic changes (e.g. upstream water extraction or changes in flow paths due to infrastructure development). Previous studies (Puckridge et al., 2000; 2010) and observations during the Cooper project (Costelloe 2013) provide insights into some of the possible consequences. For instance, reductions in the long-term frequency of inundation of wetlands and reaches could:

- Result in the decrease in native fish diversity. Puckridge et al. (2010) found that native fish diversity decreased in the wetlands and lakes of the Coongie Lakes as the frequency of inundation decreased.
- Result in increases in wetland soil salinity due to decreased flushing by flood events. Costelloe et al. (2009) found that less frequently inundated lakes in the Coongie Lakes had increasing soil salinities. Increases in soil salinity are likely to change the productivity of the wetland through the decrease in less salt-tolerant algae and zooplankton species, change the vegetation communities that can grow on the wetland soils during dry phases, and may even result in mortality events for wetland plant communities.
- The consequences of increased flow into a wetland, as is occurring at Tepamimi Waterhole from artesian bore outflow, have not been researched in detail. The fish data (Schmarr et al., 2017) from this project show that the Tepamimi fish assemblage contains large numbers of the alien species *Gambusia holbrooki*, and this is consistent with previous LEBRA and research project data (e.g. McNeil et al., 2011) for bore drains and their associated wetlands. Vegetation changes

are less clear but some mature coolibahs within the waterhole have drowned since the waterhole has been maintained at close to bankfull level. In addition, coolibahs saplings on the floodplain show damage from camel grazing, and the permanent waterhole is likely to attract herbivores and increase grazing pressure in the area.

The consequences of long-term changes in flow patterns are likely to be quite subtle at first, particularly given the natural variability of the system. However, persistent changes (particularly reductions) in flow over many years can lead to long-term changes in the soil salinity which can have cascading effects on plant and animal communities. The main management implication is that changes in flow regime in variable systems can be hard to detect without defined monitoring programs. In addition, mitigation of effects of flow regime change can be difficult and very costly to implement.

3.3 Water quality

Water quality variations are particularly pronounced in the SA reaches of the Diamantina River and salinity can vary over several orders of magnitude. Streamflow and standing water bodies in the upper reaches (e.g. Diamantina channel and Goyder Lagoon reaches) are characterised by low salinity (<300 mgL^{-1} TDS), Na-HCO_3 composition (Figure 16), circum neutral to alkaline (pH 6.8-10, median 7.8) and turbid characteristics. In contrast, in the Warburton reach, recession flow and standing waterbodies range from saline to hypersaline conditions due to groundwater interactions (see Section 3.4), however, peak flows have similar low salinity, turbid characteristics as the upper reaches, as was observed in May 2016.

The low salinity in the Diamantina channel and Goyder Lagoon reaches of streamflow and standing water bodies implies either little interaction with groundwater or that the groundwater in the vicinity of the waterholes and channels remains relatively low salinity (see next section). The refugia in these upper reaches are not constrained by water quality considerations (i.e. increasing salinity), as is the case in the Warburton reaches, and provide adequate water quality conditions for the majority of the aquatic obligate flora and fauna in the catchment. The exception to this are the salt-tolerant species that dominate in the saline Warburton reaches (e.g. Lake Eyre hardyhead and salt tolerant micro-invertebrates and algae species).

The water quality in the Warburton reach is highly dependent on flow conditions (i.e. rising, peak or falling stage) and period of time of no flow. For example, in May 2014 salinity in remnant pools of the Warburton ranged between 29-258 mS/cm. There had been no substantive flow in the Warburton since 2012 and so the range of observed salinities is probably influenced by variations in salinity of the unconfined groundwater, perhaps related to higher permeability lenses in the floodplain sediments. The variation in salinity can also occur over quite short reaches. In the channel at Ultoomurra in May 2014 the salinities of individual pools ranged from 29 to >100 mS/cm and similar variations were observed in no flow periods during the ARIDFLO project (2000-2003), as shown in Figure 17. These variations in salinity also determine which fauna can still use these saline pools as refugia.

Following streamflow events derived from local runoff, the range of salinities can be significantly less. For example, in May 2015 following a local streamflow event in January 2015, the range of salinities observed in the Warburton was 14-35 mS/cm. May 2016 encountered consistent low flow as part of the recession of the large local streamflow event in January 2016 and the streamflow had quite consistent moderate salinity levels of 7-12 mS/cm (SARDI data, Schmarr et al., 2017). Initial flows in the Warburton may have elevated salinity levels as saline pools are flushed.

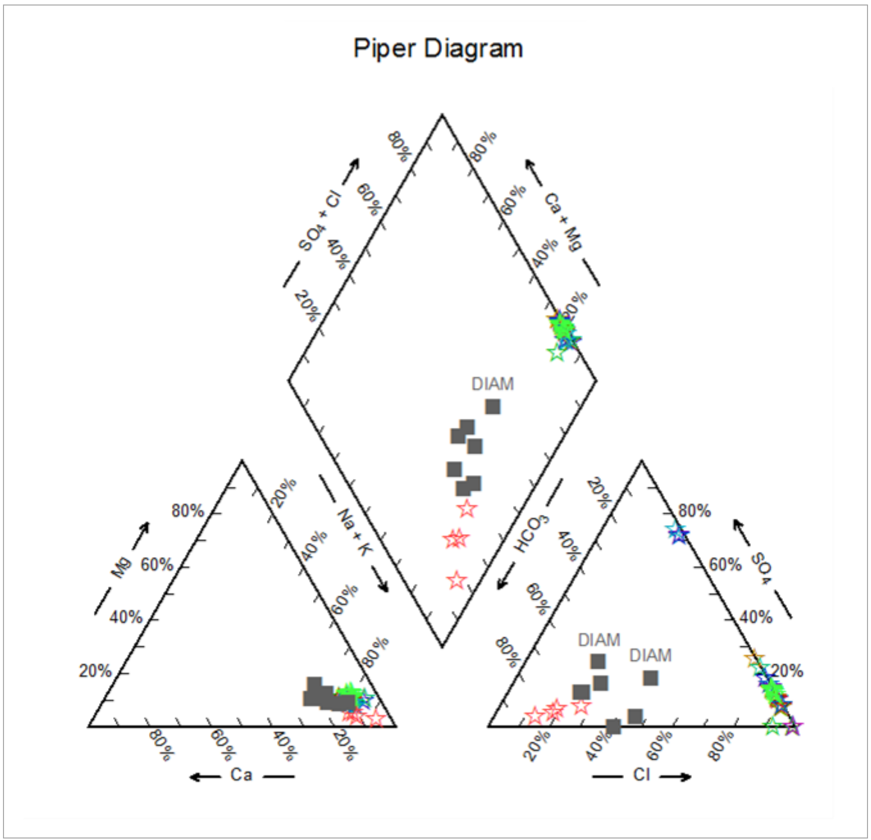
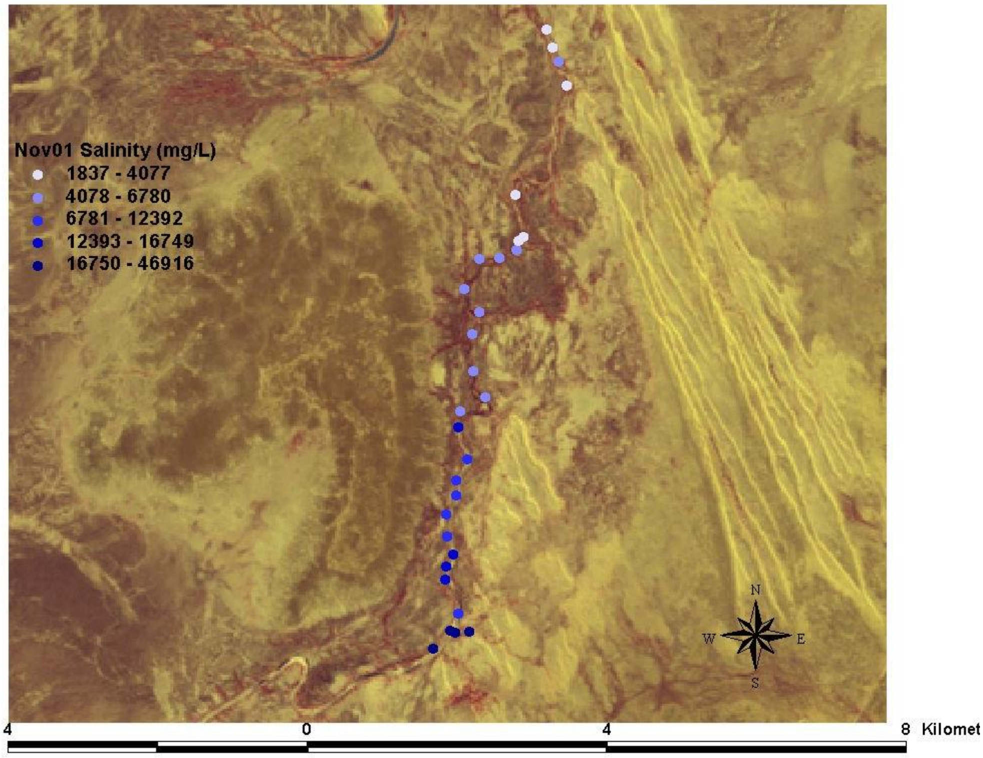


Figure 16. Piper diagram showing the chemical composition of groundwater (stars) and streamflow (squares) samples for the Diamantina River collected in the period 2004-2006. The red stars are the fresher groundwater at Yelpawaralinna Waterhole (dune area) which show a more similar composition to streamflow than the remainder of the saline groundwater samples.



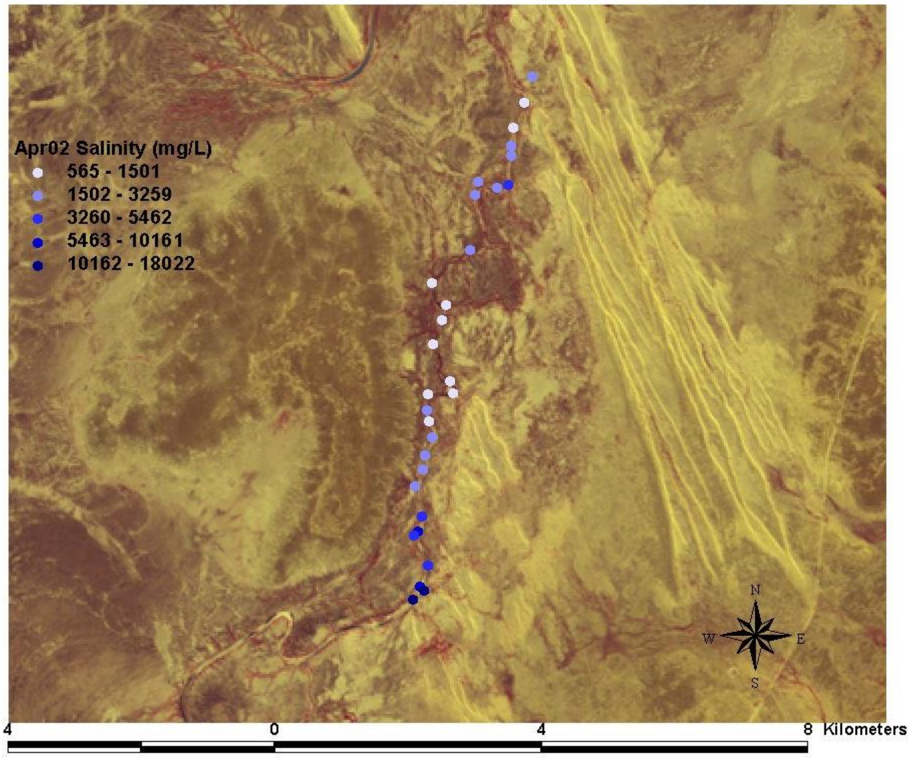


Figure 17. Variations in salinity of isolated pools during November 2001 and April 2002 (ARIDFLO data, Costelloe et al., 2004) for a short reach of the Warburton River around Ultoomurra Waterhole. Pool salinities can vary over an order of magnitude and may reflect differing salinities of discharging unconfined groundwater.

3.4 Groundwater interactions

The extent of groundwater – surface water interactions in the SA reaches of Diamantina River has been previously researched during 2004-2006 (Costelloe et al., 2012). The previous data show that the unconfined groundwater occurs at shallow depths (2.2-5.8 m below floodplain surface with an average of 4.3 m) and is typically highly saline (1200-70,000 mg L^{-1} TDS, mean of 35,660 mg L^{-1}), except around some floodplain waterholes developed near dunes (e.g. Yelpawaralinna and Koonchera). As a reference, the salinity of seawater is approximately 35,000 mg L^{-1}. The unconfined groundwater generally has a Na-Cl composition that is distinct from the Na-HCO_3 streamflow composition (Figure 16). The exception to the high salinity, Na-Cl dominant composition of the unconfined groundwater was at one site in the lower Diamantina (Yelpawaralinna Waterhole). Here, a bore constructed beside a waterhole located around a dune on the floodplain of the Diamantina had groundwater with a Na-HCO_3 composition (Figure 16) and relatively low salinity (mean 1641 mg L^{-1} TDS).

The shallowness of the groundwater in the Diamantina reaches is likely a combination of recharge from the Diamantina River and approaching the regional groundwater discharge zone of Lake Eyre (i.e. the surface of Lake Eyre is within 1 m of the water table, Tweed et al., 2011).

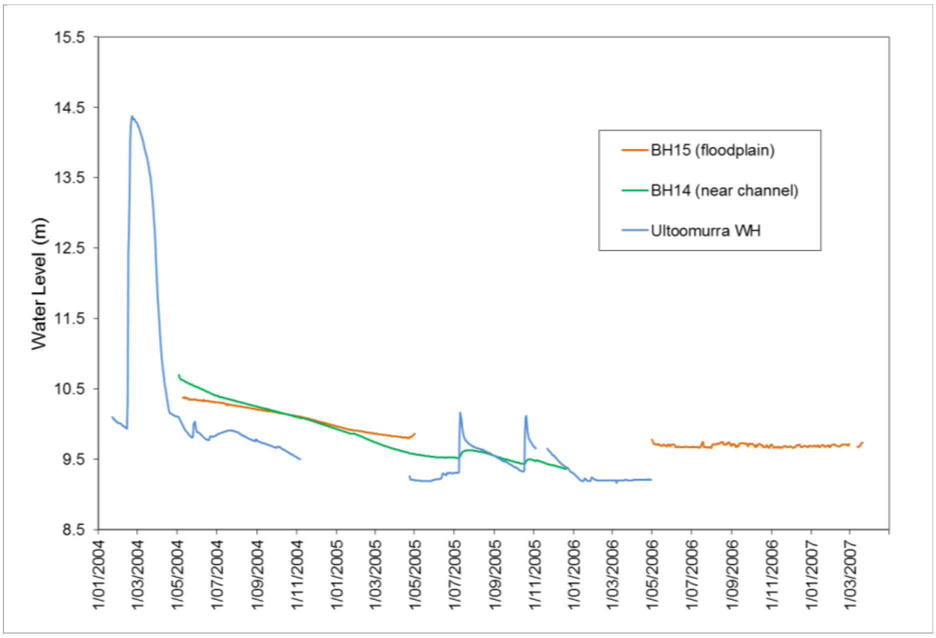
No information is available on groundwater depths and salinity in the Diamantina channel reach. However, the depth of incision of the channel below the floodplain (typically 5-10 m) and the consistent low salinity of the waterholes, even during periods of no flow, suggest that the groundwater is relatively low salinity near the Diamantina River. This is likely to be due to bank recharge occurring during flow events resulting in freshwater lenses of groundwater occurring close to the channels. However, away from the main channel the groundwater is likely to be as saline as observed in the other reaches of the Diamantina. An important implication of the presence of fresher bank storage groundwater lenses is on the riparian phreatophyte vegetation species that can occur in these reaches. For example, the Queensland bean tree (*Bauhinia gilva*) is restricted to the Diamantina channel reach (Gillen 2017). The greater diversity in the riparian vegetation of the Diamantina channel reach also influences riparian bird diversity in this reach, compared to the downstream reaches (Reid 2017).

In the Goyder Lagoon reach, bores were installed near Koonchera Waterhole and on the Lagoon floodplain near the Inside Track. The groundwater near Koonchera was quite shallow (3.1-3.7 m) following the 2004 flood and of variable salinity. Nested bores were drilled at Koonchera and the deeper bore contained highly saline groundwater (mean 46,510 mg L^{-1} TDS) while the shallower bore had substantially lower salinity groundwater (mean 11,170 mg L^{-1} TDS). Observations around Koonchera Waterhole in 2000 indicated that the groundwater around the waterhole was quite shallow (<1 m deep) and this indicates that significant bank recharge occurs in the vicinity of Koonchera Dune during larger flood events. The data from the nested bores indicates that a fresher lens can overly the regional saline groundwater for some period following larger flood events. Notably, the groundwater depths measured between 2004-2006 were below the thalweg of Koonchera Waterhole and so no groundwater discharge is likely to contribute to the persistence of the waterhole, except for an approximately 9-12 month period following large flood events (e.g. the 2000 flood, Costelloe et al., 2004). The Goyder Lagoon bore measured groundwater with a mean depth of 5.7 m and salinity of 31,360 mg L^{-1} TDS. There are no deeply incised channels in Goyder Lagoon and so there is no direct discharge of groundwater in this reach. The Goyder Lagoon bore did not show level fluctuations in response to small streamflow events in 2005 and 2006 and it is likely that groundwater interactions with the surface are minimal in this reach. Soil profiles collected from this reach (see Section 3.7) showed relatively low soil water salinity and this indicates that capillary rise from the unconfined groundwater is not influencing soil conditions.

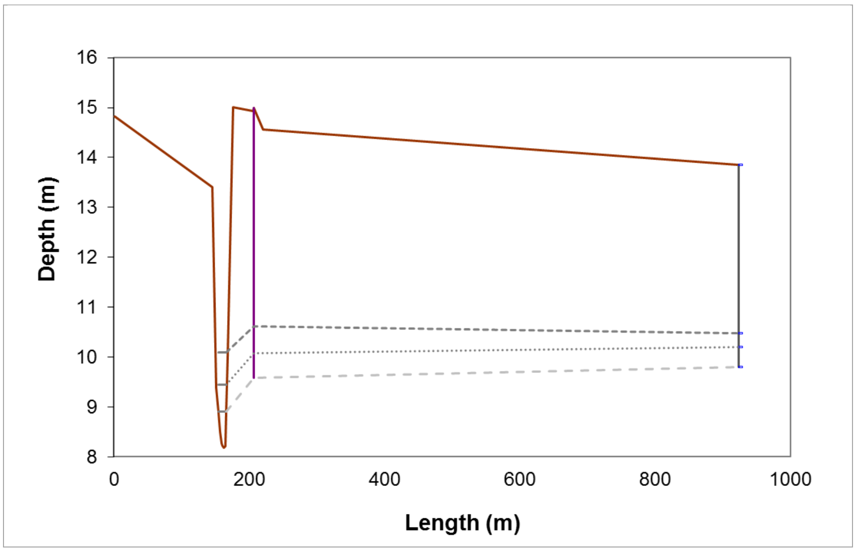
The upper part of the Warburton reach had bores installed at Ultoomurra and Pirricoogoomoo Waterholes on the Warburton, in addition to bores installed around Yelpawaralinna Waterhole on the floodplain to the west of the Warburton. The bores near the Warburton channel measured shallow (2.2-5.3 m depth) and highly saline groundwater (mean 43,860 mg L^{-1} TDS). These bores showed that during flow events the near channel ('bank storage') groundwater is recharged by streamflow but this groundwater discharges back into the channel during the low flow recession and periods of no flow (see Figure 18). The relatively high salinity of the unconfined groundwater in the 'bank storage' zone indicates limited flushing and penetration of recharge during flow events, nevertheless, this bank storage recharge is likely to be highly important for providing groundwater of suitable salinity to be used by the riparian trees, such as coolibahs. However, the bank storage salinity appears to be too high for more salt-sensitive riparian tree species, such as the Queensland Bean Tree. The high salinity of the groundwater and soil water also likely plays a role in the genetic differences between coolibahs in the Warburton reach compared to the upper reaches (Gillen 2017).

At Ultoomurra Waterhole, the bores showed that under no flow conditions the groundwater gradient is towards the Warburton channel and this drives the discharge of groundwater into the channel and is responsible for maintaining saline pools in the channel between flow events (Figure 18). Figure 18b illustrates how the Warburton channel has been incised sufficiently to intersect the unconfined water table, resulting in the groundwater discharge into the river system. In contrast, the Yelpawaralinna Waterhole channel does not incise below the water table and so a lens of freshwater has developed on top of the saline regional groundwater due to density differences (Figure 19). The development of this freshwater lens, which keeps this waterhole fresh even under low water levels, is facilitated by enhanced recharge occurring around the higher permeability Yelpawaralinna dune, in contrast to the low permeability cracking clay sediments making up the floodplain around the waterhole.

Water quality measurements of surface pools in the Warburton from 2000-2006 (e.g. Figure 17) and 2014-2016 (current project) indicate groundwater influences on recession flow and standing pools occur for the length of the Warburton, from Poothapoota Waterhole to Cliff Camp on Kalamurina Wildlife Sanctuary.



A



B

Figure 18. Relationship between water level in the Warburton (Ultoomurra Waterhole) and near channel (BH14) and floodplain (BH15) groundwater levels. Note that A shows that during low flow periods the floodplain groundwater level indicates gaining conditions (i.e. flow of groundwater into the channel) in the Warburton, while the near channel groundwater ('bank storage') is recharged by flow events in the Warburton. B shows the gradients towards the channel during low flow periods and also how the Warburton channel is incised to below the regional groundwater table in this reach. The upper dashed line is the water table and channel pool level in May 2004 (in the recession flow of a large flood even in early 2004), the middle dashed line is the level in November 2004 and the bottom dashed line is the level in April 2005, showing that 12 months after a large flood gaining conditions prevail (i.e. groundwater discharges into the Warburton channel).

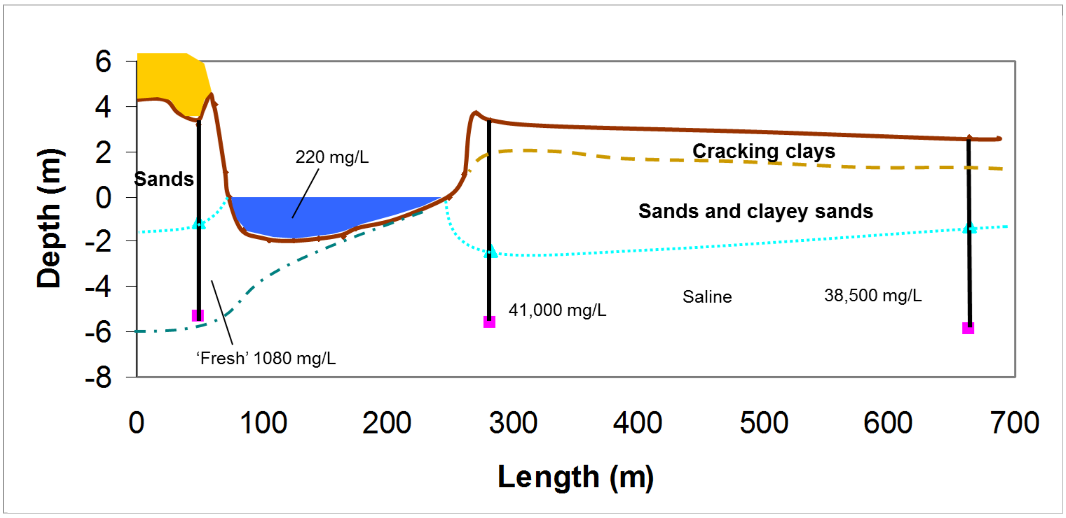


Figure 19. Cross-section through Yelpawaralinna Waterhole showing groundwater characteristics and typical water level and surface water salinity during 2004-2006.

The dynamics of groundwater levels in response to recharge during flood events may also contribute to mass mortality events for riparian trees. Groundwater data from the upper Warburton show that significant rises in highly saline water can occur in response to flood events (see drawdown response at Ultoomurra in Figure 18 in response to the 2004 flood) and this may place considerable osmotic stress on the ability of the riparian Eucalypt species to extract soil water for transpiration. A general observation in the Diamantina, particularly in the Warburton reach, is that cohorts of dead trees typically occurred on the high floodplain areas away from the main channel. A possible mechanism for the tree death and stress observed in these locations is that groundwater recharge during large flood events is focused around the areas of channelization, particularly through lateral movement of water into the bank where the underlying sand sheet is exposed. This will result in freshening of the bank storage zone but will also lead to an increase in groundwater levels away from the channel due to the pressure loading of the near-channel recharge. The increase in the groundwater level in the floodplain will occur without any significant freshening (e.g. Goyder Lagoon borehole response). This rise in saline groundwater up into the active root zone of the floodplain trees can increase the osmotic stress (i.e. the trees need to extract fresh water against a higher salinity gradient) and could lead to poor tree health and even death. This process will be balanced by the amount of vertical recharge that may occur on the floodplain during larger flood events but this could be somewhat limited by the occurrence of a thick cracking clay upper soil profile overlying the Pleistocene sand sheet (see Wakelin-King, 2017). It is quite likely that mortality events of mature trees could be driven by the occurrence of flood events as well as extended dry periods.

Research in the Currareva – Nappa Merrie reach of Cooper Creek (Cendon et al., 2010; Larsen, 2012) showed that fresher lenses of unconfined groundwater are largely confined to around the major channels and to a lesser extent around secondary, floodplain channels. Beneath the floodplain was largely saline water and this has important implications for the distribution of floodplain vegetation with deep-rooted Eucalypts mostly confined to around the deeper channels with fresher groundwater. The groundwater in the Cooper Channel Country reach was found to occur below the level of the channels and so losing conditions between the river and groundwater consistently prevailed. The Diamantina channel reach may be similar to the Cooper but we don't have any information on the depth to groundwater in that reach. As described above, the fresh lenses in the Goyder Lagoon reach are concentrated around sand dunes with waterholes developed around their termination. In the Warburton reach the unconfined water table is intersected by the Warburton channel and so fresh lenses in this reach seem to be largely absent.

3.5 Coolibah distribution

Coolibahs were commonly found on a wide variety of riparian (i.e. bank-top) and floodplain locations throughout the reach. One major geomorphic zone within the reach almost completely lacked coolibahs and this was the Goyder Lagoon floodout area which was dominated by heavy cracking clay soils and the dominant vegetation type was lignum. The relationships between tree population and different landforms is further analysed in Section 3.6.

The May 2014 field trip measured 1057 individual trees, the May 2015 trip measured 785 trees and the May 2016 trip measured 606 trees, with individual stem circumferences ranging from 0.01-3.45 m, heights from 0.06-14.00 m and crown diameters from 0.01-24.30 m. Seedlings related to recent floods in the 2009-2012 period were not obvious to identify as the majority of individuals with short heights (e.g. <1.5 m) often showed evidence of resprouting from root stock, such as multiple stems with thicker woody bases (see examples in Figure 20b). Relatively few recruits were identified that could be assigned to the sequence of large flood years in 2009-2012 (see example in Figure 20a). For example, out of 807 individual trees that were visually categorized in May 2014, only 19 were consistent with relatively recent germination (e.g. stems <0.02 m diameter and no sign of woody root stock or resprouting). From the May 2015 dataset, only 19 were consistent with being recently germinated. In contrast, 122 out of 807 trees from 2014 showed evidence of resprouting with multiple stems from woody root stock.

K-means cluster analysis (Minitab 17) was applied to the tree data (Table 4) but could not differentiate between recent seedlings (generally having circumferences of <0.02 m) and resprouted seedlings.

Figure 20. Left photo shows an example of a young coolibah seedling likely to have been germinated in the 2009-2012 period. This seedling has a single stem with a non-woody base and a single tap root of similar thickness to the stem. The right photo shows examples of small coolibahs with multiple stems emerging from a woody base and thicker root system.

Table 4. K-means cluster analysis results showing five clusters and mean characteristics for live *E. coolabah* individuals within transects.

Cluster	A	B	C	D	E
2014					
Circum. (m)	0.08	0.23	0.52	1.02	1.38
Crown (m)	0.80	2.17	4.43	8.45	13.33
Height (m)	1.19	3.15	5.78	6.70	9.09
n	533	188	159	87	51

Cluster	A	B	C	D	E
2015					
Circum. (m)	0.13	0.38	0.81	1.26	1.65
Crown (m)	1.22	3.18	6.04	9.47	13.94
Height (m)	1.57	4.32	6.23	7.75	8.92
n	256	207	147	119	56

At only one location were coolibah seedlings identified that germinated during the study period (2014-16). This was at Wadlarkaninna Waterhole in the Warburton reach (Kalamurina Wildlife Sanctuary) in May 2016. Dr Jake Gillen identified very new seedlings (Figure 21a) on the banks of this ephemeral waterhole that must have germinated in response to the January 2016 local flood event. Wadlarkaninna Waterhole is located on a floodplain flow path and did not likely connect to the Warburton during the local flood event (no fish were caught here in 2016). This demonstrates that flow events resulting from relatively local runoff, in contrast to regional floods, can generate coolibah germination and that the seed must have been of relatively local derivation. The complete lack of recent recruits from 2014-2015 suggests that small annual floods are not capable of generating any significant recruitment. This is despite fruiting observed in a significant number of mature trees in these years. The mechanisms required for germination that are lacking in these small flood years are not clear. Smaller floods will obviously have less or no opportunity to inundate floodplain in the Diamantina channel reach that is characterised by a single large meandering channel, and these floods will typically not arrive into the Warburton reach. Within Goyder Lagoon, there are large areas that completely lack any coolibahs and so are not suitable habitat for a large range of flood sizes but there are also plenty of areas of distributary channels where recruitment could occur but was not observed in 2014-2015.

The Wadlarkaninna location was characterised by considerable recruitment of young seedlings with single stems and non-woody root stock. Previous research had established three fenced exclosures in this area (see example in Figure 21b) with tagged seedlings/saplings both inside and outside of the exclosures but monitoring had ceased prior to 2014. The characteristics of tagged saplings in and outside of exclosures A and B were measured during the three field trips of 2014-16 and provide a unique dataset on field growth rates for coolibah seedlings and saplings. Note that Gillen (2017) describes extensive controlled experiments on coolibah growth rates from seed germination.

The 20 saplings measured inside Exclosures A and B (note that Exclosure C saplings were only measured in 2016) showed highly variable growth rates and conditions between 2014 to 2016. Three of the plants died between 2015 and 2016, despite the heavy rainfall in January 2016. Of the living saplings within the exclosures, 16 out of 17 showed an increase in stem circumference of 38.5% between 2014 and 2016. Only nine showed an increase in height (mean increase of 24.9%) while eight showed a decrease in height by an average of -14.2%. The saplings showed a variation in crown width between 2014 and 2016, with 10 plants decreasing (mean -36.7%) and 7 plants increasing (32.7%). Twelve of the saplings in 2014 had a single stem with the others having 2-3. Three of the multi-stemmed plants lost a stem between 2014 and 2015 while one plant increased its stem count. Overall, most saplings had khaki or brown leaves in 2014 and 2015 consistent with water stress. In 2016, a number of plants showed new leaf growth and epicormic growth consistent with the wetter conditions but the condition of most saplings was still poor to moderate. These data suggest that seedlings and saplings put most effort into increasing stem circumference, and height to a lesser extent, at the general cost of crown width. The observations are consistent with the general decline in condition being driven by water stress as herbivore grazing was prevented by the exclosures, but signs of insect attack on the leaves were observed in 13 of the 17 living plants in 2016. The observations emphasise the importance of climatic conditions allowing continued growth of seedlings following germination on a large flood event.

Of 14 tagged trees measured outside of the exclosures, only one died between 2014 and 2016. The general pattern of size increases was similar to the exclosure plants. The circumferences increased in 10 of the plants by an average of 39.7% but decreased for three plants. Presumably the decreases were due to the death of thicker stems. The height increased for only eight of the plants (average increase of 21.3%) and decreased for six plants (-31.2%). Likewise for the crown width increased for only seven plants (average increase of 18.2%) and decreased for six plants (-27.6%). The general condition and changes in characteristics for the plants outside of the exclosures was similar to those in the exclosures, indicating that herbivore grazing was not an important factor in tree health. This is not unexpected given that cattle have been removed from Kalamurina Wildlife Sanctuary but does indicate that other large herbivore grazing (e.g. camels, rabbits, plague rats) was not significant. It would appear that water stress and insect attack are the most likely stressors inhibiting growth and condition at this site.

Figure 21. Top photo shows a very young coolibah seedling identified on a shallowly sloping sandy bank of Wadlarkaninna Waterhole (Warburton floodplain anabranch) that must have germinated in response to the January 2016 local runoff and streamflow. The bottom photo shows one of the Wadlarkaninna exclosures containing young coolibah saplings that presumably germinated during the 2009-2011 wet period. Note that the saplings extend beyond the exclosure.

3.6 Typical landforms controlling Coolibah distribution

In this section the main landforms controlling, or associated, with coolibah distribution are described, along with some discussion of the probable drivers of these associations.

Riparian Zone

The landform most commonly associated with coolibah distribution is the riparian zone, the vegetated narrow corridor from the bank edge and slope to the less vegetated floodplain. Often this zone comprises a levee bank and mature coolibahs commonly occur on these bank top positions but large coolibahs also occur in bank slope positions (Figure 22a). However, in some riparian locations, such as the Warburton River, the eroding edge of the channel has no levee bank (Figure 22b). Another type of riparian zone is along waterholes where the bank gently slopes upwards and these positions can host very mature coolibahs, as well as a range of recruits (e.g. Goyder Lagoon Waterhole).

The riparian zone is typically the most heavily vegetated landform as it has the advantages of being the most frequently inundated, providing germination opportunities, as well as the bank storage flushing providing lower salinity soil and groundwater to maintain growth. It is possible that stabilisation of bank-top positions by coolibahs along the larger flood runner channels could lead to positive feedback processes where these channels then become more established and may provide preferred sites for channel avulsion.

Figure 22. Top photo shows large mature coolibah occurring below the bank-top (levee bank) position on the Diamantina channel near DSPLIT location, Note the range of other coolibahs forming the riparian zone. The bottom photo shows a mature coolibah on a bank edge position at Ultoomurra. Notice the eroding bank position and the lack of any levee bank at the bank top position. The current banktop edge is dominated by mature coolibahs and younger trees and seedlings occur towards the floodplain.

Inner Meander Bends

Inner meander bends were a consistent habitat with a high density of coolibahs in both the Diamantina Channel and Warburton reaches. These sites typically have a sand bar with a well-developed riparian fringe and then are characterised by having high-flow floodplain channels 'short-cutting' across the meander bend that are favoured locations for coolibahs on their banks and may also be associated with paleo scroll-bars (Figure 23b). These inner bends also can contain high densities of other riparian trees, particularly acacias, and also commonly contain some coolibah recruits. These locations contained the densest riparian forest observed in the field area and also some of the highest organic contents in the soil (see Figure 23a).

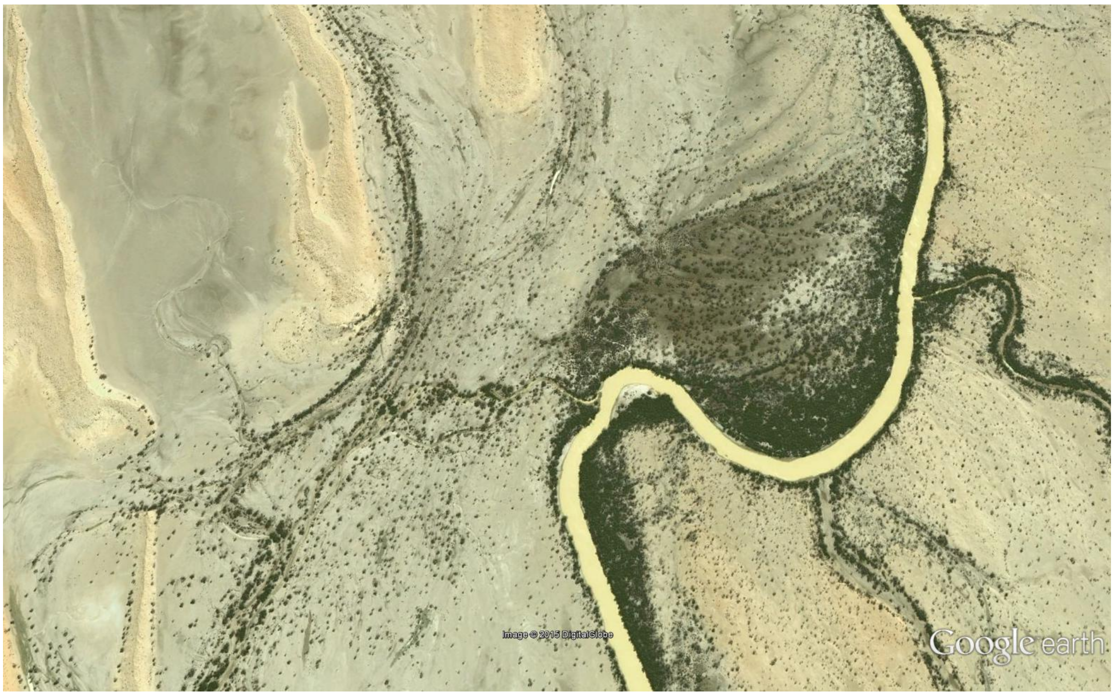


Figure 23. Top photo shows dense and diverse riparian forest in the inner meander bend position at the DSPLIT location. The site included a range of coolibah sizes, from recent seedlings to mature trees, humic soils and a dense understorey of acacias and other plants. Bottom image is a Google Earth image of the DSPLIT site showing quite dense vegetation (including coolibahs) occurring along the inner meander bends in this reach. These positions contain 'high flow' floodplain channels that 'short-cut' across the floodplain and may also be associated with paleo scroll-bars.

Flood Runner Channels

The floodplain of the Diamantina River is characterised by having gullies and channels that connect with the main channel and can direct floodwaters onto the floodplain during rising stages and also allow water to drain back into the channel during falling stages of floods. These flood runners range in scale from small gullies in the order of a few 10s m in length, to major floodplain channels of 10s km length that act as anabranches. Examples of flood runners can be seen in the Google Earth image of Figure 23b. These flood runners are commonly the focus of coolibah recruitment on the floodplain, with the majority of floodplain coolibahs occurring on the edges of flood runners (Figure 24). This location is also characterised by containing a range of tree sizes/ages and can often contain relatively young coolibah seedlings, and so are a focus of coolibah recruitment.

The flood runners provide important micro-topography and associated hydraulic gradients on an otherwise flat floodplain and this is considered to be central to their importance in facilitating coolibah recruitment. As floods recede, they leave behind an organic debris layer (presumably including coolibah seeds) in areas where the recession is relatively rapid. As the coolibah seeds are thought to float, this stranding mechanism during relatively rapid recession is probably critical for seeds to be in contact with the soil. This debris line includes edges of sand dunes and the edges of flood runner channels. The latter location have the advantage of water being able to penetrate laterally into the soil profile from the channel/gully, which would increase soil moisture availability for any germinated seedlings. Other advantages of this location is that the flood runners will direct both floodwaters and rainfall runoff into the vicinity of the seedlings in subsequent events/seasons and again optimise soil water availability and minimise solute build-up in the soil from capillary rise of saline groundwater.

Figure 24. Top photo shows a coolibah recruit, possibly from the 2009-2011 period, on the bank-top position of a flood runner at Mona Downs Waterhole. Note that mature coolibahs also occupy this position. Bottom photo shows coolibah seedlings developed on the edges of small gullies running into a larger flood runner gully at Ultoomurra. Note the occurrence of more mature coolibahs in the larger flood runner gully.

Dune Edges

Dune edges are a common location for coolibah colonisation and these positions most likely represent strand lines related to maximum flood extents for individual floods (Figure 25). As such, these positions form important flood extent markers that can be potentially related to particular flood events if the tree cohort can be aged (see Gillen, 2017 for discussion of tree ageing using ^{14}C dating). The density and age structure of dune edges can vary considerably and it is not clear what drives these differences. At some locations, the trees belong to a single apparent cohort (e.g. Figure 25a), while at others there can be a mix of ages (Figure 25b). However, in many cases, mature trees dominate these bank edge positions and recruits are less common and often show regrowth characteristics. Some dune edges do not show any coolibah colonisation, such as the southern edge of the Koonchera dune, although sparse mature coolibahs and rarer woody regrowth recruits are observed on the northern edge (Figure 25b). In contrast, Pandiburra dune (approximately 12 km west) contains more regular mature bank edge coolibahs in addition to more recruits. These variations in density may relate to the flow patterns around the dunes, particularly if coolibah seeds require some current velocity to remain afloat and so form strand lines.

Figure 25. Top photo shows a similar aged cohort of coolibah saplings occupying a dune edge position between the Andrewilla outflow distributary and Burt Waterhole (May 2015). The bottom photo shows the northern edge of Koonchera Dune in May 2016 showing a strand line associated with that flood and also the sparse mature coolibahs occurring on this flank of the dune.

Dunes

Coolibahs are also observed to occur relatively high on sand dunes and above what would be expected from maximum flood levels (Figure 26a). It is postulated that these trees have been partly buried by mobile sand dune movement and their branches have grown through the sand, and so appear to be growing high on the dune. Therefore, it is likely that the tree originally germinated in a dune edge position. Australian sand dunes in the arid zone are considered relatively immobile (Hesse, 2011) but the movement implied by this coolibah position would only require a few metres of sand dune movement along it most poorly vegetated crests. A rare occurrence at the Cowarie Crossing riparian zone shows a coolibah where root growth has occurred above the base of the tree trunk and this may be due to coverage by dune sand and subsequent erosion re-exposing the base of the tree (Figure 26b).

Figure 26. Top photo shows riparian or dune edge coolibahs being partly covered by mobile sand from a sand dune at Pelican Waterhole. Only the upper branches (>20 stems) are emerging above the sand. Bottom photo is from Cowarie Crossing riparian zone. This coolibah is growing on a low relief sand dune and the growth of roots above the main stem may be due to the tree being covered by sand and then subsequently exposed again by erosion.

High Floodplain

Higher and distal parts of the floodplain also contain scattered coolibahs, typically consisting of mature (but somewhat stunted) trees and patches of small woody regrowth (Figure 27). These areas also commonly contain more dead mature trees than other landforms. At even more distal locations, the coolibahs are replaced by bluebush communities.

Figure 27. Top photo shows a high floodplain position near Mia Mia channel. The tree in the foreground was heavily fruiting in May 2015 but beyond most of the coolibahs were dead or in very poor health with scarce leaves and a number of dead branches. Bottom photo shows similar high floodplain position near Cliff Camp channel with most mature trees either dead or in poor health (May 2015). Some small woody regrowth coolibahs also occur in these locations.

3.7 Coolibah soil associations and conditions

Coolibahs were observed growing in a wide variety of soil types, ranging from sandy (e.g. sand dune margins and back edges of point bars) to clay-silts (e.g. floodplain positions). The main soil type that appears to largely preclude coolibah establishment is thick cracking clay soils that dominate Goyder Lagoon. In this reach, coolibahs are very rare, except at some floodplain and sand dune margin sites or where there is some channelization (e.g. into and out of Goyder Lagoon Waterhole). In areas where the cracking clays are relatively thin (<0.5 m thick) coolibahs were observed growing through the cracking clays and into the underlying coarser soils. There may be several factors that result in the cracking clays being unsuitable for coolibah establishment.

- Cracking clays develop in areas of very low gradient floodplain, such as Goyder Lagoon. This landform generally has very little channelization and so the lack of channel micro-topography may limit the sites where seeds can be stranded during flow recession. As a result, it is possible that seeds become waterlogged and sink to the soil surface during the slow transmission of flow through Goyder Lagoon and become sterilised. It is noteworthy that genetic work on coolibahs described in Gillen (2017) found that Goyder Lagoon separates genetically different populations between the Diamantina channel reach and the Warburton reach.
- The cracking of the clay soils as they dry would likely place great stress on the root system of coolibah seedlings and could result in a high mortality rate of seedlings in subsequent seasons following germination. The occurrence of coolibahs where the clay soil profile is thin and overlies sandier soils (e.g. around outflow channels from Yammakira) could be explained by trees germinating in this environment having the opportunity to put down more extensive root systems before being subjected to the stresses of the upper clay layer drying out.

The conditions recorded by the soil profile data from the May 2014 field trip provide insights into the soil moisture status of the upper 0.5 m of the soil profile under the driest conditions encountered over the 2014-2016 period (Figure 28). There were no significant differences in soil moisture conditions between soil profiles collected in the vicinity of coolibahs and those collected in areas without coolibahs. The 2013 year was very dry (see Figure 2) and so the 2009-2012 wet period was immediately followed by very dry and hot conditions. The mean gravimetric soil moisture in the upper 0.5 m of the soil profile were very low (approximately <0.04 g/g) and may have placed recently germinated seedlings under stress. These dry conditions also emphasise why the tap root system of dug up seedlings (see Figure 31a) and from laboratory germinated seedlings (Gillen 2017) show such rapid root growth compared to the above ground size of the plant. Seedlings dug up in the field had tap roots greater than the above ground height of the plant (root to stem ratios >1) while the laboratory seedlings showed even more extensive root to stem ratios.

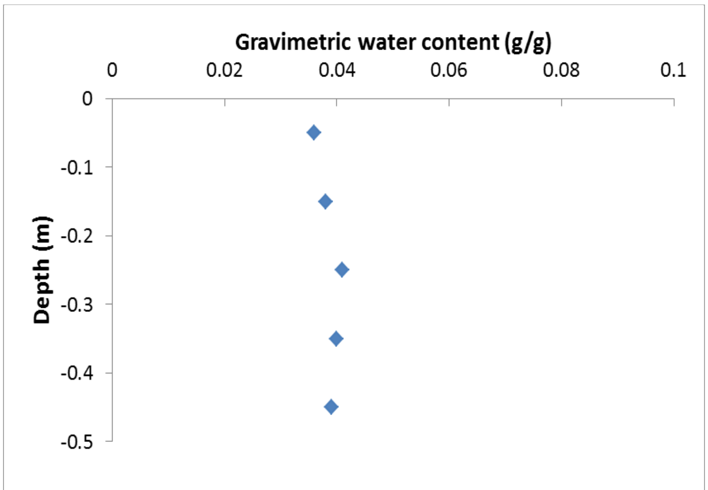


Figure 28. Mean gravimetric soil water conditions from 51 soil profiles collected in May 2014.

The soil water salinity of the soil profiles ranges from fresh to saline in the 2014 (177-16,250 mg/L, mean 1720 mg/L) and 2015 (18-17,720 mg/L, mean 1484 mg/L) samples. There was no strong spatial pattern in the salinity of soil samples, although the

Warburton reach contained more of the saline samples than the other reaches. In most profiles, the salinity was highest in the upper layer and decreased moving down profile, and this corresponds to the drying evaporative trend observed in the soil profiles. In some profiles from the Warburton reach the salinity increased moving down the profile and this suggests that presence of a higher salinity 'bulge' in the soil water driven by capillary rise from shallow saline groundwater and some fresh recharge into the upper layers of the soil.

In general, the observed salinities are not likely to affect plant growth, particularly at the very low observed soil water contents, as the coolibah seedlings and saplings are not likely to be accessing any soil water in the very dry upper 0.5 m of the soil profile observed in 2014-2015. The gravimetric soil water and soil water salinity populations for soil samples collected around coolibahs and those collected away from coolibahs (i.e. no trees group) were compared using the Kolmogorov-Smirnov test for the 2014 and 2015 datasets. There were no significant differences in soil salinity between the 'trees' and 'no trees' groups in either year, however, the 'trees' group had a significantly drier overall profile ($p=0.036$) in 2015 but not in 2014. The latter 2015 result may reflect the 'no trees' population containing more clays in the profile and hence having the capacity to maintain higher soil water contents over the period. The data indicates that capillary rise of solutes from a shallow saline groundwater table into the upper soil profile does not appear to be an inhibiting process for coolibah recruitment. It is likely that the flushing effects of floodwaters counteracts any build-up of solutes from capillary rise and evaporative processes.

3.8 Coolibah reproductive status

Field observations were made on all surveyed trees in 2015 and 2016 on whether the trees were fruiting or flowering. Little is known about the flowering and fruiting habits of *E. coolabah* but they are considered to flower in November to February and fruit in January to April (Gunn, 2001). The field data showed that fruiting was relatively common in May in 2015 and 2016, with 24% of surveyed trees containing fruit in May 2015 and 23% containing fruit in May 2016. Trees in flower were quite rare with only ten observed in 2016 and five observed in 2016. These observations confirm that the timing of coolibah reproduction is quite flexible and can occur over the summer to autumn months, thus maximising the possibility of fruiting and setting seed coinciding with the highly variable timing of flooding in the lower reaches of the Diamantina. Interestingly, trees of similar age at a given location did not display similar reproductive behaviour, with neighbouring trees at completely different reproductive stages. This lack of similar timing of reproduction is also likely to maximise the probability of some trees setting seed close to a flood event. For example, if the January 2016 rains and local flood event had triggered widespread flowering and fruiting, then trees may have missed the opportunity to set seed when the regional 2016 flood came through the Warburton reach in May 2016.

The age when coolibahs can reproduce is also not known. Fruiting and flowering was mostly observed in mature trees but apparent juvenile trees with circumferences of 0.13 m and heights of 2 m were observed with fruit (e.g. at Wadlarkaninna). However, it is possible that these apparent juveniles are resprouted and they could be relatively old.

3.9 Coolibah water use

Coolibahs instrumented with sapflow flux loggers provided information on baseline transpiration requirements and also responses to streamflow and rainfall events. These data provide insights into the flexible strategies adopted by coolibahs to cope with harsh and highly variable conditions of the arid core of Australia.

During the period of sap flow metering in 2014-15, the Diamantina sites experienced a sub-bankfull flow event that commenced on 29-Dec-2014 followed by significant rainfall (>10 mm d^{-1}) on the 03-Jan-2015 and 08-Jan-2015. The local rainfall resulted in a streamflow peak on 12-Jan-2015 followed by a smaller peak related to upper reach flow on 19-Feb-2015 (Figure 29). The riparian Andrewilla mature tree showed an initial response that coincided with the first rainfall event and the onset of the flow event but the less mature floodplain tree at Pandie Pandie only responded to the second rainfall event and associated flow peak (Figure 29). At both sites the trees showed peak increases in sap flow rates in late January and gradually receded to pre-flow levels by April 2015, but with the mature Andrewilla tree, occurring closer to the channel and at a lower relative elevation than the Pandie Pandie floodplain tree, showing the more sustained sap flow response to the increased moisture availability generated by the rainfall and flow event.

The coolibah trees measured for sap flow responses in 2015-16 (Double Bluff and Andrewilla) did not show as significant responses to streamflow (Figure 30). The Double Bluff multi-stemmed coolibah showed a seasonal signal in sap flow with low rates during winter and rising during spring and early summer prior to the arrival of the 2016 flood events. This tree showed lower sap flow flux rates than observed in the Pandie and Andrewilla trees in 2014-15. The Double Bluff tree did show apparent responses to rainfall events, with sharp, short-term reductions in sap flow flux coinciding with rainfall events. These reduction troughs are suggestive of the tree experiencing hydraulic redistribution or utilising its shallow root system in response to the rainfall. The arrival of the first Diamantina flow event in January 2016 did not result in any significant rise in sap flow flux rates compared to the pre-flood period. The sapling located next to a flood runner at Andrewilla showed much lower sap flow flux rates compared to the other trees measured during this project (much lower than the nearby mature riparian coolibah instrumented during 2014-15). This young tree responded to a rainfall event in early January 2016 but not to the arrival of the flood pulse two weeks later. This tree was found to be in quite poor health in May 2016, with fewer leaves compared to May 2015.

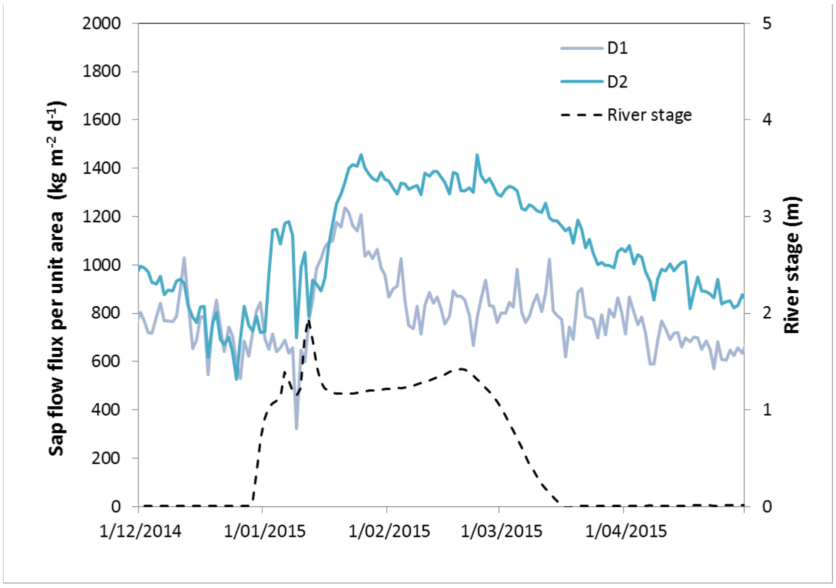


Figure 29. Sap flow responses to streamflow events in Diamantina catchment, 2014-2015. D1 refers to the Pandie Pandie floodplain tree and D2 refers to the Andrewilla riparian tree.

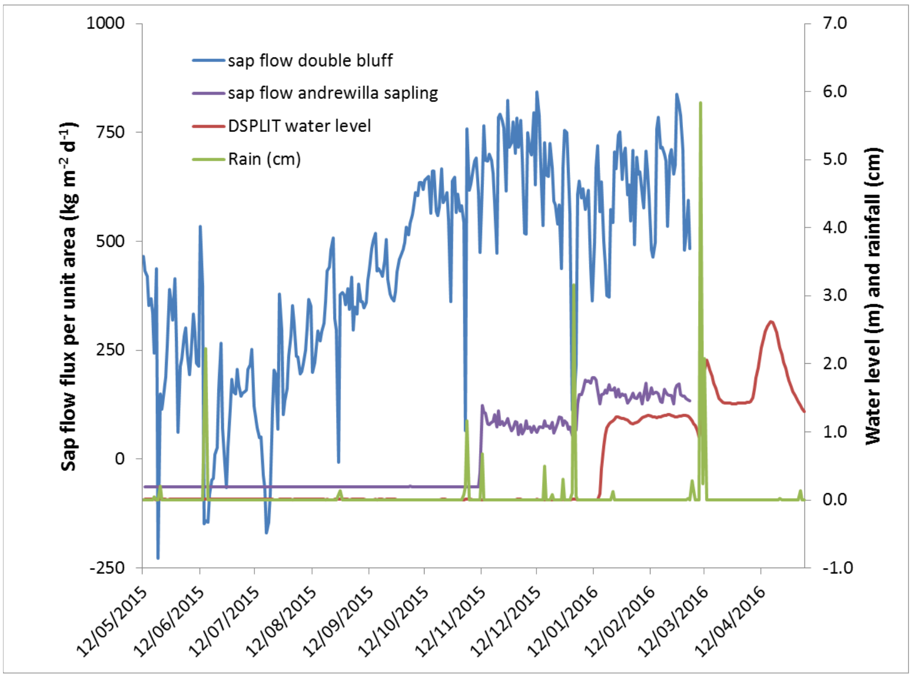


Figure 30. Sap flow responses to streamflow events in Diamantina catchment, 2015-2016.

These sapflow results, although not extensive, provide insights into the characteristics of coolibahs that allow them to dominate the riparian and floodplain tree assemblage in the Diamantina River (and elsewhere in the Lake Eyre Basin).

Firstly, the results point to a key strategy for the success of *E. coolabah* in that they show very low and consistent transpiration rates compared to other arid zone riparian trees. For example, individual tree water use of *E. victrix*, a closely related species to *E. coolabah*, on an arid zone floodplain in central Australia approximately 500 km north of the study area (O'Grady et al. 2009), was significantly higher than the transpiration rates found in this study (e.g. per unit area rates of 2363±537 to 2026±378 kg m^{-2} d^{-1} compared to results shown in Figures 29 and 30). The O'Grady et al. (2009) study measured four species (*E. victrix*, *E. camaldulensis*, *Acacia aneura*, *Corymbia opaca*) in April after a wet season and seven months later in November after a period of little rainfall. In the Diamantina, the monitored trees occurred in the Diamantina channel reach which experiences annual flows and consistently low salinity surface water conditions that suggest the presence of a freshwater lens in the bank storage zone around the channels. These conditions represent the probable best access to water in the South Australian reaches of the Diamantina and in the other reaches the trees need to deal with high soil water and groundwater salinities (e.g. Costelloe et al., 2008) and less frequent flushing by streamflow events. In these reaches, the transpiration rates of the coolibahs are likely to be lower, as has been observed in saline reaches of the Neales River (Costelloe, 2016).

The subdued, short-term response of *E. coolabah* to both streamflow and rainfall indicates that the low transpiration rate strategy is maintained even during periods of increased water availability. In conjunction with a very high salinity tolerance (Costelloe et al. 2008), this conservative approach to the erratic supply of water allows the maintenance of a perennial riparian woodland in the ephemeral rivers of the study area, even where groundwater is too deep, or too saline, to access. Arid zone ecology is known for its boom-bust responses to wet periods (Holmgren et al. 2006; Morton et al. 2011) but the 'slow and steady' transpiration approach shown by *E. coolabah* has advantages in dealing with the 'bust' cycles. For example, viable communities in the Neales River survived two years without streamflow input in a reach where groundwater availability was unlikely due to depth and salinity constraints (Costelloe, 2016). In the lower reaches of the Finke River, where groundwater was likely available, the community remained viable after three years without streamflow.

The quick responses of *E. coolabah* to both small rainfall events and more significant flow events indicates the species has root systems with the capacity to rapidly switch between shallow soil moisture stores (e.g. rainfall and streamflow infiltration) and deeper groundwater stores. The response to streamflow at the Diamantina sites were slower, ranging from 4-5 days at Andrewilla and 16-17 days at Pandie Pandie, consistent with increasing distance from the channel at the three sites (20 and 200 m respectively) and likely controlled by streamflow infiltration into the bank storage zone. The higher transpiration rates in response to the likely switching in water sources following rainfall/streamflow were sustained for periods of weeks to months. There is some evidence that the trees are capable of hydraulic redistribution with sharp decreases and negative sap flow fluxes immediately following heavy rainfall indicating movement of water from shallow soil layers to deeper soil layers. Most cases of hydraulic redistribution describe hydraulic lift, the movement of deeper soil water to shallow soil layers during dry periods (Burgess et al. 1998; Ludwig et al. 2003; Hultine et al. 2004) but the opposite direction of transport has also been observed in semi-arid riparian trees (Burgess et al. 1998; Hultine et al. 2004). The advantage of hydraulic redistribution of shallow soil moisture to deeper soil layers would be to optimise the availability of the water resource supplied by infrequent rainfall and streamflow events by reducing losses from soil evaporation and competition with shallow rooted plants.

3.10 Coolibah root distribution

Field observations provide insights into the root distribution variations of coolibahs in a range of landforms and age groups. These observations complement controlled growth experiments observations reported in Gillen (2017).

Young coolibah seedlings were found to consistently put down long tap roots with little lateral root development (Figure 31a). The tap roots were at least as long as the length of the seedlings above ground. This behaviour is consistent with the need for seedlings to access more reliable, deeper soil moisture to survive drier seasons following germination. A large tap root is also prominent in all mature coolibahs with exposed root structures (e.g. Figure 31b). It is not known how deep the tap root may extend but the groundwater observations indicate that the water table is typically within 5-8 m of the floodplain surface. Given the high salinity of the groundwater in the middle and lower reaches, it is unlikely that the tap root would extend below the water table in those reaches.

Riparian coolibahs show lateral root development that is slightly larger, but of a similar magnitude, to the crown width (Figure 32a). The root distribution, where exposed by bank retreat, is generally quite symmetrical and with some overlap in neighbouring root systems. At some riparian locations, the root distribution was more extensive along the channel direction and roots growing towards the channel show characteristic right angle bends where they became sub-aerially exposed and grew downwards in response. Floodplain coolibahs could develop very extensive shallow lateral roots (Figure 32b) to maximise their access to shallow soil water resources. At some locations, the lateral root were several times the crown width. This behaviour is likely driven by these trees dealing with relatively shallow, highly saline unconfined groundwater levels and being located at a sufficient distance from the channel so that they don't receive the bank storage freshening effect. The sap flow data indicate that the trees are able to use these shallow lateral roots to 'harvest' soil water in the upper layers replenished by rainfall and transfer this to deeper roots for future use during drier times.

Figure 31. Top photo shows single tap root forming below a seedling at DSPLIT that is longer than the height of the seedling above ground and shows little lateral root development. The seedling probably germinated in the 2009-2011 period. Bottom photo shows a massive tap root formed below a very mature riparian coolibah situated in the Yammakira outflow channel. Note the very thick lateral roots also developed around the tap root.

Figure 32. Top photo the spread of the root zone of a young coolibah exposed by bank retreat at Cowarie Crossing. The root distribution is larger than the crown width but of similar magnitude and evenly distributed. The bottom photo shows a floodplain coolibah at Yellow Waterhole (Kalamurina) with very extensive exposed lateral roots extending several times the width of the crown. At this location, the water table is relatively shallow and highly saline and the floodplain coolibahs are unlikely to receive the benefits of bank storage flushing from channel flow. As a result, they have developed extensive lateral roots to maximise access to shallow soil moisture.

3.11 Algal observations

Samples of algae were collected by a plankton net from most of the sampled waterbodies and identified by Joan Powling, a retired algal expert, who had previously analysed algae samples from the Aridflo project and other University of Melbourne hydrological trips to the Diamantina River. Special thanks go to Joan who undertakes this work on a voluntary basis and who has an extensive knowledge, and great passion, for the algae of the arid zone rivers of the LEB.

The identification of the algae in the samples has been provided as an electronic appendix (spreadsheet). The following points provide a brief overview of the results to date.

- Overall, the algal assemblage was diverse and healthy and consistent with past results from the ARIDFLO sampling program. The overall algal assemblage varied considerably between samples and this was driven by abiotic factors, including flow conditions, time since disconnection and waterhole salinity, and probable biotic factors, including grazing by fish and micro-invertebrates.
- Waterholes sampled during flowing conditions in May 2016 were characterised by containing a diverse range of desmids, a group of green algae that occur in clean, flowing water conditions in eastern Australia. Desmids were identified from the Diamantina channel reach through to the upper Warburton (Ultoomurra) in 2016. Some desmid species were also identified in the Goyder Lagoon waterholes and upper Warburton in 2015.
- Blue-green algae were a relatively minor component of the algal assemblage. Although potentially toxic species are present, such as *Anabaena circinalis*, they only occur in small amounts. No blooms of blue-green algae have been observed in the Diamantina River over the period of 2000-2016, although blooms have been observed in the Coongie Lakes of Cooper Creek (Costelloe 2013) and green algal blooms were observed in the Diamantina Channel reach (e.g. Figure 33). Blue-green species were observed in all reaches and in all three years of this project. They were most diverse and abundant in the Warburton recession flow to the January 2016 local flood event (i.e. Yellow Waterhole to Tinnie Landing).
- A diverse and generally abundant range of zooplankton (i.e. rotifers and micro-crustaceans) were observed in many samples across all reaches and trips. Zooplankton are major grazers of algae and form an important component of the diet of a number of fish species. Therefore, observing a diverse range of algae and zooplankton in the samples provides evidence of healthy ecosystems with functioning food chains.
- Tepamimi Waterhole on Eyre Creek is continuously fed by an artesian bore drain. It contained an algal assemblage dominated by diatoms but also containing some green (including desmids), blue-green and flagellate species, in addition to some zooplankton. No analysis has been done on how this assemblage differs from the other naturally fed waterholes but it would be an interesting comparison.
- The salinity of the Warburton samples is a major determinant on their algal and zooplankton communities. At moderate salinities (i.e. <30 mS/cm) the waterholes still contain some green and flagellate species but as the salinity increases, the assemblage becomes dominated by diatoms. At hypersaline levels (i.e. >100 mS/cm) only a few diatom species are present and the halophyte green flagellate species, *Dunaliella salina*. At even higher salinities (i.e. >200 mS/cm) *D. salina* is the only algae present and is probably the only living species in the extreme hypersaline conditions.

Figure 33. Green algal bloom observed at DSPLIT site in May 2014 during low flow conditions in the recession of the 2014 flood.

4 Recommendations

4.1 Hydrological monitoring and modelling

The current level of hydrological monitoring in the SA reaches of Diamantina River is adequate for a remote, arid region catchment. At present, the monitoring has the capacity for the volumetric assessment of Diamantina flow coming into the State and of monitoring flows reaching the Warburton but there is no monitoring on flows entering via Eyre Creek.

- The Birdsville gauging station is well-rated and provides an excellent record of flow coming into South Australia from the Diamantina River catchment. This is a high value gauging station and has the commitment for ongoing operation. With its relatively long length of record (1967 to present and a period of 1950-1965 by the Queensland Government at a slightly different location) it has the capacity for contributing to analysis of flow regime changes (i.e. by climate change, catchment changes or water extraction) in the Diamantina River.
- The recently installed telemetered water level monitoring station at Poothapoota Waterhole on the Warburton River provides excellent monitoring of flows entering the Warburton since 2011. Flows into the Warburton are an important indicator of any flow regime changes because Goyder Lagoon forms the terminus of the smaller annual flows. In conjunction with downstream monitoring, this station also allows the estimate of flow thresholds into Kallakoopah Creek and the lower Warburton reaches (including Lake Eyre). It is highly recommended that flow gaugings are conducted whenever possible to build-up a ratings curve for this site.
- There are currently water level loggers installed at five locations in the Diamantina as part of this project and the Lake Eyre Basin Rivers Assessment (LEBRA) project. These locations are Andrewilla channel (Diamantina Split), Yammakira Waterhole (Diamantina main channel), Warburton channel (Warburton junction), Kallakoopah Creek and Stony Crossing (Warburton). These loggers are providing important short-term information on flow distribution, timing and extents in the system and these data are useful for evaluating the Source hydrological model for the catchment. It is unlikely that these loggers will be maintained over the medium to long term but they will be collecting data until May 2017 at least.
- Flows from Eyre Creek into the Diamantina are not monitored but only occur approximately every five years during large floods in the Georgina River. Monitoring of Eyre Creek, therefore, has a low priority but reinstatement of the Glengyle gauging station in Queensland would assist in calibrating a hydrological model for Eyre Creek flow into the Diamantina.
- It is recommended that the flow data collected during this project be used to evaluate the accuracy of the Source model for the Diamantina River developed in 2014. The data could be used to further calibrate the model.
- The spatial patterns of flow in the Diamantina should be periodically assessed using the WOfS dataset, in conjunction with analysis of Birdsville and Poothapoota flow data, to determine if flow patterns are within expected bounds. This monitoring has the potential to form a hydrological 'Threshold of Potential Concern' (TPC) for the Diamantina River. This requires the mapping of flood patterns across a range of flood sizes to show the pattern of inundation for a range of recurrence intervals (e.g. 0.5, 1, 2, 3, 5, 10, 20 years). These datasets would be extremely useful for identifying and managing the link between flooding and weed and exotic animal invasion.

4.2 Refugia

The most important refugia in the SA reaches of the Diamantina are Yammakira and Andrewilla Waterholes. Neither have any significant numbers of tourists and development pressures are quite low compared to the major refuges on Cooper Creek. Yammakira Waterhole has been subject to water extraction for stock use but that has had no apparent detrimental effects. The refugial values of Yammakira and Andrewilla Waterholes are emphasised by the collection of turtles in both waterholes (Schmarr et al., 2017), the only known occurrence of turtles in the Diamantina catchment.

Tepamimi Waterhole on Eyre Creek is an interesting case as it is being maintained at cease-to-flow level by artesian bore outflow. This has significantly changed the frequency of inundation and drying for this waterhole and affected in-channel riparian vegetation. In addition, its constant water level provides a refuge for the introduced fish, gambusia, and riparian and floodplain regrowth here was particularly affected by camel grazing, presumably because of the constant water supply attracting large herbivores. It is recommended that outflow from the artesian bore be controlled and fed into troughs rather than the waterhole. The waterhole should be allowed to dry out and return to its natural water regime. At present, the waterhole presents an excellent case study in the risks of allowing discharge of groundwater into surface drainage systems. Notably, this is not permitted from mining or oil/gas activities but is allowed from pastoral bores and this is an anomaly.

4.3 Monitoring of riparian vegetation regeneration

The wet period of 2009-2011 represented a flood cluster that only occurs every 20-40 years and so this represented a once-in-a-generation regeneration event. The current project found that regeneration of the key riparian tree species, *E. coolabah*, was limited along most of the SA reaches of the Diamantina. Further monitoring of key locations showing some recruitment would assist in the sustainable management of the area (e.g. protecting key regeneration – recruitment locations from grazing).

5 References

Bunn, S.E., Davies, P.M., Winning, M. 2004. Sources of organic carbon supporting the food web of an arid zone floodplain river. *Freshwater Biology* **48**, 619-635. DOI:10.1046/j.1365-2427.2003.01031.x.

Bunn, S.E., Thoms, M.C. Hamilton, S.K., Capon, S.J. 2006. Flow variability in dryland rivers: boom, bust and the bits in between. *River Research and Applications* **22**, 179-186.

Burgess, S.S.O., Adams, M.A., Turner, N.C., Ong, C.K. 1998. The redistribution of soil water by tree root systems. *Oecologia*, **115**, 306-311

Cendón, D.L., Larsen, J.R., Jones, B.G., Nanson, G.C., Rickleman D., Hankin, S.I., Pueyo, J.J., Maroulis, J. 2010. Freshwater recharge into a shallow saline groundwater system, Cooper Creek floodplain, Queensland, Australia. *Journal of Hydrology* **392**, 150-163, doi: 10.1016/j.hydrol.2010.08.003

Costelloe, J.F., Grayson, R.B., Argent, R.M., McMahon, T.A. 2003. Modelling the flow regime of an arid zone, floodplain river, Diamantina River, Australia. *Environmental Modelling and Software* **18** (8), 693-703.

Costelloe, J.F., Hudson, P.J., Pritchard, J.C., Puckridge, J.T., Reid, J.R.W. 2004. ARIDFLO scientific report: environmental flow requirements of arid zone rivers with particular reference to the Lake Eyre Drainage Basin. Final Report to South Australian Department of Water, Land and Biodiversity Conservation and Commonwealth Department of Environment and Heritage.

Costelloe, J.F., Grayson, R.B., McMahon, T.A., Argent, R.M. 2005a. Spatial and temporal variability of water salinity in an ephemeral arid-zone river, central Australia. *Hydrological Processes* **19**, 3147-3166.

Costelloe, J.F., Powling, J., Reid, J.R.W., Shiel, R.J. and Hudson, P. 2005b. Algal diversity and assemblages in arid zone rivers of the Lake Eyre Basin, Australia. *River Research and Applications* **21**, 337-349.

Costelloe, J.F., Grayson, R.B., McMahon, T.A. 2006. Modelling streamflow in a large anastomosing river of the arid zone, Diamantina River, Australia. *Journal of Hydrology* **323**, 138-153.

Costelloe, J.F., Shields, A., Grayson, R.B., McMahon, T.A. 2007. Determining loss characteristics of arid zone river waterbodies. *River Research and Applications* **23**, 715-731.

Costelloe, J.F. 2008. Updating and analysis of the ARIDFLO water level data in the Lake Eyre Basin. Final Report to the South Australian Department of Water, Land and Biodiversity Conservation, Adelaide, July 2008.

Costelloe, J.F., Payne, E.G., Woodrow, I.E., Irvine, E.C., Western, A.W., Leaney, F. 2008. Water use by arid zone riparian trees in highly saline environments, Australia. *Oecologia* **156**, 43-52. doi 10.1007/s00442-008-0975-4.

Costelloe, J.F., Irvine, E.C., Western, A.W., Herczeg, A.L. 2009. Groundwater recharge and discharge dynamics in an arid zone, ephemeral lake system, Australia. *Limnology and Oceanography* **54**, 86-100.

Costelloe, J.F., 2013. Hydrological assessement and analysis of the Cooper Creek catchment, South Australia. Report by the University of Melbourne to the South Australian Arid Lands Natural Resources Management Board, Port Augusta.

Costelloe, J.F., 2016. Water use strategies of a dominant riparian tree species (*Eucalyptus coolabah*) in dryland rivers. Paper 26724 in, Webb, J.A., Costelloe, J.F., Casas-Mulet, R., Lyon, J.P., Stewardson, M.J. (eds.) *Proceedings of the 11th International Symposium on Ecohydraulics*. Melbourne, Australia, 7-12 February 2016. The University of Melbourne, ISBN: 9780734053398.

Gillen, J.S. 2010. An ecological study of the landscape, perennial plants and soils of the Cooper Creek floodplain, South Australia. PhD thesis, Australian National University.

Gillen, J.S. 2017. Vegetation and soil assessment of selected waterholes of the Diamantina and Warburton Rivers, South Australia, 2014-16. Report by Australian National University to the South Australian Arid Lands Natural Resources Management Board, Pt Augusta.

Good M., Price J., Clarke P., Reid N. 2012. Dense regeneration of floodplain *Eucalyptus coolabah*: invasive scrub or passive restoration of an endangered woodland community?, *Rangeland Journal*, **34**, 219-230.

Gunn, B. 2001. Australian Tree Seed Centre – Operations Manual. CSIRO Forestry and Forest Products, Canberra.

Hamilton, S.K., Bunn, S.E., Thoms, M.C., Marshall, J.C. 2005. Persistence of aquatic refugia between flow pulses in a dryland river system (Cooper Creek, Australia). *Limnology and Oceanography*, **50** (3), 743-754.

Hesse, P. 2011. Sticky dunes in a wet desert: Formation, stabilisation and modification of the Australian desert dunefields. *Geomorphology*, **134**,309-325.

Holmgren, M., Stapp, P., Dickman, C.R. et al. 2006. Extreme climatic events shape arid and semiarid ecosystems. *Frontiers of Ecology and Environment*, **4**, 87-95.

Hultine, K.R., Scott, R.L., Cable, W.L., Goodrich, D.C., Williams, D.G. 2004. Hydraulic redistribution by a dominant, warm-desert phreatophyte: seasonal patterns and response to precipitation pulses. *Functional Ecology*, **18**, 530-538.

Jarihani, A.A., Larsen, J.R., Callow, J.N., McVicar, T.R., Johansen, K., 2015. Where does all the water go? Partitioning water transmission losses in a data-sparse, multi-channel and low-gradient dryland river system using modelling and remote sensing. *Journal of Hydrology* **529**, 1511-1529.

Kingsford, R.T., Curtin, A.L., Porter, J.L. 1999. Water flows on Cooper Creek in arid Australia determine 'boom' and 'bust' periods for waterbirds. Biological Conservation **88**, 231-248.

Knighton, A.D., Nanson, G.C. 1994a. Waterholes and their significance in the anastomosing channel sequence of Cooper Creek, Australia. *Geomorphology*, **9**, 311-324.

Knighton, A.D., Nanson, G.C. 1994b. Flow transmission along an arid zone anastomosing river, Cooper Creek, Australia. *Hydrological Processes* **8**, 137-154.

Knighton, A.D., Nanson, G.C. 2000. Waterhole form and process in the anastomosing channel system of Cooper Creek, Australia. *Geomorphology*, **35**, 101-117.

Knighton, A.D., Nanson, G.C. 2001. An event-based approach to the hydrology of arid zone rivers in the Channel Country of Australia. Journal of Hydrology 254: 102-123.

Kotwicki, V., 1986. *Floods of Lake Eyre*. Engineering and Water Supply Department, Adelaide, 99 pp.

Leblanc, M.J., Tregoning, P., Ramillien, G., Tweed, S.O., Fakes, A., 2009. Basin-scale, integrated observations of the early 21st century multiyear drought in southeast Australia. *Water Resources Research* **45**, W04408, doi:10.1029/2008WR007333.

Ludwig, F., Dawson, T.E., Kroon, H., Berendse, F., Prins, H.H.T. 2003. Hydraulic lift in *Acacia tortilis* trees on an East African savanna. *Oecologia*, **134**, 293-300

McMahon, T.A., Murphy, R., Little, P., Costelloe, J.F., Peel, M.C., Chiew, F.H.S., Hayes, S., Nathan, R., Kandel, D.D. 2005. Hydrology of the Lake Eyre Basin. Final Report to Department of Environment and Heritage, Canberrra, September 2005.

McMahon, T.A., Murphy, R.E., Peel, M.C., Costelloe, J.F., Chiew, F.H.S., 2008. Understanding the surface hydrology of the Lake Eyre Basin: part 2 – streamflow. *Journal of Arid Environments* **72**, 1869-1886.

McNeil, D.G., Schmarr, D.W., Rosenberger, A.E., 2011. Climatic variability, fish and the role of refuge waterholes in the Neales River catchment: Lake Eyre Basin, South Australia. Report by South Australian Research and Development Institute (Aquatic Sciences) to the South Australian Arid Lands NRM Board, Port Augusta.

Morton, S.R., Stafford Smith, D.M., Dickman, C.R. et al. 2011. A fresh framework for the ecology of arid Australia. *Journal of Arid Environments*, **75**, 313-329.

Naiman R., Décamps H. and Pollock M., "The role of riparian corridors in maintaining regional biodiversity", *Ecological Applications*, Vol. 3, (1993), pp209-212.

O'Grady, A.P., Cook, P.G., Eamus, D., Duguid, A., Wischusen, J.D.H., Fass, T., Worldege, D. 2009. Convergence of tree water use within an arid-zone woodland. *Oecologia*, **160**, 643-655.

Puckridge, J.T., Sheldon, F., Walker, K.F., Boulton, A.J., 1998. Flow variability and the ecology of large rivers. *Marine and Freshwater Research* **49**, 55-72.

Puckridge, J.T., Walker, K.F., Costelloe, J.F. 2000. Hydrological persistence and the ecology of dryland rivers. *Regulated Rivers Research and Management* **16**, 385-402.

Reid, J. R. W. 2017. Birds of the Diamantina River and associated channel country wetlands of South Australia. Report by Australian National University to the South Australian Arid Lands Natural Resources Management Board, Pt Augusta.

Roberts J., "Regeneration and growth of coolibah, *Eucalyptus coolabah* subsp. *arida*, a riparian tree , in the Cooper Creek region of South Australia", *Australian Journal of Ecology*, Vol. 18, (1993), pp 345-350.

Schmarr, D.W., Mathwin, R. and Cheshire, D.L. 2017 Aquatic Ecology Assessment and Analysis of the Diamantina River Catchment: Lake Eyre Basin, South Australia. Report by South Australian Research and Development Institute to the South Australian Arid Lands Natural Resources Management Board, Pt Augusta.

Schmiechen, J. 2017. Human Footprint on the landscape - cultural landscape assessment and tourism management of the Diamantina River catchment, South Australia. Report to the South Australian Arid Lands NRM Board, Port Augusta.

Sheldon, F., Boulton, A.J., Puckridge, J.T. 2002. Conservation value of variable connectivity: aquatic invertebrate assemblages of channel and floodplain habitats of a central Australian arid-zone river, Cooper Creek. *Biological Conservation* **103**, 13-31.

Sheldon, F., Puckridge, J.T. 1998. Macroinvertebrate assemblages of Goyder Lagoon, Diamantina River, South Australia. *Transactions of the Royal Society of South Australia*. 122(1):17-31.

Shiel, R.J., Costelloe, J.F., Reid, J.R.W., Hudson, P. and Powling, J. 2006. Zooplankton diversity and assemblages in arid zone rivers of the Lake Eyre Basin. *Marine and Freshwater Research* **57**, 49-60.

Skinner, R., Sheldon, F., Walker. K.F. 2001. Propagules in dry wetland sediments as indicators of ecological health: effects of salinity. Regulated Rivers Research and Management **17**: 191-197.

Timms, B. V. 2001. Large freshwater lakes in arid Australia: A review of their limnology and threats in the future. *Lake Reservoir Management* **6**, 183-196.

Wakelin-King, G.A. 2017. Geomorphology of the Diamantina River Catchment (SA). Report by Wakelin Associates to the South Australian Arid Lands Natural Resources Management Board, Pt Augusta.

Appendix 1 – Flow gauging data

Location	Date	Time	Q1 (m^3/s)	Q2 (m^3/s)	Q3 (m^3/s)	Q4 (m^3/s)	Q5 (m^3/s)	Q mean (m^3/s)	Qmean (MLd^{-1})
Goyder Lagoon WH inflow channel	01/05/14	08:00						0.674	58.22
Goyder Lagoon channel, -26.7935, 139.0315	01/05/14	13:10						0.077	6.66
Goyder Lagoon channel, 305015, 7036400	01/05/14	13:30						0.029	2.50
DSPLIT main channel u/s	08/05/14	09:00	0.614	-0.575	-0.09	-0.61		0	0
Andrewilla flow path (kayak)	08/05/14	09:40	0.251	0.456	0.200	0.198	0.398	0.326	28.17
Andrewilla flow path (hand tow)	08/05/14	09:50	0.014	0.295	0.366	0.432		0.277	23.91
DSPLIT main channel d/s	08/05/14	10:20	-0.316	0.892	0.859	0.168		0.401	34.62
Andrewilla WH	07/05/14	11:45	1.291	0.207	1.823	0.592		0.978	84.52
Tepamimi bore drain outflow	05/05/14	17:00						0.039	3.35
DSPLIT main channel u/s	06/05/16	16:00	19.772	20.254	18.835	19.94		19.700	1702.1
Andrewilla flow path	06/05/16	15:00	9.049	9.324	9.595	9.383		9.338	806.8
DSPLIT main channel d/s	06/05/16	15:30	9.474	10.396	10.741	9.911		10.131	875.3
Yammakira WH	16/05/16	09:45	14.18	15.356	15.039	15.655		15.058	1301.0
Yammakira right distributary (d/s)	16/05/16	10:15	6.188	3.965	6.036	5.055		5.311	458.9
Yammakira left distributary (d/s)	16/05/16	10:30	9.868	10.445	10.369	9.806		10.122	874.5
Peraka channel	16/05/16	11:00	0.993	0.971				0.982	84.80
Andrewilla WH	09/05/16	11:00	18.204	15.786	18.590	15.127		16.927	1462.5
Andrewilla WH	10/05/16	08:15	16.232	15.754	16.783	14.815		15.896	1373.4
Andrewilla WH	11/05/16	08:20	17.373	16.200	18.157	16.993		17.272	1492.3
Andrewilla right distributary (d/s)	11/05/16	09:00	14.345	13.143	13.981	13.669		13.785	1191.0
Andrewilla left distributary (d/s)	11/05/16	09:30	2.182	2.084	2.451	2.200		2.229	192.6
Andrewilla WH	12/05/16	07:15	13.537	14.262	13.873	13.939		13.903	1201.2
Ultoomurra channel	17/05/16	11:00	42.371	41.303	40.283	40.296		41.063	3547.9
Warburton u/s of	17/05/16	16:30	41.361	41.103				41.232	3562.4

Location	Date	Time	Q1 (m^3/s)	Q2 (m^3/s)	Q3 (m^3/s)	Q4 (m^3/s)	Q5 (m^3/s)	Q mean (m^3/s)	Qmean (MLd^{-1})
Yelp channel									
Yelpawaralinna inflow channel	17/05/16	15:00	0.609	0.887	0.805	0.681	1.372	0.871	75.24
Ultoomurra channel	18/05/16	07:30	41.640	42.518	41.649	41.677		41.871	3617.7
Warburton @ Kalamunkinna crossing	04/05/16	11:00						0.585	50.55
Warburton @ Cowarie crossing	02/05/16	14:45						0.353	30.51
Warburton @ Yellow WH (outer)	01/05/16	14:30	0.349	0.466	0.263	0.277		0.339	29.27
Warburton@ Stony crossing	28/04/16	10:00	0.287	0.427	0.295	0.262		0.318	27.45
Warburton@ Mia Mia	29/04/16	14:45						0.438	37.84
Warburton@ Tinnie Landing	28/04/16	16:00						0.215	18.591