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

CARING FOR OUR COUNTRY


October 2013

South Australian Arid Lands Natural Resources Management Board

Hydrological assessment and analysis of the Cooper Creek Catchment, South Australia

Justin Costelloe

HYDROLOGICAL ASSESSMENT AND ANALYSIS OF THE COOPER CREEK CATCHMENT, SOUTH AUSTRALIA

Justin F. Costelloe[1]

October 2013

Report to the South Australian Arid Lands Natural Resources Management Board

[1]Department of Infrastructure Engineering, University of Melbourne

DISCLAIMER

This report may be cited as:

Costelloe, J.F., 2013, Hydrological assessment 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.

Cover images:

L) Outflow channel from Lake Appadare into the lower Cooper Creek during the rising phase of the 2011 flood (April 2011)

R) Minkie Waterhole, Cooper Creek, during the flood of 2011 (April 2011)

Table of Contents

Tables

Figures

Acknowledgements

This study was supported by Australian Commonwealth Government funding from the 'Caring for our Country' scheme and was part of a larger project managed by the South Australian Arid Lands Natural Resource Management Board. The project team of Henry Mancini, Dale McNeil, David Schmarr, Rupert Mathwin, Dave Cheshire, Gabe Shepherd, Jed Macdonald, Gini Lee, Brooke Madill and Gresley Wakelin-King 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 assistance of Graeme Tomlinson and Darren Ludeman. We thank the following landholders for allowing fieldwork on their properties; Graham and Maree Morton of Innamincka Station (S. Kidmans & Co.), Jason and Jayne-Marie Barnes of Gidgealpa Station, Whip Degamois of Nappa Merrie Station (S. Kidmans & Co.), Luke and Nina Betts of Mungerannie Station, Gary Overton of Mulka Station, Jason and Patsy Dunn of Etadunna Station. Gary Overton also kindly provided access to a boat while collecting data at Lake Hope. Water level data from Scrubby Camp and Embarka Waterhole loggers were kindly provided by SANTOS Limited, as was valuable information on conditions in the field by Andy Pietsch and David Olds of SANTOS. Access to the Kudnarri bridge area and assistance was provided by Doug Roberts and Rod Glover of Beach Energy. The Innamincka Reserve rangers, Darren Wilson and Trevor Whibley, provided excellent advice and assistance, particularly with access to their boat.

EXECUTIVE SUMMARY

Cooper Creek 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.

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

1**). Cooper main channel**: Nappa Merrie to Northwest Branch – Main Branch junction. This reach contains the most important fluvial refuge in the Lake Eyre Basin, Cullyamurra Waterhole. This waterhole was found to have a maximum depth exceeding 25 m and would retain water over several kilometres of river length under even severe drought conditions. The reach also contains the greatest concentration of ark refugia (waterholes >5 m depth) in the Channel Country. The constriction of flow through this reach means it has 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 also has the highest concentration of residents and tourists of the Cooper reaches.

2). Northwest Branch: Junction with Main Branch to the Coongie Lakes. This reach receives initial flows from the Cooper main channel and also contains the high environmental value Coongie Lakes wetlands at the effective terminus of flow along this distributary system. It is the occurrence of these relatively rare, open lake habitats rather than ark refugia which provide the greatest value hydro-ecological environments in the Northwest Branch. Coongie Lake is the terminus of the smallest annual flows along Cooper Creek and the Northwest Branch and so forms a valuable monitoring point for identifying possible flow regime change in Cooper Creek.

3). Main Branch: Junction with Northwest Branch to the junction with the Northern Overflow at Deparanie Waterhole. This reach requires a modest discharge threshold of approximately 1200 MLd^{-1} before flow occurs into the Main Branch. This flow path is not characterised by open lake environments or significant ark refugia and so has received less hydro-ecological attention previously. There are substantial amounts of oil-gas production infrastructure on the Main Branch and it is important that these do not alter the flow patterns or holding capacity of areas within the Main Branch, particularly the Embarka Swamp area. The areas downstream of Embarka Swamp do not receive flow annually and so any further decreases in their frequencies of inundation could have deleterious effects on these downstream ecosystems. The Embarka Swamp area is probably the most sensitive part of the South Australian reaches of Cooper Creek to changes in flow patterns from anthropogenic causes.

4). <u>Lower Cooper</u>: Main Branch – Northern Overflow junction to Lake Eyre North. This reach does not contain any significant ark refugia and receives flow approximately every 3-4 years. This reach does contain an opportunistic commercial fishery at Lake Hope that can operate following large flood (approximately 1:10 year) events.

The hydrology of the South Australian reaches remains unregulated and generally unimpeded. However, there are increasing amounts of infrastructure assets being built along the Main Branch and lower Cooper, including roads, culverts, bridges, drill pads and bund walls. Appropriate analysis and supervision is required to ensure that the infrastructure does not affect flood patterns, storage capacity or retention time of floodwaters, as these changes could adversely affect the ecosystems of Cooper Creek.

The monitoring capacity of Cooper Creek has greatly improved since 2009 with the installation of high quality monitoring sites by SANTS and LEBRA-DEWNR. The additional monitoring from the Cooper Creek project and the collection of discharge data at key distributary points along the Cooper has assisted in better understanding the flow patterns through the Cooper. The long term monitoring and management of Cooper Creek would be greatly enhanced with the construction of a new generation rainfall-runoff, hydrological model of Cooper Creek capable of simulating the complex flow patterns of this system.

1. INTRODUCTION

Cooper Creek is the largest catchment of the Lake Eyre Basin and the South Australian (SA) reaches are characterised by iconic sites and wetlands. Cooper Creek has an unregulated flow regime with minimal levels of water extraction and forms one of the type examples of low gradient, intermittent, dryland rivers in the world (Knighton and Nanson, 1994b). As Cooper Creek is unregulated, natural associations between ecology and flow patterns are largely intact (Puckridge et al., 2010) and are characterised by the 'boom and bust' dynamics that are the hallmark of arid and semi-arid environments (e.g. Bunn et al., 2006). The boom-bust sequence is driven by the interannual variablility in flow with Cooper Creek having one of the most variable flow regimes in the world (Puckridge et al., 1998).

The SA reaches of Cooper Creek have very high environmental value, typified by the Ramsar-listed Coongie Lakes wetlands, which are often the focus of large waterbird congregations (Kingsford et al., 1999; Costelloe et al., 2004) and provide important habitat for other fauna, such as fish and macroinvertebrates (Puckridge et al., 2000; Timms 2001). The South Australian reaches of Cooper Creek are also a focus for outback tourism, extractive industries (oil and gas), geothermal industry and pastoral grazing. Cooper Creek has an unregulated flow regime and relatively intact environmental assets but has a low level of information on its flow regime and general hydrological behaviour, particularly for a catchment of this size. This limits the capacity of water resource managers to identify key aquatic refugia in the Cooper and to monitor hydrological change that could occur from anthropogenic changes (i.e. upstream water extraction, land use changes, infrastructure affecting flooding patterns) or climate change.

1.1 Objectives

The original focus of this project was to identify and characterise the aquatic refugia of Cooper Creek in SA and this has been the main objective of this study. In addition, the significant floods of 2010-2012 provided an opportunity to gather additional data on the flow patterns of Cooper Creek, along with the bathymetry of the key waterbodies. Flow data in the SA reaches of Cooper Creek are very rare with the exception of the Cullyamurra gauging station record. Water level loggers were installed in the Coongie Lakes reach during the ARIDFLO project (Costelloe et al., 2004) and SANTOS Limited have telemetered water level loggers at two sites (Embarka Waterhole, Main Branch; Scrubby Camp Waterhole, Northwest Branch) since 2009. However, gauging of flow in the complex network of distributary channels in the lower Cooper is uncommon.

The delineation of flow patterns is a key obstacle in improving our capacity to hydrologically model the lower Cooper. Basic information, such as the split in flow between the Main Branch and the Northwest Branch over a range of discharges, is lacking and this makes highly uncertain the modelling or assessment of how any flow regime changes may affect key environmental assets, like the Coongie Lakes. Therefore, the identification of key aquatic refugia and an improved understanding of flow behaviour and patterns in the Cooper will greatly assist the protection and management of this unique river system.

1.2 Hydrological context of study period

The hydrological context for the Cooper Creek project was the flood responses to the large La Niña episode of 2009-2011. During the Millennium drought (1998-2009) that strongly affected rainfall and streamflow in southeastern Australia (LeBlanc et al., 2009), the Cooper generally had small annual flows with the exception of moderate floods in 2000, 2004 and 2007 (these three floods had partial flood recurrence intervals of 1.7-2.9 years). The years with small annual flows had flood recurrence intervals ≤0.5 years and mean annual flows less than the median. Therefore, this period was relatively dry and resulted in many of the downstream lakes, wetlands and waterholes drying. For instance, Coongie Lake dried in early 2003 for only the second time in the Cullyamurra gauging record (1973-2012). This relatively dry period was broken with a major flood in 2010, the third largest on record (Figure 1). Flood years 2011 and 2012 also had floods with recurrence intervals >1 year and annual totals above the 70th percentile and so the 2010-2012 period represents a 'flood cluster'. Flood clusters 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 Cooper Creek.

In 2010-2011 the Cooper flowed for 598 days through Cullyamurra and this was the first time flow has extended over two flood years in the Cullyamurra record and this did not even occur following the massive 1974 flood (largest on record). Therefore, conditions during the Cooper project were wetter than average and with highly unusual durations of connectivity. Another feature of the study period was that it was characterised by significant rainfall and local runoff events. This is illustrated in Figure 1b by the number of sharp-peaked flow events in the Cullyamurra record that resulted from local rainfall and runoff. The local rainfall is also likely to be important in the successful regeneration of native vegetation in the area.

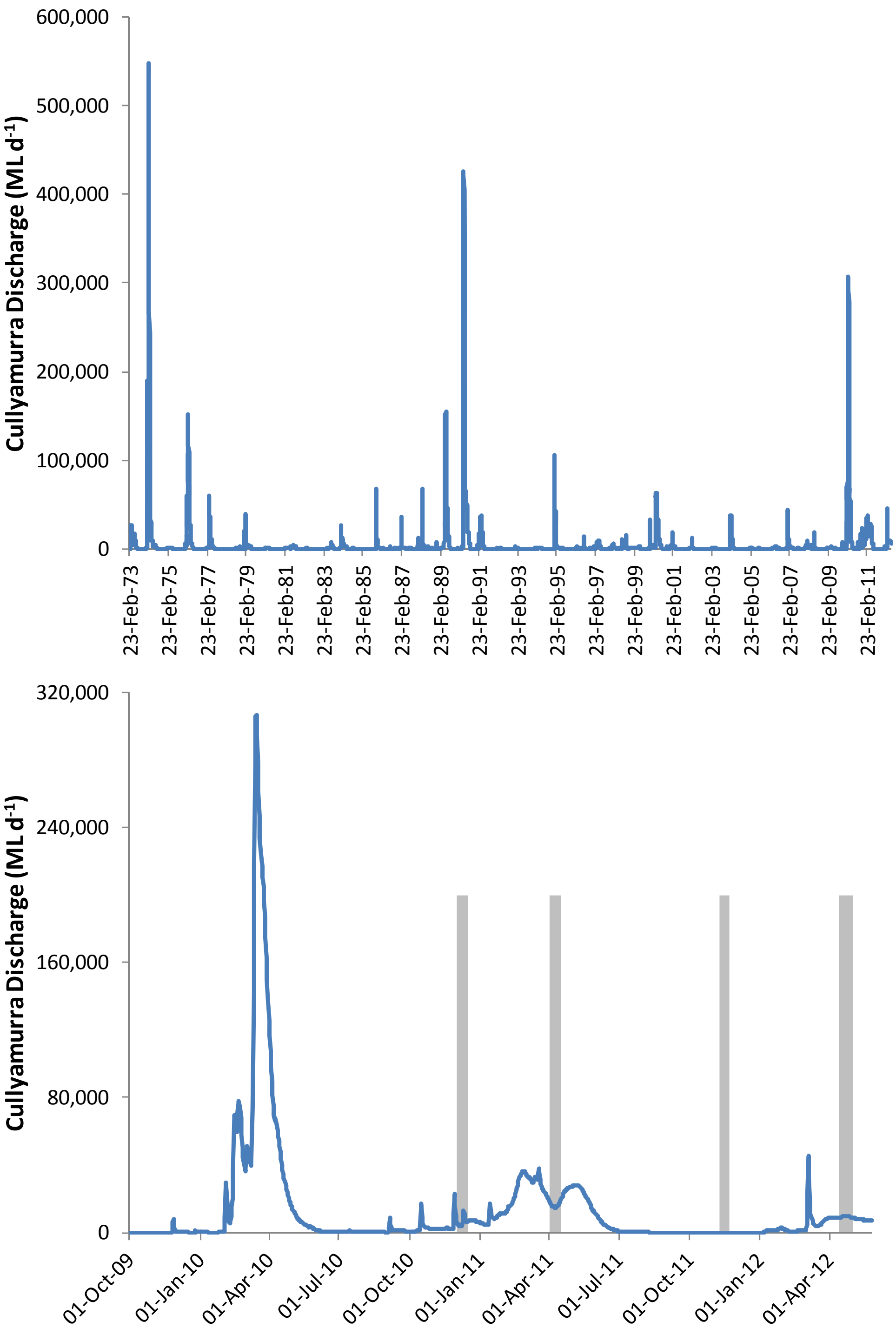


Figure 1. Hydrograph of Cullyamurra gauging station record for Cooper Creek for the period 1973-2012 (top panel).

The lower panel shows the Cullyamurra hydrograph for the flood years of 2010 – 2012. The periods of Cooper Creek fieldwork are shown by the grey columns.

1.3 Cooper Creek

Cooper Creek is an intermittent river that forms the largest catchment of the Lake Eyre Basin (LEB) with a catchment area of 306,000 km^2 and a river length of 1523 km from its upper reaches to Lake Eyre North (Kotwicki, 1986). The Cooper has a remarkably low gradient; downstream of the confluence of the Barcoo and Thomson Rivers, the mean gradient of the river decreases from $5.2x10^{-4}$ m/m to only $1.7x10^{-4}$ m/m from the junction to Lake Eyre North (Kotwicki, 1986). The decrease in gradient is accompanied by a 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, 1994b). The hydrological characteristics of Cooper Creek in the Channel Country and upper reaches have been well described in a sequence of papers by Knighton and Nanson (1994a, 2000, 2001, 2002). Within the South Australian reaches, downstream of Innamincka, the morphology of Cooper Creek changes again as it emerges onto a low-angle alluvial fan (Callen and Bradford, 1992) and forms a complex distributary network of flow paths, lakes and wetland systems as it passes through the Strzelecki Desert on its way to Lake Eyre North. Far less is known of the hydrological behaviour of Cooper Creek in its lower reaches within South Australia. There are three main distributary pathways for floodwaters passing through the lower Cooper; Northwest Branch, Main Branch and Strzelecki Creek. The Northwest Branch takes flow at all discharges, while the Main Branch is apparently separated from the Northwest Branch by a sill requiring floodwaters to exceed a modest threshold discharge. Strzelecki Creek receives inflow only during large flood events and flow into this broad flow path can occur at a number of threshold discharges. The actual channel system of the lower Cooper is not complex relative to the anastomosing form of the other reaches, as flow is often contained in a single trunk channel through much of the lower Cooper reach but is made complex by the distributary systems and associated lakes and wetlands.

The study area includes the South Australian reaches of Cooper Creek from Nappa Merrie to within 40 km of the Cooper’s inlet to Lake Eyre North (see sites in Figure 3). The South Australian reaches of Cooper Creek are located in the arid core of Australia. The closest Australian Bureau of Meteorology climate station (Moomba), has a mean annual rainfall of 210 mm, a mean maximum daily temperature of 29.0ºC and a mean annual Class A pan evaporation rate of 3518 mm.

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. The second phase occurred during the period 2004-2006 as part of a University of Melbourne research project that examined salinity processes in the Coongie Lakes. The third phase occurred over 2007-2008 and involved maintenance of the water level logger network installed as part of the ARIDFLO project. 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 2011 to April 2012 as part of the current Cooper Creek project. The first three phases were mostly concerned with collecting data from the Coongie Lakes reach but the fourth phase collected data over much of the South Australian reaches of Cooper Creek.

2.1 Flow monitoring

In hydrological terms, Cooper Creek is the best monitored of the Lake Eyre Basin rivers but very limited information has been collected in the South Australian reaches.

As part of the ARIDFLO project, five water level loggers were installed around the Coongie Lakes wetlands in 2000. These loggers were last visited in May 2008 and two were removed (Apanburra Channel, Hamilton Creek) and three retained (Northwest Branch, Browne Creek, Ellar Creek). These loggers recorded water level variations each hour and provided the first recorded time-series data of flow events in the Coongie Lakes. The history and analysis of this dataset over the 2000-2008 period is described in Costelloe (2008).

As part of the Cooper Creek project, several low cost water level loggers were installed in key distributaries and in the lower Cooper. These loggers were placed in positions that filled in some gaps in the ARIDFLO and SANTOS networks and provided targeted information on the flow initiation into key distributaries and downstream locations.

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 2).

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.

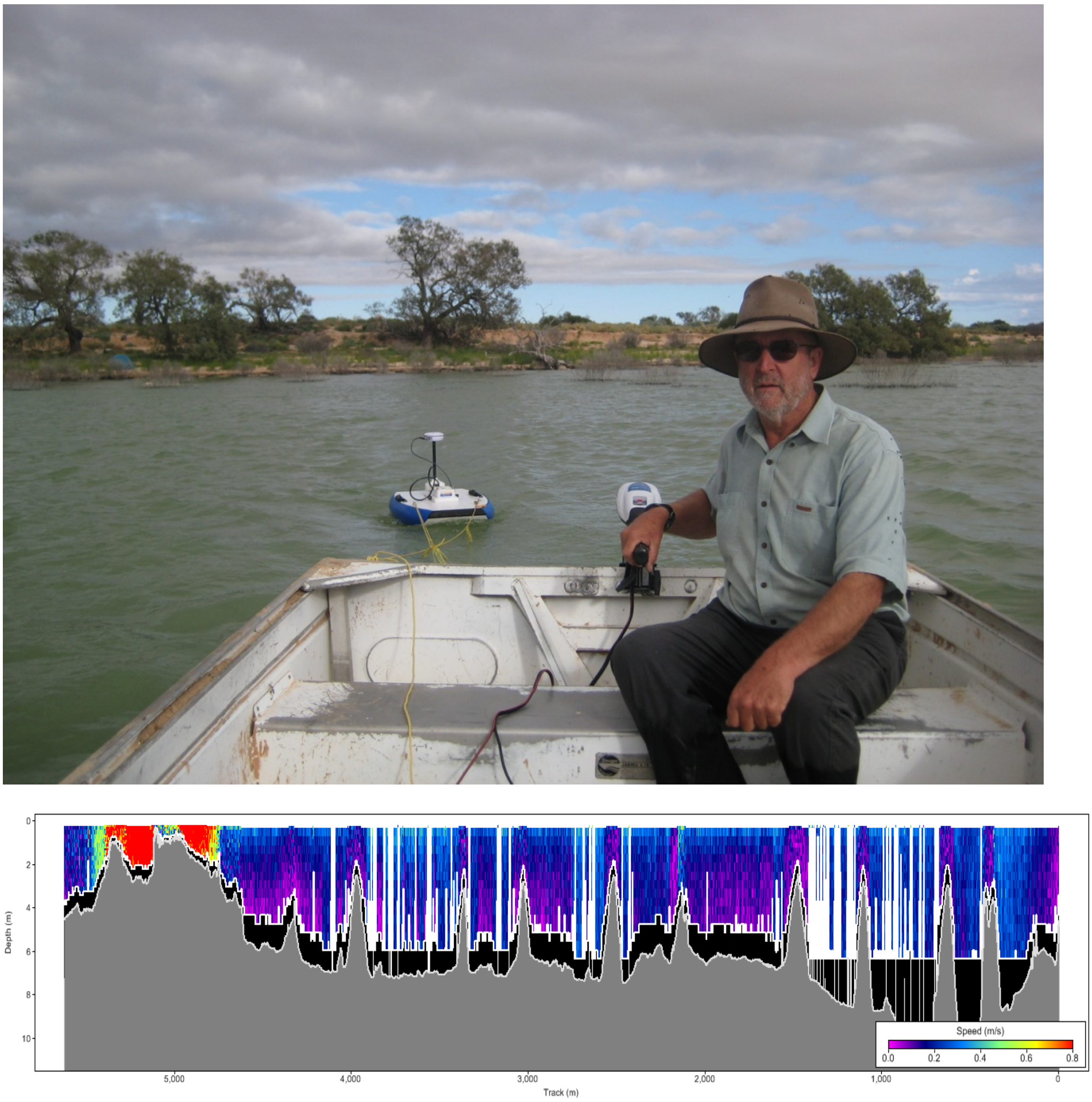


Figure 2. Top photo shows conducting a bathymetric survey at Lake Hope.

Using a boat supplied by Gary Overton and the ADCP being slowly towed behind the boat. The bottom panel shows the longitudinal profile data from the ADCP survey of the downstream half of Cullyamurra Waterhole. Typically, the ADCP is zig-zagged across the waterhole to capture as much bathymetric information as possible.

As part of this project, key waterholes were identified from local knowledge, 1:250,000 scale topographical maps and previous work (ARIDFLO). The dimensions of these waterholes were measured using the ADCP or simple 'wet survey' techniques and surveying using a total station. The wet surveys involved measuring a number of transects across the waterhole with a surveying tape to measure length and a weighted tape to measure depth along the transect. These techniques allowed the characterisation of the dimensions of the waterhole.

Surveys by total station were used to characterise the out-of-water morphology for the remainder of the waterhole survey (i.e. from water level to top of bank and onto the surrounding floodplain). The surveys utilised riparian vegetation zonation (particularly the base of the lignum zone) and downstream levees to identify cease-to-flow levels.

2.3 Water quality measurements

Water quality data were collected (particularly salinity) to identify waterholes that may be subject to groundwater inflow. Some information was also collected from a piezometer installed as part of an earlier University of Melbourne project. The earlier water quality measurements also included major ion analysis of selected surface water and groundwater samples.

2.4 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. 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.

3. RESULTS AND DISCUSSION

3.1 Distribution of refugial waterbodies

The largest waterhole on the SA reaches of Cooper Creek is Cullyamurra Waterhole. This waterhole begins where the Cooper emerges from a rocky constriction, locally known as the 'Choke', as it passes through the hills that form the Innamincka Dome. Surveying at Cullyamurra Waterhole confirmed earlier measurements by Jim Puckridge (Julian Reid, pers. comm.) and Gerald Nanson's University of Wollongong group (Gerald Nanson, pers. comm.) that depths downstream of the 'Choke' exceeded 20 m and that this waterhole is by far the deepest recorded in the Lake Eyre Basin. The measurements in the pool downstream of the Choke in April 2012 were made with a depth tape and were hindered by the relatively high current velocity at the time. The remainder of the surveying of Cullyamurra Waterhole was made using an ADCP (only capable of measuring depths <14 m).

Bathymetric surveys of 40 waterbodies (Table 1) were conducted to identify their refugia potential and the distribution of these waterbodies is shown in Figure 3. The survey of Cullyamurra recorded a maximum depth of 26.0 m (flowing), more than twice the depth of the second deepest waterhole measured, the Nappa Merrie homestead waterhole (11.7 m deep, not flowing). The results indicate that the cease-to-flow depths of waterholes in Cooper Creek upstream of the Main Branch – Northwest Branch junction are typically around 5.5 – 6.5 m while the Northwest Branch and Main Branch are mostly <5.5 m, with the exception of some of the off-channel lakes and waterholes in the lower Cooper (e.g. Eaglehawk Waterhole, Lake Hope and Lake Killalpannina). Of the latter group, the lakes typically dry out between filling events and so have limited refugial value, albeit a high productive fishery value in the case of Lake Hope. The refugial value of Eaglehawk Waterhole is uncertain as its deep section is quite limited (<50 m long) and it most likely does dry out between filling events but this may be moderated by local runoff maintaining its persistence. The capture of a Cooper Creek catfish at this location in April 2011 does suggest that the waterhole has some refugial value.

In addition to its depth, the sheer size of Cullyamurra Waterhole enhances its value as the fluvial 'super refuge', the 'Noah's Ark' of the ark refugia (see McNeil et al., 2011 for definition of ark refugia). Even if there was three years with no streamflow at all and evaporative losses in the order of 7 m, Cullyamurra Waterhole would still contain water over 4 km of its length. Under this doomsday scenario, it is likely that only Cullyamurra and Nappa Merrie Waterholes would still contain water within Cooper Creek. Other waterholes on Cooper Creek and the Diamantina River have CTFDs of 4-9 m (McMahon et al., 2005; Bunn et al., 2006) and the longest reported no-flow interval in the middle reaches of Cooper Creek for the period 1939-1988 was 21 months (data from Currareva gauging station, April 1951 – December 1952, Bunn et al., 2006). The Cullyamurra gauging station record (1973-2012) has a mean no-flow period of 73 days and a longest no flow period of 273 days (approximately 9 months), indicating that periods of no flow >1 year would be quite rare. The Cooper reach around Cullyamurra also gets a significant amount of streamflow generated from local runoff from the Innamincka Dome and this may result in generally shorter periods of no-flow than experienced by even the middle reaches in Queensland.

As shown in Figure 4, the Cooper main channel waterholes all have maximum CTFDs that exceed the approximate evaporation losses following two years without flow. In contrast, the Neales catchment only contained a single waterhole with CTFD>4 m (Algebuckina Waterhole) whereas all named waterholes upstream of the Main Branch – Northwest Branch junction exceeded this depth. For the waterholes with reported maximum depths in the Queensland reaches of Cooper Creek (Knighton and Nanson, 2000; 2001; 2002; Costelloe et al., 2004; Hamilton et al., 2005, McMahon et al., 2005), most have (presumed) maximum CTFD<4.5 m and only five have CTFD>5 m. More detailed bathymetric surveying being conducted by the LEBRA sampling will provide greater confidence in the data from the Queensland reaches but it is clear that deep waterholes are relatively uncommon in the LEB. This emphasises the importance of the Nappa Merrie to Marpoo reach of Cooper Creek in the context of the LEB and the distribution of refuges. This reach also has excellent connectivity and experiences flow every year.

The CTFDs of the refugial waterholes generally decrease moving downstream and the bankfull depth and bankfull area relationship also show a similar pattern moving downstream. These patterns are in response to the decrease in mean annual flow (and event flow) moving downstream, particularly as flow splits into the different distributary systems. As a result of the distributary splits, the distribution of the refugial waterbodies needs to be considered in terms of the following separate reaches:

1. Cooper Creek main channel – Nappa Merrie to Marpoo waterholes,
2. Northwest Branch – to Coongie Lakes,
3. Main Branch – to Deparanie Waterhole (Main Branch – Northern Overflow junction),
4. Lower Cooper.

The key refugial waterholes in each of the four recommended management reaches are the following.

Cooper Creek main channel (in SA) – Cullyamurra and Nappa Merrie are the deepest and Cullyamurra is the largest using any measures (e.g. length, width, depth, contained volume). The high degree of connectivity and focusing of all Cooper Creek 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 Cooper Creek.

Northwest Branch – Scrubby Camp and Kudriemitchie receive flow on an annual basis, are the deepest and occur upstream (Scrubby Camp) and downstream (Kudriemitchie) of distributary branches within this reach. Therefore, these waterholes have high connectivity and most flow in the Northwest Branch will go through these waterholes before reaching the Coongie Lakes. These two waterholes also have the highest tourist visitation, other than Coongie Lake, of waterbodies on the Northwest Branch. Both are monitored with SANTOS or DEWNR flow loggers.

Main Branch – Embarka and Narie Waterholes are the two deepest and largest of the more upstream waterholes on the Main Branch. Embarka receives flow in most

Table 1. Waterbodies surveyed in April 2011, November 2011 and April 2012.

Waterholes considered to have the highest refugial values in the four identified management reaches are highlighted.

Waterbody	Location	Status	Cease to flow depth (m)
Yaningurie	Strzlecki Creek	Disconnected	3.00
Nappapethera	Upper Cooper	Disconnected	6.89
Nappa Merrie	Upper Cooper	Disconnected	11.71
Booloo Booloo (Dig Tree)	Upper Cooper	Disconnected	4.16
Cullyamurra	Upper Cooper	Flowing	<26.00
Burke's	Upper Cooper	Flowing	<6.36
Mulkonbar	Upper Cooper	Flowing	<6.28
Policeman's	Upper Cooper	Flowing	<6.63
Minkie	Upper Cooper	Flowing	<6.85
Tilcha	Upper Cooper	Flowing	<6.35
Marpoo	Upper Cooper	Flowing	<7.35
Munga Munga	Wilpinnie Creek	Connected	3.81
Wattathoolendinie	Wilpinnie Creek	Disconnected	2.30
Montepirie	Northwest Branch	Disconnected	2.23
Napeowie	Northwest Branch	Disconnected	2.07
Cooquie	Northwest Branch	Flowing	<5.02
Scrubby Camp	Northwest Branch	Flowing	<5.41
Cutrabelbo	Northwest Branch	Flowing	<2.83
Tirrawarra	Northwest Branch	Disconnected	4.00
Kudriemitchie	Northwest Branch	Flowing	<5.16
Northwest Branch (Coongie)	Northwest Branch	Disconnected	3.33
Browne Creek	Northwest Branch	Flowing	1.73
Lake Toontoowaranie	Northwest Branch	Minor flow	>2.31
Ellar Creek	Northwest Branch	Flowing	2.20
Apanburra Channel	Northwest Branch	Flowing	0.70
Turra	Main Branch	Flowing	2.43
Embarka	Main Branch	Disconnected	3.80
Merimelia	Main Branch	Disconnected	1.84
Gidgealpa	Main Branch	Minor inflow	4.07
Moorari	Main Branch	Disconnected	1.61
Narie	Main Branch	Disconnected	4.10
Toonman	Main Branch	Disconnected	1.93
Cuttapirie Corner	Main Branch	Flowing	<4.97
Parachirrinna	Main Branch	Flowing	<4.14
Eaglehawk	Lower Cooper	Disconnected	6.41
Kudnarri Bridge	Lower Cooper	Flowing	<1.84
Gwydir's Crossing	Lower Cooper	Disconnected	1.86
Lake Killalpaninna	Lower Cooper	Disconnected	>8.32
Lake Hope	Lower Cooper	Minor inflow	>6.76
Cuttupirra	Lower Cooper	Minor inflow	1.58

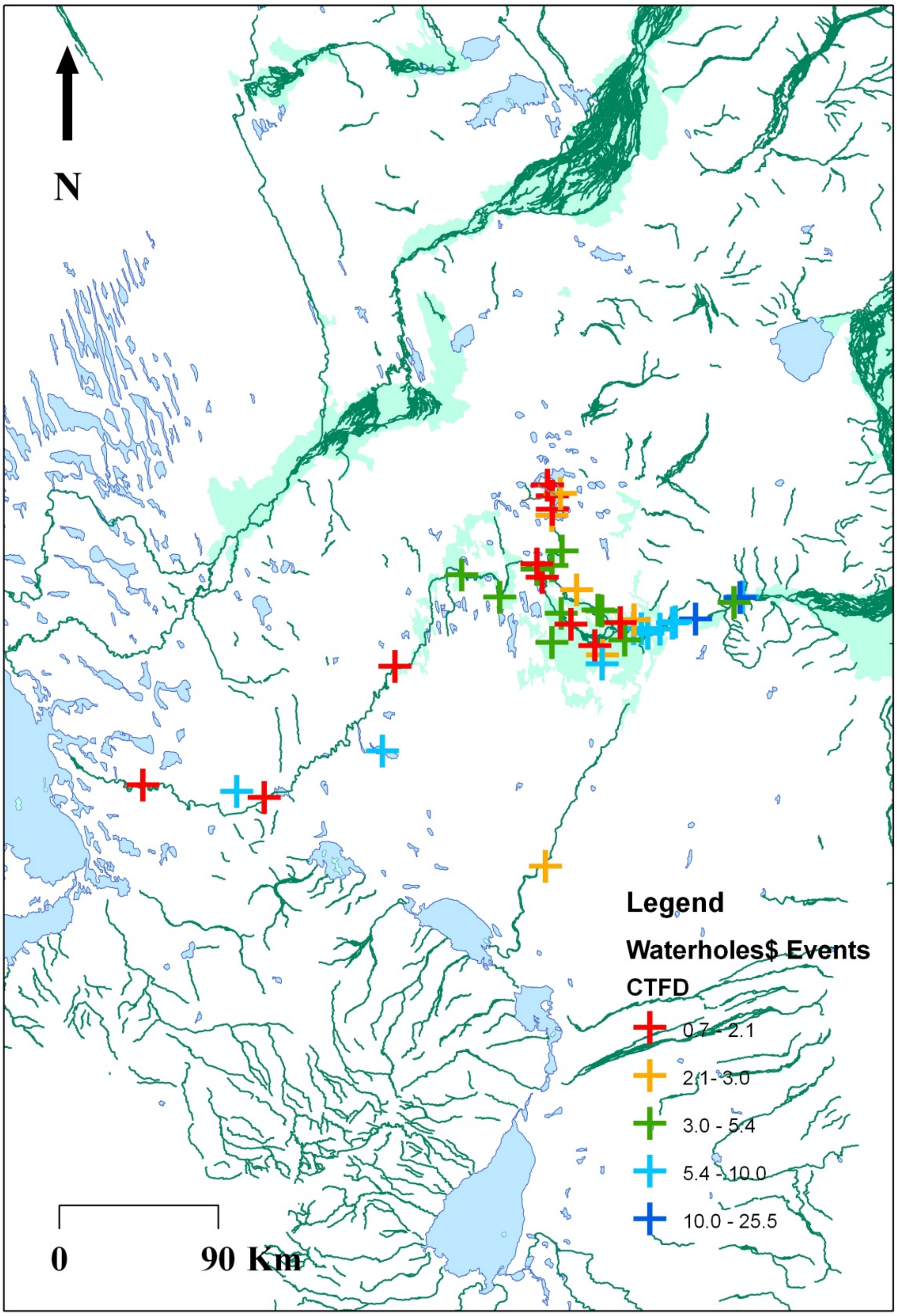


Figure 3. Distribution of waterbodies on Cooper Creek with bathymetric measurements collected during 2011-2012.

The legend shows the ranges for the observed maximum cease-to-flow depth.

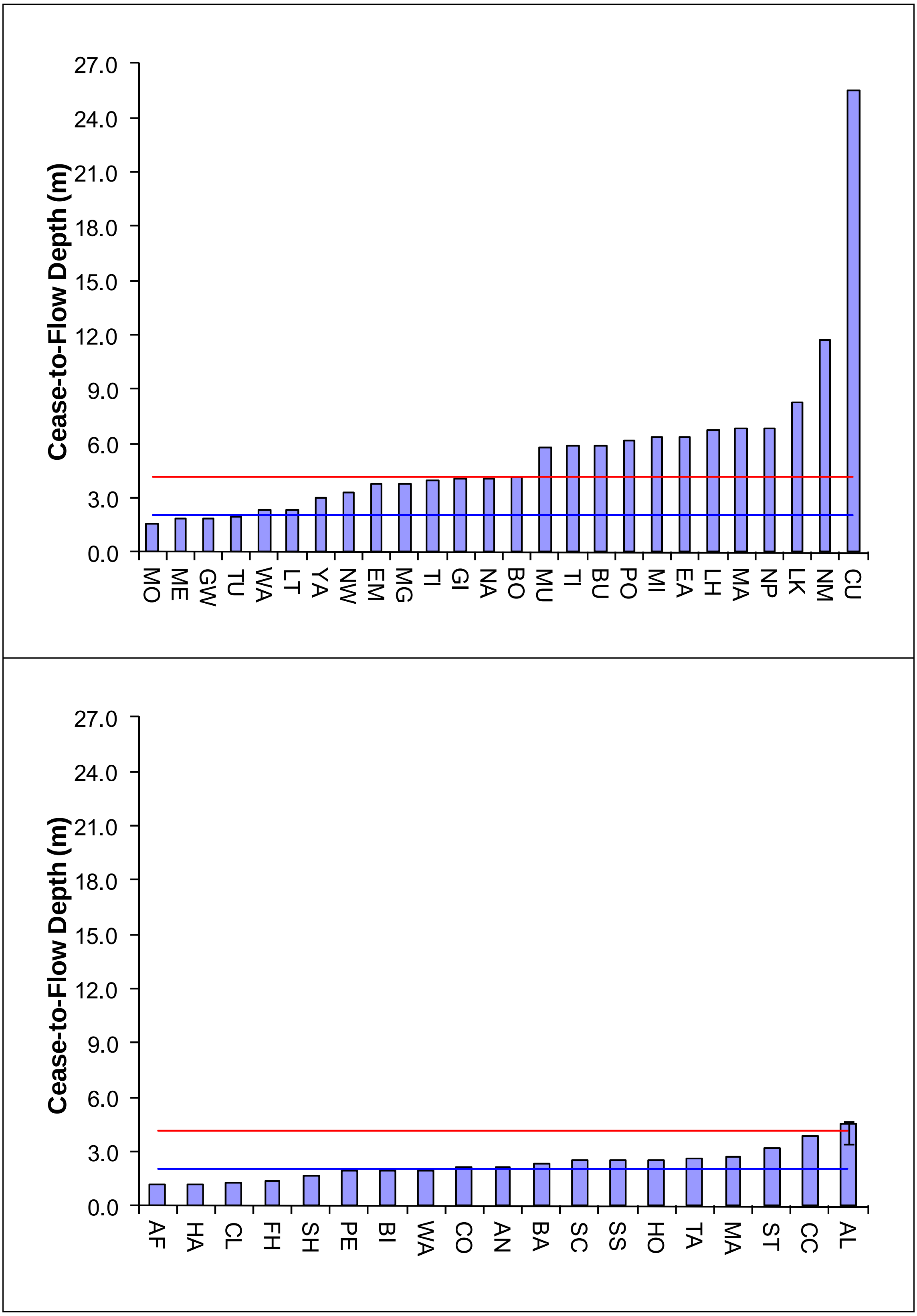


Figure 4. Maximum Cease-to-Flow Depths measured for Cooper Creek waterbodies (top panel) and Neales River watebodies (bottom panel).

The blue and red lines show the one-year and two-year open water loss rate, respectively.

years while Narie lies downstream of the Embarka Swamp outflow and so receives flow on a less frequent basis, although it has red gums in its riparian zone and turtles were observed there in 2011-2012. Both waterholes would retain water for just under two years without inflow and it is likely that Narie would dry out more often because of its location downstream of the Embarka outflow.

Lower Cooper – There are no true refugial waterholes in the lower Cooper as all those measured would dry out because of their more modest depths and lower frequency of inundation compared to those located in the upstream reaches. Eaglehawk Waterhole may have some refugial value but this is uncertain. Any refugial value is further limited by its off-channel location and the small size of the deep pool.

3.2 Streamflow distribution

A major constraint on the management of Cooper Creek and our capacity to detect adverse change is our limited capacity to model the system. This means that the effects of changes in the flow regime, either due to climate change, water extraction or changes in flow paths, are difficult to monitor or predict. The only previous hydrological models of the South Australian reaches of Cooper Creek are; (1) A whole of basin RORB model including a very coarse representation of Cooper Creek (Kotwicki, 1987), (2) A grid-based conceptual model from the ARIDFLO project including the Northwest Branch and part of the Main Branch (Costelloe et al., 2004) and (3) A link-node model using IQQM that extended from the Queensland DERM modelling of Cooper Creek and included all of the South Australian part of the Cooper catchment. The latter two models were more detailed in terms of defining and modelling flow paths in Cooper Creek but are hindered by a lack of information on transmission losses downstream of Cullyamurra and the distribution of flow amongst the complex flow paths of Cooper Creek.

In this section, information collected during the Cooper Creek 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.

3.2.1 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 April 2011 field trip coincided with elevated flow conditions but did occur between the two main flow peaks of the 2011 floods. The flow did constrain access and sub-bankfull flows were encountered from Innamincka through to Lake Hope. Very weak recession flow was occurring downstream of Lake

Hope through to Cuttupirra Waterhole and probably represented the tail of the 2010 flood in the lower reaches.

During November 2011, streamflow was only encountered in the downstream reaches of the Cooper and represented the recession tail of the April 2011 flood. No flow was encountered in the Main Branch and the outlet from Embarka Swamp was completely dry. Weak flow was encountered in the lower Cooper from the Kudnarri bridge site (Beach Energy) through to Cuttupirra Waterhole (and weak flow was probably still occurring into Lake Eyre North). We weren't able to investigate how far upstream of Kudnarri bridge that flow was occurring but the observations indicate that fish passage was still possible in November 2011 from Lake Eyre North to perhaps around the junction of the Main Branch and Northern Overflow to form the lower Cooper. There was also some minor flow still occurring between the downstream lakes of the Coongie Lakes. There was no measureable flow into Coongie Lake but the next lake in the system, Lake Toontoowaranie, was experiencing inflow (i.e. reverse of flow during flood) from Lake Goyder (downstream of Toontoowaranie) and outflow towards Lake Apanburra. Flow from the Coongie Lakes into the Northern Overflow (via the Apanburra Channel) was likely to be insignificant.

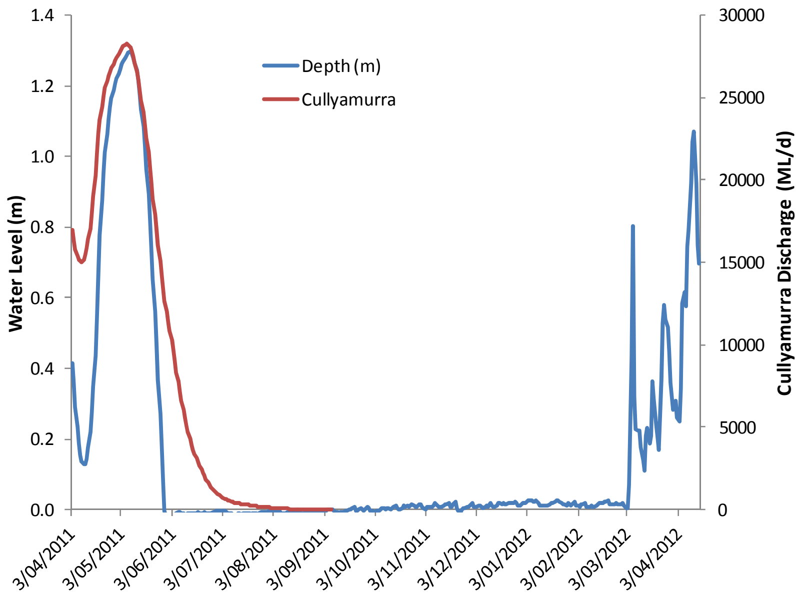
The April 2012 field trip was again characterised by sub-bankfull flows that corresponded to the approximate peak of the regional 2012 flood (as distinct from the sharp-peaked event in February 2012 caused by local rainfall). Flow was encountered from Cullyamurra through to the Coongie Lakes (rising conditions) on the Northwest Branch and to near Deparanie Waterhole on the Main Branch. Flow was not yet occurring in the lower Cooper (i.e. Kudnarri bridge to Lake Hope) during this period.

3.2.2 Distributaries from Cooper main channel (Wilpinnie and Ooranie Creeks)

Water level loggers were installed in two flow paths (Ooranie and Wilpinnie Creeks) that distribute flow away (south) of Cooper Creek towards Strzlecki Creek during larger flood events. The aim of these loggers was to fine-tune the thresholds for discharge in Cooper Creek that initiates flow into these flow paths. Early estimates of this threshold for Wilpinnie Creek was 35,000 MLd^{-1} based on broad-scale satellite observations from the 1988-1992 period (Costelloe, 1998).

The logger on Wilpinnie Creek was installed in Munga Munga Waterhole in April 2011. The waterhole was filled with water at this date from the Feb-Mar 2011 flood event (peak discharge 38,432 MLd^{-1}) but flow had not extended far past Munga Munga Waterhole. The second flood pulse of 2011 (Apr-May, peak discharge 28,245 MLd^{-1}) resulted in more inflow to Wilpinnie Creek but again not far past Munga Munga Waterhole. The close correlation between the timing of peaks and troughs (within two days) of the Cooper flow (measured at Cullyamurra) and the Wilpinnie Creek logger (Figure 5) indicate that the flow threshold for inflow to Wilpinnie Creek is lower than previously estimated but that this flowpath up to at least Munga Munga Waterhole acts as a backwater to Cooper Creek. The recession of water from Munga Munga Waterhole was very rapid and water levels dropped by approximately 2.6 m between April and November 2011 (Figure 5) which significantly exceeds the expected open water evaporation rate of 0.96-1.24 m for this period. This indicates that backflow into Cooper Creek occurred in this period. There was no evidence of significant flow past Munga Munga Waterhole in 2011. So, even though flow into Wilpinnie Creek was occurring at discharges of approximately 16,000 MLd^{-1}, the water appears to have flowed back into Cooper Creek during the recession of the flow and the threshold for flow in Wilpinnie Creek to flow south from Munga Munga Waterhole exceeds the peak discharge of the 2011 floods and is probably >40,000 MLd^{-1}.

The second water level logger was installed in Ooranie Creek which exits Cooper Creek upstream of Tilcha Waterhole (Figure 5). The channel contained some water in April 2011 and it was not clear if this was due to previous flow from Cooper Creek or local inflow. Unfortunately the logger was damaged by cows or dingos and went out of action on 29/07/11. The April to July record did not show any evidence of connection in response to the 2011 flows in Cooper Creek and so it appears the threshold is greater than the peak discharges of 2011 (e.g. >36,000 MLd^{-1}).



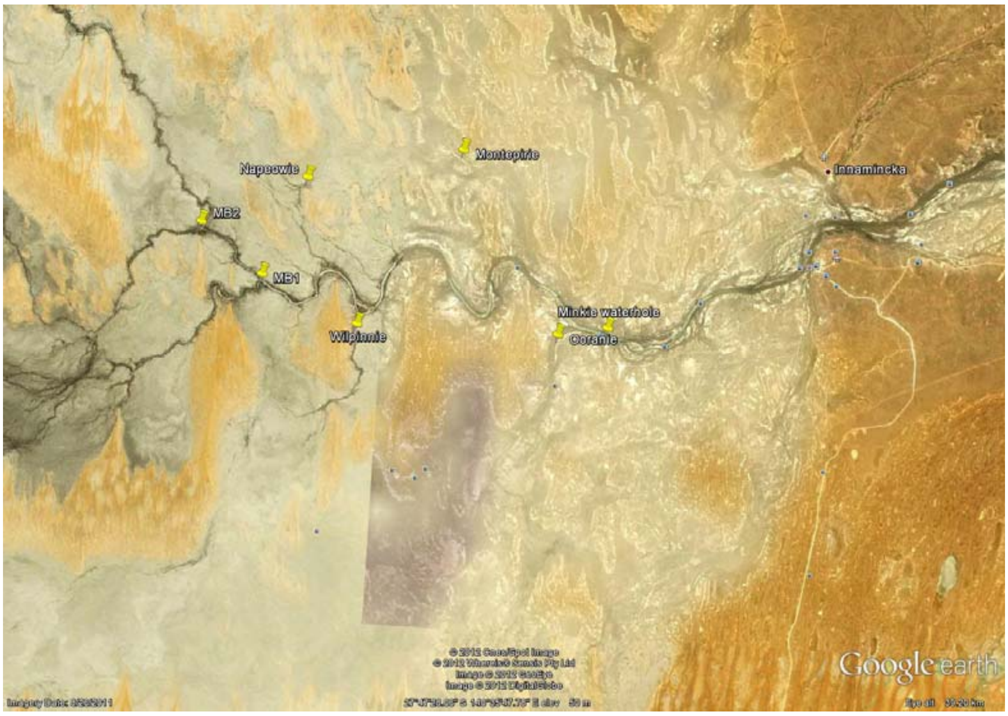


Figure 5. Hydrograph of Cullyamurra discharge compared to water level data recorded at Munga Munga Waterhole on Wilpinnie Creek.

Google Earth image shows locations of loggers at Wilpinnie Creek and Ooranie Creek.

3.2.3 Main Branch – Northwest Branch Junction

Flow gaugings were collected during the April 2011 and April 2012 field trips that provide the first measurements of flow distribution between the Main Branch and Northwest Branch flow paths (Figure 6). The gaugings from April 2011 were restricted to the Cooper Creek main channel and the south branch of the Main Branch. However, access to the DSE boat allowed all channels to be gauged in April 2012 and provided a complete picture of the flow distribution. During the sub-bankfull flow of April 2012, approximately 50% of the flow entered the Northwest Branch and 50% entered the Main Branch via its two inflow channels (see Figure 6). During the larger, but still sub-bankfull, flow of April 2011, the percentage of flow entering the southern inflow channel to the Main Branch was 34%, compared to 20% in 2012. This implies that at higher flow levels an increasing percentage of flow enters the Main Branch in comparison to the Northwest Branch. This is consistent with observations of the morphology of the Main Branch – Northwest Branch junction that show that the sills for flow into the Main Branch channels are minor.

The threshold for flow to enter the Main Branch is uncertain and the field observations suggest that there should be no clear threshold, particularly for the northern channel into the Main Branch. Comparing the Embarka Waterhole (SANTOS) record to Cullyamurra shows that flow peaks take between 5-18 days to flow between these two locations. The onset of flow into Embarka Waterhole in 2009 (first year of data from the SANTOS logger at Embarka Waterhole) started 78 days after flow commenced at Cullyamurra Waterhole, indicating that a flow threshold into the Main Branch occurs. This indicates that the threshold could be approximately 1200 MLd^{-1} at Cullyamurra (flow exceeded this threshold for 28 days prior to inflow to Embarka Swamp). In 2012, flow commenced into Embarka Waterhole 26 days after flow commenced through Cullyamurra and 17 days after the 1200 MLd^{-1} threshold was reached at Cullyamurra. It is likely that a combination of discharge threshold and total volume is required to get flow into Embarka Waterhole, i.e. significant flow could be stored upstream of Embarka Waterhole in the Main Branch before flow commences into Embarka Waterhole (see Google Earth image in Figure 6).

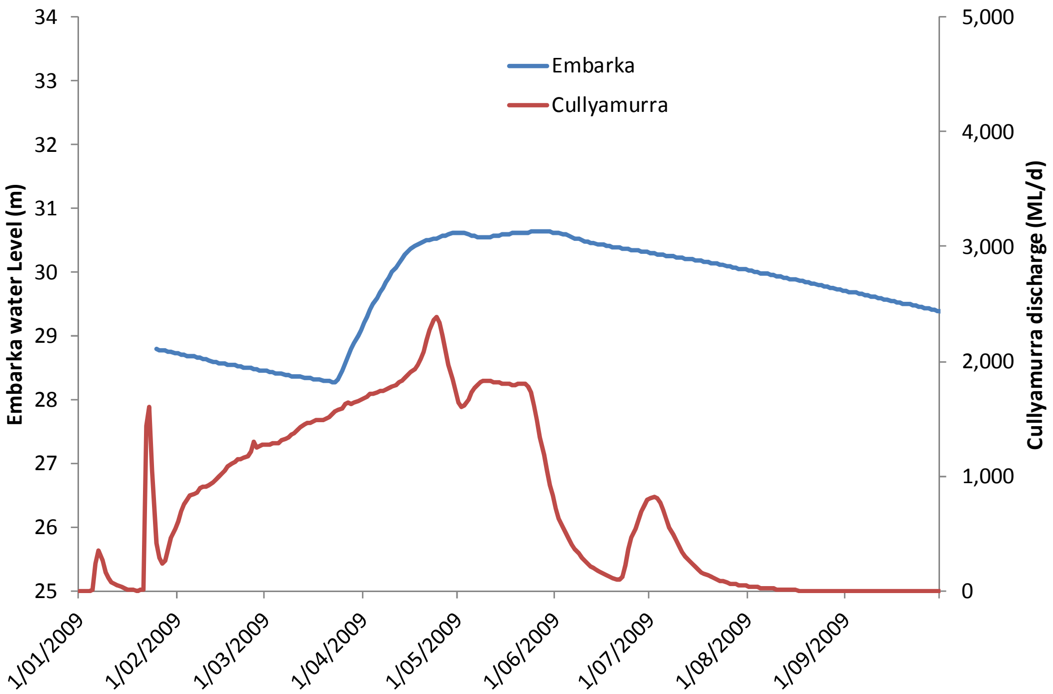
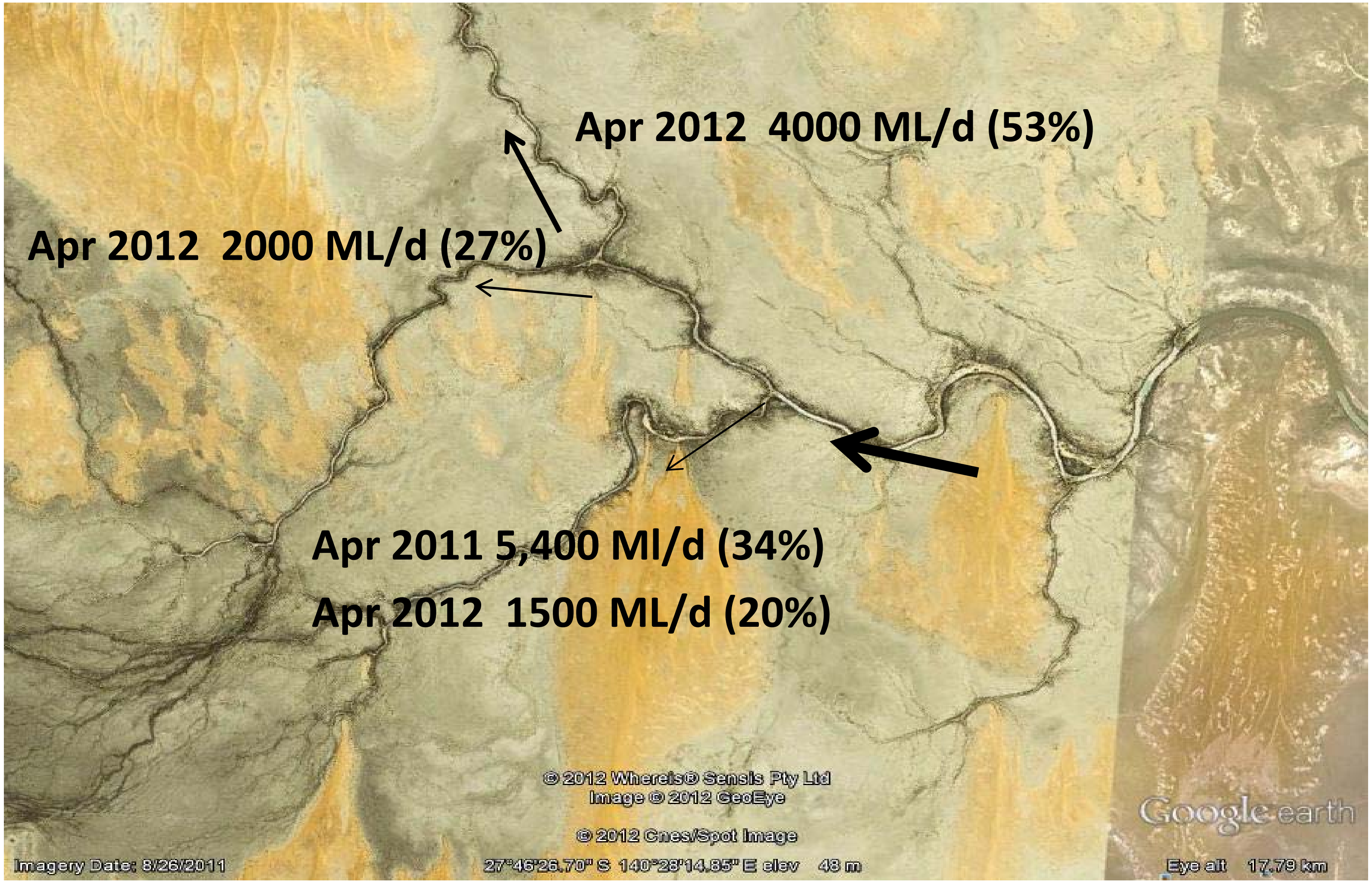


Figure 6. Top- Distribution of flow between the Main Branch and Northwest Branch during flow events in April 2011 and 2012. Bottom (next page) – hydrograph of water level at Embarka Waterhole and discharge at Cullyamurra during 2009

Satellite image courtesy of Google Earth


Apr 2012 4000 ML/d (53%)
Apr 2012 2000 ML/d (27%)
Apr 2011 5,400 Ml/d (34%)
Apr 2012 1500 ML/d (20%)
© 2012 Whereis® Sensis Pty Ltd
Image © 2012 GeoEye
© 2012 Cnes/Spot Image
Google earth
Imagery Date: 8/26/2011
27°46'26.70" S 140°28'14.85" E elev 48 m
Eye alt 17.79 km

3.2.4 Northwest Branch flow paths

Flow gaugings collected from the Northwest Branch during April 2012 also showed how flow split along two flow paths (Eulcaminga and Mudrangie, see Figure 7) that separate north of Scrubby Camp Waterhole and rejoin at Tirrawarra Waterhole. The Mudrangie flow path took approximately 70% of the flow and the Eulcaminga Waterhole took approximately 30% (allowing for uncertainties in gauged discharges, see Table 2). The split between these two flow paths is not a critical junction but the Mudrangie flow path also feeds an important waterbird breeding wetland (Julian Reid, pers. comm.). The decrease in discharge between Scrubby Camp Waterhole and Tirrawarra Waterhole also gives an indication of the significant transmission losses along the Northwest Branch (assuming relatively constant discharge through Scrubby Camp for a few days prior to the gauging), with an approximate 33% reduction in discharge from Scrubby Camp to Tirrawarra Waterhole. Only a small reduction in flow was observed between Tirrawarra and Kudriemitchie and probably represents transmission losses through Tirrawarra Swamp. A significant reduction in flow was observed between Kudriemitchie and the Northwest Branch inflow to Coongie (Table 2) and this probably represented losses from inflow to other lake systems, such as Lake Mundooroounie and Lake Apachirie.

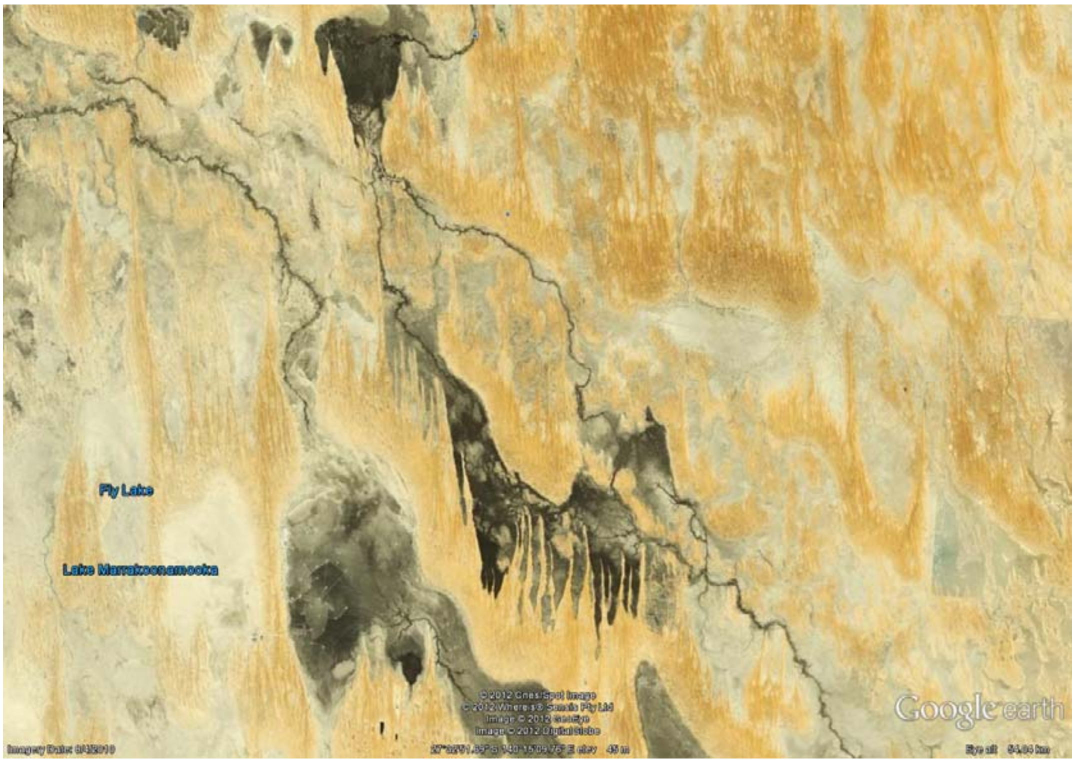


Figure 7. Distributary split in the Northwest Branch between the Eulcaminga flow path (east) and the Mudrangie flow path (west).

The two channel systems rejoin at Tirrawarra Waterhole. Note the larger floodplain area (dark colours) on the Mudrangie flowpath. Image from Google Earth.

Table 2. Flow gaugings at the Northwest Branch locations in April 2012.

Location	Date	Discharge (MLd^{-1})	Percentage flow
Scrubby Camp WH	18/04/12	3975	100
Tirrawarra upstream (Eulcaminga path)	20/04/12	823	27
Tirrawarra at Mudrangie channel	20/04/12	2138	71
Tirrawarra downstream	20/04/12	3010	100
Kudriemitchie	20/04/12	2870	100
Northwest Branch at Coongie	24/04/12	2085	100

3.2.5 Coongie Lakes

Flow gauging at the Coongie Lakes in November 2011 and April 2012 also give some insights to the complexities of the 'fill and spill' mechanism at work in these lakes. In November 2011, the level in the Northwest Branch was falling and no flow was occurring (Figure 8, note local inflow occurred in later November from local rain) while modest flow into Toontoowaranie was occurring, Ellar Creek was back-flowing (into Toontoowaranie) and flow into Apanburra Channel was a trickle (Table 3). The backflow along Ellar Creek illustrates the complexities involved in trying to model flow in this important wetland system. Interestingly, the flow record at Ellar Creek (Coongie Lakes) did not show a double peak in 2011 (in contrast to the Cullyamurra record) as it is likely that the downstream lakes filled to capacity and then began to backflow after the peak of the first event in 2011 (Figure 8 and 9). Modelling reverse flow would require a full hydrodynamic model to be developed for the Coongie Lakes. The reverse flow situation is only likely to occur following the larger flood events when Lake Goyder and its subsidiary lakes are full. This was observed occurring in 1990-1991 (Jim Puckridge pers. comm.).

During April 2012, the rising limb of the flood was entering Coongie Lake and also generating flow into the Lake Apachirie – Lake Dare – Lake Massacre flow path and moderate flow out of Lake Toontoowaranie and into Lake Goyder and the Apanburra Channel. The April 2012 data show that Ellar Creek (and Lake Goyder) is the preferential pathway out of Lake Toontoowaranie during the filling phase but that flow relations can be complex during the falling phase.

The extent of flooding during the smallest annual flows seems to be an important parameter in the ecology of Cooper Creek. For instance, Coongie Lake receives inflow on an annual basis and has not been known to miss out on inflow in any year of the Cullyamurra gauging record. This important waterbody is also the most downstream extent of red gums on the Northwest Branch and has the highest reported fish diversity of the Coongie Lakes wetlands (Puckridge et al., 2010). The lakes and channels downstream of this point receive flow less frequently and dry out more frequently. Coongie Lake, as the terminus of the smallest annual flows, is an important monitoring point for identifying any change in the Cooper Creek flow regime (e.g. from climate change, water extractions, flow path changes). If the frequency of inflow becomes persistently less common (i.e. stops receiving inflow each year) then this should be considered as a 'threshold of potential concern' as it may lead to important ecological changes (i.e. decreased fish diversity, extent of red gums moving further upstream).

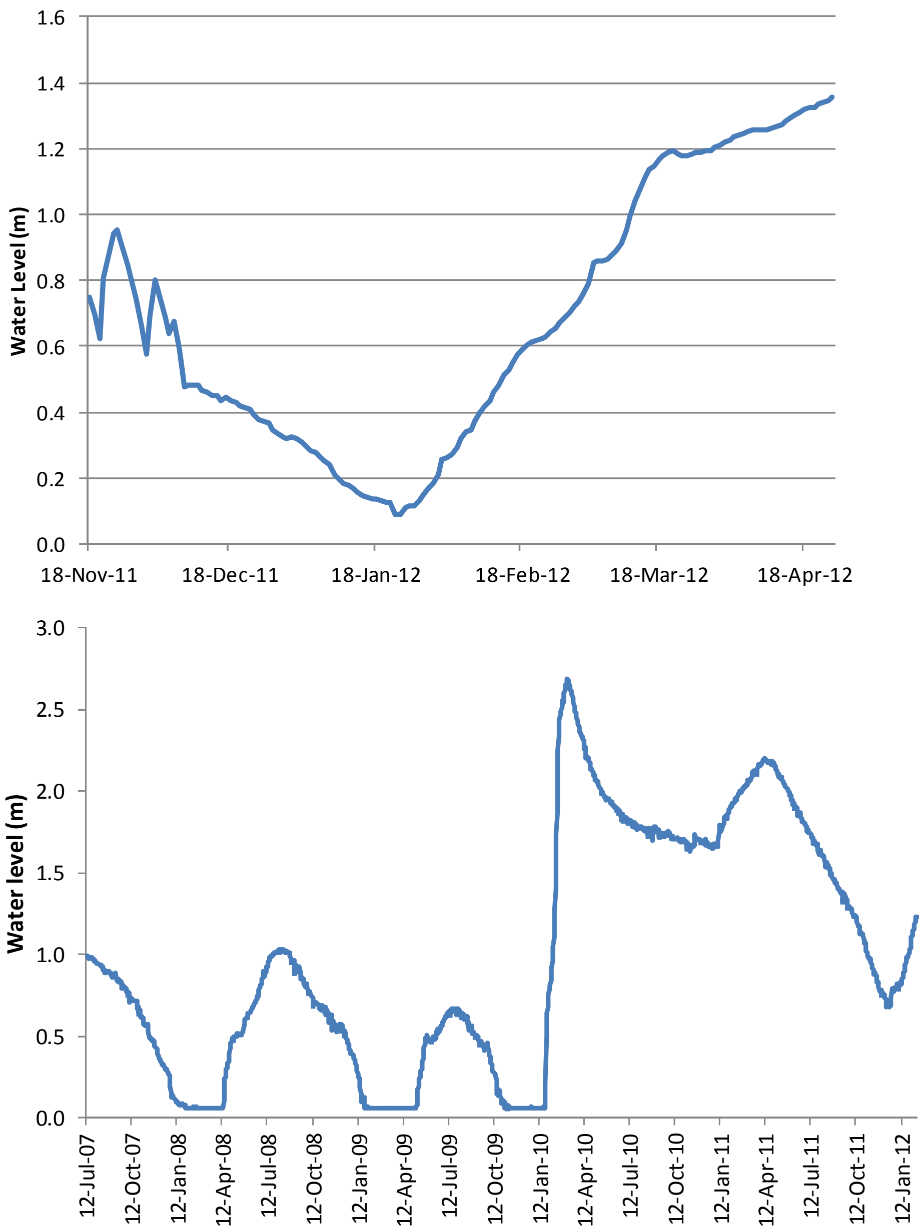


Figure 8. Water level recorded at the Northwest Branch near Coongie Lake (top panel) and at Ellar Creek near the inflow to Lake Goyder (bottom panel).

Figure 9. The logger position at the mouth of Ellar Creek and Lake Goyder.

This logger measured data from July 2007 until February 2012 without a change of battery or download. This location provides the most comprehensive record of events in the Coongie Lakes,

Table 3. Flow distribution in Coongie Lakes, November 2011 and April 2012.

Location	Date	Discharge (MLd^{-1})
Northwest Branch (Coongie inflow)	17/11/11	0
Browne Creek (Toontoowaranie inflow)	17/11/11	73
Ellar Creek (Goyder outflow)	18/11/11	-154
Appanburra Channel (Apanburra inflow)	17/11/11	23
Northwest Branch (Coongie inflow)	24/04/12	2085
Browne Creek (Toontoowaranie inflow)	24/04/12	1447
Ellar Creek (Goyder inflow)	25/04/12	1053
Appanburra Channel (Apanburra inflow)	26/04/12	319

3.2.6 Embarka Swamp outflow

There is less information available for determining the extent of the smallest annual flows in the Main Branch. There have been few ecological studies of this reach (i.e. no sampling by Jim Puckridge) and the lack of an open water body (such as Coongie Lake on the Northwest Branch) makes the identification of the extent of flooding difficult using satellite data. Given the 2009 water level record at Embarka Waterhole is suggestive of a threshold of flow approximately >1200 MLd^{-1} (at Cullyamurra) for flow to reach this point, this indicates that the extent of smallest floods may lie upstream of Embarka Waterhole. Flows in 1982 and 1985 had peak discharges <1200 MLd^{-1} and small total volumes. Interestingly, red gums occur further downstream of Embarka Swamp on the Main Branch and also turtles and water rats were identified downstream (Schmarr et al., 2012) but the distribution of the latter may reflect the influence of the 2010 flood.

The Embarka Swamp outflow (Moorari crossing) lies downstream of Embarka Waterhole and forms an important ‘choke’ point in the Cooper (see Figure 10). A logger was installed in a floodplain position at the Embarka outflow area in April 2011 and was moved to the thalweg channel position at the old Moorari culvert bridge (no longer in operation) in November 2011. Figure 10 shows the hydrographs from the outflow logger, the SANTOS Embarka Waterhole logger and the Cullyamurra gauging station. In 2012, the initial flow pulse through Cullyamurra had a peak discharge of 2634 MLd^{-1} and a total volume of 53,667 ML and this did not result in any flow through to Embarka outflow. The sharp-peaked, high amplitude event resulting from significant local rain in early March did result in flow through Embarka outflow, both from local runoff (coincident peak between Cullyamurra and Embarka outflow, Figure 10) and from flow through the Cooper main channel (second larger Embarka outflow peak). The total volume of the first two pulses through Cullyamurra before flow commenced at Embarka Outflow was 223,386 ML. The 2008 flood (22,519 ML d^{-1} peak discharge, 385,115 ML total volume) did not result in any flow downstream of Embarka Swamp (Andy Pietsch, SANTOS Limited, pers. comm.). Using a flow threshold of 1200 ML d^{-1} and a 50% split in flow above this threshold for flow to enter the Main Branch, this indicates that the Embarka Swamp reach has a holding capacity in the region of 100,000 ML and this is consistent for both the 2008 and 2012 flood events. The slightly larger 2007 flood (52,500 ML d^{-1} - 494,000 ML) did flow downstream of Embarka Swamp as far as the Main Branch – lower Cooper junction.

Given the amount of oil-gas production infrastructure in the Embarka Swamp area (see Figure 10), it is important that these structures do not impede the natural patterns of flow and storage in this area, and particularly for flow out of Embarka Swamp. Given the lack of channelization in the Embarka Swamp downstream of Embarka Waterhole, this area would be the most vulnerable to inadvertent changes in flow patterns from infrastructure and this could have substantial effects on the frequency of flow of the waterbodies on the Main Branch.

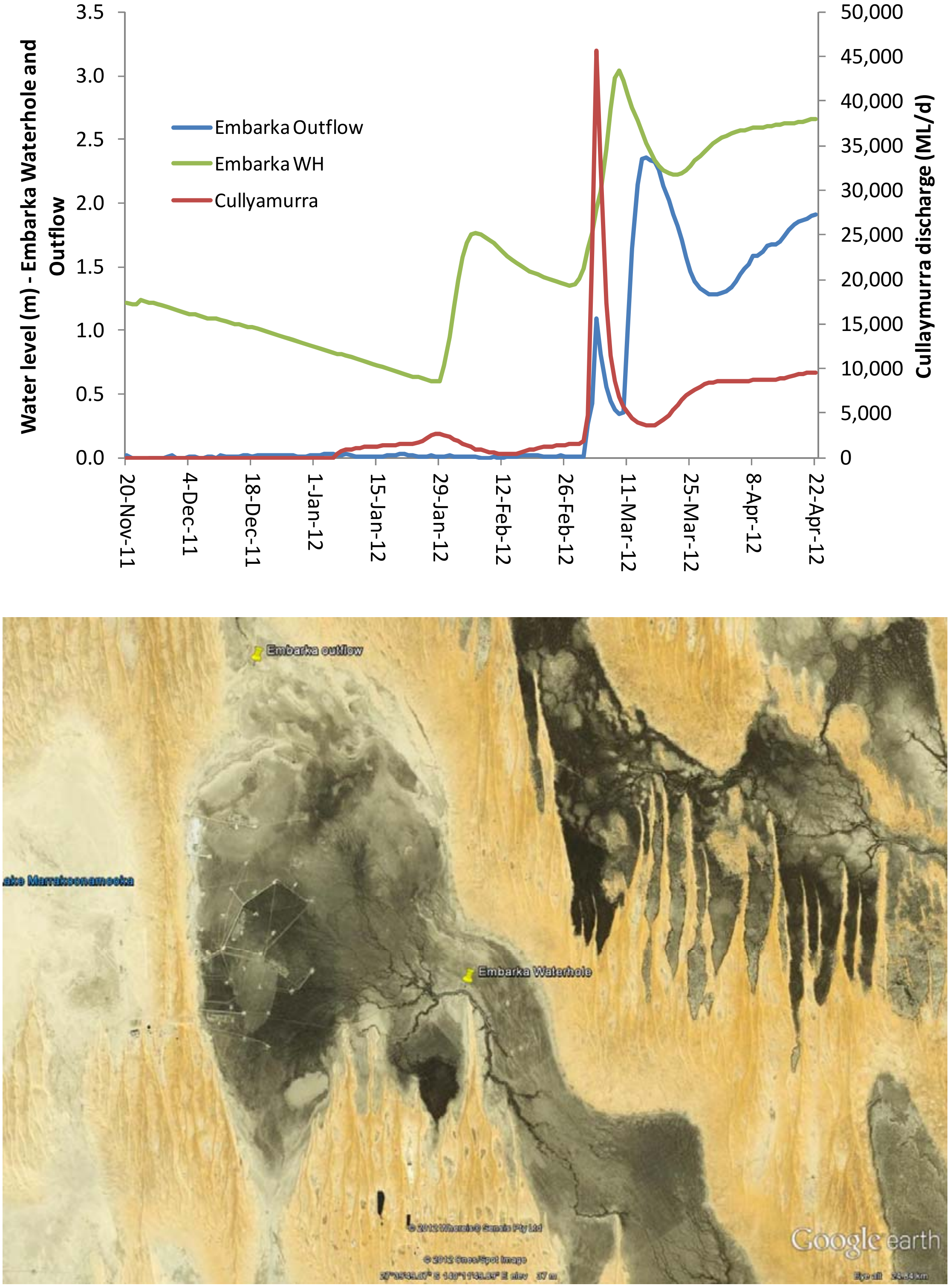


Figure 10. Top panel shows water level hydrograph at Embarka Waterhole (SANTOS) and Embarka outflow channel (old Moorari bridge) and discharge hydrograph at Cullyamurra gauging station. Bottom panel is a Google Earth image of Embarka Swamp showing location of Embarka Waterhole and the Embarka outflow logger.

Note the substantial built infrastructure downstream of Embarka Waterhole.

3.2.7 Christmas Creek flow path

Christmas Creek is a flow path that connects the Main Branch to the Northern Overflow and flows from south to north (Figure 11). Flow was observed to have commenced in the thalweg channel of Christmas Creek around 27 April 2012 and this corresponded to flow of between 1690 ML d^{-1} (measured at Cuttapirie Corner on 22 April) and 2132 ML d^{-1} (measured at Narie on 27 April) in the Main Branch at the junction with Christmas Creek. Flow into Christmas Creek was also initiated by the 2004 flood (45,270 ML d^{-1} – 1,104,000 ML) and resulted in flow into Lakes Oolgoopiarie and Androdumpa, two normally dry lakes on the Northern Overflow. A flow pulse in 1989 (36,200 ML d^{-1} – 546,000 ML) also flowed along Christmas Creek but the 2008 flood (22,519 ML d^{-1} peak discharge, 385,115 ML total volume) did not flow out of Embarka Swamp. The split in flow between Christmas Creek and the Main Branch is not known but the vast majority of the flow in late April 2012 was flowing along the Main Branch in preference to Christmas Creek. The threshold water level for flow into Christmas Creek can be monitored by the water level logger installed by SANTOS at Walkers Crossing bridge in July 2012.

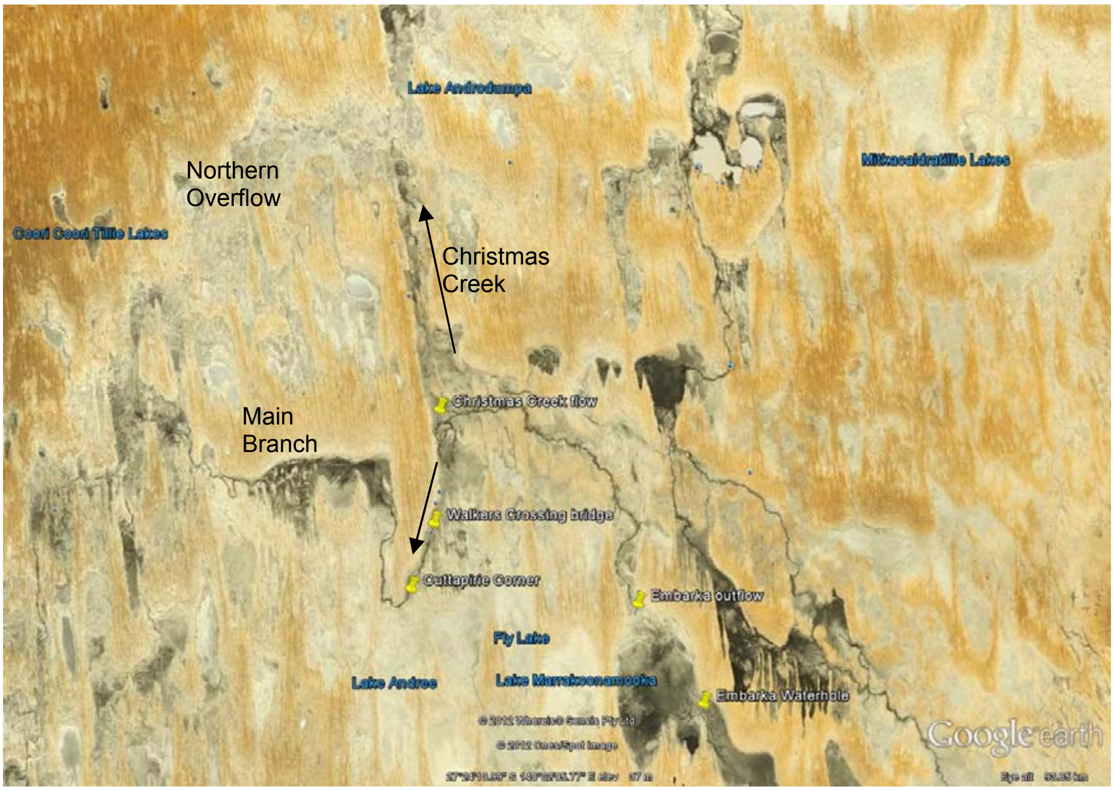


Figure 11. Google Earth image of the Christmas Creek – Main Branch junction with way-points showing the position of Christmas Creek flow in April 2012 and also the position of the Walkers Crossing bridge.

3.2.8 Lake Hope

The following observations on the connectivity status of Lake Hope during 2011-12 may be useful in the management of the Lake Hope fishery, particularly in determining at what stage Lake Hope disconnects with Cooper Creek. The configuration of Cooper Creek at the Lake Hope inflow channel is that the lower Cooper flows into Lake Appadare, which has two outlets; the inflow channel to Lake Hope and two downstream channels (Cooper Creek, see Figure 13). The 2004 flood (45,270 ML d^{-1} – 1,104,000 ML) terminated in Lake Hope and only produced a minor filling. This is consistent with the size of the 2012 flood (821,134 ML to 26 May) providing some inflow to Lake Hope but not initiating much flow beyond Lake Appadare. The 2000 flood (75,300 ML d^{-1} – 3,683,000 ML) resulted in the filling of Lake Hope and some further flow downstream but did not result in any flow into Lake Killamperpunna (immediately upstream of the Birdsville Track crossing of Cooper Creek). The 2000 filling of Lake Hope lasted through to February-March 2003. With evaporation rates of around 2 m y^{-1} (Costelloe et al., 2007) this is consistent with the measured depths of around 6 m in Lake Hope during 2011.

The timing of flow to reach Lake Hope from Cullyamurra is difficult to determine accurately. The time of peak flow at Cullyamurra until inflow to Lake Hope was observed with satellite data is shown in Table 4 along with estimates of flow timing from the 2011 and 2012 floods. The 2012 flow reached Kudnarri bridge on approximately 9th June 2012 and no data are available for the timing of peak flow.

Table 4. Timing of flows from Cullyamurra to Lake Hope.

Timings are calculated from the date of the peak discharge of the regional flood through Cullyamurra until flow is detected entering Lake Hope (using satellite data for years 1989-2010).

Year	Peak discharge (MLd^{-1})	Total volume (ML)	Days
1989	155,000	4,638,000	>46
1990	425,000	9,558,000	>33
2000	75,300	3,683,000	>47
2010	306,302	7,893,658	~39
2011	36,083	3,680,814	<44
2012	9602	821,134	>48

In April 2011 inflow of 569 MLd^{-1} was occurring into Lake Hope and this formed an early stage of the rising limb of the 2011 filling of Lake Hope. The inflow to Lake Appadare was not measured but the downstream flow out of Lake Appadare into the lower Cooper was only 18 MLd^{-1}. Therefore, early in the filling stage the Cooper preferentially flows into Lake Hope and the distribution of flow will depend on the water level in Lake Appadare (i.e. when Appadare is empty or low, most of the flow will go into Lake Hope but as the level in Appadare rises, it is likely that the relative percentage of outflow into Lake Hope will decrease and that into the lower Cooper will increase).

During November 2011, we were able to gauge all flow into and out of Lake Appadare. The Cooper inflow to Lake Appadare was 285 MLd^{-1} while the outflow into the lower Cooper from Lake Appadare was 278 MLd^{-1}. The Lake Hope channel was found to be flowing **out** – into Lake Appadare with a discharge of 38 MLd^{-1}. Given the uncertainty in the flow gauging (highest for the Lake Hope outflow because of very low current velocities) and evaporative losses from Lake Appadare, these observations indicate that when Lake Hope is full, nearly all of the Cooper flow continues downstream and that Lake Hope will also contribute some discharge to the downstream Cooper flow. At the time of the field visit in mid-November 2011, there was probable fish-negotiable connection from Lake Eyre North to some point upstream of Kudnarri Bridge, possibly as far as the lower reaches of the Main Branch. At this stage there was definitely no connection with the upper reaches of the Main Branch (e.g. the outflow from Embarka Swamp was completely dry) and connection along the Northern Overflow to the Northwest Branch was unlikely. During April 2012, no flow was observed into or out of Lake Appadare and Lake Hope, although Lakes Hope and Appadare were connected. Upstream connection was likely to be very limited as even the inflow channel to Lake Appadare was very shallow at this time (<0.3 m, not negotiable with a kayak).

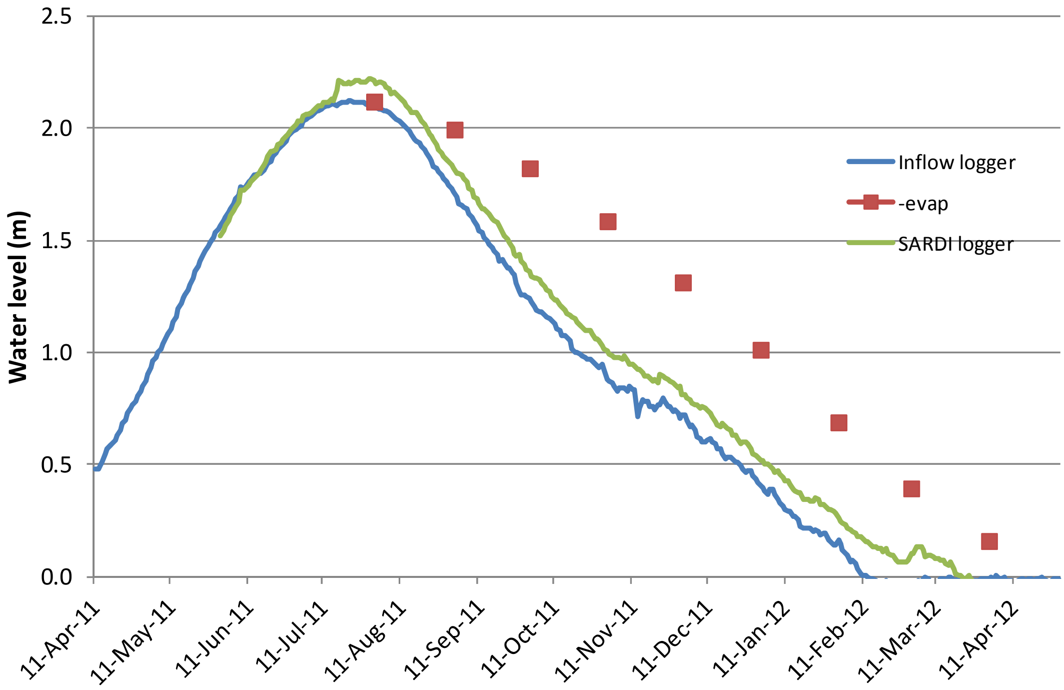


Figure 12. Hydrograph of water level at the Lake Hope inflow channel logger (blue line).

The brown squares show the expected trajectory if water loss from the peak filling is only due to evaporation. Also shown in the green is the SARDI logger daily logger data (with 2.0 m subtracted to make equivalent with the inflow logger).

The contribution of a full Lake Hope to downstream flow in the Cooper is also indicated by the Lake Hope hydrograph (Figure 12). The expected evaporative loss trajectory from a full and disconnected Lake Hope is shown in Figure 12 by the brown squares. The much higher actual loss rate (blue line) indicates that from peak levels, there must be some outflow from Lake Hope into Lake Appadare and then into the lower Cooper (as confirmed by the flow gaugings in November 2011). The observed and evaporative loss rates become approximately parallel from January 2012 and this probably coincides with cessation of flow along Cooper Creek and out of Lake Hope. Very similar data were recorded by the inflow logger and the SARDI logger located in the lake near the fishery camp (2.0 m has been subtracted from the SARDI record in Figure 12 to make it more comparable to the depth of the inflow logger). Given the similarity of these records, it is recommended that only one site be monitored and this should be the SARDI logger in the lake that will measure drawdown rates as the lake becomes fully disconnected.

Interestingly, Lake Hope appears to be an exporter of salt to Cooper Creek during flow recession. Inflow to Lake Appadare (from Cooper Creek) in November 2011 had a conductivity of 0.51 mS/cm while outflow from Lake Hope (to Lake Appadare) had a conductivity of 1.69 mS/cm, resulting in the outflow of Lake Appadare (into Cooper Creek) having a conductivity of 0.83 mS/cm.

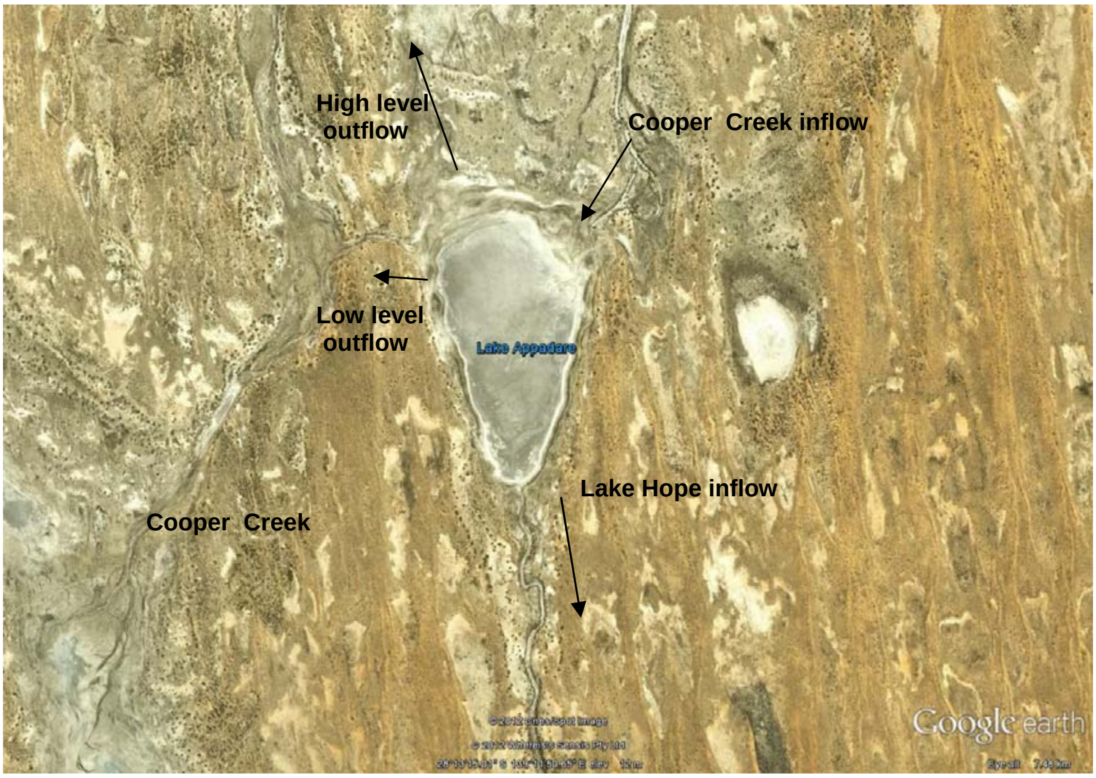


Figure 13. Google Earth image (top) showing inflow and outflow points for Lake Appadare. Middle photograph shows low level outflow channel from Lake Appadare in November 2011 and lower photograph shows Lake Appadare inflow channel under no flow conditions in April 2012.

3.2.9 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) or anthropogenic changes (e.g. upstream water extraction or changes in flow paths due to infrastructure development). Previous studies and observations during the Cooper project 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. It will be interesting to see if the Cooper project fish results show a similar finding.

- 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 long-term changes in flow patterns are likely to be quite subtle at first, particularly given the natural variability of the system. Except in the reach downstream of Innamincka, much of the Cooper Creek wetlands would have experienced drier than ‘average’ periods in the past. 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, particularly salinity, was not a significant issue during the study period. This is not surprising considering the large floods during this period resulting in remarkably consistent water quality parameters across Cooper Creek (Appendix 2). The only sites with elevated electrical conductivity (EC>1 mS/cm) were some of the lower reach sites (Lake Killalpannina, Lake Hope, Yaningurie Waterhole on Strzelecki Creek). Even the most downstream site, Cuttupirra Waterhole, had moderate EC (<1 mS/cm) despite this reach reportedly experiencing high salinity during periods of no flow (Gerald Nanson pers. comm.). The EC in the downstream lakes was typically higher than the main channel streamflow and this indicates that these lakes are significant contributors to stream salinity in the lower Cooper. For instance, in November 2011, the EC of outflow from Lake Apadare was >60% higher than the inflow due to mixing with more saline outflow from Lake Hope. The most likely mechanism for this process is that during wet periods, the lakes are zones of recharge but when they dry the salinity of the shallow groundwater and the lake sediments increases due to concentration of solutes from evapotranspiration. This build-up of solutes during the dry periods results in in-flowing floodwater re-dissolving these solutes and increasing in salinity. This process has been observed and inferred in the Coongie Lakes (Costelloe et al., 2009).

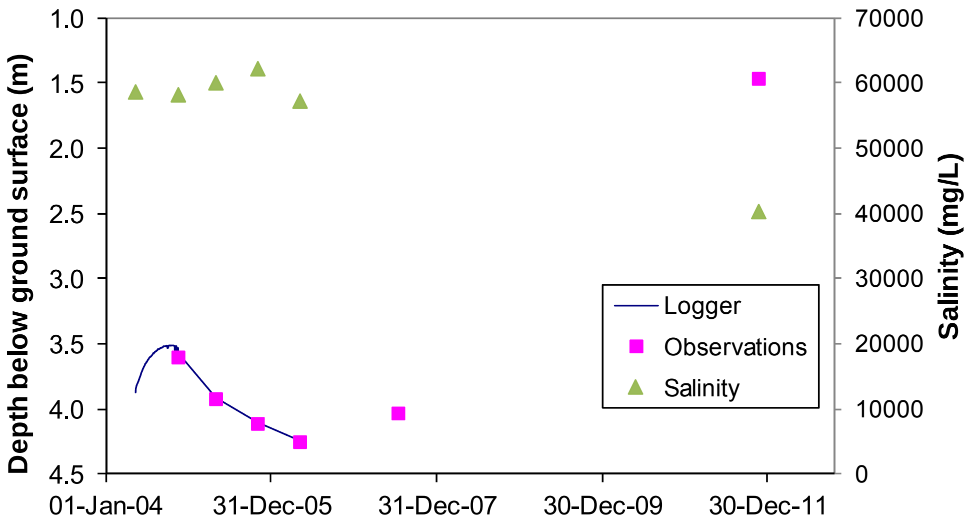
There are no management implications for these modest changes in streamflow salinity but the process understanding is useful when defining ‘thresholds of potential concern' for water quality data collected from Cooper Creek. The elevated salinity of the lower reach lakes may have important implications for understanding the lower trophic levels of the food web in these locations. For instance, the elevated EC levels observed in Lakes Hope and Killalpannina would result in changes to the zooplankton and algal assemblages of these lake ecosystems (Costelloe et al., 2005; Shiel et al., 2006).

3.4 Groundwater interactions

The extent of groundwater – surface water interactions in the SA reaches of Cooper Creek is not well understood. 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 this reach was found to occur below the level of the channels and so losing conditions between the river and groundwater consistently prevailed.

Some data have also been collected in the Coongie Lakes wetlands and this shows that the unconfined groundwater occurs at shallow depths and is typically highly saline, except under the more frequently inundated lakes (Costelloe et al., 2009). In contrast to the middle reaches of Cooper Creek in Queensland, the groundwater around the Coongie Lakes is shallower (<5 m deep). The shallowness of the groundwater is likely a combination of recharge from Cooper Creek and approaching the regional groundwater discharge zone of Lake Eyre, therefore, much of the Cooper in South Australia is likely to be characterised by shallow groundwater, although monitoring data are scarce. In the Coongie Lakes, as a result of the shallow groundwater depths, the soil water of the sediments of the more ephemeral lakes (e.g. Goyder and Apanburra) and surrounding some of the lakes (e.g. Toontoowaranie) is saline due to evaporation from the shallow water table. This is likely to result in less diverse algal seed-banks and zooplankton egg-banks in these saline lake beds (Skinner et al., 2001), as well as having an effect on the vegetation that can grow in the wetlands and the surrounding riparian vegetation (see Gillen, 2010 and Gillen and Reid, 2012 for discussion of effects of soil salinity on vegetation assemblage). While unproven, it is suspected that the distribution of red gums on Cooper Creek is related as much to the groundwater salinity as it is to the surface water regime at a site (e.g. frequency of flooding and drying).

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 Coongie Lakes show that significant rises in highly saline water can occur in response to flood events and this may place considerable osmotic stress on the ability of the riparian Eucalypt species to extract soil water for transpiration. This is illustrated using data from a monitoring bore located approximately 100-200 m from the northern riparian fringe of Lake Toontoowaranie (Figure 14). During the November 2011 field-trip, this monitoring bore was accessed and showed that the unconfined groundwater was significantly shallower and only moderately less saline compared to the 2004-2007 period, probably in response to recharge from the 2010 flood. The rise of highly saline groundwater (slightly more saline than seawater) to depths of around 1.5 m below the ground surface is likely to have significant effects on the riparian and floodplain vegetation distribution.



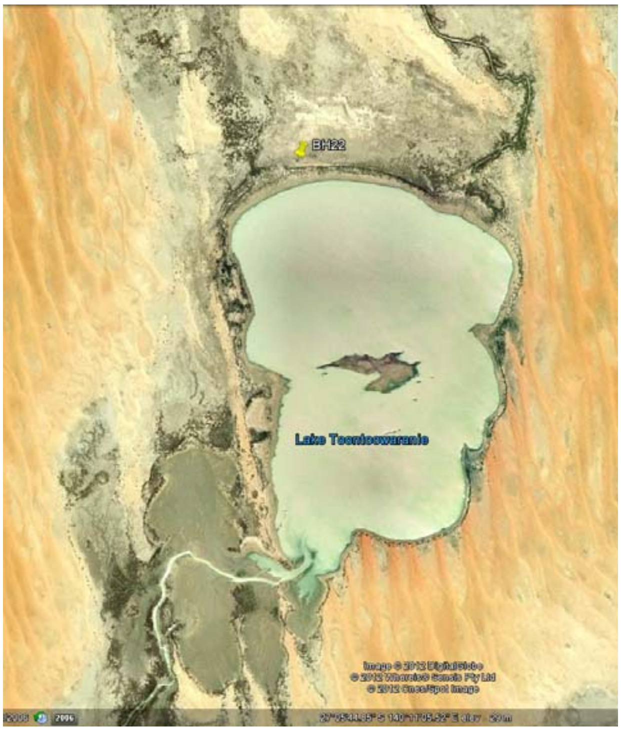


Figure 14. Upper panel shows unconfined groundwater level fluctuations from a monitoring bore located approximately 100 m north of the Lake Toontoowaranie riparian zone.

The blue line is from a logger and the purple squares show manual measurements. The lower panel shows a Google Earth image of Lake Toontoowaranie and the position of the monitoring bore.

3.5 Coolibah regeneration

The Cooper Creek project provided the opportunity to collect some data on the regeneration of *Eucalyptus coolabah*, the keystone riparian tree species of Cooper Creek, and its links to flood processes.

The key observations from the fieldwork were:

- There has been a major regeneration event in response to the 2010 flood. Eucalyptus seedlings were commonly observed throughout the study reach (see example in Figure 15), including locations on the Northwest Branch, Main Branch and lower Cooper (at least as far as Gywdir's Crossing waterhole). The small size of the seedlings (typically 0.1-0.75 m high in April 2011) is consistent with germination in response to the 2010 flood. This regeneration event is likely to be highly significant for successful recruitment of riparian eucalypt species in the catchment.

- The size of the 2010 flood and its occurrence in a flood cluster only occurs every 20-40 years and so this represents a one-in-a-generation regeneration event. Following the recruitment success of key riparian and floodplain plants would represent a unique research opportunity. In particular, mapping the distribution of areas of successful recruitment and linking these to flooding patterns, soil salinity variations and grazing pressures would greatly add to our knowledge of the eco-hydrology of Cooper Creek and assist in the sustainable management of the area (e.g. protecting key regeneration – recruitment locations from grazing.

- Most of the regeneration occurred as clusters of seedlings in floodplain positions and fewer were observed in bank-top positions, the latter being the dominant location of mature coolibahs in the riparian zone.

- Some grazing pressure was observed with the tips of the seedlings being the preferred grazing. The best evidence of this was a location at Munga Munga Waterhole (Wilpinnie Creek, a distributary from the main channel of Cooper Creek). Here a large cluster of seedlings was observed occurring on a bank position, both upgradient and downgradient of mature coolibahs. A staked position was established in April 2011 and growth in specific seedlings was observed in November 2011 but reductions in the height of seedlings, caused by grazing of the tips, were observed in April 2012. This area was open to cattle grazing but it is not known whether cattle, rabbits or native species are responsible for most of the grazing.

- The remarkable toughness and capacity for grazed or damaged coolibahs to regenerate (to some degree) is shown in Figure 16. At a floodplain waterhole on the Northwest Branch, a near dead stump of coolibah, which has been used as a rubbing post by cattle, shows some epicormic growth in response to the sequence of wet years from 2010-2012.

- In addition to the eucalypt regeneration, spectacular examples of flood-related growth of more herbaceous vegetation was observed at many locations and is more fully described in Gillen and Reid (2012). Figure 16 shows the floodplain surrounding Lake Dare where there has been amazing vegetation growth in response to the 2010-2011 floods and local rainfall.

Figure 15. Top photo shows cluster of eucalypt seedlings (could be red gums or coolibahs) growing at the Northwest Branch windmill site. Bottom photo shows the extensive root system put down by these seedlings with the root length being equal to or longer than the seedling height.

Figure 16. Top photo shows an example of the remarkable regeneration capacity of coolibahs – epicormic growth on a near-dead coolibah stump. Bottom photo shows the spectacular herbaceous growth on the floodplain surrounding Lake Dare (Coongie Lakes) in response to flooding and rainfall during 2010-2012.

3.6 Algal observations

Samples of algae were collected from most of the sampled waterbodies and qualitatively analysed by Joan Powling (University of Melbourne) who had previously analysed algae samples from the Aridflo project and other University of Melbourne hydrological trips to Cooper Creek. 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.

1. The samples collected over 2011-2012 from Cooper Creek showed a diverse and abundant assemblage of algae with representatives from all major algae phyla. Such a diverse assemblage would appear to represent healthy conditions within Cooper Creek during the flood cluster of 2010-2012.

2. Blue-green algae occurred at nearly all sites but typically had high diversity and were not the dominant phylum. Potentially toxic species were identified at a number of sites but not in high abundances. The sites with the highest blue-green algae abundances were Lake Toontoowaranie and Apanburra Channel in November 2011. During the period 2000-2012, blue-green algal blooms have been observed in the Coongie Lakes during May 2004 but with high species diversity and not dominated by any single species, potentially toxic or not (see photo in Figure 16). It appears that blue-green algal blooms are part of the natural cycle but it is unclear if they are mostly restricted to the open lake and connecting channel environment of the Coongie Lakes (as in May 2004 and November 2011) or can occur elsewhere in the system. One potentially toxic species, Cylindrospermopsis raciborski, was observed for the first time in April and November 2011 but not in April 2012. This species is most commonly found in tropical systems and its presence in the lower Cooper is probably related to the major flood of 2010.

3. Lake Hope had a diverse and abundant algal assemblage and generally low zooplankton diversity and abundance. This is consistent with a large fish population eating the zooplankton. It would be of interest to the ecology of this system to track how the algal and zooplankton assemblage changes over the course of the filling-drying cycle and how this relates to changes in the fish assemblage.

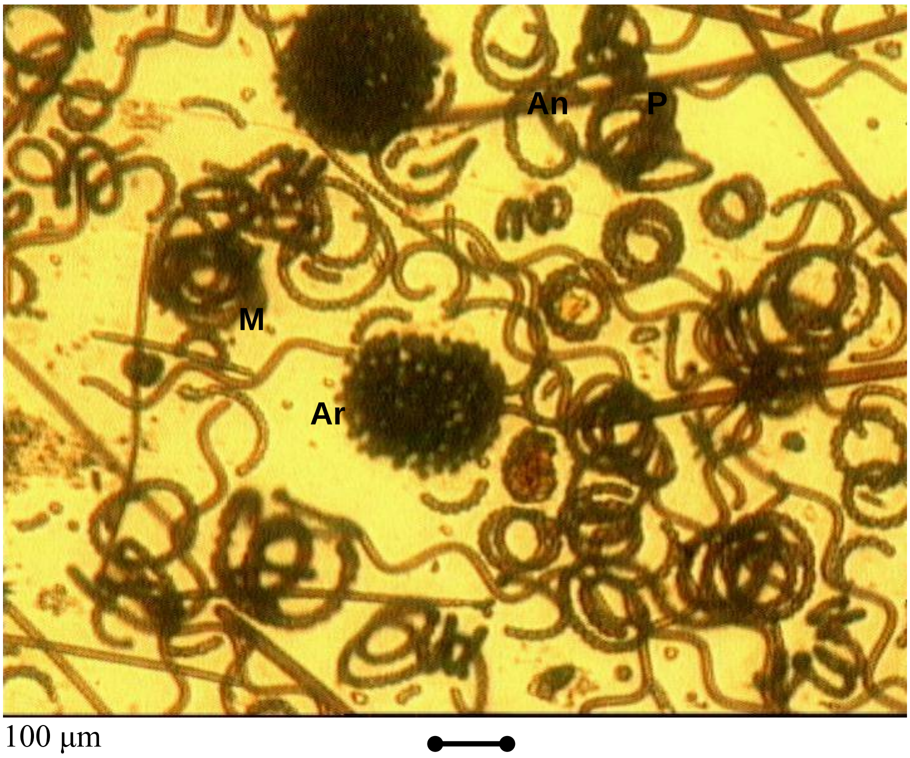


Figure 16. High diversity and abundance of cyanobacteria in a tow sample from Lake Apanburra collected in May 2004.

Sample was collected during the rising stage of the flood at this location. The more abundant taxa in the sample are; M (*Microcystis aeruginosa*), An (*Anabaena circinalis*), P (*Planktothrix* sp.), Ar (*Arthrospira* aff. *maxima*).

4. RECOMMENDATIONS

4.1 Hydrological monitoring

The level of hydrological monitoring (installed and planned) in the SA reaches of Cooper Creek is adequate for a remote, arid region catchment but could be better coordinated. At present, the monitoring has the capacity for the volumetric assessment of Cooper flow coming into the State and of monitoring flows reaching the terminal areas for smaller annual flows. There is also some capacity for monitoring flows in the lower Cooper that support a commercial fishery.

- The Cullyamurra gauging station is well-rated and provides an excellent record of flow coming into South Australia from the Cooper Creek catchment. This is a high value gauging station and has the commitment for ongoing operation. With its reasonable length of record (1973 to present) it has the capacity for contributing to analysis of flow regime changes (i.e. by climate change, catchment changes or water extraction) in Cooper Creek.

- The recently installed telemetered water level monitoring station at Kudriemitchie on the Northwest Branch should provide reasonable monitoring of flows entering the Coongie Lakes wetlands. Flows into Coongie are a key 'canary in the coalmine' indicator of critical flow regime changes because of Coongie Lake forming the terminus of the smaller annual flows and having high ecological value. It is highly recommended that flow gaugings are conducted whenever possible to build-up a ratings curve for this site.

- The SANTOS telemetered water level monitoring sites at Scrubby Camp Waterhole (Northwest Branch), Embarka Waterhole (Main Branch) and Walkers Crossing (Main Branch, only installed in July 2012) provide valuable data and it is recommended that these time-series of data be incorporated into the SA State hydrological database, if SANTOS is agreeable with this. The development of rating curves for these sites would further enhance their value. In particular, linking the Embarka Waterhole and Walkers Crossing datasets to flow out of Embarka Swamp would be very useful in monitoring potential changes in the flow regime at the current extent of the smallest annual flows on the Main Branch.

- Monitoring flows in the lower Cooper (i.e. downstream of the Main Branch – Northern Overflow junction) has lower priority because of the lower frequency of flow but is useful for monitoring condition of the lower reaches and assisting in the management of the Lake Hope fishery and oil-gas exploration and production activities. Beach Energy is currently manually measuring water levels at their Kudnarri bridge (Callawonga camp) site. This is a useful measuring point on the lower Cooper and a Project logger is currently installed at this site. It is recommended that this logger site be maintained (perhaps by Beach Energy or

LEBRA) and/or the Beach Energy observations collected on a periodic basis be incorporated into the State hydrological database.

- Since 2011, water levels at Lake Hope have been monitored by a Project logger (inflow channel) and a LEBRA logger (lake). These loggers are collecting very similar information and the LEBRA logger is best situated to measure the drawdown in Lake Hope during its drying phase. It is recommended that the LEBRA logger be maintained to capture as much of the drying phase of the lake as possible and that the Project logger be removed when convenient. Given the commercial importance of Lake Hope as a fishery, it is recommended that a water level logger be reinstalled by LEBRA prior to the next filling of Lake Hope to capture its complete filling and drying cycle.
- The collection of gauging data at monitored sites to construct ratings curves has been recommended above. In addition, the capacity to understand and model the hydrology of Cooper Creek would be greatly enhanced by the collection of additional discharge data at key distributaries in the system. The most important of these is the Northwest Branch – Main Branch junctions and if DEWNR hydrographers are collecting discharge data in the area (e.g. at Cullyamurra) it would be useful to add to the discharge data collected during the Cooper Creek project. Access to the Northwest Branch – Main Branch junctions is best achieved by boat launched at Minkie Waterhole. Gaugings at Scrubby Camp, Kudriemitchie, Embarka Waterhole and Walkers Crossing are also recommended and access to these sites is relatively straight-forward, except in very large flood events.
- The flow monitoring data need periodic analysis (e.g. 5 yearly) to identify if ‘thresholds of potential concern’ (TPC) have been reached at these sites. Useful sites for developing TPCs are the extent of the smallest annual flows into South Australia. These are Coongie Lake (Northwest Branch) monitored by the DEWNR Kudriemitchie logger and Embarka Waterhole (Main Branch) monitored by the SANTOS logger. The latter site may occur downstream of the extent of smallest flows and this should be further investigated. If the frequency of inflow becomes persistently less common into these sites (i.e. stops receiving inflow each year) then this should be considered as a TPC as it may lead to important ecological changes (i.e. decreased fish diversity, extent of red gums moving further upstream of Coongie Lake).

4.2 Cullyamurra Waterhole and other refuges

The bathymetric surveys have confirmed the importance of Cullyamurra Waterhole as the principal refuge of Cooper Creek and the entire LEB, and this underlines its ecological importance and requirement for management. In terms of further monitoring, periodic measurements of cross-sections would be useful to check that sedimentation is not affecting the waterhole (e.g. at the gauging station or downstream of the Choke pool). In addition, the installation of a couple of monitoring bores into the local unconfined groundwater near Cullyamurra Waterhole would be useful to determine if groundwater connectivity plays a role in the persistence of the waterhole. Other important management actions for the protection of Cullyamurra Waterhole are:

- No water extraction during periods of no flow,
- Monitor that drop toilets aren't leaking into the groundwater and then into the waterhole. This has implications for water quality at Innamincka.
- Improve tourist education on the need for low impact camping, particularly in protecting the riparian vegetation and limiting erosion.

The Nappa Merrie Waterhole was also identified as the second deepest refuge waterhole on Cooper Creek and some consideration should be given to its management (i.e. minimising water extraction beyond domestic use during long drought periods).

The refuge waterholes of the Northwest Branch (particularly Scrubby Camp and Kudriemitchie) and Main Branch (particularly Embarka and Narie) are less critical to the environmental health of the system but management plans should also be considered for these waterholes too. The plans should consider the points made above for Cullyamurra and Nappa Merrie.

4.3 Feral animal monitoring

The fish surveys of the Cooper Creek project did not capture any cane toads (Schmarr et al., 2012) so the best evidence to date suggests that they have not yet reached the South Australian reaches of Cooper Creek, despite the floods and general high degree of connectivity occurring since 2010. In terms of the hydrology, the confined reach between the Nappa Merrie bridge and Innamincka forms the logical place to locate targeted sampling/monitoring for cane toads. This is in accord with the recommendations of the geomorphology component of the Cooper Creek project (Wakelin-King, 2012). The confinement of this reach, with its surrounding arid hills, makes this reach the main pathway for cane toad invasion into South Australia. Audio sampling stations to identify adult cane toads and baited traps for tadpole detection during periods of no flow would be the recommended sampling techniques.

4.4 Further research and data collection

- The definition of flood patterns and linking these to the Shuttle radar digital elevation model (DEM) data would provide an invaluable database for the Cooper, both for ecological studies and management of extractive and pastoral industries. In addition, the amount of infrastructure (roads, bridges, pipelines, drill pads etc) in the area has increased over the past decade and a library of flooding patterns are required to ensure that these infrastructure assets are not resulting in any significant changes in flow patterns. 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.

- On-going management of Cooper Creek in South Australia would be greatly strengthened by the development of a new generation hydrological model that is capable of simulating the complex flow paths of this river system. A grid-based hydro-dynamic model would be ideal but this approach needs to be evaluated to determine if it is feasible given the very flat gradients, complex flow paths and paucity of data for Cooper Creek. The University of Melbourne submitted a proposal to the Australian Research Council (ARC) Discovery program for a research project that would investigate the development of a new generation hydrological model. However, this project proposal was not successful but it is hoped that this proposal can be resubmitted to funding programs in 2013.
- The size of the 2010 flood and its occurrence in a flood cluster only occurs every 20-40 years and so this represents a one-in-a-generation regeneration event. Following the recruitment success of key riparian and floodplain plants would represent a unique research opportunity. In particular, mapping the distribution of areas of successful recruitment and linking these to flooding patterns, soil salinity variations and grazing pressures would greatly add to our knowledge of the eco-hydrology of Cooper Creek and assist in the sustainable management of the area (e.g. protecting key regeneration – recruitment locations from grazing). This recommendation has been developed as a project proposal that was submitted to the Commonwealth's 2012 Biodiversity Fund. Unfortunately this proposal was not successful but it is recommended that a similar proposal be submitted to future funding rounds of the Commonwealth Biodiversity Fund.
- The link between groundwater (e.g. depth, gradient with respect to the river, salinity) and the distribution of vegetation (and linked ecological patterns, such as the distribution of riparian birds) is not well understood. For instance, it is suspected that the distribution of red gums on Cooper Creek is related as much to the groundwater salinity as it is to the surface water regime at a site (e.g. frequency of flooding and drying). Further research into the links between groundwater depth and salinity, soil salinity and vegetation patterns would provide improved understanding of causes of vegetation changes and the most appropriate management actions to protect key vegetation communities. The installation of monitoring bores into the water table at targeted locations would provide valuable information but is unlikely under the current State monitoring program. However, the evaluation of possible effects of coal-seam and

unconventional gas extraction from the Cooper Basin may provide an opportunity for specific, targeted research into this area.

- Lake Hope had a diverse and abundant algal assemblage and generally low zooplankton diversity and abundance. This is consistent with a large fish population eating the zooplankton. It would be of interest to the ecology of this system to track how the algal and zooplankton assemblage changes over the course of the filling-drying cycle and how this relates to changes in the fish assemblage. This would assist in the sustainable and optimal management of the Lake Hope fishery.

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.

Callen, R.A. Bradford, J. 1992. The Cooper Creek fan and Strzelecki Creek – hypsometric data, Holocene sedimentation and implications for human activity. *Mines and Energy Review, South Australia* **158**, 52-57.

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. 1998. Modelling of flood patterns, using remote sensing, in the Coongie Lakes wetlands, northeastern South Australia. Master of Applied Science thesis, University of Melbourne.

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., 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.

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., Reid, J.R.W. 2012.

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.

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. Flow transmission along an arid zone anastomosing river, Cooper Creek, Australia. *Hydrological Processes* **8**, 137-154.

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

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.

Knighton, A.D., Nanson, G.C. 2002. Inbank and overbank velocity conditions in an arid zone anastomosing river. *Hydrological Processes* **16**, 1771-1791.

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

Larsen, J.R., 2012. Aspects of the contemporary and Quaternary hydrology of the Lake Eyre Basin, central Australia. PhD thesis, University of Wollongong.

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.

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.

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.

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.

Schmarr, D.W. 2012

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.

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. 2012.

5. APPENDICES

5.1 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)
Yaningurie	1-Apr-11	10:00						0	
Munga Munga	2-Apr-11	14:00						0.00	0.0
Turra	3-Apr-11	12:05							
Main Branch south channel	3-Apr-11	16:00	65.3	52.53	61.1	62.24	62.16	60.67	5241.5
Minkie	4-Apr-11	10:00	195.08	183.93	180.47	186.24		186.43	16107.6
Gidgealpa	5-Apr-11	10:00						0.00	0.0
Embarka outflow	6-Apr-11	10:00	155.21	152.09	152.66	151.09		152.76	13198.7
Beach bridge LB culvert	7-Apr-11	10:00	1.74	1.75				1.75	150.8
Beach bridge main channel	7-Apr-11	10:00	7.71	6.96	7.22	7.49		7.35	634.6
Beach bridge RB culvert	7-Apr-11	10:00	0.44	0.46				0.45	38.9
Eaglehawk	7-Apr-11	10:00						0	
Gwydir's Crossing	8-Apr-11	7:30							
Lake Killalpaninna bank pit	9-Apr-11	16:00							
Lake Hope	10-Apr-11	12:00							
Lake Hope inflow	10-Apr-11	16:50	6.61	6.76	6.45	6.51		6.58	568.7
Cooper downstream of Appadare	10-Apr-11	12:30	0.253					0.25	21.9
Cuttupirra	12-Apr-11	10:30							
Lake Killalpannina	9-Nov-11								
Cuttupirra	11-Nov-11	8:00	3.21	3.16	3.33	2.8		3.13	270.0
Lake Hope Inflow	13-Nov-11	8:45	0.74	0.53	0.1	0.37		0.44	37.6
Lake Appadare outflow	13-Nov-11	9:30	3.46	3.25	3.1	3.06		3.22	278.0
Lake Appadare inflow	13-Nov-11	10:30	3.39	3.33	3.11	3.36		3.30	284.9
Callawonga Bridge	14-Nov-11	8:00	1.64	1.59	1.58	1.61		1.61	138.7
Nappeonnie	15-Nov-11	7:00	0	0	0	0		0.00	0.0
Nappa Merrie	15-Nov-11	9:00	0	0	0	0		0.00	0.0
Dig Tree	15-Nov-11	10:30	0	0	0	0		0.00	0.0
Tirrawarra	16-Nov-11	8:00	0	0	0	0		0.00	0.0

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)
Narie	16-Nov-11	11:30							
Northwest Branch near Coongie	17-Nov-11	7:30	0	0	0	0		0.00	0.0
Apanburra Channel	17-Nov-11	12:00	0.24	0.24	0.32	0.26		0.27	22.9
Lake Toontoowaranie	17-Nov-11	13:30							
Browne Creek	17-Nov-11	16:00	0.6	1.07	0.86			0.84	72.9
Ellar Creek	18-Nov-11	10:00	-1.81	-1.55	-2	-1.77		-1.78	-154.0
Moorari	19-Nov-11	10:30						0	0
Embarka WH	20-Nov-11	7:30						0	0
Merimelia WH	20-Nov-11	10:15						0	0
Munga Munga WH	20-Nov-11	14:45						3.13	270.0
Cullyamurra	14-Apr-12	10:00	85.05	86.59	89.70	84.22	86.39	7464.1	85.05
Burkes	14-Apr-12	14:30							
Policemans	13-Apr-12	11:30							
Munga Munga	15-Apr-12	8:45							
Ooranie Ck	15-Apr-12	10:55							
Minkie	15-Apr-12	14:30							
Tilcha	15-Apr-12	12:30	82.85				82.85	7158.2	82.85
upstream of Main Branch junction	17-Apr-12	14:00	86.79	88.12	85.59	84.77	86.32	7457.8	86.79
Northwest Branch at MB junction	17-Apr-12	12:00	46.17	45.01	46.70	45.56	45.86	3962.3	46.17
Scrubby Camp WH	18-Apr-12	13:30	47.27	45.65	45.44	45.69	46.01	3975.5	47.27
Cutrabelbo WH	19-Apr-12	17:00	11.37	9.66	11.26	10.06	10.59	914.8	11.37
Tirrawarra WH u/s	20-Apr-12	8:00	9.53	9.59	9.54	9.42	9.52	822.5	9.53
Tirrawarra @ Mudrangie channel	20-Apr-12	9:45	24.23	25.19	25.08	24.48	24.75	2138.0	24.23
Tirrawarra WH d/s	20-Apr-12	10:05	34.14	34.16	35.30	35.74	34.84	3009.7	34.14
Kudriemitchie WH	20-Apr-12	16:00	32.86	34.08	32.73	33.19	33.22	2869.8	32.86
Northwest Branch near Coongie	24-Apr-12	12:30	23.35	23.93	24.96	24.30	24.14	2085.3	23.35
Browne Creek (at fence-line)	24-Apr-12	16:30	15.27	18.36	17.24	16.12	16.75	1447.0	15.27

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)
Ellar Creek	25-Apr-12	10:30	12.91	12.10	11.45	12.31	12.19	1053.4	12.91
Appanburra Channel	26-Apr-12	10:10	3.40	3.34	4.04	4.00	3.70	319.2	3.40
Montepirie WH	18-Apr-12	16:15							
Napeowie	19-Apr-12	9:00							
Lake Dare inflow channel	24-Apr-12	7:15							
Main Branch junction south	17-Apr-12	13:40	17.73	16.60	17.25	17.45	17.26	1491.0	17.73
Main Branch junction north	17-Apr-12	12:30	23.94	23.00	24.21	23.59	23.69	2046.4	23.94
Embarka WH	21-Apr-21	17:00	32.23	32.69	31.53	32.07	32.13	2776.0	32.23
Embarka Outflow	22-Apr-21	9:00	20.95	21.29	22.60	22.02	21.72	1876.2	20.95
Narie WH	27-Apr-12	8:00	25.02	24.83	24.58	24.27	24.68	2131.9	25.02
Cuttapirie Corner WH	22-Apr-21	17:00	20.39	19.35	19.34	19.18	19.57	1690.4	20.39
Parachirrinna WH	27-Apr-12	16:00	13.83	14.44	13.79	13.54	13.90	1201.0	13.83
Toonman WH	27-Apr-12	10:00							
Lake Hope inflow channel	28-Apr-12	17:15	-0.20	0.00	-0.36	0.07	-0.12	-10.6	-0.20

5.2 Appendix 2 – Water quality data

Location	Date	Time	Temp □ C	pH	Eh mV	Eh ORP	Cond mS/cm	Salinity mg/L	DO mg/L	Turb NTU
Yaningurie	1-Apr-11	10:00	24.46	7.39	-12	184	1.26	0.806	11.8	96.5
Munga Munga	2-Apr-11	14:00	25.09	5.6			0.229	0.148	8.72	72.8
Turra	3-Apr-11	12:05	21.82	6.52			0.22	0.143	10.2	45
Main Branch south channel	3-Apr-11	16:00								
Minkie	4-Apr-11	10:00								
Gidgealpa	5-Apr-11	10:00								
Embarka outflow	6-Apr-11	10:00								
Beach bridge LB culvert	7-Apr-11	10:00								
Beach bridge main channel	7-Apr-11	10:00	22.7	5.98			0.337	0.219	12.65	43.4
Beach bridge RB culvert	7-Apr-11	10:00								
Eaglehawk	7-Apr-11	10:00								
Gwydir's Crossing	8-Apr-11	7:30								
Lake Killalpaninna bank pit	9-Apr-11	16:00	24.6	8.74			1.145	0.75		
Lake Hope	10-Apr-11	12:00								
Lake Hope inflow	10-Apr-11	16:50								
Cooper downstream of Appadare	10-Apr-11	12:30	24.3	7.64			0.416	0.27	13.65	172
Cuttupirra	12-Apr-11	10:30								
Lake Killalpannina	9-Nov-11		26.2	8.55			2.43	1.56	9.33	61.5
Cuttupirra	11-Nov-11	8:00	22.92	8.45	-103	114	0.888	0.569	7.31	190
Lake Hope Inflow	13-Nov-11	8:45	25.1	9.21			1.69	1.08	7.62	97.2
Lake Appadare outflow	13-Nov-11	9:30	25.1	9.39			0.826	0.527	8.24	122
Lake Appadare inflow	13-Nov-11	10:30	25.94	9.3			0.507	0.324	7.24	136
Callawonga Bridge	14-Nov-11	8:00	24.98	8.55	-108		0.526	0.337	4.13	195
Nappeonnie	15-Nov-11	7:00	25.72	7.99	-78		0.647	0.414	6.43	170
Nappa Merrie	15-Nov-11	9:00	26.9	6.59			0.516	0.33	6.04	118
Dig Tree	15-Nov-11	10:30	27.8	8.07			0.542	0.347	5.66	197
Tirrawarra	16-Nov-11	8:00	25.95	7.52			0.361	0.235	6.38	347
Narie	16-Nov-11	11:30	26.4	7.84			0.391	0.254	4.35	180
Northwest Branch near Coongie	17-Nov-11	7:30	25.34	7.66	-56		0.424	0.276	3.14	482
Apanburra	17-Nov-	12:00	25.77	8.23			0.406	0.264	7.91	656

Location	Date	Time	Temp □ C	pH	Eh mV	Eh ORP	Cond mS/cm	Salinity mg/L	DO mg/L	Turb NTU
Channel	11									
Lake Toontoowaranie	17-Nov-11	13:30	27.39	7.01	-21		0.376	0.245	12	345
Browne Creek	17-Nov-11	16:00	29.78	8.8	-125		0.494	0.322	11.97	199
Ellar Creek	18-Nov-11	10:00								
Moorari	19-Nov-11	10:30	27.6	8.32			0.441	0.286	7.89	237
Embarka WH	20-Nov-11	7:30	27.11	8.18			0.392	0.255	6.49	67.7
Merimelia WH	20-Nov-11	10:15	26.76	7.77			0.469	0.305	3.84	171
Munga Munga WH	20-Nov-11	14:45	26.22	8.71			0.44	0.285	8.9	179
Cullyamurra	14-Apr-12	10:00	20.82	7.5			0.161	0.109	7.6	68.1
Burkes	14-Apr-12	14:30	21.48	7.32	-35	139	0.166	0.108	8.58	78.3
Policemans	13-Apr-12	11:30	20.14	7.33	-35	146	0.168	0.109	8.05	74.8
Munga Munga	15-Apr-12	8:45	20.48	7.61	-52	95	0.153	0.099	6.64	552
Ooranie Ck	15-Apr-12	10:55	19.77	7.59	-53	92	0.081	0.053	5.8	>800
Minkie	15-Apr-12	14:30	22.33	7.39	-39	152	0.165	0.108	7.16	137
Tilcha	15-Apr-12	12:30	23.46	7.6	-51	67	0.166	0.108	8.1	165
upstream of Main Branch junction	17-Apr-12	14:00								
Northwest Branch at MB junction	17-Apr-12	12:00								
Scrubby Camp WH	18-Apr-12	13:30	22.18	7.82	-63	95	0.167	0.109	7.62	65.6
Cutrabelbo WH	19-Apr-12	17:00								
Tirrawarra WH u/s	20-Apr-12	8:00	23.03	7.9	-70	154	0.169	0.11	6.63	62.9
Tirrawarra @ Mudrangie channel	20-Apr-12	9:45								
Tirrawarra WH d/s	20-Apr-12	10:05								
Kudriemitchie WH	20-Apr-12	16:00	21.09	7.55	-49	159	0.17	0.111	5.81	48.3
Northwest Branch near Coongie	24-Apr-12	12:30	21.03	7.87	-67	163	0.175	0.114	4.84	30.9
Browne Creek (at fence-line)	24-Apr-12	16:30								
Ellar Creek	25-Apr-12	10:30								
Appanburra Channel	26-Apr-12	10:10	16.37	8.11	-80	137	0.297	0.193	9.39	150
Montepirie WH	18-Apr-12	16:15	22.31	8.1	-80	98	0.09	0.1	7.75	171
Napeowie	19-Apr-12	9:00	20.81	7.92	-70	56	0.115	0.075	6.45	333

Location	Date	Time	Temp □ C	pH	Eh mV	Eh ORP	Cond mS/cm	Salinity mg/L	DO mg/L	Turb NTU
Lake Dare inflow channel	24-Apr-12	7:15	18.54	8.73	-117	57	0.678	0.434	6.38	441
Main Branch junction south	17-Apr-12	13:40								
Main Branch junction north	17-Apr-12	12:30								
Embarka WH	21-Apr-21	17:00	22.55	7.75	-60	99	0.171	0.112	8.2	36.4
Embarka Outflow	22-Apr-21	9:00	22.39	7.65	-55	105	0.191	0.124	6.1	57.7
Narie WH	27-Apr-12	8:00	18.35	8.35	-94	104	0.189	0.123	6.71	103
Cuttapirie Corner WH	22-Apr-21	17:00	22.22	7.84	-66	148	0.198	0.129	5.9	310
Parachirrinna WH	27-Apr-12	16:00	18.17	8.18	-86	132	0.23	0.15	7.6	48.3
Toonman WH	27-Apr-12	10:00	17.66	8.51	-106	136	0.173	0.113	8.32	249
Lake Hope inflow channel	28-Apr-12	17:15	20.38	9.51	-163	96	3.17	2.03	11.61	113