How will declining water availability as a consequence of climate change affect habitat and species distributions in the Murray–Darling Basin?

Prepared by: Daryl Nielsen, Susan Gehrig, Nick Bond

Final report

MDFRC Publication 170

How will declining water availability as a consequence of climate change affect habitat and species distributions in the Murray–Darling Basin?

Final Report prepared for the Murray–Darling Basin Authority by The Murray–Darling Freshwater Research Centre.

Murray–Darling Basin Authority
Level 6, 33 Allara Street | GPO Box 1801
Canberra City ACT 2601

Ph: (02) 6279 0100; Fax: (02) 6248 8053

This report was prepared by The Murray–Darling Freshwater Research Centre (MDFRC). The aim of the MDFRC is to provide the scientific knowledge necessary for the management and sustained utilisation of the Murray–Darling Basin water resources. The MDFRC is a joint venture between La Trobe University and CSIRO.

For further information contact:

Daryl Nielsen

The Murray–Darling Freshwater Research Centre
PO Box 991
Wodonga VIC 3689
Ph: (02) 6024 9650; Fax: (02) 6059 7531

Email: d.nielsen@latrobe.edu.au
Web: www.mdfrc.org.au
Enquiries: mdfrc@latrobe.edu.au

Report Citation: Nielsen DL, Gehrig S, Bond N (2017). How will declining water availability as a consequence of climate change affect habitat and species distributions in the Murray–Darling Basin? Final Report prepared for the Murray–Darling Basin Authority by The Murray–Darling Freshwater Research Centre, MDFRC Publication 170/2017, Sept, 27pp.

Cover Image: Ovens River, Victoria

Photographer: Ben Gawne

Contact us

Inquiries regarding the licence and any use of the document are welcome at:

Murray–Darling Basin Authority
Level 6, 33 Allara Street
Canberra ACT 2601
Email: copyright@mdba.gov.au

Document history and status

Version	Date Issued	Reviewed by	Approved by	Revision type
Draft	9/7/2017	S Gehrig N Bond	D Nielsen	Internal
Draft	11/7	G Rees	D Nielsen	Internal

Distribution of copies

Version	Quantity	Issued to
Final	1 x PDF	Carla Tadich

Filename and path: Projects\MDBA\637 MDBA MDFRC Collaboration Agreement\BOC questions\2017-2018

Author(s): D Nielsen[1], S Gehrig[2], Nick Bond[2]

Author affiliation(s): [1]CSIRO/MDFRC, [2]La Trobe University/MDFRC

Project Manager: Daryl Nielsen

Client: MDBA and the Joints State Governments

Project Title: MDBA—MDFRC Collaboration Project

Document Version: Final

Project Number: M/BUS/637, 17/00796

Contract Number: MD2881

Finalised January 2018

Acknowledgements: The Murray–Darling Freshwater Research Centre offices are located on the land of the Latje Latje and Wiradjuri peoples. We undertake work throughout the Murray–Darling Basin and acknowledge the traditional owners of this land and water. We pay respect to Elders past, present and future. This project is supported by funding through the Murray–Darling Basin Joint Governments.

Contents

List of Tables

List of Figures

Executive summary

Rivers within the Murray-Darling Basin (MDB) and their associated floodplains and wetlands are at risk from climate change. Freshwater systems are particularly vulnerable due to their potential to become fragmented and disconnected as a consequence of reduced water availability. Climate change is likely to particularly influence rainfall patterns, temperature and evaporation rates and increase atmospheric carbon dioxide concentrations.

For many aquatic biota in the MDB, drivers of habitat change will relate to alterations in flow regimes and physiological impacts caused by increased temperatures and changes in water quantity and quality, impairing survival. Changes in rainfall and evaporation will reduce the amount of surface water run-off in the catchment, leading to diminished condition of existing communities, and an increase in fragmentation of riverine and floodplain networks and the subsequent loss of connectivity. In addition, an increase in temperature will modify the thermal habitat for many biota and increased carbon dioxide concentrations will give a competitive advantage to some species over others (e.g. C4 over C3 plants).

The characteristics and interactions of the impacts of climate change provide an indication of the type of outcomes associated with adverse conditions. These include impacts associated with increasing ephemerality, retraction of water volumes in standing water and loss of connectivity. Secondary processes including changes to food web structure, increasing predation pressure and changes to competition levels are also characteristics of impacts associated with changes in habitat under adverse conditions. These characteristics are determined by the nature of the landscape and habitat, but are also a function of the species requirements

The creation or maintenance of refuges will be particularly important for the management and conservation of freshwater ecosystems and biodiversity to stressors associated with climatic changes. Refuges must be able to facilitate key life stages for many species and provide buffering during periods of unfavourable conditions, as well as provide a recolonisation source to the surrounding area, following the return of favourable conditions.

It is recommended that research questions proposed identified in the National Climate Change Adaptation Research Plan for *Freshwater Ecosystems and Biodiversity* should be further developed. These questions relate to three key themes:

- Understanding climate change effects on freshwater ecosystems and biodiversity
- Incorporation of climate change adaptation into the policy and management of freshwater ecosystems and biodiversity
- Promote the compatibility of adaptation strategies between freshwater biodiversity conservation and management and other sectors

1 Introduction

1.1 Projected climate change and freshwater ecosystems

Freshwater ecosystems within the Murray–Darling Basin (MDB), as in many regions of the world, are vulnerable to the projected impacts of climate change (Dunlop & Brown 2008; Pittock & Finlayson 2011). Such changes pose a major threat to many ecosystems and the biodiversity that resides within them (Döll & Zhang 2010; IPCC 2014b; Willis & Bhagwat 2009). Freshwater ecosystems are likely to be particularly vulnerable to the impacts of climate change because of their relative isolation and physical fragmentation within terrestrial landscapes, their limited connectivity and their susceptibility to drying (James *et al.* 2013). Climate change may lead to a number of stressors affecting freshwater biotic communities and habitats (James *et al.* 2013). Of particular importance are changes to rainfall patterns, temperature, evaporation and increased atmospheric carbon dioxide concentrations.

The MDB contains the longest river system in Australia (Figure 1), and is characterised by the occurrence of temporally and spatially variable rainfall and temperature conditions (Dunlop & Brown 2008; Pittock & Finlayson 2011). Rainfall in the southern part of the Basin is derived from low-pressure systems that typically form in the winter–spring period, whereas the majority of rainfall in the northern part of the Basin is derived from tropical rainfall systems that form in the summer–autumn periods (Chiew *et al.* 2011; Gallant *et al.* 2012). Accordingly, rainfall in the northern part of the Basin is lower and more variable, and evaporation rates higher, compared with those in the southern part of the Basin. Due to the differing weather systems, climate change will have spatially variable effects on water availability in the Basin (Chiew *et al.* 2011; Dunlop & Brown 2008).

1.2 Climate modelling

Climate models are used to examine future global and regional climate change. These models are founded on well-established physical principles and are similar to models used to successfully forecast weather patterns. The climate projections used in this report are based on outputs of global climate models (GCMs) and in particular the ensemble of model simulations brought together for the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor *et al.* 2012). Phase 5 represents the most recent comparison of model simulations addressing projections of future climates. Greenhouse gases, such as carbon dioxide have a warming effect on global climate, by absorbing heat that would otherwise be lost to space and re-radiating it back into the earth's atmosphere (IPCC 2014a). It is extremely likely that observed global increases in average surface air temperatures between 1951– 2010 were caused by anthropogenic increases in greenhouse gas emissions, primarily because of burning fossil fuels. The CMIP5 model simulations provides climate projections based on the climate response to a set of greenhouse gas emissions that are consistent with socio-economic assumptions of how the future may evolve. Known as the Representative Concentration Pathways (RCPs), four main scenarios represent a plausible range of radiative forcing (in W m^2) in the 21st century relative to pre-industrial levels. The RCP 2.6 represents a low radiative forcing (low emissions), RCP 4.5 and RCP 6.0 represent intermediate radiative forcing (intermediate emissions) and RCP 8.5 represents high radiative forcing (high emissions). It should be noted that this report focus on the projected emissions and consequences of RCP8.5 high-emission scenario, which predicts carbon dioxide concentration stabilising around 940 ppm by the end of the 21st century.

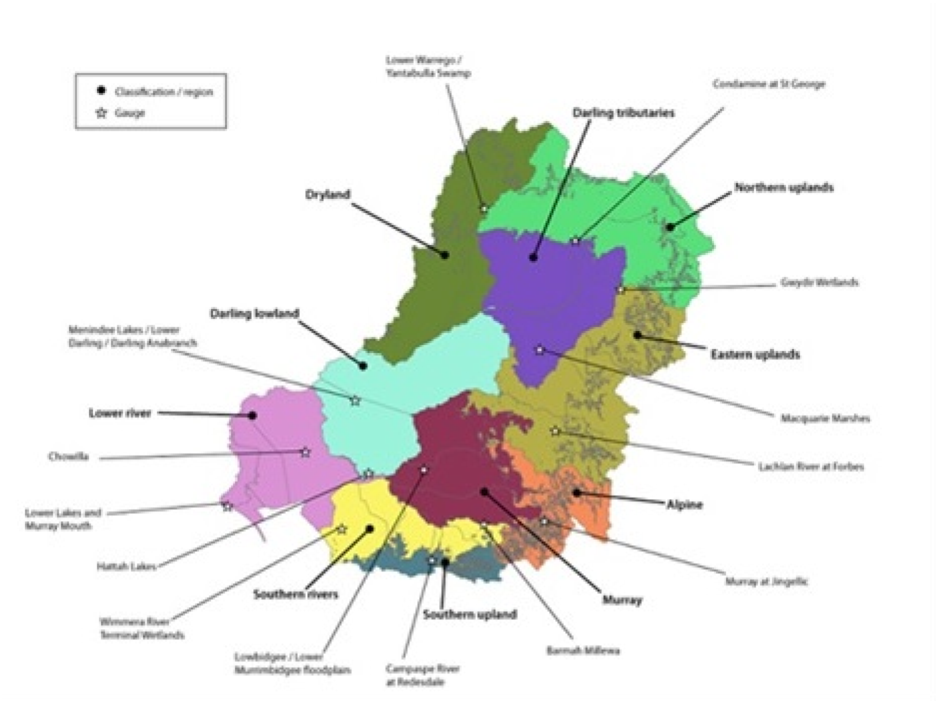

Figure 1. Climatic regions of the Murray–Darling Basin (Sheldon *et al.* 2010)

Table 1. Definition of representative concentration pathways (CSIRO and Bureau of Meteorology, Climate Change in Australia website (www.climatechangeinaustralia.gov.au/), cited *August 2017)*

Representative Concentration Pathways (RCPs)	Representative Concentration Pathways follow a set of greenhouse gas, air pollution (e.g. aerosols) and land-use scenarios that are consistent with certain socio-economic assumptions of how the future may evolve over time. The well mixed concentrations of greenhouse gases and aerosols in the atmosphere are affected by emissions as well as absorption through land and ocean sinks. There are four Representative Concentration Pathways (RCPs) that represent the range of plausible futures, from the published literature. **RCP 2.6** - represents a low radiative forcing (low emissions). Present trajectories suggest that, at least in terms of Australia, the intermediate to high emission scenarios are more likely. **RCP4.5 & RCP 6.0** - lower emissions of CO_2 achieved by application of some mitigation strategies and technologies peaking around 2040, and the CO_2 concentration reaches 540 ppm by the end of the 21st century. **RCP8.5** - a future with little curbing of emissions, with a CO_2 concentration continuing to rapidly rise, reaching 940 ppm by the end of the 21st century. CSIRO and Bureau of Meteorology, Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/), cited *August 2017.*

Present trajectories suggest that, at least in terms of Australia, the intermediate to high emission scenarios are more likely. The most recent comprehensive best estimate projections for Australia in 2030 indicate a rise in average temperature of 0.7–1.2°C, little change in annual rainfall in the far north and decreases of 2–5% elsewhere, and 2% increased potential evapotranspiration (CSIRO and Bureau of Meteorology- www.climatechangeinaustralia.gov.au). There is uncertainty associated with these projections due to differences between models and uncertainty in the likely greenhouse emissions in future years and gaps in our understanding of some biological process (e.g. relationship between CO_2 concentrations and vegetation growth).

Projected climate change will affect freshwater ecosystems globally (Doll & Zhang 2010), through changing temperature and changes in flow regimes. Unfortunately, the Murray–Darling Basin (MDB) already represents a highly modified aquatic system where the effects of a dramatically altered flow regime, as a result of flow regulation and water resource allocation, are especially apparent in the southern part of the basin (Davies *et al. 2010)*.

The northern and southern parts of the MDB can be further separated into five broad climatic regions based on rainfall patterns and geography. These include the northern arid (<250 mm rainfall per annum), northern temperate (>500 mm rainfall per annum), southern semi-arid (250–500 mm rainfall per annum), southern temperate (>500 mm rainfall per annum) and alpine (≥1200 metres above sea level) regions (Figure 1) and within each of these regions the impact of climate change will vary (Table 2).

Table 2. Predicted impacts of climate change in each of the regions of the MDB (Ning *et al.* 2015)

Region	Impact
Alpine:	It is anticipated that most climate change impacts on alpine biota may be associated with higher temperatures and alterations to flow.
Northern Arid:	Rivers in this region are largely unregulated with natural variations in temperature and flow. Most species present are generalists and potentially have some resilience and adaptive capacity to increased temperatures and reduced flows associated with climate change.
Northern temperate:	Most of the aquatic habitat for this climatic zone is associated with the MacIntyre, Gwydir and Naomi Rivers and their tributaries. These rivers are highly regulated and potentially environmental flows could be used to maintain species that are vulnerable to climate change related flow impacts.
Southern Semi-arid:	Rivers within this zone are highly regulated, and potentially environmental flows could be used to maintain species that are vulnerable to climate change related flow impacts. Providing environmental water to the upper reaches may have positive flow on impacts to the more vulnerable downstream habitats along the Murray River. However many wetland associated biota will become vulnerable due to reduced frequency and duration of flooding.
Southern Temperate:	Rivers within this zone are highly regulated, and potentially environmental flows could be used to maintain species that are vulnerable to climate change related flow impacts.

For many aquatic biota in the MDB drivers of changes in habitat will relate to changes in flow regimes and the physiological impacts caused by increased temperatures and/or associated changes in water quality, such as dissolved oxygen impairing survival. Changes in rainfall and evaporation will reduce the amount of water available, leading to fragmentation of riverine and floodplain networks and loss of connectivity. In association with this will be an increase in temperature, which will change the thermal habitat for many biota (Figure 2). However, it is worth noting that water resource development will continue to have a major impact on the distribution of species (Balcombe *et al.* 2011; Kingsford 2003).

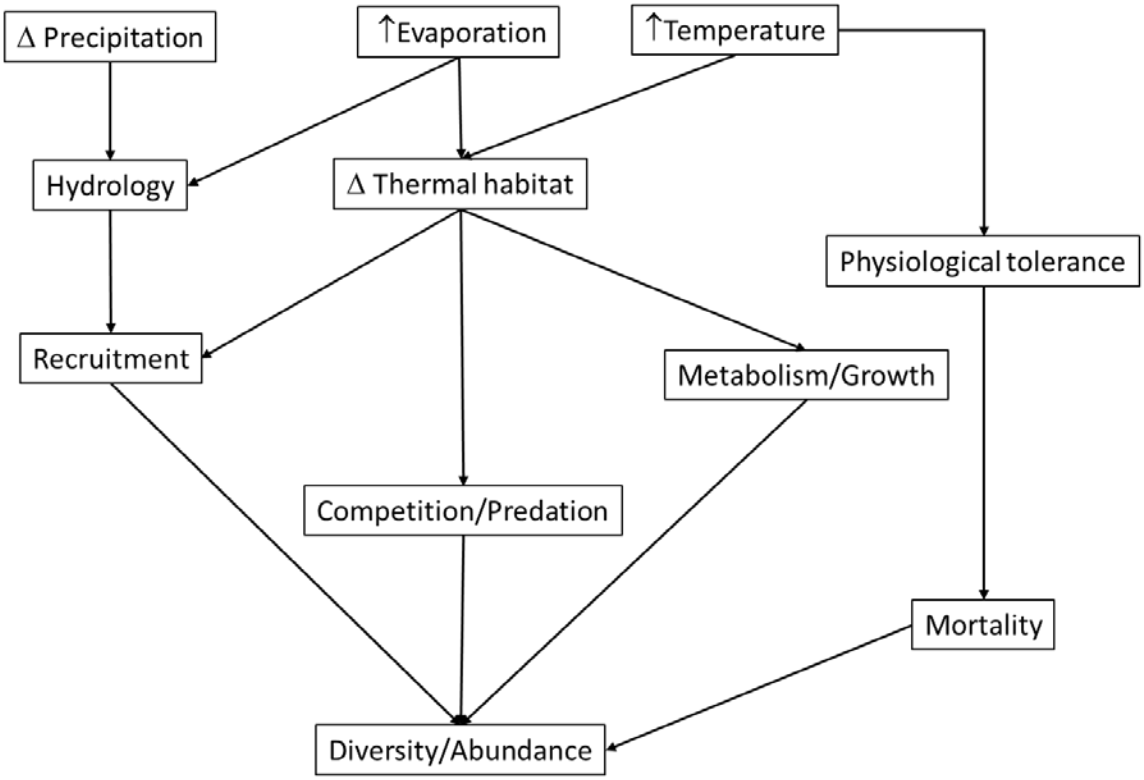

Figure 2. Conceptual model of the impacts of climate change (rainfall, temperature and evaporation) on aquatic and riparian biota. Δ = change; ↑ = increase (modified from Balcombe *et al*. (2011).(Kingsford 2003)

1.3 Rainfall and run-off

Care needs to be taken in interpreting predictions of rainfall and run-off as recent research has demonstrated that for many catchments, conceptual models of rainfall run-off substantially over estimate the amount of water that will be available under current climate change scenarios (Saft *et al.* 2016). That said, predictions are that across the whole of the MDB, conditions will get hotter, and the southern part of the Basin will become drier with less rainfall, particularly in the winter months, while the northern part is likely to become wetter (CSIRO 2012; Pittock 2003; Suppiah *et al.* 2007). Changes in rainfall combined with evaporation will affect surface water runoff and stream flows, which will result in reduced flows in many rivers (Dunlop & Brown 2008). In higher alpine regions, decreased precipitation and increased temperatures will result in a reduction in snow cover, which will affect a range of habitats, such as peat bogs and fens (Dunlop & Brown 2008). The combination of generally declining rainfall and increased evaporation suggests that the availability of freshwater resources will be reduced (Neave *et al.* 2015). Indeed, a modelling study by CSIRO (2008) on the influence of climate change on the hydrology of the MDB suggested that a median climate change scenario will result in the average volume of the surface water resource declining by 11% by 2030, surface water use declining by 11% and flows at the Murray Mouth declining by 24% (CSIRO 2008). Under a climate change scenario of RCP8.5 by 2050, most models predict a decline in rainfall by up to 2.5% across the MDB (Table 3; Figure 3).

Table 3. Projected reductions in mean inflows by 2030 in each catchment (Adamson *et al.* 2009).

Catchment	Reduction in mean inflows (%)
Condamine	27
Border Rivers, Queensland	24
Warrego–Paroo	22
Namoi	25
Central West	19
Maranoa–Balonne	13
Border Rivers–Gwydir	14
Western	13
Lachlan	12
Murrumbidgee	9
North East	11
Goulburn–Broken	12
Wimmera	10
North Central	12
Murray	13
Mallee	13
Lower Murray-Darling	12
South Australia Murray Basin	13

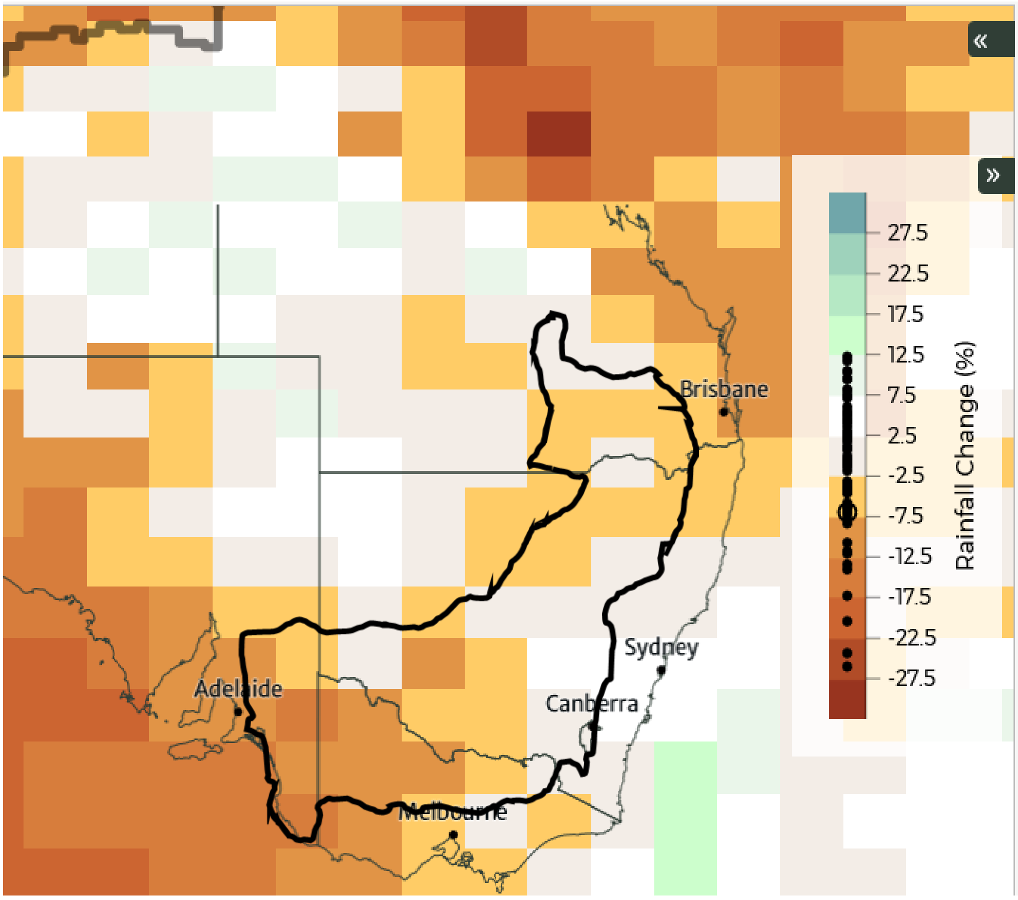

Figure 3. Changes in mean annual rainfall relative to 1986 - 2005 in MDB RCP8.5 by 2050 (source; CSIRO and Bureau of Meteorology, Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/), cited *August 2017*)).

1.4 Temperature

In combination with reduced flows, increasing temperature will modify the distribution of aquatic plants, animals and invertebrates as water temperatures reach and exceed thermal tolerances (Caissie 2006). Predictions are that across the whole of the MDB, conditions will get hotter with temperatures predicted to increase by up to 3°C by 2050, compared to the period between 1986-2005 (Figure 4).

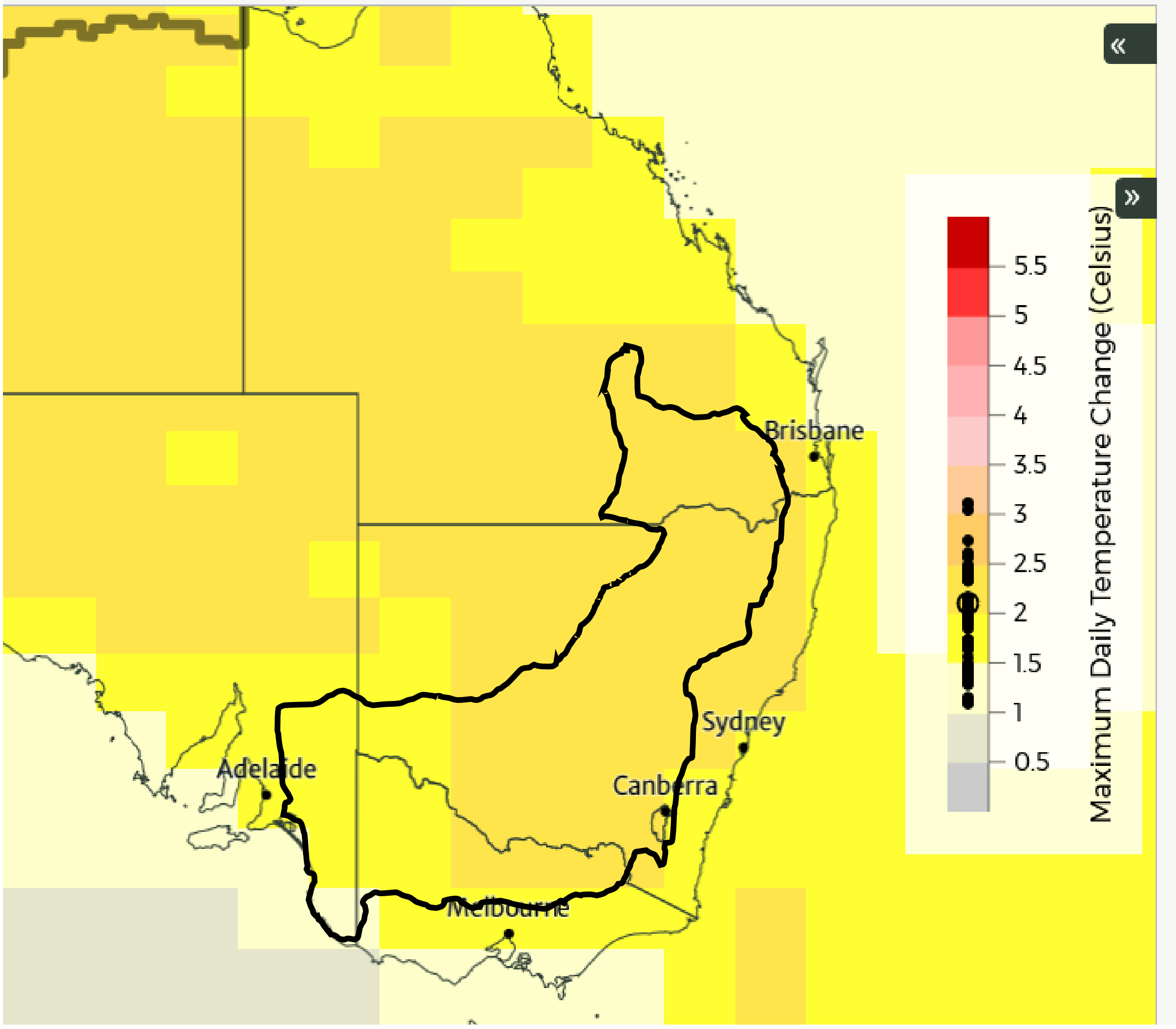

Figure 4. Changes in mean annual maximum temperature relative to 1986 - 2005 in the MDB (top) under RCP8.5 by 2050 (source; CSIRO and Bureau of Meteorology, Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/), cited *August 2017*)).

River temperature is an important physical characteristic of water quality and rises in annual mean temperature broadly follows changes in air temperature (Webb & Nobilis 2007). Temperature has a strong influence on the many aspects of aquatic ecology through its influence on physical characteristics such as dissolved oxygen and suspended sediment. Significant changes in water temperature are projected to occur as a consequence of climate change. Changes in annual temperatures of approximately 1.5°C are likely to have an impact on the thermal habitats of freshwater fauna (Webb & Nobilis 2007).

Across MDB climate predictions are that there will be an increase between 2 – 5 °C. Such increases are likely to significantly modify the thermal regimes of rivers and modifying the distribution of many biota. Predictions are that the most affected regions are likely to be the lower Murray region in the Southern MDB and less severe in the northern MDB (Balcombe *et al.* 2011).

Increases in annual air temperatures (Figure 4) will have multiple effects on the distribution of riparian and aquatic biota by changing the thermal regimes in which biota can survive. As air temperatures increase there will be a corresponding increase in water and sediment temperatures, which will lead to changes in the distribution of biota. Changes in water temperature for a given change in air temperature will depend on a range of factors such as waterbody size and shading (Caissie 2006), but nevertheless air temperature has been shown to be a useful proxy for thermal regimes of rivers at broad spatial scales that also correlates with the distribution of aquatic biota (Bond *et al.* 2011). Intersecting projected changes in air temperature with the river network throughout the MDB shows the potential scale of impacts of climate change. For example, of the nearly 450,000 km of river length in the Murray-Darling Basin, historically approximately 377,000 km (~84%) have experienced mean maximum temperatures of less than 35°C during the warmest month. Under current forecasts, this figure rises considerably over time (to 2030 and 2050) even with efforts to reduce CO_2 emissions (the RCP4.5 scenario). Under the worst case scenario less than 255,000 km of river falls below the 35°C threshold (around 56%), a reduction of nearly 30%. Similar trends are evident for a range of temperature thresholds, and thus, these coarse analyses demonstrate the potential scale of range reductions of fish, invertebrates and other taxa that may occur where temperature thresholds are exceeded (Figure 5).

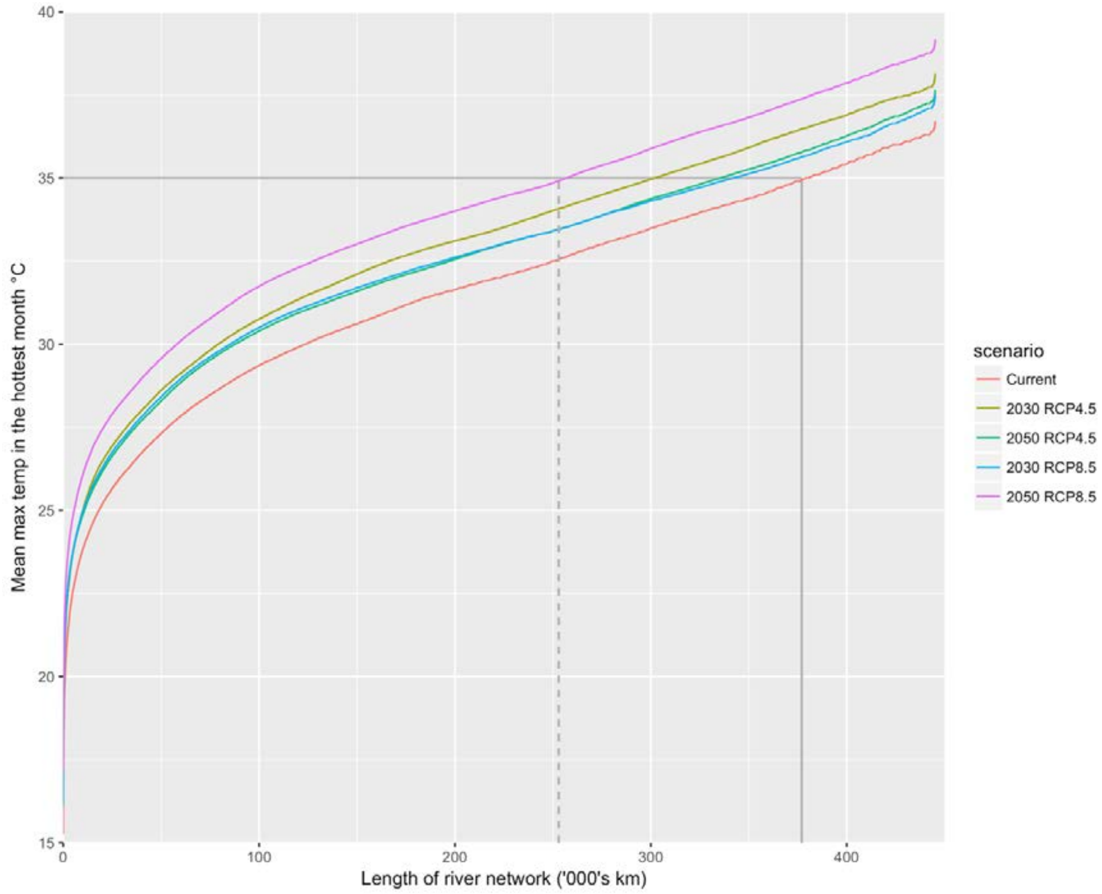

Figure 5. Cumulative distribution of maximum average temperatures in the warmest month experienced across the river network within the MDB. Data from the Australian Hydrological Geospatial Fabric (the Geofabric) and Climate Change in Australia (https://www.climatechangeinaustralia.gov.au/). Scenario temperatures are from the Access 1.0 model [CSIRO], which is deemed among the more appropriate GCM models for application in Australia.

These likely range reductions may also occur alongside range expansions, although these can be more difficult to predict (Balcombe *et al.* 2011). Balcombe *et al.* (2011) grouped fish into three groups. Those that were likely to increase in range, decrease in range or those were temperature may allow an increase in range but these increases may be offset by other changes in habitat (Table 4). For example, increasing temperature will reduce the range of Mountain galaxias, however the distribution of this species had been affected by predation by trout. Increasing temperature will reduce the range of trout potentially allowing the Mountain galaxias to increase in abundance (Balcombe *et al.* 2011).

Table 4. Predicted changes in the abundance and distribution of native fish (Balcombe *et al.* 2011)

Group	Species
Decreased distribution and abundance	Murray cod Northern river blackfish Trout cod Macquarie perch

	Australian smelt Un-specked hardyhead Southern pygmy perch Murray–Darling rainbowfish
Increased distribution and abundance	Golden perch Hyrtl's tandan Spangled perch Bony bream Carp gudgeons Mountain galaxias
Potential increases or decreases in abundance	Eel-tailed catfish Silver perch Two-spined blackfish Northern river blackfish Flat-headed gudgeon

Elevated annual air temperature changes associated with climate change can influence plant metabolism. The ability of plant species to acclimate to different temperatures may influence their growth and survival and potentially lead to range shifts within the landscape (Lenoir & Svenning 2013; Mulholland *et al.* 1997). Established plants must be able to respond to short-term changes in temperature (seconds or minutes) and long-term (weeks or years) (Eggert *et al.* 2006). Plants may use strategies of either acclimating photosynthetic apparatus to optimise growth (Atkin *et al.* 2006) or employ a photoprotective strategy to limit temperature-induced damage (Eggert *et al.* 2006).

Many wetland and floodplain plants are are reliant on a long-lived dormant seed bank that is capable of persisting in sediment for many years and confer a measure of resilience (Brock 2011). Once favourable conditions occur, many of these seeds germinate and communities re-establish. Sediment temperature is highly correlated with maximum daily temperatures (Ooi *et al.* 2009; Ooi *et al.* 2012) and these relationships have indicated that a 4°C increase in the maximum air temperature will equate to a 10°C increase in sediment temperature (Ooi *et al.* 2009). Research has indicated that once sediment temperatures exceed 40°C for extended periods there will be declines in the viability and germination of many wetland plants (Nielsen *et al.* 2015). While such occurrences historically would have been rare, recent research has indicated that such extremes are occurring within the MDB (Wilson unpublished data) (Figure 6).

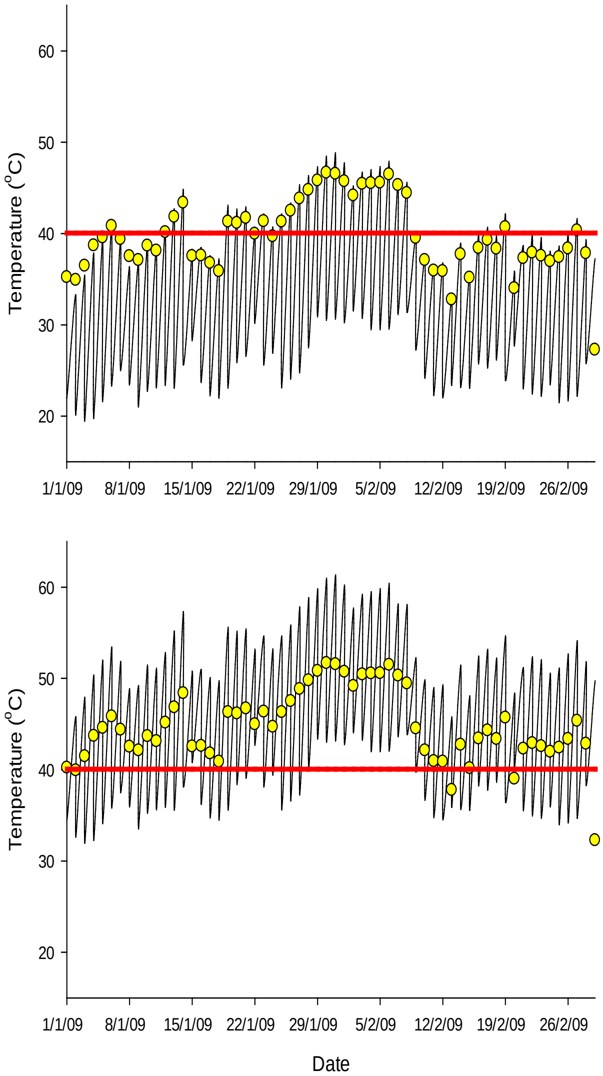

Figure 6. Temperatures recorded from Yanga wetlands on the lower Murrumbidgee river floodplain. Yellow symbols represent maximum daily air temperature. Black line indicates sediment temperature. Top graph demonstrates current temperatures. Lower graph indicates shift in temperatures when a 4°C increase in air temperatures is applied. Red line indicates when ecological effects are likely to occur (unpublished data curtesy Jessica Wilson).

1.5 Evapotranspiration

In the MDB, there is likely to be an increase in evaporation by up to 8% (Adamson *et al.* 2009). In the southern and northern parts of the MDB, predictions are that evapotranspiration will increase up approximately 7% across the MDB (Figure 7). These predicted changes in potential evapotranspiration may contribute to the quantity of surface run-off (Potter *et al.* 2010).

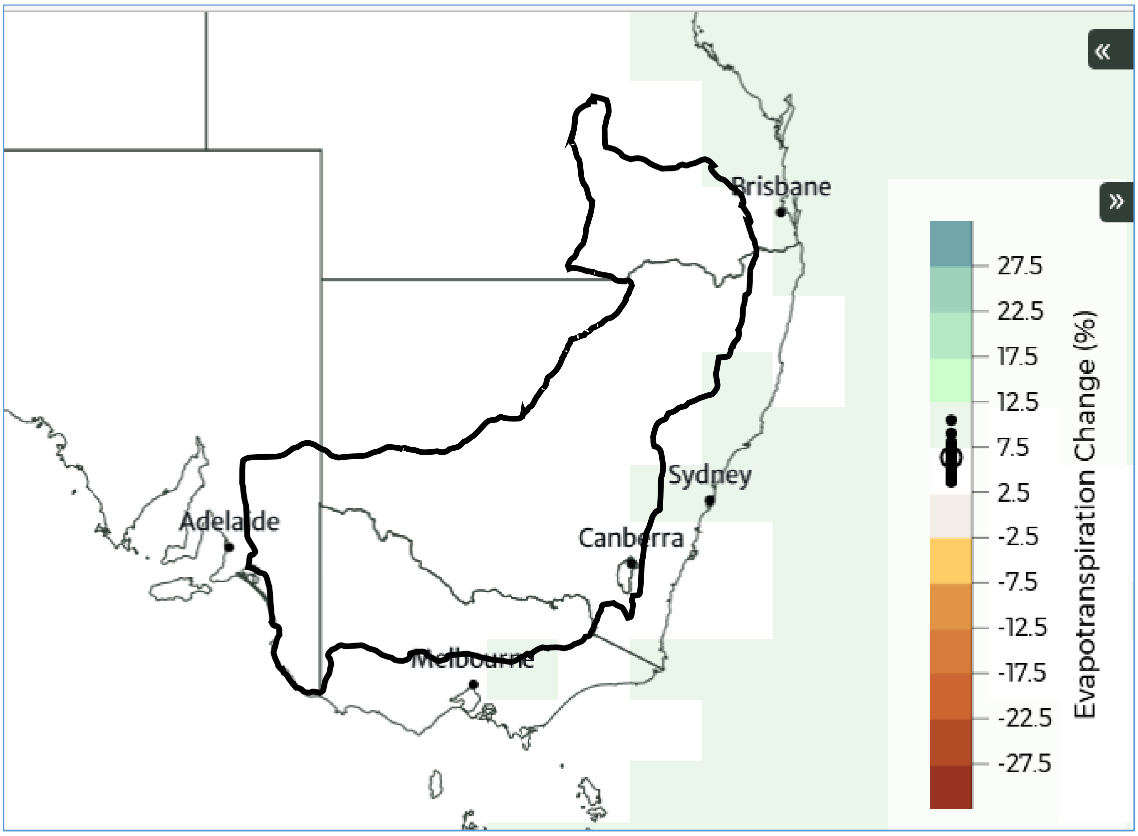

Figure 7. Changes in mean annual evapotranspiration relative to 1986 - 2005 in the Southern MDB (top) and Northern MDB (bottom) under RCP8.5 by 2090 (source; CSIRO and Bureau of Meteorology, Climate Change in Australia website (http://www.climatechangeinaustralia.gov.au/), cited *August 2017)).*

Increases in potential evapotranspiration could potentially have localised through to extensive catchment scale impacts on water balances, although the direct relationship between increasing maximum daily temperatures and an increase in potential evapotranspiration rates are often difficult to disentangle from other hydroclimatic variables, such as wind speed and direct solar radiation (Lockart *et al.* 2009; Potter & Chiew 2009). The largest driver in surface run-off appears to be annual rainfall, especially the timing and reliability of rainfall, but potential evapotranspiration is a contributing factor to mean annual water yields (Potter & Chiew 2009; Zhang *et al.* 2001).

1.6 Carbon dioxide (CO_2) concentrations

For vegetation, increasing concentrations in atmospheric CO_2 may also influence the energy and water balances of vegetated landscapes by increasing the water-use-efficiency of photosynthesis in the majority of plant species (Donohue *et al.* 2009; Farquhar 1997). An increase in atmospheric CO_2 concentrations is equivalent to a proportional increase in effective precipitation, potentially inducing an increase in CO_2 assimilation and vegetation cover (Gedney *et al.* 2006). However, it is uncertain how elevated CO_2 will affect various plant functional types (Poorter & Navas 2003). Each plant species (more than 6,000 wetland plants have been identified worldwide) may respond somewhat differently, although certain general responses may be expected. For example, increased atmospheric CO_2 levels generally increase plant growth rates and biomass accumulation when other factors are not limiting. Increasing CO_2 levels enhances the growth and expansion of C3 photosynthetic plants such as Eucalypts and shrubs compared to growth of C4 photosynthetic plants, such as grasses (Drake 1992). This has led to speculation that perennial, woody species, such as trees and shrubs may increase growth and primary production and their distributions may expand (Mulholland *et al.* 1997). However, there may be a corresponding decrease in the distribution of floodplain, aquatic grasses and reeds, such as Moira grass (*Pseudoraphis spinescens*) (Saintilan & Rogers 2015). The predominance of some plant functional types will transform vegetation community structures, which will in turn have impacts at higher trophic levels (Burkett & Kusler 2000). However, for some species, stomatal conductance may acclimate to increased atmospheric CO_2 levels, therefore significantly reducing the expected benefits to some plant functional types. A better understanding of plant responses amongst wetland and floodplain plant functional groups to predicted climate changes is required to determine whether the primary drivers in vegetation responses may be changes to water and/or energy availability (Flexas *et al.* 2014).

2 Changes in vegetation distribution

Floodplain systems are important contributors to plant diversity at regional scales and are characterised by high levels of spatial and temporal heterogeneity (Lawson *et al.* 2015). Floodplains providing a shifting mosaic of habitats related to hydrological gradients, with flood-tolerant and ephemeral species occupying wetter areas and perennial or drought-tolerant species dominating the drier areas (Capon 2005). This hydrological gradient is reset by flooding, initially influencing plant diversity as its becoming more homogenous, and then increasingly diverges during dry, inter-flood periods as other local factors exert more influence (Capon & Brock 2006). However, under extreme dry condition floodplain plant diversity becomes extremely low (James *et al.* 2015) and ecosystem processes and services are then disrupted (Mac Nally *et al.* 2011). The potential impacts of climate change on floodplain systems in the MDB will vary depending upon the magnitude and rate of changes in temperature, precipitation, evaporation, runoff, atmospheric CO_2 concentration and other factors. Predicted changes to temperature, precipitation, evaporation and surface run-off will influence catchment-scale water availability. For most riparian and floodplain vegetation communities this will likely correspond to reduced flows, changes to the timing, duration and frequency of inundation and greater drying of wetland soils, as these riparian/floodplain vegetation communities are dependent on water availability and flow regime for key life stages (Table 5).

Table 5. Table illustrating the dependence of water availability and flow regime for key life stages of vegetation communities within the Murray-Darling Basin (darker shading represents increased dependence on water availability and flow regime

Broad habitat classifications	Adult maintenance	Reproduction and seed dispersal	Vegetative	Seed germination	Seedling/propagule establishment
Riparian forests and Floodplain woodlands	Low–Moderate	Moderate	N/A	Moderate–High	High
Shrublands	Low–High	Moderate–High	Moderate–High	Moderate–High	High
Aquatic grasslands and reedlands	Moderate–High	Moderate–High	Moderate–High	Moderate–High	Moderate–High
Sedgelands and rushlands	Moderate–High	High	High	High	High
Aquatic herblands	High	High	High	High	High

2.1 Riparian Forests and Floodplain Woodlands

In the MDB, changes in flow regimes and increasing water resource allocations have led to widespread dieback of riparian forests and floodplain woodlands, particularly in the arid to semi-arid regions (Holland *et al.* 2009; Walker *et al.* 1993). Climate change will potentially further impact these communities by decreasing water availability and reducing soil moisture (Roberts & Marston 2011). The dominant, long-lived riparian and floodplain tree species, such as River Red Gum (*Eucalyptus camaldulensis* subsp. *camaldulensis*), Black Box (*Eucalyptus largiflorens*) and Coolibah (*Eucalyptus coolabah*) have varying inter-specific water requirements (Table 6).

Table 6 Current distribution and water requirement for key tree species in the MDB

Species	Distribution	Water requirements	Flooding requirement (Roberts & Marston 2011)
Coolibah	Predominantly found in the north-west parts of the MDB	Not dependent on surface flows, preferring to use a mixture of fresh to saline groundwater or shallow, rainfall derived-soil water, rather than	10-20 years

		surface water directly (Costelloe *et al.* 2008).	
Black Box	Mid- to southern MDB	Opportunistically use surface water, soil water and ground water source, transpiring freely when water is available (Holland *et al.* 2006; Holland *et al.* 2009; Mensforth *et al.* 1994) .	3-7 years
River Red Gum		Opportunistically use surface water, soil water and ground water source, transpiring freely when water is available (Holland *et al.* 2006; Holland *et al.* 2009; Mensforth *et al.* 1994)	1-7 years

If the duration between floods exceeds the thresholds established trees will decline in conditions and there will be a shift in community composition to more terrestrial species (Catford *et al.* 2014; McGinness *et al.* 2013; Perry *et al.* 2012).

2.2 Floodplain Shrublands

Lignum (*Duma florulenta*) is one of the most ecologically significant floodplain shrubs of Australia. Water regime has a very strong influence on Lignum growth (Craig *et al.* 1991). In the MDB, where Lignum is common in arid and semi-arid locations, river regulation and extraction of water has led to a reduction in the frequency, extent and duration of flooding events and a deterioration in condition of Lignum communities (Freestone *et al.* 2017). Mature, established Lignum plants are highly resilient and can persist in an inactive, dormant state for long periods, actively growing again when conditions become favourable during flooding or heavy rainfall (Craig *et al.* 1991). However, the likelihood of successful regeneration from dormancy becomes highly variable if flood frequencies decline and dry periods become extended (Freestone *et al.* 2017). Predicted increase in the frequency of droughts and a decline in rainfall and surface water availability as a result of climate change is likely to significantly impact the condition and extent of existing mature Lignum shrublands and their capacity to regenerate from dormancy (Freestone *et al.* 2017; Roberts & Marston 2011). Similar to riparian forests and floodplain woodlands, regeneration processes of Lignum shrublands is most likely to be critically affected by decreases in surface water availability due to climate change. An increase in the duration of dry, inter-flood periods is likely to result in a loss of condition and/or mortality of established Lignum shrubs over time, altering their value as habitat (Balcombe *et al.* 2011; Capon *et al.* 2009).

2.3 Wetland species

Non-woody wetland species exist in a transition zone between aquatic and terrestrial environments, which can be altered by subtle changes in hydrology. Reduced rainfall and increased evaporation that alter surface or ground water level by only a few centimetres will be enough to reduce or expand many wetlands converting some wetlands to drylands. Wetlands that depend primarily upon precipitation as a primary water source are the most vulnerable to changes in climate (Burkett & Kusler 2000). The impact of climate change and subsequent loss of water will increase the competition for water between human consumptive use and environmental needs, and many wetlands will potentially become more managed and more isolated in the landscape (Angeler & Alvarez-Cobelas 2005; Angeler & García 2005; Nielsen & Brock 2009; Nielsen *et al.* 2013). Changes in the availability of water will lead to changes in the composition of plant communities. As wetlands become increasingly dry wetland plants will be lost and replaced by more terrestrial species (Nielsen *et al.* 2013).

3 Refuges

There is growing recognition of the importance of refuges in mitigating the effects of climate change in climate change adaptation planning (Ashcrot *et al.* 2009; Davis *et al.* 2013; Keppel *et al.* 2012; Reside *et al.* 2014). Refuges are particularly important for the management and conservation of freshwater ecosystems and biodiversity to stressors associated with climatic changes (James *et al.* 2013). Refuges must be able to facilitate life support and provide buffering during periods of unfavourable conditions, and be able to provide a recolonisation source to the surrounding area following the return of favourable conditions. Refuge mechanisms are reflective of the ecosystem functions or processes that maintain viable populations of individuals during adverse conditions and then enable the populations to recover after the disturbance. It is essential that refuges not only buffer species from harsh environmental conditions, but that they also enable the recovery and a source for recolonisation once more favourable conditions re-occur. Areas identified as potential refuges may be prioritised to receive environmental water and/or associated environmental works and measures (Pittock & Finlayson 2011). Despite the importance of climate refuges, however, most of the published literature concerning climate change adaptation for freshwater biodiversity provides little guidance for managers other than recommending that refuges be conserved (Bond *et al.* 2008; Pittock & Finlayson 2011).

Increases in ambient temperatures associated with climate warming, in conjunction with associated increases in water temperatures, may provide unsuitable conditions for some species. Any changes that affect the quality of the environmental template, such as blue-green algal blooms, changes in food-web structure, disease prevalence and/or invasion of alien species, associated with changes in climate are also of concern. In addition, the identification and management of climate refuges for some species may have unintended effects on other species or habitats in some instances (Table 7) (Ning *et al.* 2015). For example, while flooding (either natural or managed) may be beneficial for supporting the creation and/or persistence of climate refuges, there is a moderate risk that it may lead to poor water quality in some parts of the MDB where there is potential for hypoxic blackwater generation (Whitworth *et al.* 2012) or acidification (Baldwin & Fraser 2009). There is also a high risk that it may lead to the introduction of invasive species (Rahel & Olden 2008).

Table 7. Potential unintended consequences associated with climate refuge management and their associated risk to the Murray–Darling Basin (Ning *et al.* 2015).

Aspect of refuge management	Potential problems	Risk to MDB
Flooding (natural or managed)	Poor water quality (e.g. hypoxic blackwater events causing local extinctions)	Moderate
	Introduction of invasive species (e.g. Introduced species outcompeting natives)	High
Maintenance of isolated refuges with no or limited connectivity	Isolation of populations (e.g. genetic bottlenecks causing inbreeding depression)	Moderate
Refuge sites are poorly prioritised for protection	Choosing to protect refuge sites where there is nowhere for the biota to recolonise after the disturbance passes, so the refuges can only function as 'living museums' rather than as viable sources of colonists	Moderate
	Choosing to protect refuge sites that are already (or face the threat of being) degraded from the effects of other	Moderate
Refuges become the only sources of permanent water in the landscape	Refuges become subject to high water extraction pressure	High
	Refuges become threatened by feral species such as water buffalo or pigs that alter habitat or water quality	High

Note: the likely risk was estimated as a function of the likelihood of occurrence and the magnitude of the impact

4 Discussion

Freshwater ecosystems contain high biodiversity, but are especially vulnerable to the impacts of climate change because of their relative isolation within terrestrial landscapes and their susceptibility to drying. There is plentiful evidence indicating that climate change is already affecting the environment, species and ecosystems in many ways, and that the impacts are going to become more severe as climate change continues (Dunlop & Brown 2008). Some impacts are better known and more easily conceptualised than others, and some have obvious implications for biodiversity conservation while others do not. Environmental changes will lead directly to a cascade of impacts on individuals, populations and ecosystems. Many species will also be affected indirectly via their interactions with affected species and ecosystems, by other feedbacks from the environment (Table 7). Reduced flows and increasing stream temperatures associated with human-induced climate change pose two of the greatest threats to the ecology and maintenance of biodiversity in lotic ecosystems (e.g. (Caissie 2006; Chessman 2009). The natural Australian landscape sustains a mosaic of wetlands that range from permanently wet to temporary. This diversity of wetland types and habitats provides for diverse biotic communities, many of which are specific to individual wetlands. Extended droughts predicted as a consequence of climate change (lower rainfall and higher temperatures) combined with human-induced changes to the natural hydrological regime will lead to reductions in the amount of water available for environmental and anthropogenic uses. Reduced run-off and river flows may cause the loss of some temporary wetland types that will no longer hold water long enough to support hydric communities. Species distributions will shift and species extinctions may result particularly across fragmented or vulnerable landscapes (Nielsen & Brock 2009).

Predicted changes to temperature, precipitation, evaporation and surface run-off will influence catchment-scale water availability. For most riparian and floodplain vegetation communities this will likely correspond to reduced flows, changes to the timing, duration and frequency of inundation and greater drying of wetland soils. The ecological effects of reduced flows can be significant, including loss and degradation of wetlands and riparian habitats, loss of native species and increase of invasive species, and increases in toxic algal blooms (Kingsford 2000; Overton & Jolly 2004). Flow reductions also reduce the resilience of aquatic systems to other threats to water quality such as point and non-point source pollution, salinity, erosion and exposure of acid sulfate soils (Walker et al. 2006). The deterioration in condition and potential loss of riparian forests and floodplain woodlands over the long term is likely to affect habitat quality key ecosystems processes and services. Such, cascading effects on the amount of carbon that is available for incorporation into aquatic food webs will further modify the distribution of key biota such as fish (Balcombe *et al.* 2011; Mac Nally *et al.* 2011).

The characteristics of the impacts provide an indication of the type of outcomes associated with adverse conditions. These include impacts associated with increasing ephemerality, retraction of water volumes in standing water and loss of connectivity. Secondary processes including changes to food web structure, increasing predation pressure and changes to competition levels are also characteristics of impacts associated with changes in habitat under adverse conditions. These characteristics are determined by the nature of the landscape and habitat, but are also a function of the species requirements.

During adverse conditions, the main biodiversity consequences include the loss of species richness, population declines, loss of genetic diversity and failed recruitment. Changes to species distributions and loss of connectivity associated with declines in water availability also have consequences for biodiversity.

5 Research Priorities

A working group of scientist from across Australia (including members of the MMCP project team) recently was funded by The National Climate Change Adaptation Research Facility (NCCARF), revised the National Climate Change Adaptation Research Plan for *Freshwater Ecosystems and Biodiversity*. The draft report lists 12 overarching priority research questions across three research themes (Capon *et al.* 2017). These areas remain priorities for future research:

Theme 1. To understand climate change effects on freshwater ecosystems and biodiversity.

1. How do changes in climatic components interact with each other and with other stressors to affect freshwater biodiversity, individual species and ecosystems in space and time? Including the direct and indirect effects of:
  - 1.1. Multiple interacting climatic stressors?
  - 1.2. Multiple interacting climatic and anthropogenic stressors (legacies and current) including effects of climate change on terrestrial and marine systems?

2. What is the sensitivity to climate change effects of different freshwater ecosystems and species?
  - 2.1. What attributes determine the sensitivity of freshwater ecosystems and species to climate change effects?
  - 2.2. Which freshwater ecosystems and species are most sensitive to climate change effects?

3. What influences the capacity of freshwater biodiversity to adapt to, and ecosystem processes to be maintained, in the face of climate change?

3.1. What range shifts and migration of freshwater species and ecosystems can be expected in response to climate change?

4. How can novel ecosystems conserve freshwater biota and maintain ecosystem processes under climate change?

Theme 2. To incorporate climate change adaptation into the policy and management of freshwater ecosystems and biodiversity.

5. What is the range and efficacy of existing policies and management approaches for conserving and managing freshwater ecosystems and biodiversity under climate change (including those focused on climate change explicitly and others)?

   5.1. What are the barriers to and opportunities for improved adaptation of policy and management for the conservation and restoration of freshwater ecosystems and biodiversity under climate change across multiple scales?

   5.2. How can existing policies and management approaches be better aligned to improve the conservation and restoration of freshwater ecosystems and biodiversity under climate change?

6. What are the aims, goals, objectives and targets of climate change adaptation for freshwater ecosystems and biodiversity?

   6.1. How can the natural sciences contribute to the elicitation and development of societal values of freshwater ecosystems and biodiversity under climate change?

7. What existing and potential adaptation options are available for policy and management of freshwater ecosystems and biodiversity?

   7.1. What are the benefits and risks (including uncertainties) associated with different adaptation options?

Theme 3. To promote compatibility of adaptation strategies between freshwater biodiversity conservation and management and other sectors.

8. What are the risks and opportunities to adaptation of freshwater ecosystems and biodiversity associated with adaptation strategies and actions in other sectors?
9. How can adaptation options and strategies for freshwater ecosystems and biodiversity be integrated into adaptation strategies in other sectors?
10. What are the risks and benefits of climate change adaptation for freshwater ecosystems and biodiversity to other sectors (e.g. changes to ecosystem services)?
11. How can novel/hybrid freshwater ecosystems benefit other sectors (e.g. flood mitigation)?

12. How can existing monitoring networks in other sectors be expanded to establish long-term monitoring for freshwater ecosystems and biodiversity?

6 References

Adamson D, Mallawaarachchi T, Quiggin J (2009) Declining inflows and more frequent droughts in the Murray–Darling Basin: climate change, impacts and adaptation*. *Australian Journal of Agricultural and Resource Economics* **53**, 345-366.

Angeler DG, Alvarez-Cobelas M (2005) Island Biogeography and Landscape Structure: Integrating Ecological Concepts in a Landscape Perspective of Anthropogenic Impacts in Temporary Wetlands. *Environmental Pollution* **138**, 421-425.

Angeler DG, García G (2005) Using emergence from soil propagule banks as indicators of ecological integrity in wetland: advantages and limitations. *Journal of the North American Benthological Society* **24**, 740-752.

Ashcrot MB, Chisholm LA, French KO (2009) Climate change at the landscape scale: predicting fine-grained spatial heterogeneity in warming and potential refugia for vegetation *Global Change Biology* **15**, 656-667.

Atkin OK, Scheurwater I, Pons TL (2006) High thermal acclimation potential of both photosynthesis and respiration in two lowland Plantago species in contrast to an alpine congeneric. *Global Change Biology* **12**, 500-515.

Balcombe SR, Sheldon F, Capon SJ*, et al.* (2011) Climate-change threats to native fish in degraded rivers and floodplains of the Murray–Darling Basin, Australia. *Marine and Freshwater Research* **62**, 1099-1114.

Baldwin DS, Fraser M (2009) Rehabilitation options for inland waterways impacted by sulfidic sediments - A synthesis. *Journal of Environmental Management* **91**, 311-319.

Bond N, Thomson J, Reich P, Stein J (2011) Using species distribution models to infer potential climate change-induced range shifts of freshwater fish in south-eastern Australia. *Marine and Freshwater Research* **62**, 1043-1061.

Bond NR, Lake PS, Arthington AH (2008) The Impacts of Drought on Freshwater Ecosystems: an Australian Perspective. *Hydrobiologia* **600**, 3-16.

Brock MA (2011) Persistence of seed banks in Australian temporary wetlands. *Freshwater Biology* **56**, 1312-1327.

Burkett V, Kusler J (2000) Climate Change: Potential Impacts and Interactions in Wetlands of the Untted States. *JAWRA Journal of the American Water Resources Association* **36**, 313-320.

Caissie D (2006) The thermal regime of rivers: a review. *Freshwater Biology* **51**, 1389-1406.

Capon S, Chambers J, Barmuta L*, et al.* (2017) National Climate Change Adaptation Research Plan for Freshwater Ecosystems and Biodiversity: update 2017, National Climate Change Adaptation Research Facility, Gold Coast, 41pp.

Capon SJ (2005) Flood variability and spatial variation in plant community composition and structure on a large arid floodplain. *Journal of Arid Environments* **60**, 283-302.

Capon SJ, Brock MA (2006) Flooding, soil seed bank dynamics and vegetation resilience of a hydrologically variable desert floodplain. *Freshwater Biology* **51**, 206-223.

Capon SJ, James CS, Williams L, Quinn G (2009) Responses to flooding and drying in seedlings of a common Australian desert floodplain shrub: *Muehlenbeckia florulenta* Meisn. (Tangled Lignum). *Environment of Experimental Botany* **66**, 178-185.

Catford JA, Morris WK, Vesk PA, Gippel CJ, Downes BJ (2014) Species and environmental characteristics point to flowregulation and drought as drivers of riparian plant invasion. *Diversity and Distributions* **20**, 1084-1096.

Chessman BC (2009) Climatic changes and 13-year trends in stream macroinvertebrate assemblages in New South Wales, Australia. *Global Change Biology* **15**, 2791-2802.

Chiew F, Young W, Cai W, Teng J (2011) Current drought and future hydroclimate projections in southeast Australia and implications for water resources management. *Stochastic Environmental Research and Risk Assessment* **25**, 601-612.
Costelloe JF, Payne E, Woodrow IE*, et al.* (2008) Water sources acccessed by arid zone riparian trees in highly saline environments. *Oecologia* **156**, 43-62.
Craig A, Walker K, Boulton A (1991) Effects of Edaphic Factors and Flood Frequency on the Abundance of Lignum (<I>Muehlenbeckia florulenta</I> Meissner) (Polygonaceae) on the River Murray Floodplain, South Australia. *Australian Journal of Botany* **39**, 431-443.
CSIRO (2008) Water availability in the Murray-Darling Basin. A report to the Australian Goverment from the CSIRO Murray-Darling Basin Sustainable Yields project., p. 67pp., CSIRO, Australia.
CSIRO (2012) Climate and water availability in south-eastern Australia: A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI), p. 41. CSIRO, Australia.
Davies PE, Harris JH, Hillman TJ, Walker KF (2010) The Sustainable Rivers Audit: assessing river ecosystem health in the Murray-Darling Basin, Australia. *Marine and Freshwater Research* **61**, 764-777.
Davis J, Pavlova A, Thompson R, Sunnucks P (2013) Evolutionary refugia and ecological refuges: key concepts for conserving Australian arid zone freshwater biodiversity under climate change. *Global Change Biology* **19**, 1970-1984.
Doll P, Zhang J (2010) Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences* **14**, 783-799.
Döll P, Zhang J (2010) Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences* **14**, 783-799.
Donohue RJ, McVicar TR, Roderick ML (2009) Climate-related trends in Australian vegetation cover as inferred from satellite observations, 1981–2006. *Global Change Biology* **15**, 1025-1039.
Drake BG (1992) A field-study of the effects of elevated CO2 on ecosystem processes in a Chesapeake Bay wetland. *Australian Journal of Botany* **40**, 579-595.
Dunlop M, Brown PR (2008) Implication of Climate Change for Australia's national reserve system: A preliminary assessment. Department of Climate Change and the Department of the Environment, Water, Heritage and the Arts, Canberra.
Eggert A, Visser RJW, Van Hasselt PR, Breeman AM (2006) Differences in acclimation potential of photosynthesis in seven isolates of the tropical to warm temperate macrophyte Valonia utricularis (Chlorophyta). *Phycologia* **45**, 546-556.
Farquhar (1997) Carbon dioxide and vegetation *Science* **278**, 1411-1411.
Flexas J, Diaz-Espejo A, Gago J*, et al.* (2014) Photosynthetic limitations in Mediterranean plants: a review. *Environmental and Experimental Botany* **103**, 12-23.
Freestone FL, Brown P, Campbell CJ*, et al.* (2017) Return of the lignum dead: Resilience of an arid floodplain shrub to drought. *Journal of Arid Environments* **138**, 9-17.
Gallant A, Kiem A, Verdon-Kidd D, Stone R, Karoly D (2012) Understanding climate processes in the Murray-Darling basin for natural resources management. *Hydrology and Earth System Sciences* **16**, 2049-2068.
Gedney N, Cox PM, Betts RA*, et al.* (2006) Detection of a direct carbon dioxide effect in continental river runoff records. *Nature* **439**, 835-838.
Holland K, Tyerman S, Mensforth L, Walker G (2006) Tree water sources over shallow, saline groundwater in the lower River Murray, south-eastern Australia: implications for groundwater recharge mechanisms. *Australian Journal of Botany* **54**, 193-205.
Holland KL, Charles AH, Jolly ID, Gehrig S, Simmons CT (2009) Effectiveness of artificial watering of a semi-arid saline wetland for managing riparian vegetation health. *Hydrological Processes* **23**, 3474-3485.

IPCC (2014a) *Climate Change 2014–Impacts, Adaptation and Vulnerability: Regional Aspects* Cambridge University Press.
IPCC (2014b) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the intergovernmental panel on Climate Change. IPCC, Geneva, Switzerland.
James C, VanDerWal J, Capon S*, et al.* (2013) Identifying climate refuges for freshwater biodiversity across Australia, p. 150. National Climate Change Adaptation Research Facility.
James CS, Capon SJ, Quinn GP (2015) Nurse plant effects of a dominant shrub (Duma florulenta) on understorey vegetation in a large, semi-arid wetland in relation to flood frequency and drying. *Journal of Vegetation Science* **26**, 985-994.
Keppel G, Van Niel KP, Wardell-Johnson GW*, et al.* (2012) Refugia: identifying and understanding safe havens for biodiversity under climate change. *Global Ecology and Biogeography* **21**, 393-404.
Kingsford RT (2000) Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* **25**, 109-127.
Kingsford RT (2003) Ecological Impacts and Institutional and Economic Drivers for Water Resource Development--a Case Study of the Murrumbidgee River, Australia. *Aquatic Ecosystem Health & Management* **6**, 69-79.
Lawson JR, Fryirs KA, Lenz T, Leishman MR (2015) Heterogeneous flows foster heterogeneous assemblages: relationships between functional diversity and hydrological heterogeneity in riparian plant communities. . *Freshwater Biology* **60**, 2208-2225.
Lenoir J, Svenning JC (2013) Latitudinal and elevational range shifts under contemporary climate change. . In: *Encyclopedia of Biodiversity* (ed. Levin S). Academic Press, Waltham.
Lockart N, Kavetski D, Franks SW (2009) On the recent warming in the Murray-Darling Basin: Land surface interactions misunderstood. *Geophysical Research Letters* **36**, 1-7.
Mac Nally R, Cunningham SC, Baker PJ, Horner GJ, Thomson JR (2011) Dynamics of Murray-Darling floodplain forests under multiple stressors: The past, present, and future of an Australian icon. *Water Resources Research* **47**, W00G05.
McGinness HM, Arthur AD, Davies M, McIntyre S (2013) Floodplain woodland structure and condition: the relative influence of flood history and surrounding irrigation land use intensity in contrasting regions of a dryland river. *Ecohydrology* **6**, 201-213.
Mensforth LJ, Thorburn PJ, Tyerman SD, Walker GR (1994) Sources of water used by riparian Eucalyptus camaldulensis overlying highly saline groundwater. *Oecologia* **100**, 21-28.
Mulholland PJ, Best GR, Coutant CC*, et al.* (1997) Effects of Climate Change on freshwater ecosystems of the south-eastern United States and the Gulf coast of Mexico. *Hydrological Processes* **11**, 949-970.
Neave I, McLeod A, Raisin G, Swirepik J (2015) Managing water in the Murray-Darling Basin under a variable and changing climate. *Water: Journal of the Australian Water Association* **42**, 102.
Nielsen DL, Brock MA (2009) Modified water regime and salinity as a consequence of climate change: prospects for wetlands of Southern Australia. *Climatic Change* **95**, 523-533.
Nielsen DL, Jasper EW, Ning N, Lawler S (2015) High sediment temperatures influence the emergence of dormant aquatic biota. *Marine and Freshwater Research* **66**, 1138-1146.
Nielsen DL, Podnar K, Watts RJ, Wilson AL (2013) Empirical evidence linking increased hydrologic stability with decreased biotic diversity within wetlands. *Hydrobiologia* **708**, 81-96.
Ning N, Stratford D, Nielsen D*, et al.* (2015) A review of climate refuge science and its application in the Murray-Darling Basin. Final Report prepared for the Murray-Darling Basin Authority, p. 72pp, The Murray-Darling Freshwater Research Centre, MDFRC Publication 75/2015.
Ooi MKJ, Auld TD, Denham AJ (2009) Climate change and bet-hedging: interactions between increased soil temperatures and seed bank persistence. *Global Change Biology* **15**, 2375-2386.

Ooi MKJ, Auld TD, Denham AJ (2012) Projected soil temperature increase and seed dormancy response along an altitudinal gradient: implications for seed bank persistence under climate change. *Plant and Soil* **353**, 289-303.
Overton I, Jolly I (2004) *Integrated Studies of Floodplain vegetation Health, saline groundwater and flooding on the Chowilla floodplain South Australia* CSIRO Land and Water.
Perry LG, Andersen DC, Reynolds LV, Mark Nelson S, Shafroth PB (2012) Vulnerability of riparian ecosystems to elevated CO2 and climate change in arid and semiarid western North America. . *Global Change Biology* **18**, 821-842.
Pittock B (2003) Climate change: an Australian guide to the science and impacts. *Australian Green House Office, Canberra*.
Pittock J, Finlayson CM (2011) Australia's Murray-Darling Basin: freshwater ecosystem conservation options in an era of climate change. *Marine and Freshwater Research* **62**, 232-243.
Poorter H, Navas ML (2003) Plant growth and competition at elevated CO2: on winners, losers and functional groups. *New Phytologist* **157**, 175-198.
Potter N, Chiew F (2009) Statistical characterisation and attribution of recent rainfall and runoff in the Murray-Darling Basin, 2812-2818.
Potter NJ, Chiew FHS, Frost AJ (2010) An assessment of the severity of recent reductions in rainfall and runoff in the Murray-Darling Basin. *Journal of Hydrology* **381**, 52-64.
Rahel FJ, Olden JD (2008) Assessing the effects of climate change on aquatic invasive species. *Conservation Biology* **22**, 521-533.
Reside AE, Welbergen JA, Phillips BL*, et al.* (2014) Characteristics of climate change refugia for Australian biodiversity. *Austral Ecology* **39**, 887-897.
Roberts J, Marston F (2011) Water regime for wetland and floodplain plants: a source book for the Murray–Darling Basin. National Water Commission, Canberra.
Saft M, Peel MC, Western AW, Perraud J-M, Zhang L (2016) Bias in streamflow projections due to climate-induced shifts in catchment response. *Geophysical Research Letters* **43**, 1574-1581.
Saintilan N, Rogers K (2015) Woody plant encroachment of grasslands: a comparison of terrestrial and wetland settings. *New Phytologist* **205**, 1062-1070.
Sheldon F, Balcombe SR, Capon SJ*, et al.* (2010) Modelling the impacts of climate change on aquatic ecosystems of the Murray-Darling Basin. *MDBA Publication*.
Suppiah R, Hennessy KJ, Whetton PH*, et al.* (2007) Australian climate change projections derived from simulations performed for the IPCC 4th Assessment Report. *Australian Meteorological Magazine* **56**, 131-152.
Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society* **93**, 485-498.
Walker J, Bullen F, Williams BG (1993) Ecohydrological changes in the Murray-Darling Basin: 1. The number of trees cleared over two centuries. *Journal of Applied Ecology* **30**, 265-273.
Webb BW, Nobilis F (2007) Long-term changes in river temperature and the influence of climatic and hydrological factors. *Hydrological Sciences Journal* **52**, 74-85.
Whitworth KL, Baldwin DS, Kerr JL (2012) Drought, floods and water quality: Drivers of a severe hypoxic blackwater event in a major river system (the southern Murray–Darling Basin, Australia). *Journal of Hydrology* **450-451**, 190–198.
Willis KJ, Bhagwat SA (2009) Biodiversity and climate change. *Science* **326**, 806-807.
Zhang L, Dawes W, Walker G (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* **37**, 701-708.