A Review of River Ecosystem Condition in the Murray-Darling Basin

Prepared by: Ben Gawne, Rhonda Butcher, Jennifer Hale, Richard Kingsford, Kate Brandis, Viyanna Leo, Leanne Wheaton and Sally Hladyz

The Murray-Darling Freshwater Research Centre

Final Report

MDFRC Publication 01/2011
A Review of River Ecosystem Condition in the Murray-Darling Basin

Final Report prepared for the Murray-Darling Basin Authority (MDBA) by The Murray-Darling Freshwater Research Centre

Murray-Darling Basin Authority
Level 4, 51 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 the Murray-Darling Basin Authority, La Trobe University and CSIRO (through its Division of Land and Water). Additional investment is provided through the Australian Government Department of Sustainability, Environment, Water, Population and Communities.

For further information contact:
Ben Gawne
The Murray-Darling Freshwater Research Centre
PO Box 991
Wodonga Vic 3689
Ph: (02) 6024 9650; Fax: (02) 6059 7531
Email: B.Gawne@latrobe.edu.au
Web: www.mdfrc.org.au
Enquiries: info@mdfrc.org.au


Cover Images: (l to r) Macquarie Marshes, Gunbower Forest and Ovens River at Peechelba (Ben Gawne)

MDBA Copyright:
© Copyright Commonwealth of Australia / The Murray-Darling Freshwater Research Centre 2011
Enquiries in respect of this copyright may be directed to the Murray-Darling Basin Authority.
This work is copyright. With the exception of the photographs, any logo or emblem, and any trademarks, the work may be stored, retrieved and reproduced in whole or in part, provided the information is not sold or used for commercial benefit. Any reproduction of information from this work must acknowledge the Murray-Darling Basin Authority, the Commonwealth of Australia, The Murray-Darling Freshwater Research Centre, or the relevant third party, as appropriate, as the owner of copyright in any selected material or information.

Apart from any use permitted under the Copyright Act 1968 (Cth) or above, no part of this work may be reproduced by any process without prior written permission from the copyright owners obtained via the Murray-Darling Basin Authority.
MDBA Disclaimer:
The information contained in this publication is intended for general use, to assist public knowledge and discussion and to help improve the integrated and sustainable management of the Basin’s natural water resources. It may include general statements based on scientific research. Readers are advised that this information may be incomplete or unsuitable for use in specific situations. Before taking any action or decision based on the information in this publication, readers should seek expert professional, scientific and technical advice and form their own view of the applicability and correctness of the information.

To the extent permitted by law, the Commonwealth of Australia, the Murray–Darling Basin Authority (including its employees and consultants), The Murray-Darling Freshwater Research Centre (including their employees and consultants), and the authors of this publication do not assume liability of any kind whatsoever resulting from any person’s use or reliance upon the content of this publication.

The MDBA will where possible and possibly subject to certain limitations make project information and intellectual property available for general use provided that ownership and funding is acknowledged and that it is not used for commercial purposes.

Document History and Status

<table>
<thead>
<tr>
<th>Version</th>
<th>Date Issued</th>
<th>Reviewed by</th>
<th>Approved by</th>
<th>Date Approved</th>
<th>Revision type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draft</td>
<td>27 January 2011</td>
<td>Rhonda Sinclair</td>
<td>Ben Gawne</td>
<td>28 January 2011</td>
<td>Internal edit</td>
</tr>
<tr>
<td>Draft</td>
<td>10 April 2011</td>
<td>Nina Schuurman</td>
<td>Ben Gawne</td>
<td>15 April 2011</td>
<td>External edit</td>
</tr>
<tr>
<td>Draft</td>
<td>24 June 2011</td>
<td>Rhonda Sinclair</td>
<td>Ben Gawne</td>
<td>24 June 2011</td>
<td>QA check</td>
</tr>
</tbody>
</table>

Distribution of Copies

<table>
<thead>
<tr>
<th>Version</th>
<th>Quantity</th>
<th>Issued to</th>
</tr>
</thead>
</table>


Author(s): Ben Gawne, Rhonda Butcher, Jennifer Hale, Richard Kingsford, Kate Brandis, Viyanna Leo, Leanne Wheaton and Sally Hladyz

Project Manager: Ben Gawne

Client: Murray-Darling Basin Authority

Project Title: A Review of River Ecosystem Condition in the Murray-Darling Basin

Document Version: Final

Project Number: M/BUS/248

Contract Number: MD1123

Acknowledgements:
This project was funded by the Murray-Darling Basin Authority. Special thanks to Dr Rhonda Butcher (Water’s Edge Consulting), Professor Richard Kingsford (Professor of Environmental Science, School of Biological, Earth and Environmental Sciences, University of New South Wales), Jennifer Hale (Jennifer Hale Consulting) and Kate Brandis and Viyanna Leo (School of Biological, Earth and Environmental Sciences, University of New South Wales).
Executive Summary

The management of water in the Murray-Darling Basin (MDB) became contentious within a few short decades of European settlement and as development of MDB water resources progressed, the trade-offs among users and the unintended consequences of managing a complex system began to emerge. The proposed Basin Plan represents the latest attempt to resolve the many issues that have emerged from water management over the last 150 years; however, given the complex nature of the MDB system in terms of both its human and natural components and the potential effects of management change on all elements of the system, it is no surprise that the Basin Plan is controversial. The MDBA commissioned a review of the evidence of environmental degradation of water dependent ecosystems (WDE) in the MDB and the major drivers of change, to generate discussion of appropriate solutions. The paper provides five different perspectives on the issue. The sections are:

- A definition of WDEs and conceptualisation of the way they function.
- A summary of the major pressures applied to WDEs in the MDB.
- A review of some institutional condition assessment programs.
- Some examples of key environmental assets and their documented changes in condition.
- Some examples of changes in biota that have occurred in the MDB.

This approach was chosen to facilitate access to the information available and to provide multiple lines of evidence concerning the condition of WDEs and the associated pressures.

Ecosystems are functional units consisting of living things in a given area, non-living chemical and physical factors of their environment; linked together through nutrient cycles and energy flow. Water dependent ecosystems are either surface or groundwater ecosystems, including their natural components and processes that depend on periodic or sustained inundation, water-logging or significant inputs of water to sustain their ecological integrity. While the scope of the Basin Plan encompasses all water-dependent ecosystems, this paper will focus on river ecosystems that are complex systems comprised of a mosaic of interconnected components, floodplain wetlands, floodplains, estuaries and groundwater aquifers connected to river channels.

Water Dependent Ecosystems (WDEs) are a component of the larger continental water cycle that circulates water between the oceans, atmosphere and land mass. The movement of water and associated sediment, nutrients and biota vary in response to climate, geology and ecosystem character and this variation has given rise to the spectacular diversity of rivers, wetlands and floodplains seen on the planet’s continents. Given the role of rivers in a cycle of movement and the fact that they represent a connection, it is perhaps not surprising that river modification has consequences at a variety of scales from individual wetlands and aquifers up to the global scale. The challenge is to understand the changes that have occurred and the consequences for WDEs and their values.
Water dependent ecosystems are complex, dynamic networks with multiple interactions and feedback mechanisms that will respond to changes in either the physical or biological environment or the movement of material between components of the system in ways that can be difficult to predict. This places ecosystems in a similar category to the stock market or the human brain. This complexity affects our capacity to clearly ascribe causality to system changes, especially in situations where there have been various applications of multiple interacting pressures applied to the system depending on the region of the MDB being discussed. The issue can be clarified to some extent by looking at the problem from a variety of angles.

**Pressures**
There are four major categories of pressure that have been applied to WDEs in the MDB, specifically;

- habitat modification, including
  - flow modification
  - land use change
  - water quality change
- overexploitation
- fragmentation
- introduced species.

Each of these pressures has had a profound impact on at least some components of the WDE in the MDB. More importantly, these pressures interact to further stress the system, with ‘flow’ interacting with all of them. Flow is a major driver of water quality, partially through its interaction with the land which is influenced by patterns of land use. Overexploitation of fisheries is more severe when flow modifications undermine a species capacity to recruit the next generation to the population. The alienation of flow from floodplains is a major element in the fragmentation of the system and introduced species appear to have a greater chance of succeeding when flow regimes are modified.

**Condition assessments**
A number of condition assessment programs are undertaken throughout the Basin. The degree of environmental degradation reported depends on the question that they were set up to answer and the indicators included in the program. All programs report significant degradation of the systems they examined. None of the established programs was in operation during the period of greatest water resource development and so all are heavily reliant on their reference condition and the application of system understanding to inform their assessments.

**Site assessments**
For a limited number of sites around the MDB, information has been generated that provides a more detailed examination of changes in condition through time. The sites included in this report are;

- Barmah-Millewa Forest
- Macquarie Marshes
- Barwon-Darling River
- Coorong-Murray Mouth
**Barmah-Millewa Forest:** There is strong evidence of a decline in ecosystem condition at Barmah-Millewa Forest. This evidence ranges from empirical scientific investigations to more broad condition monitoring and inferential studies. There is evidence of decline from before the recent drought and indications that condition has continued to decline since 2000. Although there are various factors that have and are impacting the forest, altered water regimes due to water resource use and development, are the most commonly cited causes of deteriorating ecosystem health at this floodplain wetland site.

**Macquarie Marshes:** Changes in the use and management of land and water in the Macquarie Valley have greatly influenced the extent and health of the Macquarie Marshes. The Macquarie Marshes have existed in their current location and maintained their general wetland state for the last 6000 to 8000 years. Irrigated agriculture began during the 1840s in the South Marsh; however, it was not until the completion of Burrendong Dam in 1967 that large scale irrigation began. By the mid 1990s, irrigated agriculture on the lower Macquarie Floodplain had reached its peak both in terms of area and water use.

**Barwon-Darling River:** Hydrological changes in the Barwon-Darling River are well studied and documented. There is also evidence of a decline in river health of the Barwon-Darling River compared to pre-European condition in terms of geomorphology, particularly; bank instability, water quality and algal blooms, aquatic invertebrates, fish and riparian vegetation. In particular, there is a body of evidence across disciplines that indicate poorer condition in the regulated river reaches of this system than unregulated reaches, providing evidence that water resource management and river regulation has had an effect on river health in the Barwon-Darling River.

**Coorong and Murray Mouth:** The Coorong and Murray Mouth is the only estuary within the Basin and therefore a critical window on cumulative change evident across the Basin, particularly in the lower sections. In recent years the Coorong, Lower Lakes (Lake Alexandrina and Lake Albert) and Murray Mouth have become the focus of concentrated research and management planning aimed at retaining some ecological values whilst the site suffered significant declines in condition. The primary cause of decline across the Coorong, Lower Lakes and Murray Mouth has been identified as reduced inflows, changed magnitude and frequency of flooding exacerbated by drought.

The evidence of the relationship between reduced inflows and declining ecological condition has been well documented and researched. The Coorong and Lower Lakes are listed as a Ramsar Wetland of International Importance, with an Ecological Character Description benchmarked for 1985 when the site was listed. In preparing the Ecological Character Description clearly stated that the character of the site at the time of listing was already ‘seriously degraded’. The overriding driver of the condition of the Coorong and Lower Lakes is altered hydrology. Reduced flow volumes, reduced frequency and duration of medium-sized flood events in spring, and increased risk of the Murray Mouth closing are the main factors implicated in observed environmental changes at the site.
Condition of specific organisms

Invertebrates: The Sustainable Rivers Macroinvertebrate Index showed that communities in the Border Rivers, Upper Murray and Paroo Valleys were in moderate condition, and those in the Avoca and Wimmera Valleys were in very poor condition. The remaining valleys within the MDB were rated as in poor condition. 18% of the invertebrate families encountered were common to all 23 valleys.

Rare families tended to be those that contained species sensitive to pollution and other human disturbances, whilst the common families were characterised as being tolerant.

Trees: A survey in 2007 found only 30% of the area containing river red gum stands along the Murray River is currently in good condition and that there is a downstream decline in stand condition, which is related to more extreme declines in flooding, due to water harvesting and drier climate found in the Lower Murray region. The declines are not surprising given the habitat requirements of red gum and black box adult health and germination. As an example, the maximum inter-flood period that can be tolerated is two to three years for red gums and seven to 10 years for black box. In SA, floodplains that would historically have been inundated once every three years are now only inundated once every 11 years thereby rendering them as unsuitable habitat for either red gum or black box. As a consequence, flow regulation was sufficient to significantly modify tree habitat in some regions of the MDB and the drought has merely pushed the trees beyond their capacity to survive. The latest assessment suggests that current watering regimes (rainfall and flooding) below the Yarrawonga Weir are insufficient to maintain the majority of river red gum stands in good condition. Of longer term concern is that flow regimes may be inadequate to support black box breeding and marginal for red gum breeding in many areas where populations currently exist.

Fish: Native fish are among the best understood biotic groups and significant effort has gone into their restoration. Native fish populations are estimated to be less than 10% of what they were prior to European settlement. In addition, the population status of some populations is tenuous with little evidence of recruitment. While early declines may be attributed to overexploitation there was a significant decline in the period from 1955 to 1980 in Murray cod, silver perch and freshwater catfish.

Birds: Surveys of eastern Australia have indicated long-term declines in waterbird numbers. Much of this decline is attributable to significant changes in waterbird numbers on wetlands in the Murray-Darling Basin. Such impacts have also affected migratory and resident shorebird species where impacts appear to be higher on regulated wetlands in the Murray-Darling Basin. This includes regulated lakes as well as large wetlands such as the Macquarie Marshes and Lowbidgee Wetlands. A decrease in numbers of waterbirds has occurred, coinciding with decreased flooding and extent of wetlands in the Murray-Darling Basin.

In the Murray-Darling Basin, water resource development has changed the natural flow regimes of many river systems affecting colonial waterbird breeding, reducing the frequency of breeding opportunities and impacting on reproductive success. In species that are nomadic and opportunistic and breed on relatively few wetlands, this may have significant implications for continental waterbird populations.
Implications

The WDEs of the MDB are a complex system comprised of a mosaic of interconnected components, including river channels, floodplain wetlands, floodplains, estuaries and groundwater aquifers linked together through the exchange of sediment, nutrients, energy and organisms. In order to achieve the objectives of the Water Act (Australia 2007), the MDBA is required to manage WDEs to protect biodiversity (as required by international agreements) and protect, restore and provide for the ecological values and ecosystem services of the Murray-Darling Basin.

This section will apply the current knowledge of WDEs and their condition to describe some of the implications for achievement of the Water Act’s objectives.

Under natural conditions, WDEs sustain biodiversity and provide a range of ecosystem services through a diversity of environmental and climatic conditions. As WDEs are modified, biodiversity is reduced and the delivery of services, on which MDB communities are reliant, changes. Due to the nature of complex systems, the changes are unlikely to be a gradual change in average conditions; rather the system is more likely to either;

- Cross thresholds that will lead to step changes in the condition of the system and/or delivery of services. or;
- Exhibit less stability as resilience declines resulting in greater variation in both the condition of the system and delivery of services which may, in turn, result in;
- Increases in the magnitude or severity of extreme events.

As noted earlier, our capacity to predict the behavior of WDEs is, and may always be, relatively limited; however, it is possible to make some general predictions based on the following characteristics of WDEs in the MDB.

- The MDB’s WDEs are naturally characterised by a high degree of disturbance (e.g. flood, drought, fire).
- Natural disturbances and anthropogenic pressures tend to interact to increase pressure on the system or decrease resilience.
- River floodplain ecosystems are a network of interconnected or interdependent components (e.g. habitats or assets).
- There can be significant delays between the implementation of a change and the system achieving a new state.
- There are likely to be feedback mechanisms that may reinforce and amplify change.
- Extinctions are often driven by synergistic, feedback processes or stochastic events that either occur or have a greater impact due to the state of the system.

Given these characteristics, it appears probable that without significant management change there will be ongoing and increasing degradation of WDE in the MDB.
# Table of Contents

Executive Summary ........................................................................................................ iii

Table of Contents ........................................................................................................... viii

Introduction .................................................................................................................... 1

Water Dependent Ecosystems ....................................................................................... 2

How WDE Function ...................................................................................................... 3

Major Pressures ............................................................................................................ 5

- Habitat modification ................................................................................................. 7
- Overexploitation ......................................................................................................... 12
- Fragmentation ........................................................................................................... 13
- Introduced species .................................................................................................... 16

Condition assessments ................................................................................................. 18

Assessment programs ................................................................................................. 18

Condition of some key environmental assets ................................................................ 25

- Barmah-Millewa Forest Site Assessment .................................................................. 25
- Macquarie Marshes Site Assessment ...................................................................... 38

Trends in condition and evidence of decline ............................................................... 39

- Barwon-Darling River Site Assessment (upstream of Weir 32) ............................... 47
- Coorong and Murray Mouth Site Assessment: ....................................................... 57

Condition of specific organisms ................................................................................. 75

- Invertebrates ........................................................................................................... 75
- Vegetation ................................................................................................................ 78
- Fish .......................................................................................................................... 86
- Birds ......................................................................................................................... 92
- Frogs ........................................................................................................................ 96
- Reptiles in the Murray-Darling Basin .................................................................... 98

Implications .................................................................................................................. 100

References .................................................................................................................... 105

Attachment A. Chronology of significant steps in addressing environmental degradation .... 131

Attachment B. Additional references on the condition of WDE in the MDB sourced from Richard Kingsford’s WISE database ........................................................................... 134
Introduction
The management of water in the Murray-Darling Basin (MDB) became contentious within a few short decades of European settlement. Initial controversies concerned South Australia’s access to water in the 1850s (Connell 2007) and the management of the fishery in the 1880s (Humphries & Winemiller 2009). As the development of MDB water resources progressed, the trade-offs among users and the unintended consequences of managing a complex system began to emerge. Among the first of the unintended consequences to emerge was salinity which became evident in the 1960s. Improved knowledge of the relationship between water and land management and environmental issues initiated a broadening of the role of the River Murray Commission (RMC) to include responsibility for water quality in 1982.

Responsibility for water quality signified a major change away from a focus on water resource development to a focus on resource management. Internationally, this change was associated with the emergence of Integrated Catchment Management as a means of managing the entire system to deliver desired outcomes rather than attempting to manage components in isolation. This philosophy was one of the influences on the formation of the Murray-Darling Basin Commission (MDBC) in 1987 that included Queensland and the ACT, ensuring that all the jurisdictions involved in managing water in the MDB were included.

Once this philosophical transition had taken place, the challenge was to develop an understanding of the system that was being managed and this meant that the MDBC included consideration of biodiversity and sustainability in its water management (Connell 2007). In response, the MDBC implemented the Natural Resources Management Strategy (NRMS) in 1990 that set the framework for coordinated action and provided funding to on-ground works and knowledge based activities such as research, investigation, monitoring and education.

Subsequently, the MDBC and its successor in December 2008, the Murray-Darling Basin Authority (MDBA), have sought to improve their understanding of system function to enable achievement of strategic goals through the management of trade-offs and risks. Examples of this endeavor include significant investments in The Murray-Darling Freshwater Research Centre (MDFRC) and the Cooperative Research Centre for Freshwater Ecology (CRCFE). The imperative to change and improve water resource management has been punctuated by a number of significant events, including the 1991 blue-green algal bloom in the Darling River, the closure of the Murray mouth, declining wetland health, blackwater events in 2005 and 2010 and the millennium drought.

The challenge of sustainable management of water resources in the MDB remains complex, but the need for fundamental change appears to be growing due to the coincidence of a number of factors, including:

- A gradual increase in water use that incrementally imposed greater change on the system.
- The time lag between management change and emergence or recognition of the consequences.
• Improved knowledge that made documentation and explanation of the changes more broadly available.
• The occurrence of a significant drought.

The proposed Basin Plan represents the latest attempt to resolve the many issues that have emerged from water management over the last 150 years; however, given the complex nature of the MDB system in terms of both its human and natural components and the potential effects of management change on all elements of the system, it is no surprise that the Basin Plan is controversial. The controversy is difficult to resolve in part due to the complex nature of the debate that includes;

• The goal. A summary of the values we are trying to sustain.
• The relationship and trade-offs among values. It is unlikely that the MDB can sustain all aspirational values and so there needs to be agreement on the trade-offs.
• The condition of the system. A description of the system and the extent to which the current condition aligns with values articulated in the goal.
• The solution. The management actions required to move from the current situation to the goal. This discussion requires an understanding of the major drivers of change in order to optimise the probability of success.

The Water Act (Australia 2007) provides an articulation of the goal for water management in the MDB. Our scientific, social and economic knowledge attempts to quantify the trade-offs with varying degrees of success. The MDBA has commissioned a review of the condition of the environment at the 188 sites used for the development of the Basin Plan. The objective of this paper is to provide further insight into the condition of WDEs and the major drivers of change to generate discussion of appropriate solutions.

This paper provides four sections, each of which provides a perspective on the condition and drivers of WDE condition. The sections are;

• A definition of WDEs and conceptualisation of the way they function.
• A summary of the major pressures applied to WDEs in the MDB.
• Some examples of key environmental assets and their documented changes in condition.
• Some examples of changes in biota that have occurred in the MDB.

This approach was chosen because the authors believed that it would both make the information accessible and also provide multiple lines of evidence concerning the condition of WDEs and the associated pressures.

**Water Dependent Ecosystems**

Ecosystems are functional units consisting of living things in a given area, non-living chemical and physical factors of their environment, linked together through nutrient cycles and energy flow. Water dependent ecosystems are either surface or groundwater ecosystems, including their natural components and processes that depend on periodic or sustained inundation, water-logging or significant inputs of water to sustain their ecological integrity.
While the scope of the Basin Plan encompasses all water-dependent ecosystems, this paper will focus on river ecosystems that are complex systems comprised of a mosaic of interconnected components, floodplain wetlands, floodplains, estuaries and groundwater aquifers connected to river channels.

**How WDE Function**

Water Dependent Ecosystems (WDEs) are a component of the larger continental water cycle that circulates water between the oceans, atmosphere and land mass. The water cycle plays a significant role in the climate, ecology and biogeochemistry of the planet (Vorosmarty & Sahagian 2000). The water cycle includes a number of natural stores including oceans, the atmosphere, aquifers, soil and wetlands. Rivers represent the connection between water that leaves the atmosphere, terrestrial water storages and the ocean. The movement of water and associated sediment, nutrients and biota vary in response to climate, geology and ecosystem character and this variation has given rise to the spectacular diversity of rivers, wetlands and floodplains seen on the planet’s continents. Given the role of rivers in the cycle of movement and the fact that they represent a connection, it is perhaps not surprising that river modification has consequences at a variety of scales from individual wetlands and aquifers up to the global scale (Vorosmarty & Sahagian 2000). The challenge confronting science is to understand the changes that have occurred and the consequences the changes will have on the values of WDEs we would like to sustain.

The interaction of variable flow with landscape produces a mosaic of interconnected habitats with each habitat type providing a suite of challenges and opportunities. Within each habitat a suite of organisms co-evolve to exploit the opportunities available and, in the process, modify the habitat.

Sediment is eroded from landscapes where the rate of erosion is determined by geology, slope and vegetation cover (Wilkinson et al. 2009; Young 2001). Once it enters an aquatic system the key processes of transport, erosion and deposition are controlled by flow and its interaction with geomorphology and vegetation. High flow events are particularly important for scouring sediment and modifying habitat through either small scale changes in sediment composition or larger scale changes in geomorphology. Drying events can also be important as they provide an opportunity for the consolidation of sediments.

Nutrients are chemicals that are essential to sustain life. As a consequence, nutrients cycle between physical and biological components of the system with the nature of a specific nutrient cycle influenced by the chemical properties of that nutrient, the ecosystem and the flow regime. One of the major nutrients is phosphorus which is widely associated with WDE degradation through nutrient addition (Carpenter et al. 1998; Khan & Ansari 2005). In Australia, phosphorus rose to prominence in the 1990s due to its role in promoting blue-green algal blooms (Bormans & Condie 1998; Bowling & Baker 1996; Davis & Koop 2006; Webster et al. 2000). There are three major stocks of phosphorus in aquatic systems; sediment, water and biota (Khan & Ansari 2005). The key exchanges between these stocks are driven through uptake by plants, fungi and bacteria, excretion by animals, and sorption and release from sediments.
One of the major drivers of phosphorus release from sediments is oxygen depletion in sediments that arises due to an interaction between organic matter, current speed and sediment composition (Baldwin & Williams 2007). Flow influences phosphorus cycling in three major ways;

- Through its influence on sediment composition, oxygen levels and accumulation of organic matter.
- Cycles of wetting and drying also promote the release of phosphorus into the water column (Baldwin & Mitchell 2000).
- High flow events mobilize sediments to which phosphorus is bound, moving phosphorus between components of the system (McKee et al. 2000; Wilson 2008).

Nitrogen is another important nutrient that may limit the rate of key processes such as primary production and decomposition (Harris 2001). The addition of nitrogen to WDEs is also associated with degradation (Bianchi et al. 2010; Schindler et al. 2006). Knowledge of nitrogen cycles in Australian systems is less well known due to the complexity and diversity of nitrogen cycling processes (Baldwin et al. 2006; Harris 2001). The major stocks of nitrogen are nitrogen gas, the sediments, water column, and biota. The critical processes include uptake by algae, bacteria and fungi, conversion and excretion by biota, fixation of nitrogen gas to nitrogen compounds and the conversion of nitrogen compounds to gas (Young 2001). Major sites of nitrogen transformation include organically rich sediments and biofilms (Baldwin et al. 2006). Flow has an influence on nitrogen cycling through; cycles of wetting and drying, influence on patterns and rates of primary production and its influence on decomposition which influences conversion of nitrogen compounds to gas. Drying and rewetting is associated with the release of nitrogen into the water column (Baldwin & Mitchell 2000; Kobayashi et al. 2009). Floods are associated with the transport of large amounts of nitrogen (McKee et al. 2000; Mitchell et al. 1997; Wilson 2008).

Carbon is one of the fundamental building blocks of life and the movement of carbon is one of the processes that link organisms and habitats as a part of a system. Carbon exists in an astounding diversity of forms with the major stocks being gaseous, dissolved inorganic and living and dead organic matter. The conversion of gaseous and dissolved inorganic carbon into organic matter is undertaken by plants, including algae, macrophytes and trees. The conversion of organic matter into different forms and into inorganic forms is undertaken by all life forms. The movement of carbon through freshwater food webs remains an area of uncertainty; however, bacteria and fungi appear to play an important role processing up to 80% of organic matter in a river channel (Gawne et al. 2007; Rees et al. 2005b). Algae appear to be an important carbon source for river food webs (Bunn et al. 2003; Burford et al. 2008) with higher plants playing an important role in smaller streams (e.g. (Reid et al. 2008)). Food webs are complex due to the high degree of variation in both space and time, but can include a diversity of bacteria, fungi, invertebrates, fish, birds (e.g. ducks, heron, sea-eagles) reptiles (e.g. turtle, snakes, lizards), frogs and mammals (e.g. platypus, kangaroo, human).
Flow is a fundamental driver of carbon cycles in WDEs. Flow influences levels of production with events like floods producing an increase in floodplain productivity in trees (Sims et al. 2009) and algae (Bunn et al. 2006). Flow can also have a significant influence on patterns of production by acting as a disturbance to algal communities (Bunn et al. 2003) or changing habitat availability (Gawne et al. 2007). Changes in flow can also influence food web dynamics as food availability and prey vulnerability vary (e.g. Burford et al. 2008; Gawne & Scholz 2006; Kingsford et al. 2004; Wantzen et al. 2002).

The movement of water, sediment and the cycling of nutrients and carbon occurs at a range of spatial and temporal scales with processes such as the suspension and deposition of sediments or the cycling of nutrients between sediments, vegetation and the water column taking place within a wetland or river reach. These exchanges and cycles also take place at larger spatial and temporal scales with water, sediment, nutrients and carbon exchanged between components of the landscape mosaic, including river channels, wetlands and floodplain. The ongoing interaction between the movement of water, sediment, nutrients and carbon interacts with the ecosystem to sustain the mosaic of physical habitats and influence the rate of critical processes such as primary production and decomposition. The resultant characteristics of the physical habitat and flux of material sets a template for the biotic community that will exploit the system in order to complete their life cycle. In the process, the living system influences the physical environment and the movement of material to other components of the system.

What rapidly becomes apparent is that ecosystems are complex, dynamic networks with multiple interactions and feedback mechanisms that will respond to changes in either the physical or biological environment or the movement of material among components of the system in ways that can be difficult to predict. This places ecosystems in a similar category to the stock market or the human brain with the exception that the components of a stock market or brain have a greater degree of similarity than a natural ecosystem which may have some impact on our ultimate capacity to predict their behavior. This complexity affects our capacity to clearly ascribe causality to system changes, especially in situations where there have been various applications of multiple interacting pressures applied to the system depending on the region of the MDB being discussed. The complexity of the issue can be addressed by looking at the problem from a variety of angles. The rest of this review provides a number of lines of evidence to evaluate the major drivers of WDE change in the MDB, starting with the pressures society have imposed.

**Major Pressures**

This section examines the four major categories of pressure that have been applied to WDEs in the MDB and provides specific examples within each category. A clear understanding of the pressures will facilitate interpretation of condition assessments and facilitate identification of appropriate remedial action. The diversity and scale of the pressures identified and the way that they interact should also make it clear that there are no simple solutions to the challenges faced.
The pressures described may appear different to the four major risks to water resource condition and continued availability identified by the MDBA which are:

- insufficient water for the environment
- water quality unsuitable for use
- poor health of water-dependent ecosystems
- risk to water resource availability.

There is however, a reasonable alignment between the risks and pressures. Water quality is one of the major characteristics defining habitat, but it is also one of the key ecosystem services on which our utilisation of the resource is reliant. Flow is also a key habitat characteristic which also influences the delivery of ecosystem services through a healthy ecosystem. The other two pressures identified also have an influence on the health of water-dependent ecosystems and therefore align with the identified risks (Figure 1).

Figure 1. Flow chart of the relationship between the risks identified in the Guide to the Basin Plan and the pressures described in this document. Grey boxes are pressures and aqua boxes are risks.
Habitat modification

Globally, habitat modification or destruction is one of the major causes of environmental degradation (Brook et al. 2008; Pimm & Raven 2000; Venter et al. 2006). Before it is possible to understand habitat modification, it is necessary to understand the habitat concept. Habitat is defined as the environment in which a particular organism lives and is usually described in terms of the physical, chemical and biological environment that a nominated organism requires to live which will be specific to that organism (Figure 2).

The habitat concept appears deceptively simple, but can be quite difficult to define, firstly because the habitat characteristics required by an organism may vary through the course of its life (Marsh & Cuddy 2010). For example, an aquatic insect’s life cycle commences as an egg that has specific requirements (e.g. Reich & Downes 2004). The egg hatches into an aquatic larva that has specific aquatic characteristics that may change as the larva grows, becomes less susceptible to erosion by current, consumption by predators and can access different food resources. Finally, the larvae will emerge from the river as an adult whose habitat is defined by characteristics of the riparian, floodplain or terrestrial environment.

The second issue that complicates habitat definition is the issue of scale (Kingsford et al. 2010). The factors that define habitat vary depending on the scale being considered. For example, at a small spatial scale and over a short period of time, one suite of habitat features may appear critical while over larger spatial and longer time periods, a different suite of characteristics will be the drivers. For example, for golden perch, persistence in a river reach may depend on the current speed, water quality and the presence of snags. Over longer time periods, important features may include the duration of a dry phase, the presence of refuge pools and the occurrence of floods that influence the morphology of the channel (including refuge pools), opportunities to disperse, and cues and opportunities for recruitment.

In general, in aquatic systems, habitat is defined by some combination of hydraulic, water quality and physical structure (comprised of geomorphology and vegetation). For example, water couch (*Paspalum distichum*) habitat is defined as floodplains that are inundated to a depth of 10-15 cm for a median of 163 days in two years or a maximum of 552 days in two years. Flood timing is believed to be critical as maximum growth is achieved between 30 and 40°C and flowering and seed production occur over summer, therefore flooding provides the greatest benefit when it occurs in spring and summer (Rogers & Ralph 2010). Water couch is however, sensitive to intense grazing (Rogers & Ralph 2010). There is a steadily growing body of literature describing the habitat requirements of MDB biota which has been synthesised through the publication of books (Roberts & Marston 2000; Rogers & Ralph 2010) and development of habitat preference curves (eWater 2010).

Habitat modification occurs when the physical, chemical or biological environment is modified in such a manner as to compromise a population’s capacity to sustain itself. Habitat availability in WDEs of the MDB has been modified in a variety of ways, of which we will consider three that are believed to be among the most significant, specifically changes to the flow regime, land use and water quality.
Figure 2. A depiction of the major characteristics of an organism’s environment. The physical environment would include factors such as current speed, sediment composition or disturbance (fire, drought) regime. The chemical environment would include factors such as turbidity, salinity or pH.

Flow change

One of the major effects of the management of WDEs has been profound modification of the flow regime (Murray-Darling Basin Authority 2010). The types of flow change vary depending on the location within the Basin and the system being considered.

One of the fundamental flow changes associated with water resource development is a reduction in the frequency and magnitude of floods (Arthington & Pusey 2003b; Kingsford 2000a). As flooding is a key component of the habitat requirements for many aquatic and floodplain organisms (Roberts & Marston 2000; Rogers & Ralph 2010), changes to flooding regimes inevitably mean either a decline in the condition or viability of existing species or a transition to a different biological community.

The decline in the condition of red gums in the South Australian reach of the River Murray provides an obvious example of reduced flooding leading to a decline in condition and in some areas - death of a large proportion of individuals (Cunningham et al. 2007). Given the age of the trees and their roles in the ecosystem (habitat provision (McGinness et al. 2010), source of organic matter (Gawne et al. 2007)), their loss represents a significant change that will not be quickly reversed.

Examples of changes in ecological character due to changes in flow regime have been documented at both the Barmah Forest and the Macquarie Marshes. At Barmah, changes in the depth and duration of flooding has led to the invasion of Moira grass plains by red gums (Bren 1991, 1992) and invasion of open water wetlands by giant rush (Juncus ingens) (Mayence et al. 2010; Stokes et al. 2010).
Both of these invasions represent stable states that are difficult to reverse. At the Macquarie Marshes, 7500 ha of wetland vegetation has become dominated by drought-tolerant chenopod shrubland (Bowen and Simpson 2008 cited in (Saintilan et al. 2010)).

A further significant impact of changed flooding regimes has been reductions in waterbird numbers across the Basin (Kingsford & Thomas 1995). Waterbird breeding habitat is generally defined in terms of flood characteristics and vegetation (Leslie 2001; Reid et al. 2009; Rogers & Ralph 2010). Most species have a critical flood duration threshold that needs to be exceeded if breeding is to succeed (Reid et al. 2009). As a consequence, changes to flooding regimes undermine two aspects of many waterbirds breeding habitat by both degrading the vegetation and reducing the duration of floods.

Given the importance of floods to many water-dependent organisms, it is perhaps not surprising that modification of flood regimes has had a significant effect on the condition and character of WDEs in the Murray-Darling Basin.

Another effect of water resource development in some regions of the MDB has been a reduction in the magnitude, frequency or duration of low flow periods (Antidrought: (McMahon & Finlayson 2003)). In river channels, this is manifest through both the elimination of cease-to-flow events and the conversion of periods of low flow to periods of high flow (seasonal reversal of flows). There has been no systematic examination of the effects of eliminating cease-to-flow events, although it is probable that it affects nutrient cycles (Baldwin et al. 2005). There is however, evidence accumulating the effects of seasonal reversal of flows on rivers. A number of fish species reproduction occurs over summer when water temperatures are high and flows low (Humphries et al. 1999). Seasonal reversal does not appear to prevent spawning but does affect survival of larval fish (Humphries & Lake 2000). There are a number of potential mechanisms to explain this pattern including increased energetic demands placed on larval fish due to the faster currents, changes in patterns of productivity (Gawne et al. 2007) or reductions in the abundance of microinvertebrates which are a critical food resource for larval fish (Humphries et al. 1999). Whatever the mechanism, seasonal reversal of flow appears to have had a detrimental impact on native fish communities.

The effect of elimination of a dry phase has been much more widely examined in wetlands where permanent inundation is associated with declines in the diversity and abundance of waterbirds (Kingsford et al. 2002; Kingsford et al. 2004) and declines in aquatic vegetation (Brock & Casanova 1991; Poiani & Johnson 1993; Walker et al. 1994). The declines appear to be driven by a combination of changes in vegetation as a dry phase is an important habitat character (Rogers & Ralph 2010), as are changes in nutrient cycles (Baldwin & Mitchell 2000) and food web changes that occur due to the lack of a drying disturbance (Gawne & Scholz 2006).
Land use change – vegetation clearing
Floodplains are attractive places for humans to settle due to their fertile soils and the availability of water. As a consequence, floodplains have been the focus of agricultural development in the MDB. The utilisation of floodplains for agriculture has led to significant changes for the indigenous biota. These changes are complex and arise from a variety of management changes. In the southern MDB, the change from indigenous human management to European management initially led to the elimination of reed beds and chenopod shrublands and a thickening of floodplain forests (Jurskis 2009). The spread of farming led to the clearing of land with around 40% of floodplain forests being cleared (Jurskis 2009). More recently, changes in fire and grazing regimes have been associated with changes and thickening of understorey vegetation (Jurskis 2009). In the northern MDB, areas such as the Gwydir Wetlands have seen the clearing of 45% of coolibah woodland and 34% of river coobah/lignum shrubland between 1996 and 2005 (Bowen et al. 2008 cited in (Saintilan et al. 2010)).

As noted above, vegetation is often a major habitat characteristic for organisms. Live vegetation provides a place for animals to live (e.g. regent parrots), feed (McGinness et al. 2010) and breed (Mac Nally et al. 2010). Some species of tree and macrophyte also modify the environment to create habitat for other types of vegetation (Colloff & Baldwin 2010). Dead vegetation also plays a role in providing both habitat (e.g. fish and invertebrates) and food for animals (Ballinger et al. 2010; Mac Nally & Horrocks 2007; Mac Nally et al. 2001). As a consequence, widespread changes to vegetation represent significant change to the amount or quality of habitat available to a wide variety of organisms.

Land use change did not just affect terrestrial and floodplain habitats. The modification of landscapes to enable farming and mining activities led to a dramatic increase in soil erosion to the extent that former Victorian Premier, Sir Henry Bolte observed that ‘We could not have made a bigger mess of the soil of the country if its destruction had been carried out under supervision’. The degradation of soils resulted in dramatic increases in the amount of sediment entering WDEs. Rates appear to have peaked in the second half of the 19th and first half of the 20th century and have abated since the establishment of soil conservation services in the 1940s. Rates of sediment input to rivers and streams remains much higher than natural levels (Scott 2001a).

Increased sediment inputs have two broad effects, specifically changes to water quality (see next section) and geomorphology. Increased sediment inputs led to some river reaches becoming dominated by sheets of sand rather than a mix of material such as silt, clay, gravel or cobble (Moran et al. 2005). The effects of this change appear variable (Bond & Downes 2003; Downes et al. 2006) but may represent a decrease in habitat heterogeneity. Increased sediment inputs also led to the infilling of deep water holes in river channels. Water holes represent a critical refuge habitat and their persistence is heavily dependent on their depth. Reductions in water hole depth reduces the availability of refuges making systems less resilient to drought (Bond & Lake 2005).
Importantly, the effects of changing two habitat characteristics are unlikely to simply be the sum of the effects of the individual changes. The effects of changing both vegetation communities and flow regimes are likely to interact in ways that may be difficult to predict; however, the system’s response to flooding is likely to be different if the vegetation is changed. For example, floods may still provide the habitat required for breeding by the green and gold bell frog (*Littoria raniformis*), but vegetation changes may reduce survival (Wassens et al. 2010). A second example relates to the interaction between sedimentation and drought, where the loss of refuge and any increase in the magnitude or duration of a cease-to-flow period, would increase the magnitude of the disturbance for fish.

**Water quality change**

For water-dependent organisms, water quality is a key habitat characteristic. Quantifying changes in water quality is however, challenging due to the daily, monthly, annual and decadal variations in water quality that occur in response to variations in flow, season and climate. Some of the best evidence comes from the limited palaeolimnological investigations undertaken in the Basin. These studies reveal significant increases in salinity, turbidity and nutrients (Gell et al. 2005a; Gell et al. 2005b) with variable trends in pH (Gell et al. 2005a; Tibby et al. 2003). Many of these changes appear to have occurred quite quickly after European settlement (Gell et al. 2005b; Reid et al. 2007).

Turbidity is a measure of light’s capacity to travel through water which is influenced by suspended particles. Shading due to turbidity is known to reduce the biomass of attached algae (Cook 1999), the density of macroinvertebrates (Bennison et al. 1989; Cook 1999) and productivity of aquatic plants if light is limiting (Ryan 1991). Some macroinvertebrates (Leptophlebiidae, Leptoceridae and Gripopterygidae) are sensitive to very minor increases in turbidity with significant reductions in abundance once turbidities exceed 5 NTU (Gawne & Gigney 2005). It is possible that early dramatic increases in turbidity had a significant effect on macroinvertebrate communities, but that the changes went unrecorded.

There has been no evaluation of aquatic vegetation’s tolerance of turbidity, but turbidity has been found to influence plant morphology and growth (Blanch et al. 1998) and increases in turbidity in the late 19th century are associated with the loss of submerged vegetation from billabongs (Reid et al. 2007).

Fish have been found to be very tolerant of high levels of turbidity; however, turbidity has been found to affect fishes foraging efficiency which may have long-term population consequences.

pH is a measure of the acidity or alkalinity of a given substance on a scale of 0 to 14, where 0 is the most acidic, 14 is the most alkaline (or basic) and 7 is neutral. The pH scale is logarithmic and the pH of a substance is measured by the concentration of hydrogen ions within it. As noted above, there have been records of both pH increases (declining acidity (Tibby et al. 2003)) and decreases (Howitt et al. 2005) in addition to acute acidification that has occurred in some wetlands and river sections (Baldwin & Fraser 2009; Hall et al. 2006; Rees et al. 2010).
There is limited data available on the pH tolerances of organisms with some observational data suggesting that most have a relatively narrow tolerance range (Pusey et al. 2004), although some species were quite resilient. For example, *Retropinna semoni* (Australian smelt) has been observed in water with pH ranging from 3.7 to 9.8. It is likely however, that changes in pH may have subtle effects on ecosystem processes which are poorly understood (Watson et al. 2009).

Salinity is one of the better documented water quality changes (e.g. (Close 1990)) that has occurred in the MDB and has been a major driver of management change (MDBC 1988). The response of aquatic organisms is undoubtedly the most studied parameter in Australian literature. Morris et al. (2002) compiled a salt sensitivity database for more than 1200 species of Australian taxa, while another more recent salinity review addresses data collected since the compilation of the salinity sensitivity database (Watson et al. 2008). Most noteworthy is data suggesting that WDEs are being negatively impacted by salinity levels less than 1000 mg/L. Our understanding of salinity tolerance has been historically dominated by adult life form data but recent research (over the last decade) finds early life stages of biota are generally more sensitive than their adult counterparts. The differences can be quite significant, for example Murray cod have a reported 12 day critical egg development period with mortality occurring at levels over 340 mg/L, while their juvenile fingerling counterparts have an LC50 of 13 700 mg/L (Chotipuntu 2003).

A second development is the emergence of ecosystem impacts of salinity due to the interdependence of organisms. The effects of salinity on Murray hardyhead (*Craterocephalus fluviatilis*) provide an example. The Murray hardyhead is a small native fish found in saline lakes where they lay their eggs on aquatic vegetation (Lintermans 2007). Hardyhead populations in saline lakes undergo dramatic declines as the salinity thresholds of their prey (microinvertebrates) and submerged vegetation (*Ruppia* spp) are affected by increasing salt concentrations (Ellis 2007).

**Overexploitation**

Overexploitation is another way that ecosystems are degraded. This is particularly common in aquatic systems where the overexploitation of fisheries is a global phenomenon (Allan et al. 2005; Humphries & Winemiller 2009). In many instances, fishing results in the removal of larger species and individuals that are often the top predators (Welcomme et al. 2010). The removal of top predators is a concern due to the role that they play across a variety of systems including terrestrial, marine (Borrvall & Ebenman 2006; Myers et al. 2007; Sergio et al. 2008) and freshwater systems (Humphries & Winemiller 2009). In freshwater systems, top predators affect the system through the consumption of prey (e.g. Lieschke & Closs 1999), alterations to the behavior of prey (e.g. Jacobsen et al. 1997; McIntosh et al. 2004) or nutrient recycling (e.g. Attayde & Hansson 2001; Vanni & Layne 1997). These effects mean that predation can be a major driver of ecosystem function in WDEs (Carpenter & Kitchell 1993; Gawne & Scholz 2006).
Early explorers commented on the abundance of fish in the MDB and it didn’t take long for the establishment of commercial fishing (Humphries & Winemiller 2009). By the late 1800s, between 40,000 and 150,000 kg of Murray cod were removed from the river and fish numbers had begun to decline prompting the Government to conduct commissions of enquiry (Humphries & Winemiller 2009). In 1928, there were 1300 commercial fishermen operating in the Murray/Riverina area, this declined to 48 in 1993. Commercial fishing had started to become economically unviable by the 1930s due to declining fish numbers (Humphries & Winemiller 2009). During the mid 1940s, the fishery represented between 42 and 65% of the inland fishery and this declined to around 10% in the 1950s (Faragher & Harris 1993). While direct cause-effect relationships were not determined, it appears likely that the level of exploitation was a major factor in the decline of the fishery (Faragher & Harris 1993).

Commercial fishing has now ceased on the Murray River, but recreational fishing is a popular and economically important recreational activity. There is fish survey data that strongly suggests that for at least some sites, recreational fishing may be having an impact on the population structure of adult fish. While the fishery may be managed to ensure ongoing availability of fish for angling, the altered population structure probably means that the role of top predator in the system is not being fulfilled with unknown consequences for the system (Humphries & Winemiller 2009).

The overexploitation of fish is similar to land use change, in that it interacts with flow changes to increase the stress placed on the native fish community. For fish in some regions of the Basin, the amount of habitat available for adults has been reduced through flow changes, the habitat required for breeding has been reduced due to seasonal reversal of flows or reductions in the frequency of flooding and depending on the species, levels of adult mortality have increased due to exploitation and the quality of many habitats has been reduced due to deteriorating water quality.

Fish are not the only group to suffer due to overexploitation. The collection of firewood from floodplains is also thought to have a significant negative effect on floodplain vertebrates (Mac Nally et al. 2001). It should be noted that the amount of wood found on floodplains before European settlement is a contentious issue (Jurskis 2009). Regardless, it appears that the utilisation of wood on floodplains involves a trade-off between human utilisation, the floodplain environment and that firewood collection will also interact with changes in flow as floods have been found to be one of the major drivers of invertebrate abundance on floodplains (Ballinger et al. 2005). As invertebrates represent a major source of food for floodplain vertebrates, the combination of wood removal and altered flows represent a significant degradation of habitat.

**Fragmentation**

Fragmentation often refers to either the division of a system into components, for example clearing forest to produce a number of small forest patches (e.g. Laurance et al. 2011) or the isolation of system components. While WDEs may appear naturally fragmentated, the movement of materials and organisms among components is a critical aspect of ecosystem function with floods representing a particularly important connection (Balcombe et al. 2007; Galat et al. 1998; Junk et al. 1989). The issue of connectivity and fragmentation is believed to be a core principle in the maintenance of viable populations (Bunn & Arthington 2002).
Fragmentation may mean that materials that are required are not delivered or materials that would otherwise be exported from the system accumulate within the system causing change. Alternatively, fragmentation may prevent organisms accessing the requisite food, avoiding disturbances or predation, or completing their life cycle. Fragmentation also reduces the effective size of habitat patches which can increase the risk of extinction within a fragment.

Water dependent ecosystems have been fragmented in a number of ways, including construction of over 3000 dams and weirs, levies and regulators in the MDB (Arthington & Pusey 2003a). Land use changes, particularly vegetation clearing, have also caused the fragmentation of floodplain and riparian vegetation (Mac Nally et al. 2010). The importance of fragmentation has been recognised for some time; however, evidence of patterns of connectivity are emerging with the development of radio and PIT tags (e.g. Ebner et al. 2009; Meynecke et al. 2008) and genetic population analysis (e.g. Cook et al. 2007; Masci et al. 2008).

**Fragmentation example: Flow**

Reductions in the frequency of flooding through water resource development and the construction of levies has significantly reduced the exchange of sediment, nutrients and organic matter between river channels and their floodplains. A significant proportion of the sediment carried by rivers is exported onto floodplains under natural circumstances as part of the soil formation process that underpins floodplain fertility. It is this interaction between flooding and sediment deposition that determines floodplain forest composition (Pacala 1987; Poff et al. 1997; Stokes et al. 2010) and the reason that alienation of floodplains means that this ecosystem service will be compromised.

Similarly the exchange of nutrients and organic matter will be altered by the alienation of rivers from their floodplains. The 2005 watering of the Barmah Forest was associated with significant deposition of particulate carbon on the floodplain and the export of dissolved carbon from the floodplain back to the river (Gigney et al. 2006). In the Macintyre River, a 55% reduction in connection meant a decrease of up to 98% in the amount of dissolved organic carbon imported from some anabranch channels (Thoms et al. 2005). While the environmental consequences of this type of change are not known, some large rivers have been found to be carbon limited (Rees et al. 2005a) and so fragmentation may reduce the productivity of at least some components of the system (Thoms et al. 2005).

One of the consequences of floodplain alienation is reduced frequency of flooding that allows organic matter to accumulate for longer. The accumulation of organic matter and delays in the timing of inundation while dams are filled, conspire to increase the likelihood of blackwater events (Howitt et al. 2007). Blackwater events are caused by the rapid decomposition of large amounts of dissolved organic matter, leached primarily from Eucalypt leaf litter (Howitt et al. 2007). While these events occur naturally, it appears that the magnitude and severity of these events has increased as a consequence of flow regulation.
Floods are also important drivers of sediment movement and the alienation of floodplains also means that sediments being transported down rivers are not deposited on floodplains. During the 1996 Murray River flood, 13% of the suspended load was found to be retained within a 15 km reach near Mildura and 23 202 tonnes of sediment was deposited on the floodplain (Thoms et al. 2000). It has been estimated that over the last 100 years, the rate of sediment accumulation on the Barmah Forest to be around 0.8 mm/year (Kenyon & Rutherfurd 1999). This depositional is an important part of the soil formation ecosystem service that takes place on floodplains.

Dams also disrupt the longitudinal transport of sediment (Young 2001). For example, research undertaken in the 1970s found that between 67 and 84% of suspended sediment entering Lake Hume was deposited in the lake and that over the period 1974 to 1981, 630 000 tonnes of suspended material was deposited in the lake ((Howitt et al. 2005) and references therein). Given the increases in sediment supply to many rivers, trapping sediments in dams may provide some protection for downstream systems; however, the reach immediately downstream of the impoundment is likely to be sediment starved and this will lead to changes in river morphology (Young 2001). Sediment settles behind dams and water released from dams is sediment poor leading to erosion downstream of dam. Both sedimentation and erosion alter habitat characteristics.

Fragmentation is widely recognized as influencing the viability of populations of animals (Rosenzweig 1995). In rivers around the world, fragmentation has been found to affect the diversity of fish communities (e.g. Bain & Wine 2010; Compton et al. 2008; Dudley & Platania 2007). There has been no systematic examination of the effects of fragmentation on fish of the MDB; however, evidence of the movements of fish is accumulating. For example, studies of golden perch (Crook et al. 2001; O'Connor et al. 2005), Murray cod (Jones & Stuart 2007; Koehn et al. 2009) and trout cod (Ebner & Thiem 2009) found the species were relatively sedentary for extended periods of time but could undertake extended movements of up to 290 km (O'Connor et al. 2005). The implications for populations if fish are not able to make these excursions are not known; however, an experiment is currently underway with the installation of fishways from Lake Hume to the Sea, which will provide data on changes to a fish community once passage is restored.

Lateral fish movement is also important. Ephemeral wetlands are known to support productive and diverse native fish communities and these are only possible if fish are able to move from permanent wetlands or the river channel once the dry wetland refills (Beesley et al. 2010; Gawne & Scholz 2006). Fish also appear to make regular movements into and out of wetlands in response to changes in flow (Lyon et al. 2010). Somewhat surprisingly, the nature of the connection is a more important determinant of fish utilisation of a wetland than the habitat characteristics of the wetland (Beesley et al. 2010). Research in the Cooper Creek has also found that changes to the nature of the connection affected diversity within the wetland (Sheldon et al. 2002). These findings mean that either the elimination or modification of the connection through the installation of a levy or a regulator, may have consequences for the fish community.
One example is that while wetlands that have water pumped into them may still develop a reasonable fish community, unless connection is made back to a refuge, the drying of the wetland will result in the extirpation of any resident fish. An additional example was observed at Barmah where a large proportion of fish trapped behind a regulator were in poor condition as a consequence of not being able to disperse (Jones et al. 2004).

Seed dispersal is an important component of vegetation dynamics. Dams represent a barrier to seed dispersal (Brown & Chenoweth 2008; Merritt & Wohl 2006) which may have long-term implications for vegetation community dynamics. Dams acting as barriers can be a good thing when they impede the spread of invasive species (Rood et al. 2010).

Finally, floodplain fauna are susceptible to the effects of fragmentation from vegetation clearing. One of the prime examples is the regent parrot that requires treed flight corridors between red gum nesting habitat and their Mallee woodland foraging habitat. Feeding and movement corridors have been extensively cleared which represents a significant threat to the species (Baker-Gabb & Hurley 2010).

**Fragmentation example: Salt**

Increasing salinity levels have been a major cause for concern in the MDB (MDBC 1988), these have risen due to a combination of both increased connectivity and fragmentation. Australia’s dry landscape has accumulated salt over millennia. Under natural conditions, salt was leached out of surface soils and into the groundwater, where much of the salt is retained due to the relatively impermeable landscape. Land clearing and irrigation resulted in an increase in the movement of water into groundwater aquifers bringing saline groundwater to the surface. Only a small proportion of this salt leached into rivers where it was exported to the sea. Despite this, rivers were once one of the major ways of exporting salt from the MDB. The relationship between rivers and groundwater aquifers is complex and varies from place to place. In at least some areas, changes to the flow regime or the construction of storages has reduced the drainage of salt into rivers and contributed to its accumulation in floodplain soils.

**Introduced species**

For WDEs, biotic exchange or the introduction of species is recognised as an important driver of biodiversity change (Sala et al. 2000). Introduced species are a major issue for WDEs around the world (Moyle & Light 1996) and the MDB is no exception, with the introduction of a wide variety of plants and animals that have been associated with the degradation of the MDB’s WDEs. Water dependent ecosystems appear particularly vulnerable to invasive species, perhaps in part due to their extensive modification by humans, the potential for flow to facilitate dispersal and because cycles of flood and drought act as disturbances that create opportunities for establishment within the habitat mosaic (Stokes et al. 2010). The MDB now has a highly modified biota with the vegetation (e.g. willow, arrowhead, blackberry and water hyacinth), fish (e.g. carp, gambusia, weatherloach) and mammal (e.g. fox, pig, rabbit) communities undergoing the greatest change. Our knowledge of the effects of these invasions on their host ecosystems remains limited for the majority of species as does our knowledge of the factors, including our management of the system, that may have enabled successful invasion. This section provides a brief summary of four successful invasive species and what we currently know about their effects on their host ecosystems.
Carp
Carp have become one of the dominant species in regulated rivers in the MDB where they can achieve biomasses as high as 3144 kg ha$^{-1}$ and densities of up to 1000 individuals’ ha$^{-1}$ (Harris & Gehrke 1997) and are recognized as a powerful invader (Koehn 2004). Carp have been associated with the destruction of aquatic plants (Fletcher et al. 1985; Roberts et al. 1995) and increasing turbidity whilst feeding (Fletcher et al. 1985; King et al. 1997; Robertson et al. 1997).

While carp have often been blamed for river degradation, there is evidence to suggest that river regulation has facilitated their invasion as carp dominance is correlated with the extent of river regulation (Gehrke & Harris 2001; Gehrke et al. 1995). The underlying mechanism has not been elucidated as floods appear to promote carp recruitment (Driver et al. 2005; Fletcher et al. 1985) but it is possible that regulation provides a refuge for carp (Driver et al. 2005).

Gambusia
*Gambusia holbrooki* were introduced in the 1920s (McDowell 1996). Early evidence suggested that colonisation by gambusia was associated with declines in native fish including purple-spotted gudgeon (*Mogurnda adspersa*) and southern pygmy perch (*Nannoperca australis*; Lloyd & Walker 1986; Rowe et al. 2008). Gambusia are now widespread throughout the Basin and are implicated in the declines of native fish and frogs through predation (Howe et al. 1997; Ivanstoff & Aarn 1999) and fin nipping (Rowe et al. 2008). It has been suggested that the success of gambusia has been facilitated by flow modifications; that flow stabilisation and habitat homogenisation have benefited gambusia to the detriment of natives (Bunn & Arthington 2002).

Arrowhead
*Sagittaria* is an emerging threat in the Murray-Darling Basin. It spreads rapidly and has the capacity to regenerate from fragments. It can choke water courses and greatly alter flow patterns, but is tolerant to high doses of herbicides. While there is little data currently available, it appears to have the potential to have a detrimental impact on biodiversity values within the MDB, with a negative impact on native flora and fauna (Nitschke et al. 2006).

Willow
Willows *Salix* spp. (Salicaceae) were introduced to the Murray River in Australia by 19th century European settlers (Cremer et al. 1995; Frankenberg 1995; Smith & Starr 1999), mainly to act as channel markers for river boats and as stabilising agents protecting reclaimed riparian wetlands (Ladson et al. 1997; Perkins 1903). Since then, more trees have been planted to stabilise riverbank levees and the margins of the weir pools constructed in 1922-1937 (Walker & Thoms 1993). Today more than 100 species, varieties, cultivars and hybrids of willows are present in Australia (Cremer et al. 1995) with subsequent hybrids still arising (Ladson et al. 1997). One of the first species planted, the weeping willow (*S. babylonica*), now rivals the native river red gum (*Myrtaceae: Eucalyptus camaldulensis*) as the dominant riparian tree along some reaches of the River Murray (Walker et al. 1994).
In Australia, willows are generally seen as a serious weed threat to stream and wetland environments due to their highly invasive and adaptive qualities (Frankenberg 1995; Ladson et al. 1999; Ladson et al. 1997; Schulze & Walker 1997). A widely accepted view has emerged that fundamental stream ecological processes may be affected by willow spread, causing a broad range of detrimental impacts to WDEs (Bobbi 1999; Campbell 1993; Frankenberg 1995; Ladson et al. 1997; Smith & Starr 1999). Such concern has resulted in willows attracting national attention. In 1999, all but three willow (Salix) species were included on the Weeds of National Significance (WONS) list, which declares Australia’s 20 worst weed species (ARMCANZ 2001).

Willow studies have historically focused on allochthonous (leaf litter) inputs, leaf breakdown rates, canopy cover, stream shading and temperature, and macroinvertebrate feeding preferences (e.g. (Collier & Winterbourn 1986; Parkyn & Winterbourn 1997; Pidgeon & Cairns 1981; Pidgeon 1978; Schulze & Walker 1997; Yeates 1994)). In Australia, previous studies on willow effects have included comparisons of willow and native leaf pack decomposition and colonisation, and field surveys of aquatic biota and thermal changes at willow and native forest lined reaches (Besley 1992; Pidgeon & Cairns 1981; Schulze & Walker 1997). Few studies have actually examined or quantified the impacts of willows on in-stream fauna, despite reviews by various authors (Ladson et al. 1997). A number of studies comparing biota under native and willow vegetation have been inconclusive (Besley 1992; Pidgeon 1978; Schulze & Walker 1997). In fact, to date, only three peer-reviewed journal papers have investigated direct willow-stream interactions in Australia (Cremer et al. 1995; Pidgeon & Cairns 1981; Schulze & Walker 1997). Evidence for such interactions is still inconclusive with inconsistent or contradicting results warranting further research.

**Condition assessments**

**Assessment programs**

Condition assessments are an important component of natural resource management within an adaptive management framework. They provide an assessment of the state of the environment that can be used to inform the development of objectives, prioritising actions or assessing the effectiveness of past interventions. In general, condition assessments are not designed to detect the major drivers of any change in condition and can only do so when the assessment program includes the period of time over which the management intervention occurred in the absence of other changes that may confound the analysis. All of the major condition assessment programs run within the MDB have been developed after the period of greatest development; in recognition that water resource development had led to unforeseen consequences, including the decline in the condition of key environmental assets. Further, many are targeted at measuring the outcomes associated with specific management actions aimed at improving condition such as the allocation of environmental water which is a different question and may not necessarily allow quantification of historical change.
Current condition assessment programs provide an assessment of condition over the period of the program but will seldom identify the causes of decline. As a consequence, generating insight into the major drivers of ecosystem change relies on either targeted research or the application of our understanding of how the system functions. The following section provides a brief summary of some of the major condition assessments as a further line of evidence concerning the condition of WDEs in the MDB.

The NSW State of the Environment Report (NSW SoE)
The NSW SoE is undertaken once every three years in accordance with the requirements of the NSW Protection of the Environment Administration Act (1991) NSW. The Report synthesises available environmental information to provide an overview of environmental condition in the state. The report includes an overview of water including water resources, river health, wetlands, groundwater, marine and estuarine systems.

The river section assesses fish, macroinvertebrates, water quality, hydrology and algal blooms. The NSW SoE draws heavily on the MDBA’s Sustainable Rivers Audit (SRA) for its hydrology, macroinvertebrate and fish assessments which will be covered separately. In addition the NSW SoE Report (DECCW 2009) reports that seven of the 25 native freshwater species found in lowland rivers are listed as threatened, which represents a doubling since the 2006 report. The report also notes that there are now three aquatic communities listed as endangered, specifically the Lowland Murray, Lowland Darling and Lowland Lachlan River ecological communities. The water quality assessment reports a decrease in riverine salinity over the previous six years, which is ascribed to the isolation of floodplains.

The NSW SoE Wetlands section includes an assessment of wetland extent, wetland condition and waterbird abundance and diversity. While no state-wide assessment was available for wetland areas, ongoing remote sensing of key wetland complexes (including Gwydir and Macquarie) indicated reductions in the frequency and duration of inundation and that the areas of wetland that receive high frequency flooding have declined. NSW has a unique waterbird data set that enables assessment of waterbird numbers from 1983 to present day. These data indicate dramatic declines in waterbird numbers. The NSW SoE 2009 report found that there had been a slight increase in waterbird numbers since the last assessment in 2006 due to flooding in the Paroo-Warrego Wetlands and Narran Lakes. The trend analysis still indicates overall declines.

Victorian Index of Stream Condition (ISC)
The ISC (DSE 2005) was established in 1999 to provide an assessment of river condition to both improve natural resource planning and evaluation of past management. The program is based on five categories of indicators, specifically: hydrology, physical form, water quality, riparian vegetation and macroinvertebrates (aquatic life). Each category is comprised of a range of individually measured variables that are assessed against a natural reference and scored out of 10, then combined through a weighting process.
The ISC undertakes an assessment of river reaches that enables the reporting of the proportion of stream length in the catchment in each of five categories from excellent to very poor. In 1994, two rivers (Ovens and Upper Murray Rivers) were reported as having 31-50% of their length in good or excellent condition while the Kiewa and Goulburn Rivers were reported as having 11-30% of their length in good or excellent condition. All other Victorian rivers within the MDB were reported as having less than 10% of their length in good or excellent condition. In 2004, the status of the Kiewa River had improved to the point that 31-50% of its length was good or excellent while the condition of the Ovens River had declined such that only 11-30% of its length was in good or excellent condition, although this was ascribed to a methodological change in the hydrology index.

In general the ISC detects a decline in condition as one moved west, which appears to be related to low scores for both flow modification and riparian condition. There were also significant water quality issues identified for some rivers including salinity (Loddon and Wimmera Rivers), phosphorus (Campaspe and Wimmera Rivers) and turbidity (Mallee section of the Murray River). Interestingly, the macroinvertebrate index didn’t appear to provide a great deal of discrimination which may reflect a variety of issues including the way that invertebrate samples are collected and the difficulties associated with developing an appropriate natural reference for invertebrates.

**SA Wetland Baseline**

In 2007, the South Australian Government undertook a condition assessment of River Murray wetlands with the objective of establishing a baseline that would both facilitate the development of management objectives and enable the identification of changes through time. The surveys included water quality, vegetation, macroinvertebrates, fish and acidification risk; however, the invertebrate data was not available for this report. The assessment did not attempt to compare the condition of wetlands to a natural benchmark and so does not provide evidence of degradation. The authors of the vegetation report did however; make a number of observations about the condition of the wetlands compared to their expectations which indicate some degree of degradation. The following quote is taken from their report;

‘The floodplain and riparian zones of Lyrup forest were sparsely vegetated with native species and bare soil and salt scald dominated the dry creek beds and riparian zones. Poor health of *Eucalyptus largiflorens* in the survey area was also evident. Both past and current land usage and salinisation of the soil in the survey area seems to have heavily impacted the species present at this location’ (Marsland & Nicol 2008).

The fish and water quality report found several wetlands with some risk of acidification but relatively abundant native fish communities dominated by three species (carp gudgeon, un-specked hardyhead and bony herring) with carp and gambusia representing around 15% of the catch. Without a reference to a benchmark, it is difficult to know whether this pattern of community composition represents a healthy or degraded condition.
River Murray Water Quality Monitoring Program
The MDBC commenced a Murray River water quality monitoring program in 1978 in line with their responsibilities in the area of water quality. The program samples a range of chemical parameters (35 sites), blue-green algae (nine sites) and macroinvertebrates (seven sites) along the Murray River and the lower reaches of its major tributaries. The program did not attempt to assess condition against a natural reference but assessed changes downstream, through time and against national water quality guidelines. A review undertaken in 1999 (AustralianWaterTechnologies 1999), found trends downstream but did not find any changes through time in the chemical data but did find an increase in the frequency of blue-green algal blooms throughout the 1990s. In some ways, the lack of any change through time is surprising as one might have expected either declining water quality in response to ongoing degradation or improvements due to the implementation of initiatives to reduce both salt and nutrient inputs to the river. The review highlights that the chemical characteristics of Murray River water is heavily influenced by tributary inflows and it is possible that short-term variations caused by variations in flow and tributary inflows may mask gradual changes through time.

A more recent review of the macroinvertebrate data was undertaken (Hoenderdos 2006) and a more detailed review is currently underway. The 2006 review found that the macroinvertebrate community had remained relatively stable except for a couple of major community shifts that occurred in response to drought conditions. Given the occurrence of a major drought and floods in 1996, 2000 and 2005 the relative stability of the invertebrate community appears intriguing as one might have expected significant changes to the invertebrate community particularly after the blackwater event that occurred in 2005. It will be interesting to see the results of the more detailed review currently being undertaken.

The Living Murray (TLM)
In November 2003 the MDB Ministerial Council committed to the Living Murray First Step in response to substantial evidence that the River Murray system was degraded and its concern that this degradation threatens the Murray-Darling Basin’s agricultural industries, communities, natural and cultural values, and national prosperity. A key component of the initiative was a commitment to the principles of adaptive management which includes regular assessments of asset condition.

The TLM Condition Assessment is focused on measuring progress of the initiative toward achieving the agreed objectives for each of the key assets. Generally, the targets were set around birds, fish and vegetation. Similar to other large collaborative initiatives (e.g. SRA), it has taken some time to initiate the program but there are now regular assessments of the condition of the assets. The TLM condition assessment program was established to assess the performance of the TLM First Step and therefore is only designed to provide an assessment of changes in condition since the inception of TLM. Despite this, there is information in the reports that provide information on the extent of degradation (Table 1).
The 2008 Living Murray Condition Report (MDBC 2008a) found widespread degradation at the icon sites. Evidence of degradation over the period of 2005 to 2008 included a decline in abundance and recruitment of native fish, including a 96-99% reduction in the number of common galaxias. Most wading birds declined in numbers except banded stilt and red-necked avocet who benefited from increased food availability in the South Lagoon. Trees at Chowilla, Lindsay-Wallpolla and Hattah all declined in condition with a high proportion of black box on Lindsay Island dying during the reporting period. For birds, those wetlands that held water (Hattah Lakes) during the survey period in November 2007 were found to support populations of grey teal, hardhead, Eurasian coot, Pacific black duck and Australasian shoveler, while sites without water (Gunbower-Koondrook-Perricoota) had very few water birds.

Overall, the assessment reveals a decline in the condition of floodplain and wetland vegetation as a result of dry conditions, confirming the importance of flooding as a habitat requirement. For birds and fish it is more difficult to make a definitive assessment as both groups are well adapted to dealing with cycles of wetting and drying and the absence of species or reductions in numbers on a particular date may not be significant if the species has the capacity to recover when wetter conditions return. This represents a significant challenge for condition assessments as it means either that it will take an extended period of time to identify trends in condition or that the reference for an assessment should be appropriate for the context in which the assessment is taken. This would represent a significant scientific challenge.
Table 1. Summary of findings of the 2008 Living Murray Icon Site Condition Assessment (MDBC 2008a).

<table>
<thead>
<tr>
<th>Site</th>
<th>Birds</th>
<th>Fish</th>
<th>Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coorong</td>
<td>Steady decline in most wading birds</td>
<td>Decline in abundance and recruitment</td>
<td>Decline or loss of submerged vegetation</td>
</tr>
<tr>
<td>Chowilla-Lindsay-Wallpolla</td>
<td>22 species identified in response to environmental watering</td>
<td>Little change between 2005 – 2008 Spawning of golden perch and carp</td>
<td>Declining tree condition and death Declining wetland vegetation diversity</td>
</tr>
<tr>
<td>Hattah</td>
<td>16,097 birds, no breeding</td>
<td>Significant fish community with few introduced species</td>
<td>Trees in poor condition Absence of flood responsive understorey</td>
</tr>
<tr>
<td>G-K-P</td>
<td>2 species recorded in response to environmental flow</td>
<td>6 species recorded in response to environmental flow</td>
<td>Declining canopy condition</td>
</tr>
<tr>
<td>Barmah</td>
<td>13 species on two wetlands with water</td>
<td>Decline due to wetland drying</td>
<td>Limited understorey</td>
</tr>
<tr>
<td>Murray Channel</td>
<td>Low numbers and diversity</td>
<td>SRA: Poor Condition</td>
<td>Not available</td>
</tr>
</tbody>
</table>

Snapshot of Basin Condition (2001)

In the late 1990s, the MDBC was in the process of developing a number of strategies to achieve sustainable management including a Flow Management Plan, a Floodplain and Wetlands Strategy and the Native Fish Strategy all of which had implications for flow management. The move toward implementation of environmental flows increased the need for a condition assessment on which to build the case for environmental flows and in response, the Chair of the MDB Ministerial requested an interim snapshot assessment of river health to aid council decisions on the allocation and management of environmental flows. The snapshot was undertaken by the CRC for Freshwater Ecology (Norris & Young 2001) using existing data. In order to ensure the integrity of the assessment, the MDBA had the report reviewed by its Independent Sustainable Rivers Audit Group.

The assessment used five themes, specifically;

- biota: Macroinvertebrates due to the lack of other available data at the time
- hydrological
- water quality: Nitrogen, phosphorus, suspended sediments and salinity
- physical form: Bed condition, riparian vegetation, connectivity (dams and levies)
- catchment disturbance: Land use
The assessment found that over 95% of the river length assessed was degraded and 30% was substantially modified from the natural condition. The largest influences on this assessment were water quality and catchment disturbance. Catchments in the central and western regions of the Basin were only moderately modified in comparison to catchments in the south eastern regions that were found to be substantially modified.

Of the indices examined, the one with the poorest data coverage was the biota theme in which South Australia and Victoria were the only states with reasonable data coverage. Of the reaches assessed, 62% were assessed to be in reference condition; however, these reaches were clustered in the upland and montane sections of the Basin where pressures have not been as great. Of the remaining 38% of reaches assessed, 10% of all reaches were found to be significantly impaired.

Due to the MDBC’s Murray River Water Quality monitoring program, a more comprehensive assessment was possible in the Murray and Lower Darling Rivers. It found that macroinvertebrate communities were significantly modified (poor condition) in all zones and severely impaired (very poor condition) in the reaches between Yarrawonga and Torrumbarry and between Lock 11 to Lock 3. Riparian vegetation ranged from good in the upper reaches to extremely poor in lower reaches.

**SRA**

In addition to the growing need to quantify the need for environmental flows the MDBC was also interested in evaluating the performance of policy initiatives, including the Cap in diversions. In 2000, the MDBC undertook a review of the effectiveness of the Cap on diversion. The review reinforced the need for a standardised assessment of condition. In response, the MDBC initiated development of the *Sustainable Rivers Audit* (SRA) in collaboration with the jurisdictional agencies.

The SRA currently combines information about the status and trends of three themes in each of the 23 river valleys of the MDB with two additional themes under development. The three active themes are hydrology, fish and macroinvertebrates. The SRA has been set up explicitly to assess both condition and trends through a comparison with a reference condition, which in the case of condition is the state of the system in the absence of significant human intervention. The reference condition description is synthesised from historical data, expert knowledge and modeling.

The strength of the SRA is that it undertakes a standard assessment of river valleys that enables both a comparison across the Basin and integration to provide a Basin-scale assessment. At this stage, one of the limitations of the SRA is that it only assesses indicators within the main river channels and important components of the system, including floodplains and wetlands, are not part of the assessment.

The SRA is in the process of developing its report for the period 2004 to 2010, but at the time of preparation, only the 2004 to 2007 results were available. As was widely publicised at the time of its release, the 2007 report found that only one river (Paroo River) was in good condition with two in moderate condition, 12 in poor and 30 valleys in very poor condition with the Murrumbidgee and Goulburn Rivers being in poorest condition.
Due to the number of gauging stations and variation along rivers, the hydrology index could be presented as a range. Minimum scores ranged from 16 (Lower Murray River) to 100 (Castlereagh and Paroo Rivers). Among the biological indicators the fish index ranged from the mid 70s in the Paroo River to less than 10 in the Mitta Mitta, Campaspe and Goulburn Rivers. The macroinvertebrate index showed less variation ranging from mid 60s in the Border Rivers, Upper Murray and Paroo Rivers down to the low 30s in the Avoca and Wimmera Rivers.

Valleys in the northern MDB were generally in better condition that those in the south. The Lower Murray and Lower Darling Valleys were toward the middle suggesting that impacts do not accumulate as one moves downstream. Many of the upland and montane sections were rated poor or very poor which was often a product of the high number of alien fish in upper catchments.

**Condition of some key environmental assets**

As noted above, none of the current condition assessment programs cover the period of greatest development of water resources in the MDB. A complementary approach to the identification of the pressures responsible for the current condition of WDEs is to synthesise information from the limited number of sites for which there is longer term data available. This section has selected some of the MDB’s best known sites and provides a brief overview of the available information on condition changes at these sites. The sites have been selected because they provide both a long-term record and represent a cross-section of the major components of WDEs.

**Barmah-Millewa Forest Site Assessment**

**Summary**

There is strong evidence of a decline in ecosystem condition at Barmah-Millewa Forest. This evidence ranges from empirical scientific investigations (e.g. Bacon et al. 1993; Cunningham et al. 2009; Leslie 2001; Stokes et al. 2010) to more broad condition monitoring (e.g. MDBC 2007, 2008a; Norris & Young 2001) and inferential studies (e.g. Jones & Stuart 2004; Jones & Stuart 2008; Quinn et al. 2000). There is evidence of decline from before the recent drought (Bren 1992; Bren 1988; Kenyon & Rutherfurd 1999; Leitch 1989; Leslie 2001) and indications that condition has continued to decline since 2000 (Cunningham et al. 2009; Kingsford & Porter 2009b; MDBC 2007, 2008a). Although there are various factors that have and are impacting the forest, altered water regimes due to water resource use and development, are the most commonly cited causes of deteriorating ecosystem health at this floodplain wetland site (Bacon et al. 1993; Bren 1992; Bren 1988; Cunningham et al. 2009; Department of Sustainability and Environment 2008; Harrington & Hale in prep; Leslie 2001; Stokes et al. 2010).

**Trends in condition and evidence of decline**

Numerous investigations in the past thirty years have reported a decline in the condition of various attributes of the ecology of the Barmah-Millewa Forest. Much of this was summarised in the *Living Murray Foundation Report* (MDBC 2005); which is outlined below and augmented with more recent information.
Hydrology
There has been a decline in moderate floods that inundate low lying areas of the floodplain including the areas of river red gum (*Eucalyptus camaldulensis*) forest (Harrington & Hale in prep; Leitch 1989; Murray-Darling Basin Authority 2010). In addition, there has been an increase in small floods in summer and autumn, that cover 10% of the forest, particularly low lying wetland areas (Ladson & Chong 2005). Large floods that result in widespread inundation (including black box; *E. largiflorens*; communities higher on the floodplain) have been less affected (Maheshwari et al. 1995) and flood recurrences remain close to natural (Harrington & Hale in prep; Murray-Darling Basin Authority 2010).

Vegetation
There is evidence of a decline in river red gum extent and health spanning back to the 1960s, with extensive tree deaths reported in 1967 (Murphy 1990). Links between river red gum growth and condition, and frequency and duration of inundation were established experimentally in Barmah-Millewa Forest by Bacon et al. (1993) and Bren (1988) linked tree quality (for timber harvesting) with flood frequency. Bren (1988) also suggested that a continued decrease in floodplain inundation would lead to a decline in tree health and a shift in understorey composition. More recent investigations have indicated that in 2003; more than half of the river red gum and black box trees within the Barmah-Millewa Forest were in stressed condition (moderate or less condition) and by 2009, this had increased to 79% of trees (Cunningham et al. 2009). Small areas where stand condition improved from stressed to good condition between 2003 and 2009 corresponded to areas that received environmental watering over this period (Cunningham et al. 2009). This adds further weight to the evidence linking water resource development and decreased floodplain inundation to declining tree condition.

Vegetation community composition has changed in parts of the Barmah-Millewa Forest and these changes have been linked to altered water regime. Areas of Moira grass (*Pseudoraphis spinescens*) have declined, both from replacement by *Myriophyllum propinquum* due to increased frequency of small floods; and from encroachment by river red gum attributed to a decrease in medium floods (Bren 1992). Prior to 1945, the boundary between Moira grass and river red gum was relatively stable; however, from 1957 to 1985, there was a decline in Moira grass extent by over 60% (Bren 1992). This was attributed to a combination of both grazing (resulting in reduced density of grasslands) and decreased frequency and duration of inundation, both of which favoured the germination and establishment of river red gums in these areas (Bren 1992).

Studies on the pollen record (Kenyon & Rutherfurd 1999) and vegetation surveys (Stokes et al. 2010) indicate an increase in exotic flora species. Stokes et al. (2010) suggested that altered water regimes (reduced frequency and duration of inundation) provided increased opportunities for exotic species to dominate, with sites of low flood frequency more sensitive to future exotic weed invasion.
**Waterbirds**

Barmah-Millewa Forest has been recognised as internationally significant with respect to waterbirds in general and colonial nesting waterbirds in particular (Department of Sustainability and Environment 2008; Harrington & Hale in prep). Maximum counts of in excess of 100,000 birds were recorded in the 1970s (Chesterfield et al.1984 as cited in Department of Sustainability and Environment (2008)). Analysis of observational data (collected annually from 1979 to 1997) together with modelled data indicates a significant decline in the occurrence of successful waterbird breeding events in the Millewa Forest (Leslie 2001). The author concluded:

‘River management since the mid-1950s is associated with the loss of breeding colonies of at least eight formerly abundant species, a significant decline in breeding numbers of at least a further 11 species, and abandonment of numerous traditional nest sites. The results also indicate a 20-year delay period between the time that river management began to affect waterbird breeding and waterbird abundance and diversity declining significantly in the forest.’

Recent monitoring of waterbirds from the forest has indicated very few waterbird breeding events, with the only two recorded events in 2000/2001 and 2005/2006, both of which were the direct result of environmental water provisions to the site (MDBC 2007). Waterbird numbers in the remaining years of the past decade have been low (1500 in 2007 and 23 in 2008 from aerial surveys; Kingsford & Porter 2009b).

**Fish**

Much of the information on fish in the Barmah-Millewa Forests comes from studies of the main channel of the Murray River between the two forests. Gehrke et al.(1995) examined the distribution of fish populations throughout the Murray-Darling Basin and concluded that the site near Barmah-Millewa had a high proportion of exotic fish compared to other sites (such as the Darling River). This finding was further emphasised by studies of carp from within the forest. Between November 1999 and July 2001, carp were the most abundant large fish species collected in the Murray River and floodplains in the Barmah-Millewa Forest, forming 86% of the biomass (Jones & Stuart 2004). This study also found from radio tracking carp that floodplain habitats of the Barmah-Millewa Forest are a major point source of carp in the mid-Murray region.

River regulation has had an impact on native fish within the Barmah-Millewa Forest, with large numbers of native fish stranded below regulators in Gulf Creek, including threatened species (Jones & Stuart 2008). The authors concluded that floodplain regulators interrupt the movements of fish between lateral floodplain areas and the Murray River. This is consistent with the findings of King and Mahoney (2010) who concluded that restoring water regimes is just one aspect of flow management that needs to be considered and that there are positive and negative outcomes from forest flooding for native fish. The authors advocated a cooperative and adaptive management approach to flow management for environmental outcomes.
The Living Murray condition monitoring (MDBC 2008a) reports on fish numbers and spawning activity within the Barmah-Millewa Forest. However, this is not reported as a condition rating referential to a baseline or natural conditions. The 2008 monitoring reported lower numbers of fish than in 2007 and an absence of the southern pygmy perch from any sites. In addition, low flow conditions had negative effects on the spawning and recruitment of native fish, including the reduction in the recruitment of carp gudgeons, southern pygmy perch and golden perch; but large numbers of carp spawning and recruitment were reported.

Other characteristics
Macroinvertebrates in the low lying wetlands of the Barmah-Millewa Forest were found to lack species typical of non-flowing waterbodies (Quinn et al. 2000) and this was attributed to the unseasonal and prolonged flooding of low lying wetlands in the forest. Measures of condition based on macroinvertebrates are more commonly associated with the river channel than the forest itself. According to Norris and Young (2001), macroinvertebrate communities in the Yarrawonga to Torrumbarry zone of the Murray River are in extremely poor condition resulting from unseasonal high flows and reduction of available habitat through erosion of banks and in-channel benches.

Barmah Forest has a depauparate small mammal fauna with only arboreal and semi-arboreal species persisting (Loyn et al. 2002) as cited (Thomson et al. undated). Thomson et al. (undated) attributed this to a range of factors including grazing and trampling by feral animals (which has altered the floral composition), the systematic removal of fallen timber cover and predation by introduced species. Lada et al. (2007) demonstrated positive effects of proximity to inundations, higher fallen-timber loads and abundances of large/very large trees on the abundance of the native marsupial - yellow-footed antechinus (Antechinus flavipes) on the Murray River floodplains. The authors suggested that these outcomes were consistent with a suggestion of an association between floods and antechinus population.

Studies on structural habitat have also indicated a decline since pre-European conditions. Structural complexity of the forest floor (as indicated by loads of coarse woody debris) have declined significantly from an average of 125 t/ha in pre-European times to just 19–20 t/ha in 1999–2001 (Mac Nally et al. 2001). The authors reported a correlation between coarse woody debris and the diversity and density of birds and mammals and concluded that the change in wood loads had implications for fauna populations in floodplain forests. Modelling of tree hollow density in the Barmah-Millewa Forest indicated stability in the density of hollow-bearing (habitat) trees from 1961 to 2006, but predicted a substantial decrease in the future (Thomson et al. undated). The predicted decline was attributed to decreased inundation resulting in declining growth rates in river red gums and forestry practices at the time.
### Key information sources

Detailed key information sources for Barmah-Millewa Forest are listed in Table 2.

#### Table 2. Key information sources.

<table>
<thead>
<tr>
<th>Citation</th>
<th>Attribute</th>
<th>Time period</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrology</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ladson A and Chong J (2005) Unseasonal flooding of the Barmah-Millewa Forest. Proceedings of the Royal Society of Victoria, Conference on the Barmah Forest, Melbourne, June 2005.</td>
<td>Floodplain inundation</td>
<td>1908 – 2008 (modelled)</td>
<td>Compared to natural conditions, flooding is now less frequent in winter and spring and more frequent, unseasonal, in summer and autumn. In particular, small unseasonal floods that cover less than 10% of the forest are eight times more frequent now than before regulation.</td>
</tr>
<tr>
<td>Maheshwari BL, Walker KF and McMahon TA (1995) Effects of flow regulation on the flow regime of the River Murray, Australia. Regulated Rivers: Research and Management 10: 15–38.</td>
<td>River flow</td>
<td>1891 – 1986 (modelled)</td>
<td>Compared current (1986) condition with natural and concluded: - Average monthly and annual flows of the Murray River are lower under regulated conditions than under natural conditions, due to storage and diversions, mainly for irrigation use. - The magnitude of average annual floods have been reduced by more than 50%, whereas large floods (recurrence interval 20 years or more) are little affected.</td>
</tr>
<tr>
<td><strong>Birds</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leslie DJ (2001) Effect of river management on colonially-nesting waterbirds in the Barmah-Millewa Forest, south-eastern Australia. Regulated Rivers: Research and Management 17: 21-36.</td>
<td>Waterbird breeding</td>
<td>1979-1997 (measured) 1891–1992 (modelled)</td>
<td>‘River management since the mid-1950s is associated with the loss of breeding colonies of at least eight formerly abundant species, a significant decline in breeding numbers of at least a further 11 species, and abandonment of numerous traditional nest sites. The results also indicate a 20-year delay period between the time that river management began to affect waterbird breeding and waterbird abundance and diversity declining significantly in the forest.’</td>
</tr>
<tr>
<td>Reference</td>
<td>Topic</td>
<td>Year</td>
<td>Summary</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------</td>
<td>---------------------------</td>
<td>------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Kingsford RT and Porter JL (2009) Annual survey of waterbird communities of the Living Murray icon sites - November 2008. School of Biological, Earth and Environmental Sciences, University of New South Wales. Report to Murray-Darling Basin Authority.</td>
<td>Waterbird abundance</td>
<td>2007 and 2008</td>
<td>Annual waterbird surveys of icon site (including the Barmah-Millewa forest) under The Living Murray Condition Monitoring Program. Reports annual survey results and statements on trends. Conclusions relevant to Barmah-Millewa: ‘Wetland habitat in the Barmah-Millewa Forest icon site was restricted to the main river channels and Moira Lake, and waterbird abundance was low.’ ‘Numbers of waterbirds were considerably lower in 2008 compared to 2007 on four of the six icon sites (Barmah-Millewa, Hattah, River Murray, Lower Lakes and Coorong). Numbers of species were also lower in 2008 compared to 2007 on these four sites.’</td>
</tr>
<tr>
<td>Jones M and Stuart I (2004) Impact of flow regulation structures on fish in the Barmah-Millewa Forest. Report to the Barmah-Millewa Forum. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg.</td>
<td>Native fish</td>
<td>2002-2003</td>
<td>Higher abundance of native fish were found in regulated versus unregulated streams (mean CPUE (native fish) of 0.6 (fish/Min EF Time) in unregulated vs 0.1 (fish/Min EF Time) in regulated stream). A large proportion of fish that are trapped behind regulators had ulcers/lesions/lernia; with all silver perch (eight adults), 38.5% of Murray cod (five juveniles), 29.8% of golden perch (12 adults and two juveniles), and 0.2% carp (one adult) being affected. In contrast, no ulcers/lesions/lernia were present on fish stranded in the unregulated Black Engine Creek.</td>
</tr>
<tr>
<td><strong>Invertebrates</strong></td>
<td><strong>King AJ, Ward KA, O’Connor P, Green G, Tonkin Z and Mahoney J (2010)</strong></td>
<td><strong>Fish spawning</strong></td>
<td><strong>2005/2006</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Tonkin Z, King A and Mahoney, J (2009)</strong></td>
<td><strong>Recruitment</strong></td>
<td><strong>2003-2008</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Quinn GP, Hillman TJ and Cook R (2000)</strong></td>
<td><strong>Species composition</strong></td>
<td><strong>1990-1995</strong></td>
</tr>
<tr>
<td>Mammals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Positive effects to Antechinus from proximity to flooding, higher wood loads and an abundance of large, hollow-bearing trees. Mean trapping rates of antechinuses were lowest in 2003 following a 3-year period with no inundation, higher in 2004 following the first breeding season during a small, controlled flood in 2003, and higher again in 2005, following a small, controlled flood in 2004. In 2004 and 2005, trapping rates declined with distance from floodwaters.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compared loads of coarse woody debris on three floodplains (Barmah Forest, Gunbower Forest and Ovens River) with diversity and abundance of birds, mammals, reptiles and amphibians. Found that variation in the density of coarse woody debris influences the densities and diversity of native birds and mammals; but not reptiles and amphibians. However, the reptile and amphibians in the forests was depauperate and may have been due to past removal of coarse woody debris from the floodplain or from the effects of river regulation. Current loads of woody debris (19–20 tonnes/hectare) are significantly reduced from per-European loads of 125 tonnes/hectare which has implications for fauna diversity and abundance.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Title</td>
<td>Year</td>
<td>Condition</td>
</tr>
<tr>
<td>-----------</td>
<td>-------</td>
<td>------</td>
<td>-----------</td>
</tr>
<tr>
<td>Bacon PE, Stone C, Binns DL, Leslie DJ and Edwards DW (1993)</td>
<td>Relationships between water availability and Eucalyptus camaldulensis growth in a riparian forest. <em>Journal of Hydrology</em> 150: 541-561</td>
<td>1990-1992</td>
<td>River red gum</td>
</tr>
<tr>
<td>Bren LJ (1988)</td>
<td>Effects of river regulation on flooding of a riparian red gum forest on the River Murray, Australia. <em>Regulated Rivers: Research and Management</em> 2(2): 65-77.</td>
<td>1988</td>
<td>River red gum</td>
</tr>
<tr>
<td>Bren LJ (1992)</td>
<td>Tree invasion of an intermittent wetland in relation to changes in the flooding frequency of the River Murray, Australia. <em>Australian Journal of Ecology</em> 17: 395-408.</td>
<td>1945-1985</td>
<td>Succession</td>
</tr>
<tr>
<td>Cunningham SC, Mac Nally R, Griffioen P and White M (2009)</td>
<td>Mapping the Condition of River Red Gum and Black Box Stands in The Living Murray Icon Sites. A Milestone Report to the Murray-Darling Basin Authority as part of Contract MD1114. Murray-Darling Basin Authority, Canberra.</td>
<td>2003-2009</td>
<td>Floodplain forests</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Year</td>
<td>Ecology Type</td>
<td>Key Findings</td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>--------------</td>
<td>--------------</td>
</tr>
</tbody>
</table>
- A decrease in river red gum pollen over the past 100 years  
- An increase in terrestrial grasses and decrease in aquatic taxa  
- A decrease in forest fires since European settlement. |
| Robertson AI, Bacon P and Heagney G (2001) | The responses of floodplain primary production to flood frequency and timing. *Journal of Applied Ecology* 38(1): 126-136. | 1990-1995 | Compared the effects of spring versus summer flooding on trees, macrophytes and biofilms. Found that greatest macrophyte diversity and productivity occurred with spring flooding. Similarly, biofilm accumulation (as indicated by chlorophyll a) was significantly higher from spring flooding. Tree production, however, was better under summer flooding regimes. The paper concludes: 'Spring flooding, while not as beneficial for tree growth, is critical for the growth of wetland macrophytes, the macrophyte species richness, and favours better development of biofilms. Thus maintaining the conservation values of wetlands within River Red Gum forests will require a focus on the return of small and medium flood flows in the spring period.' |
| Thomson J, Horrocks G, Cunningham S and Mac Nally R (undated) Modelling Tree Hollow Availability Over Time in the Barmah Landscape Zone. A Report to the Goulburn-Broken CMA. | Tree hollows | 1961-2006 | Using historical records and modelled data, the density of hollow-bearing trees in the Barmah Forest from 1961 to 2006 was estimated. Although there had been some decline in the numbers and density of hollow-bearing trees over this time, it was not a significant decrease. Timber harvesting and forestry codes at the time were considered sufficient to maintain the density of existing hollow-bearing trees. However, growth rates of river red gum appear to have declined in the last decade, almost certainly due to reduced frequency of flooding, decreased rainfall and falling water tables. Modelling suggests that under current conditions it would take > 150 years for trees to reach hollow bearing size and predicted a decline in habitat trees over the next 100 years. |

**General references**

<p>| DSE (2008) Ecological Character Description of the Barmah Forest Ramsar Site,. Victorian Government Department of Sustainability and Environment Melbourne. | Ecological character (Barmah portion of site only) | Benchmarked at 1982 | Describes the ecological character of the Barmah Forest at the time of listing. Cites altered hydrology as a major threat. |</p>
<table>
<thead>
<tr>
<th>Harrington B and Hale J (in prep) Ecological Character Description for NSW Central Murray Ramsar Sit., A Report to DSEWPaC.</th>
<th>Ecological character (Millewa portion of site only)</th>
<th>1982 and 2010</th>
<th>Describes the ecological character of the Barmah Forest at the time of listing. Sets limits of acceptable change and compares current conditions against those limits. Concluded that limits for hydrology and waterbird breeding have been exceeded.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDBC (2007) The Living Murray Icon Site Condition Report 2008, MDBC, Canberra</td>
<td>Vegetation, birds and fish</td>
<td>2006-2008</td>
<td>Report on the monitoring of vegetation, birds and fish referential to the icon site objectives. For Barmah-Millewa these were: Successful breeding of thousands of colonial waterbirds in at least three years in ten (2007 and 2008). Healthy vegetation in at least 55% of the area of the forest (including virtually all of the giant rush, Moira grass, and river red gum forest) (2007 and 2008). Enhance forest, fish and wildlife values (2008). Although not explicitly stated, the data from within the reports indicates that the objective for waterbirds has not been met in the ten years 2000–2009.</td>
</tr>
</tbody>
</table>

**Other information sources**

In addition to the key information sources detailed above, there is a very wide body of research and monitoring that indicates a link between water regimes and the ecology of the Barmah-Millewa Forest. Many of these are associated with environmental flow allocation monitoring and provide another line of evidence to support the hypothesis that altered food regimes have lead to a decline in ecosystem condition at this site. A selection of these papers is provided below.


**Macquarie Marshes Site Assessment**

**Summary**

Changes in the use and management of land and water in the Macquarie Valley have greatly influenced the extent and health of the Macquarie Marshes. The Macquarie Marshes have existed in their current location and maintained their general wetland state for the last 6000 to 8000 years (Yonge & Hesse 2002). Irrigated agriculture began during the 1840s in the South Marsh; however, it was not until the completion of Burrendong Dam in 1967 that large scale irrigation began. By the mid 1990s irrigated agriculture on the lower Macquarie floodplain had reached its peak both in terms of area and water use (CSIRO 2008b).
**Trends in condition and evidence of decline**

The greatest threat to the Macquarie Marshes is the alteration of the natural flow regime through river regulation which has changed the seasonality and magnitude of the Macquarie Marshes. These threats include; upstream extraction of water which has reduced the size of flows reaching the Marshes, and development of structures that alter flow paths within the Marshes and along the Macquarie River and its distributaries.

The most significant impacts documented in the Marshes as a result of changing flow regimes include changes to floodplain vegetation distribution and composition, and changes in frequency and abundance of colonial waterbird breeding. For example, in the southern section of the Macquarie Marshes Nature Reserve, Bowen and Simpson (2010) found ‘catastrophic’ changes since 1991 with the loss of almost 100% of semipermanent wetland vegetation, a decline in the condition of river red gum, coolibah and black box communities and a 100% loss of grassland communities. Chenopod shrubland now covers over 90% of the southern section of the Macquarie Marshes Nature Reserve.

In 1986, the time of Ramsar listing, 4,590 colonial waterbird nests were counted within the Macquarie Marshes Nature Reserve. Since then, the number of nests, frequency of breeding and location of active breeding colonies has declined throughout the Macquarie Marshes and the Nature Reserve. There have been two colonial nesting waterbird breeding locations recorded in the southern section of the Macquarie Marshes Nature Reserve but breeding has not occurred at these sites since the 1960s.

**Hydrology**

Flows to the Macquarie Marshes come primarily from the Macquarie River fed by the major tributary rivers; the Fish, Cudgegong, Bell, Little and Talbragar Rivers. The Macquarie River splits into several distributaries before reaching the Macquarie Marshes: the Marra, Crooked and Duck Creeks and the Macquarie River. The Marthaguy and Merri Merri Creeks flow in independently from the east while Marra Creek flows predominantly north-west from the Macquarie River. The main supply of water to the Macquarie Marshes comes down the Macquarie River, bifurcating after Marebone Weir into the main channel of the Macquarie River and Marebone Break.

Several studies using both measured and modelled flow data have shown changes to flow frequency and duration particularly since the construction of Burrendong Dam. They include:

- An estimated more than 50% reduction in natural flows reaching the Oxley flow gauge:
  
  51% of flows reached the Oxley flow gauge before river regulation compared to only 21% after regulation (Kingsford & Thomas 1995)

- A significant reduction in moderate to high flows in the Macquarie River and end-of system flows (CSIRO 2008b)

- A 114% increase in the average period between large flows which are important inundation events for the Marshes and a reduction in the average volume of these events (CSIRO 2008b)
• A reduction in the number of smaller flows likely to cause flooding (greater than 1,000 ML/d) passing the Oxley Gauge following the construction of Burrendong Dam (Jenkins et al. 2007)

• A reduction in flood frequency, particularly of smaller size floods (Brereton et al. 2000)

• The imposition of permanent low flows in previously intermittent streams (Grimes 2001)

• A significant reduction in area inundated and frequency of floods to the Marshes (Thomas et al. 2009).

Vegetation
Within the Murray-Darling Basin, the Macquarie Marshes Nature Reserve supports one of only three extensive river red gum (*Eucalyptus camaldulensis*) woodlands (approx 6000 ha), the other two being in the southern half of the Murray-Darling Basin on the Murrumbidgee and Murray Rivers. These woodlands in the Macquarie Marshes Nature Reserve provide nesting sites and habitat for both waterbirds and woodland birds. The Macquarie Marshes is also one of only two sites in the Murray-Darling Basin (the Macquarie Marshes and the Great Cumbung Swamp) supporting extensive common reed (*Phragmites australis*) reedbeds. The Macquarie Marshes Nature Reserve supported in 1991 approximately 2000 hectares of common reed in two main reed beds, one in the northern and one in the southern section of the Nature Reserve. The Macquarie Marshes is also one of only two sites (the Macquarie Marshes and Gwydir Wetlands) with extensive water couch (*Paspalum distichum*) marsh (approx. 900 ha) in the Murray-Darling Basin. These wetland vegetation communities provide habitat for 77 waterbird species and 15 frog species (Atlas of NSW Wildlife, [DECCW](#)).

The northern portion of the Macquarie Marshes Nature Reserve supports the most extensive area of river red gum forest and woodlands in the Macquarie Marshes. The area of river red gum forest and woodland has remained relatively stable from 1991-2008; however, the condition of these communities has declined both in overstorey condition (tree health) and understorey composition (species richness and type) ([DECCW](#) 2009). Bowen and Simpson (2010) found that only 23% of the river red gum communities in the northern Macquarie Marshes Nature Reserve were in good condition (<10% dead canopy). These healthy river red gum communities were only found along the Bora Channel. The majority (57%) of river red gum communities in the northern reserve were classed as in poor condition (80-100% dead canopy) (Bowen & Simpson 2010).

Nairn (2008) also surveyed tree heath and demographics in the Macquarie Marshes and found that 73% of sites surveyed within the northern section of the Nature Reserve were under extreme water stress and only 8% of sites were showing a demographic profile which indicated a fair regenerative potential - none were found to be good. The composition of the understorey of river red gum woodland is now dominated by chenopod shrub species (black roly poly and buckbush) more indicative of dryland communities (Bowen & Simpson 2010). Chenopod shrubs have replaced the grass and forb species formerly described by (Paijmans 1981) as the understorey dominants in this community.
The death of more than 30% of river red gums in the woodlands of the North Marsh has been attributed to lack of flooding (Bacon 2004). River red gums in the Marshes need floods every 1-2 years and Bacon found that trees that received a flood in 2000 but were not flooded in 2003 were under severe stress or dead. Since 2001, the Marshes have received less than 25% of the environmental water that would be available at 100% general security allocation which means less than 5000 ha of the Marshes has received a flood every 1-2 years. The mapped area of river red gum forest and woodland in the Marshes was 40 000 ha in 1991 (Wilson et al. 1993), a large proportion of this is in the North Marsh. In 2008 it is likely that as much as 75% of these woodlands have not received adequate flooding for their survival.

In the Macquarie Marshes most areas of water couch have not received the flows they need for the past three years and some areas have not received flows at all for more than six years. Bowen and Simpson (2010) found no water couch remaining in the southern portion of the Macquarie Marshes Nature Reserve, a loss of 220 ha since 1991.

In 1981, Paijmans mapped approximately 500 ha of cumbungi rushland in the southern portion of the Nature Reserve, most of it outside the southern section of the Macquarie Marshes Nature Reserve. In 2006, cumbungi was only found in one location in the South Marsh at Buckiinguy Lagoon (DNR 2007). Bowen and Simpson (2010) found no cumbungi remained in the southern section of the Macquarie Marshes Nature Reserve.

Waterbirds
The Macquarie Marshes represent highly significant habitat for colonially-breeding waterbirds. They are one of the few sites supporting large breeding colonies of straw-necked ibis (Threskiornis spinicollis) in Australia and one of only a few sites in NSW where magpie geese breed (Kingsford and Thomas 1995). They also support some of the largest breeding colonies of intermediate egret (Ardea intermedia), rufous night heron (Nycticorax caledonicus) and royal spoonbill (Platalea regia) in southern Australia, as well as a rich diversity of other waterbirds including cormorants, herons, spoonbills and ducks, many of which breed here.

The Macquarie Marshes also provides important habitat for 17 species of migratory bird species covered under the Japan-Australia, China-Australia and South Korea–Australia Migratory Bird Agreements (JAMBA, CAMBA and ROKAMBA). These are the white-bellied sea-eagle (Haliaeetus leucogaster), cattle egret (Ardea ibis), great egret (Ardea alba), caspian tern (Sterna caspia), bar-tailed godwit (Limosa lapponica), black-tailed godwit (Limosa limosa), common greenshank (Tringa nebularia), common sandpiper (Actitis hypoleucos), curlew sandpiper (Calidris ferruginea), latham’s snipe (Gallinago hardwickii), marsh sandpiper (Tringa stagnatilis), red-necked stint (Calidris ruficollis), sharp-tailed sandpiper (Calidris acuminata), wood sandpiper (Tringa glareola), glossy ibis (Plegadis falcinellus), fork-tailed swift (Apus pacificus) and white-throated needletail (Hirundapus caudacutus).

There was only one waterbird breeding event in the Marshes during 2000-2010. In 2008, a relatively small flood supported a successful nesting of approximately 2,000 egrets and cormorants in river red gum forest on the Bora Channel. This was unpredicted with such low flows and the first record of colonial-nesting waterbirds breeding at only one location in the Marshes.
In October 2010, following significant rainfall and flooding, straw-necked ibis were recorded breeding in the Macquarie Marshes.

**Fish**

Examination of historical records, using 1975 as a benchmark, indicates that native fish may have declined in the Macquarie Marshes over the past 30 years. In 1975, eight species of native fish were recorded in the lower Macquarie system and Marshes, compared to three species in 1989, five species in 1995 and three species in 2004 (Jenkins et al. 2004). Furthermore, all native species captured in 2003 were *Hypseleotris* sp, small native fish. Records from long-term residents of the region support findings of declining native fish species, as fewer native fish are captured currently, compared to the past (pers. comm. K. Jenkins anecdotal interviews with landholders). There are; however, episodic increases in native fish numbers associated with sporadic rising river levels (Macquarie Marshes Management Committee anecdotal records).

In surveys in 2003, the only native fish species captured was the carp gudgeon complex; however, during more intensive surveys in 2006 seven native species were captured (Jenkins et al. 2007). They were the carp gudgeon complex, golden perch, bony herring, Australian smelt, rainbow fish, Murray cod and spangled perch. Three exotic fish species are now abundant in the Marshes (goldfish *Carassius auratus*, European carp *Cyprinus carpio* and gambusia *Gambusia holbrooki*) with a fourth species, redfin perch (*Perca fluviatilis*) captured less frequently (Gehrke 1997a).

In a study by Rayner et al. (2009), the authors found that native fish populations in the lower Macquarie River were in poor health - native species richness is low and alien species dominate fish abundance and biomass. This assessment is consistent with the Sustainable Rivers Audit (SRA) (Davies et al. 2008), a regional-scale monitoring program, which described fish community health as very poor in the Macquarie River Valley as a whole and poor in the lowland zone. The SRA collected six native species from seven lowland sites (<200-m elevation) out of a potential 12 native species predicted under reference conditions (Davies et al. 2008). In that study, Murray cod were conspicuously absent. Three alien species dominate fish assemblages and biomass in the lower Macquarie River. European carp, goldfish and gambusia, outnumbered native species by more than 3:1 (Rayner et al. 2009).

**Frogs**

Fifteen species of frogs have been detected in the Macquarie Marshes. They are found around all types of waterbodies including dam ponds, reed beds, flooded woodland and rain-fed ephemeral ponds. There is some indication that the reduction in the number and size of floods in the Marshes has reduced the number and size of their breeding events. Frogs and tadpoles are an important source of food for a number of animals. The health and numbers of snakes, especially red-bellied snakes, are closely linked to the abundance of frogs. Waterbirds, such as egrets, herons and pelicans, have been observed eating adult frogs and tadpoles. While the amphibian disease chytridiomycosis has also been detected, it is not known how it is impacting frogs in the Marshes.
Reptiles
There are 60 reptile species in the Macquarie Marshes, none of which are considered threatened in NSW (*Atlas of NSW Wildlife*, DECCW). Of the 60 reptile species; three are tortoises, seven are geckoes, 33 are lizards and 17 are snakes. The number of red-bellied black snakes in the Marshes was once one of the highest in Australia but in the last 20 years there has been a dramatic decline in both the number and condition of these snakes (Phillips 2006).

While most snakes and lizards do not depend on water, several are wetland specialists. The red-bellied black snake diet includes fish, tadpoles, frogs, lizards, snakes, mammals and the occasional aquatic invertebrate (Greer 2006). Shine (1983) found that frogs made up 88% of the diet of De Vis’s banded snake, a small snake found commonly in the Marshes. The three tortoise species, the broad-shelled tortoise, the long-necked tortoise and the short-necked tortoise are water dependent, only leaving the water to lay their eggs. To breed successfully tortoises need good reserves of fat that can only be obtained during floods. Their main foods are fish, yabbies, aquatic invertebrates and algae. Unlike frogs that need a flood to trigger their breeding, tortoises need a flood to provide ample food before they can lay eggs. They lay their eggs in a shallow burrow of wet soil next to water. Changes to floodplain soils through compaction or earthworks can have a big impact on their ability to dig burrows and predation by foxes can cause up to 95% mortality of eggs and young.

Aquatic invertebrates
In the Macquarie Marshes densities of microinvertebrates in recently inundated floodplain habitats are amongst the highest recorded in the world (Jenkins & Wolfenden 2006). Epibenthic habitats (close to wetland bottom) in temporary floodplains and creeks contain a rich soup of microinvertebrates available as potential prey to macroinvertebrates and fish. The four main types of microinvertebrates found within floodplain and temporary channels in the Macquarie Marshes are rotifers, cladocerans, ostracods and copepods. The latter three types are all microcrustaceans, the preferred prey (particularly cladocerans) for the larvae of most native fish species.

More than 50 macroinvertebrate taxa were recorded in the Macquarie Marshes in small surveys in 2004 and 2005, but as samples are processed from more extensive surveys in 2006 this number is approaching 100 taxa (Jenkins et al. 2007). During the 2005 flow the highest diversity and abundances of macroinvertebrates were found in floodplain habitats and temporary creeks (Bora Creek and Gum Cowal-Terrigal Creek) compared to constantly flowing creeks. There was a distinct separation between community composition from creek and floodplain samples. The samples from Bora Creek and Gum Cowal-Terrigal Creek were closer in composition to those from the floodplain than samples from the constantly flowing creeks. Numbers of taxa were unexpectedly high in constantly flowing creeks during the dry period in 2006, suggesting these creeks are important refugia for macroinvertebrates. Abundances were comparable between wet and dry periods in constantly flowing creeks but tended to be higher in the dry period (Jenkins et al. 2007).
Other characteristics
In a catchment that has been modified by agricultural activities, these remaining wetlands have become a regionally important refuge for wildlife. Similarly, they represent an important drought refuge during periods when many other inland wetlands have dried out.

Key information sources
Detailed key information sources for the Macquarie Marshes are listed in Table 3.

Table 3. Key information sources.

<table>
<thead>
<tr>
<th>Citation</th>
<th>Attribute</th>
<th>Time period</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrology</td>
<td>Impacts of regulation on flow and flooding</td>
<td>1944-1993</td>
<td>The area flooded by large floods has contracted by at least 40-50% during the last 50 years (1944-1993).</td>
</tr>
</tbody>
</table>
### Vegetation

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Year</th>
<th>Source</th>
</tr>
</thead>
</table>

### Waterbirds

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Year</th>
<th>Source</th>
</tr>
</thead>
</table>

**Vegetation**

Atlas of NSW Wildlife Flora catalogue

Vegetation changes 1991-2008

Vegetation changes 1934-1987

Vegetation changes 1983-1994

Vegetation health

Vegetation type and distribution

Vegetation type and distribution

Impacts on waterbirds 1983-1993

Waterbird survey

Impacts on waterbirds
<table>
<thead>
<tr>
<th>Reference</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fish</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Reptiles</strong></td>
<td></td>
</tr>
<tr>
<td>NSW Wildlife Atlas</td>
<td></td>
</tr>
<tr>
<td><strong>Frogs</strong></td>
<td></td>
</tr>
<tr>
<td>Ocock J pers.comm.(2011) PhD Candidate Australian Wetlands and Rivers Centre, UNSW.</td>
<td></td>
</tr>
<tr>
<td><strong>Aquatic invertebrates</strong></td>
<td></td>
</tr>
</tbody>
</table>
Barwon-Darling River Site Assessment (upstream of Weir 32)

Summary
Hydrological changes in the Barwon-Darling River are well studied and documented (e.g. CSIRO 2008b; Thoms & Sheldon 2000; Webb et al. 2007). There is also evidence of a decline in river health of the Barwon-Darling River compared to pre-European condition in terms of geomorphology, particularly bank instability (Sheldon & Thoms 2006; Thoms 1997), water quality and algal blooms (Bowling & Baker 1996; Mitrovic et al. 2006; Oliver et al. 1999; Olley & Caitcheon 2000), aquatic invertebrates (Chessman et al. 2010; Jenkins & Boulton 2007), fish (Boys et al. 2005; Gehrke 1997b; Harris & Silveira 1997; Reid et al. 1997) and riparian vegetation (Hale et al. 2007). In particular, there is a body of evidence across disciplines that indicates poorer condition in the regulated river reaches of this system than unregulated reaches (Boys et al. 2005; Chessman et al. 2010; Gehrke 1997b; Sheldon & Thoms 2006; Thoms 1997) providing evidence that water resource management and river regulation has had an effect on river health in the Barwon-Darling River.

Trends in condition and evidence of decline
Evidence related to river health and condition of the Barwon-Darling River from key information sources is summarised below. Information on the condition of the Barwon-Darling River is limited in comparison to some other sites within the MDB (particularly those icon sites identified in the TLM program); however, the majority of information has been derived from peer-reviewed scientific papers and provides a compelling indication of ecosystem decline and the effects of river regulation on ecosystem condition.

Hydrology
There has been a decline in total flow volume within the Barwon-Darling River as a result of water resource development and river regulation (CSIRO 2008b; Thoms & Sheldon 2000; Webb et al. 2007). There has been a one third reduction in average annual flow (Webb et al. 2007); with the greatest reduction in small (two year ARI) flood events, which have reduced by 35–70 % (Thoms & Sheldon 2000). Five and ten-year ARI floods have decreased by around 30% (CSIRO 2008) and this has reduced the average number of days when floodplain wetlands are joined to the river by 30% or more (Webb et al. 2007).

Geomorphology
During the 1996 floods in the Barwon-Darling River, rates of fall of up to 5 metres a week were recorded. This resulted in bank slumping and consequent erosion of over 90,000 tonnes of sediment, 70% of which was from the Brewarrina to Louth reaches (Thoms 1997). Although Thoms (1997) indicated that bank slumping is a natural process in Australian rivers, the combination of artificially stable water levels followed by a large flood and then rapid drawdown resulted in severe alteration to the channel. In addition, the sandy material from the banks and benches was deposited over the finer clays of the riverbed, further altering the geomorphology of the system. Sediment covering woody debris and other structural habitat was observed to be a cause of fish habitat decline in the system (Boys et al. 2005; see fish summary below).
A comparison of channel cross sections in 1996 with those of 1886 from both regulated and unregulated sections of the river revealed that flow regulation had reduced channel complexity. Channels in regulated river reaches were wider with less in-channel benches in 1996 as compared to 1886; whereas in unregulated reaches, channel morphology had not changed significantly over the 110 years (Sheldon & Thoms 2006). The decrease in channel complexity was shown to have an affect on organic matter within the river channel, with lower retention of organic matter in the less complex, regulated river systems.

**Water quality**

In 1991, a significant phytoplankton bloom extended over almost 1000 km of the Barwon-Darling River (Bowling & Baker 1996). It was dominated by the toxic cyanobacteria *Anabaena circinalis* and had a range of consequences, including the death of sheep and cattle along the river\(^1\). While there were no reports of native animal deaths associated with the bloom, and phytoplankton blooms can be considered part of the natural cycle in river ecology, the extent of this bloom was considered an indicator of poor river health and the factors that contributed to the bloom - a threat to ecosystem integrity (Whittington 1999\(^2\)).

There is strong evidence linking low flows and river regulation (weirs and weir pools) to the formation of algal blooms in the Barwon-Darling River. The comprehensive investigation by (Oliver et al. 1999) determined an inverse relationship between concentrations of cyanobacteria in the Bourke Weir Pool and discharge rate. The mechanism for increased phytoplankton growth is related to increased temperatures and thermal stratification during low flow conditions. In addition, the increases in salinity, which occur as water levels drop, result in increased water clarity as salts facilitate particle aggregation and sedimentation (Oliver et al. 1999). The greater water clarity, warm temperatures and calm conditions during low flow in weir pools provide optimum conditions for cyanobacterial growth.

Although algal blooms in Australian WDEs are a natural phenomenon, Mitrovic et al. (2006) concluded that the frequency of algal blooms was double that expected under natural flow conditions. Water impoundment and extraction were considered responsible for approximately half of the blooms in the Barwon-Darling River from 1990–2000.

Oliver et al. (1999) also suggested that phosphorus was the limiting nutrient in algal blooms in the Barwon-Darling River. Phosphorus concentrations however, have not changed in the river (and catchment) in the past 200 years (Olley & Caitcheon 2000). Olley and Caitcheon (2000) suggests that the best strategy to limit excess algal growth is to manage flow so that the river remains turbid and stratification of the pools is prevented.

---


Aquatic invertebrates
There is limited information on aquatic invertebrates from the Barwon-Darling River. River health assessments such those of Norris et al (2001) and Gehrke et al. (2003) did not include assessments of the Barwon-Darling River above Menindee. Chessman et al. (2010) sampled macroinvertebrates at 17 sites in the Barwon-Darling catchment, including eight in the Barwon-Darling River. Lowest taxonomic diversity was recorded in the main stem of the Barwon-Darling River and the highest in the intermittent tributaries. In addition, there was a greater abundance of the yabbie (*Cherax destructor*) in intermittent streams versus the perennial Barwon-Darling River. However, the same relationship did not extend to the freshwater prawn (*Macrobrachium australiense*) and there was no difference in macroinvertebrate assemblages in the regulated versus unregulated tributaries.

Egg bank studies of micro-invertebrates in floodplain wetlands along the Barwon-Darling River indicate that increased intervals between inundation reduce the abundance and diversity of micro-invertebrate taxa (Jenkins & Boulton 2007). As these invertebrates often form the basis of the food chain in boom and bust ephemeral and intermittent wetlands, the authors suggested that this had implications for fish and waterbirds in the system.

Fish
Comparisons of native fish from regulated and unregulated reaches in the Barwon-Darling River indicated a 60% lower native fish abundance in regulated reaches (Gehrke 1997b). This corresponded with a higher number of juveniles in unregulated reaches, leading the authors to suggest that recruitment success for native fish is higher in unregulated reaches of this river. These results are consistent with the work of Boys et al. (2005) who reported a decline in habitat diversity between the upper Barwon River and downstream reaches. In particular, they reported high levels of bank collapse, coupled with lower frequencies of high flows had lead to an accumulation of sediment in the channel, which covered woody debris, and limited fish passage during low flow conditions.

Evidence for changes in fish abundance and composition in the Barwon-Darling River over time is scant. The river is in remote west NSW and there are few biological surveys pre 1990. However, an assessment of inland commercial fish catches in the Barwon-Darling River from 1955 to 1997 indicates a decline in total native catch from the mid 1970s/early 1980s – an average of over 50,000 individuals per year to less than 20,000 individuals per year in the 1990s (Reid et al. 1997). The authors attributed the decline to water resource development, habitat degradation, over-exploitation and introduced species.

A river condition index based on native fish was developed and implemented in NSW by Harris and Silveira (1997). The assessment of the Barwon-Darling River indicated that half of the sites/sampling events were in poor condition; only 6% of sites were rated as good and no sites on the Barwon-Darling River were rated as excellent.

---


Vegetation
There is very little information on vascular plants in the Barwon-Darling River. The river itself contains very few emergent and submerged macrophytes due to the high turbidity (Sheldon & Thoms 20045). The condition of riparian vegetation was assessed at 47 sites along the Barwon-Darling River using a modified version of the RARC (Rapid Assessment of Riparian Condition) and an assessment of tree health (Hale et al. 2007). Results indicated that the majority of sites (almost 60%) were in poor or very poor condition and no sites were scored as excellent. Although most sites had a high degree of nativeness, regeneration was poor and canopy cover moderate. An assessment of tree health indicated that most trees within 50m of the top of the bank were in good condition, but age structure was heavily biased towards mature trees with very few juveniles or saplings (Hale et al. 2007).

Key information sources
Detailed key information sources for Barwon-Darling River are listed in Table 4.

Table 4. Key information sources.

<table>
<thead>
<tr>
<th>Citation</th>
<th>Attribute</th>
<th>Time period</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSIRO (2008) Water availability in the Barwon-Darling. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia</td>
<td>Flood intervals</td>
<td>1895-2006</td>
<td>Water resource development across the Darling Basin has not significantly altered the seasonality of streamflow in the Barwon-Darling region but has reduced the magnitude of two-year average return interval floods by 41%, and the magnitude of five- and ten-year average return interval floods by around 30%. Water resource development in this and upstream regions has nearly doubled the average and maximum periods between substantial flows.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Data/Methodology</th>
<th>Time Frame</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thoms MC and Sheldon F (2000)</td>
<td></td>
<td>Average flows,</td>
<td>1936-1996</td>
<td>‘Flows are highly modified through the presence of nine headwater dams, 15 main channel weirs and 267 licensed water extractors. Median annual runoff has been reduced by 42% over a 60-year period. Small flood events (e.g. Average Recurrence Interval of &lt; 2 years) have suffered the greatest impact with reductions in magnitude of between 35 and 70%. The seasonality of flows has also been affected with a distinct shift in seasonal flow peaks relating to irrigation diversions. Overall, flows show a marked increase in predictability and consistency.’</td>
</tr>
<tr>
<td>Webb McKeown &amp; Associates (2007)</td>
<td></td>
<td>Volume (river)</td>
<td>1922-2002</td>
<td>Compared modelled natural flow with current (2002) development and concluded: Reduction in average flows in the Darling River by one third. Large reductions in the size and frequency of all flood events, linked to irrigation. The number of days when wetlands along the Barwon-Darling are joined to the river, and are receiving water, have also dropped – in most cases by a third or more. Migration of fish along the Barwon-Darling River is only possible when flows are high enough to drown out the many weirs that now exist.</td>
</tr>
</tbody>
</table>

**Geomorphology**

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Data/Methodology</th>
<th>Time Frame</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheldon F and Thoms M (2006)</td>
<td></td>
<td>Channel complexity and organic matter</td>
<td>1886 and 2006</td>
<td>Compared cross sections in channel profiles and organic matter of regulated and unregulated reaches of the Barwon-Darling River with cross sections surveyed in 1886. Concluded that flow regulation has greatly reduced channel complexity, resulting in a potential decrease in the retention of organic matter in the river. Suggested that this had repercussions for ecosystem health through reduced resources through the food chain.</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Source</th>
<th>Title</th>
<th>Year</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thoms M (1997)</td>
<td>An investigation of river bank instability along the Barwon-Darling River following the February 1996 flood: A preliminary geomorphological assessment. CRC for Freshwater Ecology, Canberra.</td>
<td>1996</td>
<td>Assessed the effects of the 1996 flood on bank stability in the Barwon-Darling River. Results included: 91,660 tonnes of sediment was eroded from the river banks in the 1996 flood, with 70% of this from reaches between Brewarrina and Louth. Bank slumping was the dominant instability mechanism. Rapid falls in water level contributed to the instability and high erosion. This was linked to upstream water resource management that resulted in falls of &gt; 5m per week.</td>
</tr>
<tr>
<td>Bowling LC and Baker PD (1996)</td>
<td>Major cyanobacterial bloom in the Barwon-Darling River, Australia, in 1991, and underlying limnological conditions. Marine &amp; Freshwater Research 47: 643-657.</td>
<td>1991</td>
<td>Analysed the hydrological, chemical and algal data from the 1991 algal bloom that extended across 1000km of the Barwon-Darling River. Attributed the cyanobacterial bloom to a range of factors including: very low flows, high concentrations of nutrients (particularly phosphorus), warm temperature, elevated pH, reduced turbidity. Bloom persisted for a number of weeks but was eventually flushed from the river by increased flows following heavy catchment rainfall.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Study Title</th>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oliver RL, Hart BT, Olley J, Grace M, Rees C and Caitcheon G (1999)</td>
<td>The Darling River: Algal Growth and the Cycling and Sources of Nutrients. CRC for Freshwater Ecology.</td>
<td>Algal blooms</td>
<td>1999</td>
</tr>
<tr>
<td><strong>Olley J and Caitcheon G (2000)</strong></td>
<td><strong>Major element chemistry of sediments from the Darling–Barwon river and its tributaries: implications for sediment and phosphorus sources. Hydrological Processes 14: 1159–1175.</strong></td>
<td><strong>Nutrient and sediment sources</strong></td>
<td><strong>1991 - 1993</strong></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>Fish</strong></td>
<td><strong>Nutrient and sediment sources</strong></td>
<td><strong>1991 - 1993</strong></td>
<td><strong>Determined sources of sediment and sediment-associated phosphorus in the Barwon-Darling River. Determined that the sediment in the channel is derived from lowland areas of the catchment and that phosphorus concentrations have not changed significantly in the past 200 years. Suggested that the best strategy to limit excess algal growth is to manage flow so that the river remains turbid and stratification of the pools is prevented.</strong></td>
</tr>
<tr>
<td><strong>Boys CA, Esslemont G and Thoms M (2005)</strong></td>
<td><strong>Fish habitat and fish populations</strong></td>
<td><strong>2001-2003</strong></td>
<td><strong>Assessed physical habitat in-stream in the Barwon-Darling River, habitat at high flow, fish abundance and community composition. Conclusions included: Upper Barwon River had a higher degree of habitat complexity with abundant matted bank and woody debris. This decreased downstream. The presence of numerous weirs that have altered natural flows, and block the passage of fish. The accessibility of medium and high-flow habitats to fish has potentially been reduced because of water resource development. Indications of high levels of bank collapse in certain regions relative to the whole river. Attributed to a decrease in overbank flows resulting in accumulation of sediment in channel. Observed sections of river that had shallow pools and runs, structural woody habitats smothered by sand, and sand bars that limited fish passage during low flow. Habitat alteration and reduced water quality have resulted from accentuated bank collapse.</strong></td>
</tr>
<tr>
<td>Author(s)</td>
<td>Title</td>
<td>Year</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>-------</td>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>Gehrke P (1997)</td>
<td>Differences in composition and structure of fish communities associated with flow regulation in New South Wales rivers.</td>
<td>1996</td>
<td>Assessed fish abundance and species richness in regulated and unregulated river reaches across NSW including the Barwon-Darling River. Species richness was marginally lower in regulated versus unregulated reaches of the Barwon-Darling River, but abundance of native fish was 60% lower in regulated reaches. There was a greater abundance of juveniles in unregulated reaches, suggesting higher recruitment success in unregulated rivers in the Darling.</td>
</tr>
<tr>
<td>Harris JH and Silveira R (1997)</td>
<td>Assessing the condition of rivers in New South Wales, Australia: A test of the index of biotic integrity.</td>
<td>1996</td>
<td>Developed and applied a condition index for rivers based on fish. Metrics included indices of species richness and composition, trophic composition and fish abundance and health. Results for the Barwon-Daring River indicated that approximately 50% of sites and sampling events rated poor, only 6% of sites/samples were considered good and no sites were rated as excellent.</td>
</tr>
</tbody>
</table>
### Invertebrates

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Year</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jenkins KM and Boulton AJ (2007)</td>
<td>Detecting impacts and setting restoration targets in arid-zone rivers: aquatic micro-invertebrate responses to reduced floodplain inundation. <em>Journal of Applied Ecology</em> 44: 823–832.</td>
<td></td>
<td>Assessed the emergence of micro-invertebrates from resting eggs in terms of taxa richness, densities and community composition in floodplain lakes on the Barwon-Darling River. Found that increased drying of floodplain lakes reduced the number of micro-invertebrate taxa. Several key taxa were absent and faunal densities (particularly cladocerans) were reduced when the duration of drying increased from six to 20 years.</td>
</tr>
</tbody>
</table>

### Vegetation

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Year</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hale J, Roberts J, Cottingham P, Butcher R, Gippel C and Kobryn H (2007)</td>
<td>Riparian Zone Management: Barwon-Darling Rivers. A report to the Western Catchment Management Authority, Regional Ecosystem Services and Associates.</td>
<td>2006-2007</td>
<td>Assessed 47 sites along the Barwon-Darling River using a modified version of the RARC (Rapid Assessment of Riparian Condition) and an assessment of tree health. Results indicated that the majority of sites (almost 60%) were in poor or very poor condition and no sites were scored as excellent.</td>
</tr>
</tbody>
</table>
Coorong and Murray Mouth Site Assessment:

Summary

The Coorong and Murray Mouth is the only estuary within the Basin and therefore a critical window on cumulative change evident across the Basin, particularly in the lower sections. In recent years the Coorong, Lower Lakes (Lake Alexandrina and Lake Albert) and Murray Mouth have become the focus of concentrated research and management planning aimed at retaining some ecological values whilst the site suffered significant declines in condition. The primary cause of decline across the Coorong, Lower Lakes and Murray Mouth has been identified as reduced inflows, changed magnitude and frequency of flooding exacerbated by drought.

The evidence of the relationship between reduced inflows and declining ecological condition has been well documented and researched (e.g. DEH 2010; DENR 2010; Geddes 1987; Kingsford & Porter 2009b; Krull et al. 2008; MDBC 2007, 2008a; Rogers & Paton 2009a, 2009b). The Coorong and Lower Lakes are listed as a Ramsar Wetland of International Importance, with an Ecological Character Description benchmarked for 1985 when the site was listed. In preparing the ecological character description Phillips and Muller (2006) clearly stated that the character of the site at the time of listing was already seriously degraded. The overriding driver of the condition of the Coorong and Lower Lakes is altered hydrology. Reduced flow volumes, reduced frequency and duration of medium-sized flood events in spring, and the increased risk of the Murray Mouth closing are the main factors implicated in observed environmental changes at the site (Lamontagne et al. 2004; MDBC 2005; Phillips & Muller 2006).

Trends in condition and evidence of decline

A significant number of research investigations over the past several decades have reported a decline in the condition of various attributes of the ecology of the Coorong, Lower Lakes and Murray Mouth (CLLAMM). Much of this was summarised in the Living Murray Foundation Report (MDBC 2005), the Ecological Character Description of the site (Phillips & Muller 2006) and more recently by DEH (2010). Major findings from these reports are outlined below and augmented with information collected by the CLLAMMecology Research Cluster. The CLLAMMecology Research Cluster is a partnership between CSIRO, the University of Adelaide, Flinders University and SARDI Aquatic Sciences that is supported through CSIRO’s Flagship Collaboration Fund. In response to the ongoing decline at the site, the CLLAMM program of collaborative research was initiated to establish a better understanding of the links between flow, other key ecosystem drivers (such as water level and salinity) and ecological responses (generation of bird habitat, fish recruitment etc.).

The decline in many of the attributes of the Ramsar site led the South Australian and Australian Governments to formally notify the Ramsar Secretariat in 2008 (Article 3.2 Notification), that the ecological character of the Coorong and Lower Lakes Ramsar site had changed since the time of listing in 1985. Whilst the whole site has undergone significant change this case study focuses predominantly on the Coorong section of the Ramsar site. DEH (2010) states that the Coorong has lost much of its productivity. Conditions are now such that it is unsuitable for much of the wildlife the Coorong previously supported, it no longer sustains the full range of economic activities it once did and there has been a significant impact on the cultural life of the Ngarrindjeri people (DEH 2010).
Overview of hydrological change – closure of the Murray Mouth

Inflows to the Coorong and Lower Lakes have changed significantly since European settlement, resulting in a significant decline in the environmental values of the site (DENR 2010; Kingsford & Porter 2009b). Pre water resource development, an average of 12,200 GL/year would reach the Murray Mouth. Current water extraction across the Murray-Darling Basin is 48%. Water extraction combined with natural transmission losses has reduced the average annual outflows through the Murray Mouth to 4700 GL, a reduction of 61% (CSIRO 2008a; DEH 2010). However, average flows do not occur consistently, with the frequency of no water passing over the barrages now 40% of the time due to water consumption (DEH 2010) compared to 1% without development. CSIRO (2008a) predicts severe drought inflows to the Lower Lakes (<1500 GL/year) to occur in 9% of years with the current levels of water resource development. Prior to water resource development, severe drought conditions (as defined by CSIRO 2008a) did not occur – the minimum annual inflow was 2,250 GL. Inflows from the Upper South East and the Mount Lofty Ranges have also declined in the past decades through drainage and increased consumption, although some flows are being returned from the Upper South East. However, this only represents a very small proportion of the natural inflows which occurred previously and has not had a significant impact on freshening the South Lagoon.

Prolonged drought has exacerbated the problem. The average inflow over a 117 year record is 11,030 GL. In the period 1892 to 1997 the average was 11,600 GL. In the period 1998-2008, 5,700 GL (DEH 2010). The current dry period and low water availability can be put into perspective by comparisons with similar extended droughts in the early and mid-twentieth century. The average annual Murray inflow of 3800GL/yr during the current drought (2002 to 2008) is lower than that experienced in the previous worst two droughts on record – 4900GL/yr in 1897 to 1904, and 5600GL/yr in 1938 to 1946.

Extended periods where the Murray Mouth is closed affects water level, salinity and oxygen levels in the Coorong, resulting in biological impacts including changes in fish, plant and waterbird populations (Rogers & Paton 2009a, 2009b). This also has implications for tourism and threatens important Indigenous values (Lamontagne et al. 2004).

Salinity in the Coorong

The reduced inflows over past decades have led to a series of cascading effects which have ultimately led to biological impacts. With reduced flows entering the Lower Lakes in recent years, very little water has flowed into the Coorong and out to the sea since 2005. With water levels below sea level and evaporation in the Lower Lakes exceeding inflows, there has been a buildup of salt (DENR 2010). Reduced flushing of the Murray Mouth has also contributed to rising salinity, particularly in the South Lagoon. Over the entire Coorong, Lower Lakes and Murray Mouth rising salinity has had significant impacts on physical and ecological condition.

Salinity is variable across the different parts of the Coorong, being determined by freshwater inflows, evaporation, mixing of water within and between the North and South Lagoons and groundwater. Reduced tidal exchange, particularly into the South Lagoon, has also led to increased salinity. Hypersaline conditions prevail in the South Lagoon at levels that exceed the tolerances of many species.
Seawater is 35‰. In recent years the South Lagoon has exceeded 150‰ (MDBC 2008a; Paton 2005 cited in DENR 2010). In 2005, more than three quarters of the Coorong had salinities more than double that of seawater.

Sustained high salinity, linked to decreasing inflows, has led to a dramatic decline in species diversity in the Coorong (Paton 2005 cited DENR 2010; Kingsford & Porter 2009b; Paton & Rogers 2009; Paton et al. 2009). Salinity is the key determinant of the Coorong food web (Deegan et al. 2009) and ecology of the site. During the reporting period of the Icon Condition Monitoring for 2008 and 2009, the lack of freshwater flows over the barrages has resulted in no estuarine conditions in the Coorong, rather marine conditions in the North Lagoon and hypermarine conditions in the South Lagoon have prevailed (Frears & Taylor 2010).

**Organic matter**
*Ruppia megacarpa* contributed a significant input to organic matter in the North Lagoon of the Coorong in pre-European times. The condition of the Coorong has declined in recent decades to such an extent that carbon from this source is no longer a major component of sediment layers (Krull et al. 2008). Terrestrially derived carbon transported by inflows from the River Murray and Upper South East is not considered a significant contributor to the organic carbon of the sediments of the Coorong. However, changed compositions of organic matter do reflect impacts from altered hydrology, with salinisation leading to changes in carbon sources (e.g. loss of *Ruppia*). Krull et al. (2008) postulates that most organic inputs from the River Murray may bypass the Coorong during floods and move directly out to sea.

**Ruppia**
Changing salinity gradients brought about in part by reduced freshwater inflows over the barrages and from the Upper South East, have led to dramatic declines in distribution of key aquatic vegetation within the Coorong. In the South Lagoon sustained hypersaline conditions have resulted in contraction of *Ruppia* into the Northern Lagoon. This plant provides critical habitat for fish, most notably the smallmouth hardyhead, and is also an important food resource for waterbirds. The Icon Condition Monitoring shows that measures of abundance for the key aquatic plant *Ruppia tuberosa*, smallmouth hardyhead fish and chironomid larvae all suggest an overall reduction of available food for a wide range of waterbirds in the South Lagoon (MDBC 2008a; Rogers & Paton 2008).

**Fish**
Ongoing drought and reduced freshwater inflows to the Murray Mouth and Coorong are having negative implications for more estuarine species such as black bream *Acanthopagrus butcheri*, greenback flounder *Rhombosolea tapirina*, mulloway *Argyrosomus hololepidotus* and congolli *Pseudaphrites urvillii* (Brookes et al. 2009; Deegan et al. 2009). Impacts on three other key fish species are unknown (yelloweye mullet *Aldrichetta forsteri*, smallmouth hardyhead *Atherinosoma microstoma* and Tamar River goby *Afurcagobius tamarensis*) (Brookes et al. 2009).
Zampatti et al. (2010) found species richness to be similar to numbers recorded in the 1990s, but that composition and abundances had changed. Smallmouth hardy head, the most abundant species in the North Lagoon, is the only species to have been recorded in the South Lagoon, being able to tolerate salinities up to 134 g/L (Brookes et al. 2009). Large fish have been restricted to the Murray Mouth as salinities are too high in the North and South Lagoons. In the past, large fish species were recorded throughout the Coorong (Geddes 1987; Phillips & Muller 2006).

**Waterbirds**

Substantial declines in waterbird abundance including shorebirds, fish eating species and other species reliant on vegetation (DENR 2010; Nebel et al. 2008; Rogers & Paton 2009a; Wainwright & Christie 2008) are indicative of global trends in waterbird population declines (Nebel et al. 2008; Wetlands International 2006). Declines at the Coorong have been attributed to altered habitat and resources, caused by altered water regimes and changing water quality, most notably increasing salinity. Despite the Coorong supporting the largest proportion of waterbirds among the Living Murray Icon sites in 2008, this still represents a decline from abundances supported by the site in the 1980s. Changes in habitat extent and condition and key food resources in response to reduced flows may involve lag effects, with further declines in populations possible.

Some species have increased in numbers since 2000. For example, banded stilt and red-necked avocet both had significant increases in numbers in 2008 compared to previous years; however, overall there has been an 85% decline in the numbers of shorebirds in the Coorong since the 1980s (Wainwright & Christie 2008). Banded stilt have increased in number as brine shrimp (*Parartemia zietziana*) have taken advantage of this hypersaline conditions and flourished in the South Lagoon (Brookes et al. 2009).

**Key information sources**

Detailed key information sources for the Coorong and Murray Mouth are listed in Table 5.

**Table 5. Key information sources.**

<table>
<thead>
<tr>
<th>Citation</th>
<th>Attribute</th>
<th>Time period</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hydrology – Murray Mouth closure</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDBC (2008a) The Living Murray Icon Site Condition Report, October 2008.</td>
<td>Multiple attributes</td>
<td>2007-2008</td>
<td>‘The ecological health of the Lower Lakes, Coorong Murray Mouth icon site continues to decline. The decline is due primarily to the reduction of freshwater inflows.’ ‘No flows were released over the barrages during 2007/2008 with the result that dredging is essential to maintain an open Murray Mouth; this also maintains the targeted variable salinity and water regimes.’</td>
</tr>
<tr>
<td>Source</td>
<td>Study Area</td>
<td>Year</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------------------------------------------------------------</td>
<td>----------------------</td>
<td>------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Close AF (2002) Options for reducing the risk of closure of the River Murray mouth. MDBC Technical Report 2002/2, Options, Version 3, Murray-Darling Basin Commission, Canberra, ACT, 24 April.</td>
<td>Murray Mouth closure</td>
<td>2002-modelled</td>
<td>This resulted in several cascading effects including impacts on fish passageway and increasing salinity in the South Lagoon. Average outflows over the barrages are only 39% of the pre development levels due to upstream water development. In April 1981, the Murray Mouth completely closed for several months due to build up of silt. A flood event later in the year opened the mouth again. Modelled current conditions indicate the percentage of years at risk of Mouth closure is 31.5% which could be reduced to 7.4% if the SA entitlement was increased to 2000ML/d plus regulating the barrages to draw down the level in the lower lakes and extending the period with a flow of 2000ML/d.</td>
</tr>
</tbody>
</table>
| DWLBC (2002) The Murray Mouth: Exploring the implications of closure or restricted flow. Report prepared for the Murray-Darling Basin Commission, Department of Water, Land and Biodiversity Conservation, Adelaide. | Multiple – compilation of papers addressing implications of reduced flow | 2002 | Accumulation of sediment at the Murray Mouth due to reduced flows and associated altered physical conditions is considered ‘symptomatic of the condition of the entire Murray-Darling Basin’. A series of papers are presented in relation to the affects of altered flow on the Murray Mouth and related ecological impacts. Common findings include:  
- The accumulation of sediment at the Murray Mouth reflects the vastly altered hydrology of the River Murray and is symptomatic of the condition of the entire Murray-Darling Basin.  
- The implications of closure depend on its duration, timing and frequency – that is the period for which the Mouth stays closed, the time of year when this happens and the interval between closures.  
- Current, the risk of long-term closure is greater than ever before due to the condition of the River Murray – that is, negligible river flows reaching the Mouth, and a major reduction in big flood events.  
- Long-term closure would have serious deleterious, and in some cases irreversible, impacts on the ecology of the area and those who depend on it. |
### Organic matter

<table>
<thead>
<tr>
<th>Authors</th>
<th>Study Title</th>
<th>Location</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krull ES, Lamontagne S, Haynes D, Broos K, McKirdy D, McGwan J, Gell P and Wakelin S (2008)</td>
<td>Changes in organic matter chemistry in the Coorong Lagoons over space and time.</td>
<td>Coorong Lagoons</td>
<td>Algae are the main primary producers in the Coorong, with Ruppia contributing significant amounts of carbon in the past in the North Lagoon. The River Murray is not considered a significant source of carbon for the Coorong with most discharged to the sea. However, reduced flows affect carbon sources by affecting salinity levels and the loss of primary producers, such as Ruppia in the North Lagoon. Overall findings support the hypothesis that the loss of food resources that has accompanied hypersalinisation of the South Lagoon is an important driver of the Coorong ecosystem decline. This is especially true for waterbirds, which are not directly affected by high salinity but are indirectly impacted by altered food resources.</td>
</tr>
</tbody>
</table>

### Salinity

<table>
<thead>
<tr>
<th>Authors</th>
<th>Study Title</th>
<th>Location</th>
<th>Period</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geddes M (1987)</td>
<td>Changes in salinity and in the distribution of macrophytes, macrobenthos and fish in the Coorong Lagoons, South Australia following a period of River Murray flow.</td>
<td>Coorong Lagoons</td>
<td>1983-1984</td>
<td>Mixing of freshwater southwards in the Coorong is influenced by River Murray flow as well as sea levels, lagoon levels, wind direction and evaporation. Freshening of salinity in response to inflows dropped levels to 50–70‰, which were still well above those recorded in 1975 (30-40‰) following heavy rain in 1973 and up to 1975. A previous study of the Coorong (Geddes and Butler 1984; Kangas and Geddes 1984) was undertaken during a 16-month period (December 1981 to March 1983) of no outflow from the barrages. During this time the Coorong’s salinities were marine to moderately hypermarine in the North Lagoon (35-50 ‰) and strongly hypersaline (80-110 ‰) in the South Lagoon. These conditions greatly restricted the distribution of the marine derived estuarine-lagoonal fauna in the Coorong.</td>
</tr>
<tr>
<td>Invertebrates</td>
<td>Water quality</td>
<td>2007-2008</td>
<td>Measurements at five sites in the Coorong all exceeded seawater salinity ranging from 50 to 190‰. Reduced inflows, evaporation and tidal exchange were listed as causes.</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>--------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
</tbody>
</table>
Macrobenthic survey 2004 in the Murray Mouth, Coorong and Lower Lakes Ramsar site, with an evaluation of food availability for shorebirds and possible indicator functions of benthic species. Department for Environment and Heritage, Adelaide. | Benthic (mudflat) invertebrates | 2004                                                                                                                                                                                                      | Within the Coorong, the highest abundances of macrofauna were located in the marine/estuarine areas where salinity ranged from 26 to 32‰ (hypersaline areas with salinities over 100‰ were almost devoid of macrofauna).  
Overall, the diversity in mudflat macrofauna was low, with no typical estuarine macrobenthos. Species richness was highest near the Murray Mouth (between Goolwa Barrage and the northern end of the North Lagoon) with abundances comparable to densities recorded in estuarine mudflats in other subtropical locations.  
Mean abundances of total macrofauna near the Murray Mouth were 5 to 37 times higher than in the South Lagoon (which had the lowest number of species and individuals and many sites were devoid of macrofauna altogether).  
‘Compared to other estuaries along the flyway of the shorebirds, biomass in the study area was about 10 times lower. The benthic food available for migratory shorebirds in mudflats of the Coorong as revealed by this study may not sustain their food requirements.’ Dittman et al. (2006) did not directly attribute findings to reduced inflows, but rather emphasised salinity as a driver of the macrobenthos. |

| Macrobenthos 2006-2008 | Salinity, tidal exposure and to a lesser extent sediment organic content are the driving environmental parameters behind both macrobenthos and juvenile macrobenthos distribution. Adult and juvenile macrobenthic diversity and abundance were greatest in the Murray Mouth region before decreasing in the North Lagoon. The greatest abundance of both adult and juvenile macrobenthos occurred at Pelican Point, which was also distinct from other sites in terms of sediment grain size. In December 2006, only insect larvae were present in the South Lagoon. No taxa were present in the South Lagoon in January and March 2007. Although the low macrobenthic diversity currently present in the Murray Mouth and Coorong Lagoons suggests that the region is in poor ecological health, the system appears to presently be in a state of relative stability when compared with macrobenthic surveys of previous years. Despite the lack of water released into the region over the past five years, macrobenthic communities have not changed significantly over that time. |

**Fish**


|  | ‘From July 2005 to February 2006, water was released through the Barrages including seven months of continuous fishway operation, timed so that several native fish species could move between the Lower Lakes and Coorong to breed and complete their life cycles. This was the longest period of fishway operation since they were constructed. Research on the fish assemblages of the Lower Lakes has been carried out since 2003. Spawning and recruitment of Murray hardyhead, southern and Yarra pygmy perch has been detected in all years between 2003 and 2006. In summer 2007, Murray hardyhead and pygmy perch species were collected in much lower abundances than in 2005 and 2006.’ |
The closure of fishways resulted in the decline in abundance of a number of fish species. The closure of the fishways in early 2007 was necessary due to low levels in Lake Alexandrina and Lake Albert and the potential for reverse head (i.e. intrusion of salt water into the Lower Lakes because lake water levels can be lower than Coorong levels). There was a 96% and 99% decline in young-of-year common galaxias and congolli respectively within the estuary last year. Intermediate sized male congolli were sampled on the Coorong side of Tauwitchere barrage, with female congolli sampled on the other side. The separation of males and females has prevented spawning and recruitment for this species. No adult lampreys were sampled attempting to migrate at the barrage fishways or (saltwater) leakage sites. Estuarine and catadromous fish spawning and recruitment has significantly declined due to a lack of freshwater outflows and subsequent loss of connection between the lakes and the estuary.

Total annual catch declined steeply from 58.2 t to 4.6 t between 1986-87 and 1991-92. Total annual catch remained below 12 t after this and was 4.5 t in 2006-07. The catch in 2006-07 was 42% below the most recent five year average (7.6 ± 1.36). An increase in CPUE corresponded with a decline in available habitat and may reflect an increase in catchability as the population contracted due to poor environmental conditions.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year(s)</th>
<th>Attributes</th>
<th>Years</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frears A and Taylor P (2010)</td>
<td>2008-2009</td>
<td>Multiple attributes including fish</td>
<td>‘In the area of the Murray Mouth closest to the barrages, populations of diadromous fish (those which complete their lifecycles in both freshwater and marine environments) are being recorded in increasingly low numbers, and showing vastly reduced reproductive outputs (Jennings et al. 2009). It is likely that congolli, an iconic fish of the region, will become locally extinct if connection between the fresh and estuarine environments is not reinstated in the next 1-2 years.’</td>
<td></td>
</tr>
<tr>
<td>Zampatti BP, Bice CM and Jennings PR (2010)</td>
<td>2005-2009</td>
<td>Fish</td>
<td>Freshwater inflows to the estuary diminished and ultimately ceased over the length of the study, disconnecting freshwater and estuarine environments. As freshwater flows over the barrages stopped, salinity rose from brackish to marine–hypersaline. Species richness and diversity decreased and freshwater and diadromous species became less abundant. Fish assemblages became increasingly characterised by marine species. Overall, 36 species were collected which was comparable to numbers recorded in the 1990s but considerably more than reported by Geddes (1987).</td>
<td></td>
</tr>
</tbody>
</table>

**Vegetation - Ruppia**


<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year(s)</th>
<th>Attributes</th>
<th>Years</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDBC (2007)</td>
<td>2006-2007</td>
<td>Ruppia species distribution and abundance</td>
<td>During 2006/2007, water levels in the South Lagoon were the lowest on record. As a consequence, no <em>Ruppia tuberosa</em> reproduced. During summer, <em>Ruppia tuberosa</em> beds were exposed and did not provide a food resource for waterfowl or invertebrates. ‘The quality and quantity of habitats for waterfowl in the Coorong have been greatly reduced in recent years and continue to deteriorate.’ Nicol (2007 cited MDBC 2007) found no live plants (from the initial 22 sites sampled) despite two controlled barrage releases that provided conditions suitable for recruitment. Preliminary findings suggest</td>
<td></td>
</tr>
</tbody>
</table>
that the likely cause of the absence of live plants was high salinities prior to dredging to open the Murray Mouth which commenced in October 2002.

| Rogers DJ and Paton DC (2009b) Changes in the distribution and abundance of Ruppia tuberosa in the Coorong, Technical Report, CSIRO Water for a Healthy Country Flagship, CSIRO, Canberra. | 1998-2008 | *Ruppia tuberosa* was historically recorded along the entire length of the Coorong, providing critical habitat/food resources for fish and birds; however, it has virtually disappeared from the South Lagoon in the past decade. It is the major food resource for several waterbirds including black swan and *Calidris* species. Recruitment of the smallmouth hardyhead *Atherinosoma microstoma* may also be reliant on *R. tuberosa*.

There has been a significant change in the distribution and abundance of *R. tuberosa* since 1998. The changes are also spatially-explicit, with declines in *R. tuberosa* density and cover occurring earlier in the southernmost sites than northern sites. ‘*R. tuberosa* shoots were last recorded at Tea-tree Crossing and Salt Creek (2004), at Policeman Point (2005) and at Villa dei Yumpa (2007). The observed pattern of staged extinction from south to north suggests a range contraction for *R. tuberosa* in the South Lagoon. Conversely, *R. tuberosa* was first recorded at Noonameena (2005), suggesting recent range expansion into the North Lagoon.’

There was also a decline and change in spatiotemporal changes in the propagule density of *R. tuberosa*.

‘For all three South Lagoon regions, a decline in propagule density has been observed between 2001-2008, although *R. tuberosa* propagules were still recorded within all three regions in 2008.’

The best model which accounted for the observed patterns included mean daily salinity, maximum average monthly salinity, minimum average monthly salinity and water level regime. Of these, water level regime was the least important in explaining the patterns.

The response of *R. tuberosa* cover to water level suggests that low water levels are more significant in limiting *R. tuberosa* than high water levels.
### Waterbirds

<table>
<thead>
<tr>
<th>Source</th>
<th>Year Range</th>
<th>Description</th>
</tr>
</thead>
</table>

Reports on data from 10 sites across southeast Australia including the Coorong. At the Coorong, the numbers of shorebirds in years with water declined significantly over time ($F_{1,21} = 6.56, p = 0.018$) over the 24 year study.

(From Nebel et al. 2000: Dashed line indicates no water. X axis is years from 1992-2007, Y axis is number of shorebirds)

The decline was largely attributed to upstream water resource development. Similar declines in shorebird numbers at the Coorong were reported by (Phillips & Muller 2006) and (Gosbell & Christie 2005) indicating a decline of more than 50% between the 1980s and 2005/2006.
<p>| Rogers DJ and Paton DC (2009a) | Waterbird counts | 2000-2007 | Key waterbird species have declined in abundance over multiple time scales, most notably in the South Lagoon. Changes in hydrology indirectly impacted on waterbirds through changes in the abundance of key food resources – particularly species which depend on aquatic vegetation and fish. Physical habitat, which was directly affected by changes in water levels, is a critical factor affecting the abundance of some species. Changes in flow regimes affected both food resources, by affecting salinity levels, as well as physical habitat which when combined drives waterbird abundance in the Coorong. |
| Kingsford RT and Porter JL (2009) | Waterbird abundance | 2007 and 2008 | Annual waterbird surveys of icon site (including the CCLLAMM) under The Living Murray Condition Monitoring Program. Reports annual survey results and statements on trends. Conclusions relevant to the Coorong and Lower Lakes are: ‘Waterbird abundance and breeding were concentrated in the Lower Lakes, Coorong and Murray Mouth Icon site which supported a mean total of 134,635 waterbirds, comprising 46 species (96% of survey total), with Cape Barren Geese, Banded Stilt, Australian Shelduck, Great Cormorant and migratory shorebirds.’ ‘Within the Lower Lakes, Coorong and Murray Mouth Icon site, most waterbirds were distributed in the Coorong (59,645) and Murray Mouth (54,620). Lakes Albert (9,397) and Alexandrina (10,983) supported lower numbers of waterbirds. No waterbird breeding was recorded, a considerable decrease compared to 2007 (3,951 mean breeding index).’ ‘Water levels in the southern Coorong were low (&lt;40 % full by area) in 2008 while the northern Coorong and lower lakes held considerably more water, they were lower than in 2007.’ |</p>
<table>
<thead>
<tr>
<th>Source</th>
<th>Method</th>
<th>Year</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDBC (2008a) The Living Murray Icon Site Condition Report. October 2008.</td>
<td>Multiple – including waterbird counts</td>
<td>2007-2008</td>
<td>‘Long-term monitoring indicates a steady decline in abundances of many key wading species in the Coorong. The exceptions to the rule are banded stilt and red-necked avocet, which are able to feed on brine shrimp in the South Lagoon and have been recorded in record numbers. While an increase in mudflat exposure in the Lower Lakes seems likely to be beneficial to wading birds, benthic invertebrate monitoring indicates that key food species are only able to survive up to one week without re-inundation, rendering the majority of exposed lake edge barren. The Annual Aerial Waterbird Survey of all icon sites indicated that the Lower Lakes, Coorong and Murray Mouth icon site has waterbird abundance in order of magnitude greater than any other icon site.’</td>
</tr>
<tr>
<td>DENR (2010) Breeding Australian pelican, Pelecanus conspicillatus, in the Coorong National Park, South Australia 2009-2010. Department of Environment and Natural Resources, Adelaide.</td>
<td>Pelican numbers and breeding</td>
<td>1985–2010</td>
<td>Past records indicate the number of eggs and chicks vary from 500 to 2000 over the period 1910 to 1965 (Chapman 1963; Paton 1982 cited DENR 2010). Total abundance of Australian pelican in the Coorong has declined over the period 2000 to 2010 (Paton 2010 cited DENR 2010). The current study indicates a decline in the abundance of breeding birds on North Pelican Island in the South Lagoon of the Coorong of 34.5 % relative to the abundances recorded in 1985 at the time of listing of the Coorong and Lower Lakes as a Ramsar site. This is despite a 384% increase in numbers in 2010 compared to 2008 and 2009, but still representing only 30% of the total abundance of Australian pelicans reported in 1985.</td>
</tr>
</tbody>
</table>

Waterbirds 2008

Numbers of migratory shorebirds have undergone a dramatic decline over the last 20 years. In February 2008 (excluding ephemeral species banded stilt *Cladorhynchus leucocephalus* and red-necked avocet *Recurvirostra novaehollandiae*), the number counted was 25,889; the lowest on record since 1982. ‘This represents an 85% reduction in migratory shorebirds since the early 1980s.’

‘The decline this year was notable for the absence of Red-necked Stint *Calidris ruficollis*, nominally the most abundant migratory wader species at the site. In contrast, Sharp-tailed Sandpiper *C. acuminata* and Curlew Sandpiper *C. ferruginea* were present in higher numbers when compared with the 2007 data. Banded Stilt were highly abundant in the Coorong’s Southern Lagoon, where a flock exceeding 250,000 was observed. This is possibly the largest recorded Banded Stilt flock in Australia.’

‘When compared with historical data, 1981 for example, Curlew Sandpiper abundance has declined more than 90%.’

‘The ecology of the Coorong has deteriorated significantly over the last eight years largely as a result of the lack of fresh water flows from the River Murray through the barrages.’

**Other information sources (not exhaustive)**

In addition to the key information sources detailed above, there is a considerable body of research and monitoring that indicate a link between water regimes and the ecology of the Coorong and Lower Lakes. Many of these are associated with finding environmental management options in response to the ongoing reduced flows and drought. Several of these provide a further line of evidence to support the fact that reduced inflows have had profound implications for the ecological integrity and functioning of the Coorong and Lower Lakes. A selection of these papers is provided below.


Condition of specific organisms

Invertebrates

Condition assessments and response to flow

Invertebrates (macro and micro) are critical components of the ecology of rivers and floodplains, underpinning in-channel, riparian and floodplain food webs, contributing to the processing of organic matter and transporting energy through WDEs (Boulton & Lake 1992). Their fundamental importance in WDEs is reflected in the fact that aquatic invertebrates are now routinely assessed as measures of ‘river health’ (e.g. Davies et al. 2008; Norris & Young 2001). Invertebrate monitoring has predominantly been undertaken in rivers and streams, with assessment of wetland condition using invertebrates less common as much greater temporal and spatial variation is exhibited by wetland invertebrate fauna (Baldwin et al. 2005; Boulton & Lake 1992).

Whole of Basin assessments using macroinvertebrates include the SRA (Davies et al. 2008), (Davies et al. 2010), National River Health Program (NRHP) (Davies 2000) and the audit of the ecological condition of Australian Rivers (Norris & Young 2001) - which used the data from the NRHP). It should be noted that the metrics used in the SRA and NHRP are not specific to changes in river health caused solely by changes in flow. The metrics capture broad scale change which include but are not limited to altered hydrology. Sheldon et al. (2000) noted that the poor condition rating in six large dryland rivers may reflect impacts of hydrological change. Comparisons to the Diamantina River, which has no water resource development and had relatively high species richness, suggested that the depauperate communities collected in the six reference rivers reflected hydrological changes in these rivers. However, they did note that the short life cycles and generation times meant that invertebrate response to hydrological change is rapid and therefore assigning causality is difficult (Sheldon et al. 2000).

Davies et al. (2008) reports that macroinvertebrate samples taken from 773 sites in the MDB included over 209 100 specimens in 124 families. The Sustainable Rivers Macroinvertebrate Index showed that communities in the Border Rivers, Upper Murray and Paroo Valleys were in moderate condition, and those in the Avoca and Wimmera Valleys were in very poor condition. The remaining valleys within the MDB were rated as in poor condition. Eighteen percent of the families encountered were common to all 23 valleys. Rare families tended to be those that contained species sensitive to pollution and other human disturbances, whilst the common families were characterised as being tolerant (Davies et al. 2008).
Rivers naturally go through periods of flooding, low flow and drought (Death 2008; Lake 2000, 2003). Therefore, it is not surprising that aquatic invertebrate fauna are well adapted to hydrological variation and that response to altered hydrology varies among invertebrate groups and locations. For example, aquatic invertebrates in upland constrained streams and floodplains display a different set of adaptations to flooding or increased flow (Lake et al. 2006). Floodplain aquatic invertebrates are characterised by traits associated with rapid growth and reproduction during inundation such as small body size, high adult mobility and generalised diets (Lake et al. 2006). Upland aquatic invertebrates have adaptations to deal with increased hydraulic stress, including smaller bodies and means of attaching themselves to secure substrates (Lake et al. 2006). Invertebrate communities immediately below large dams tend to have a different community composition than further downstream and this is probably due to the fact that the dams prevent, or at least limit, downstream drift of colonists. However, it is the disruption of colonisation processes rather than an affect of discharge which leads to different community structure. Sustained discharge which ‘drowns out’ riffles as well as increased deposition of sediments, will lead to a sustained change in benthic faunal composition (Walker 1985 and references therein). It should be noted however, that whilst floods and high discharges can be quite devastating to the in-channel invertebrate fauna, particularly in constrained channels, recovery tends to be swift in most cases (Death 2008; Lake 2000; Lake et al. 2006).

**Lowland river impacts from river regulation**

Sustained increased discharge can have a marked affect on lowland rivers. For example, prior to regulation the lower River Murray had a highly variable flow regime but was substantially changed with the installation of 10 low level weirs in 1922-1935 and the effects of upstream storages (Walker & Thoms 1993). Of particular note is the five-fold decrease in low flows (100-300 GL per month) and a two fold increase in moderate flows (500-1500 GL per month) (Walker & Thoms 1993). In the lower River Murray the littoral zone supports a large proportion of the biodiversity (Sheldon & Walker 1998; Walker & Thoms 1993; Walker et al. 1992). Plants and animals adapted to floodplain conditions, have invaded the littoral zones of the river as the conditions have changed from a flowing environment to a pool environment, with several river species undergoing a decline in range and abundance (Walker 1985).

The freshwater mussel *Alathyria jacksoni* is a river species which has undergone decline and is being replaced by *Velesunio ambiguus* which has adapted to still water habitats (Walker 1985). Some evidence for this change in species can be seen by examining Aboriginal shell middens along the lower River Murray (Walker 1985). The freshwater mussel *V. ambiguus* is able to endure dry periods, a characteristic of floodplain species, where as the river mussel *A. jacksoni* can only tolerate a short period out of the water (Walker 1985). The river snail *Notopala sublineata*, which is listed as threatened in NSW and Victoria, was once common in the lower reaches of the Murray and elsewhere in the MDB, but has declined since the 1950-1970s and may now be extinct. Potential reasons for the decline include changes in food quality and habitat brought about by river regulation Sheldon and Walker (1997) and also impacts from predation by carp (DEWHA 2007), ([http://www.environment.gov.au/biodiversity/threatened/species/river-snail.html](http://www.environment.gov.au/biodiversity/threatened/species/river-snail.html)).
Another river specialist species affected by altered flow regimes is the Murray crayfish *Euastacus armatus* which has been displaced by the common yabbie, *Cherax destructor*, a floodplain specialist. Once common in South Australia, the Murray crayfish is now virtually extinct in South Australia (Sheldon & Walker 1998; Walker 1982; Walker 1985). Combined, these changes in the river fauna indicate an impact of altered flow regime in the lower River Murray.

Humphries et al. (2006) identified another potential impact of altered flow regimes on shrimp. Slackwater patches were shown to be important areas for the development of young fish and shrimp, and that these habitats were likely refuges from the current of the main channel of rivers. Invertebrate food standing crop did not differ between slackwater and flowing patches which suggested the habitats were providing energetic advantages to young fish and shrimp (Humphries et al. 2006). The loss of such habitats in regulated rivers may influence shrimp distributions and abundances. It is important to note that invertebrate respond to very small scale conditions, hydraulic stresses surrounding a rock, or the presence of slackwater habitats, and rapid rises and falls in water levels. All of these may influence benthic invertebrates; however, attributing a decline in condition in invertebrate communities to altered hydrology alone is difficult.

**Low flow and floodplain impacts**

The impacts of reduced flows in channel are not as well studied (Dewson et al. 2007). Low water volume reduces available habitat and changes the physical environment for aquatic invertebrates which will affect community composition, behaviour and biotic interactions. Invertebrate abundances have been shown to both decrease and increase in response to reduced in-channel flow however, invertebrate richness typically decreases reflecting reduced habitat diversity (Dewson et al. 2007). Dispersal ability is a key feature enabling invertebrates to adapt to their changing environment. Aquatic invertebrates which are poor dispersers or which have very narrow environmental requirements are more susceptible to the impacts of altered hydrology. Changed hydrological regimes, in the short-term, have also been shown to trigger drift, both for increased flow and decreased flow (e.g. Bond & Downes 2003; Brooks 1997).

Many floodplain and wetland invertebrates are adapted to extended dry periods by having desiccation-resistant life history stages (Boulton & Lloyd 1992; Jenkins & Boulton 2003). Invertebrates in intermittent streams are also well adapted to surviving dry periods (Boulton & Lake 1992). Desiccation resistant life stages, including eggs, are one strategy for dealing with drought and dry periods. Different species have different cues and hatching requirements and this diversity contributes to maintaining a diverse invertebrate fauna on floodplains and in temporary wetlands (Brock et al. 2003). Brock et al. (2003) suggests that multiple generations in the egg banks along with the complexity of environmental cues for dormancy breakage influence a wetland/floodplain’s ability to recover after a drying event. Overall, floodplain and wetland invertebrate fauna are quite resilient to natural drying patterns, with persistent egg banks, rapid establishment of species-rich communities that reproduce rapidly and leave many propagules in the egg bank (Brock et al. 2003; Nielsen et al. 2002).
However, egg bank studies of micro-invertebrates in floodplain wetlands along the Barwon-Darling River indicate that increased intervals between inundation reduce the abundance and diversity of micro-invertebrates (Jenkins & Boulton 2007). Nielsen et al. (2002) suggested that the egg bank is more important to sustaining diversity in ephemeral wetlands rather than permanent wetlands. As these invertebrates often form the basis of the food chain in ephemeral and intermittent wetlands, Jenkins and Boulton (2007) suggested that this had implications for fish and waterbirds in the system. For example, changes in the egg banks and abundance and richness of micro-invertebrates have the potential to impact on the successful recruitment of many native fish, including golden perch *Macquaria ambigua*, silver perch *Bidyanus bidyanus* and Murray cod *Maccullochella peeli*. These species have been shown to rely on micro-invertebrate prey for their first meal after hatching (Culver & Geddes 1993; King 2005). Several waterbird species also feed on micro-invertebrates. Loss of viability and richness of floodplain egg banks has the potential to have significant trophic impacts.

**Summary**

Altered hydrology will impact on aquatic invertebrates and there are a number of examples of this including loss of riverine species in the lower Murray. However, most condition assessments which incorporate invertebrates are not targeted at identifying impacts from altered hydrology alone. Invertebrate indices assessed across the MDB indicate poor to moderate condition, but this cannot be attributed solely to changes in hydrology. Impacts on floodplains and changes to habitats caused by altered flow regimes have been shown to impact on egg banks leading to reduced invertebrate diversity. This in turn has the potential impact on river and floodplain food webs, with higher consumers possibly being affected. Impacts on invertebrates from altered hydrology can be more severe if coupled with significant shifts in water quality (e.g. Lind et al. 2006; Nielsen et al. 2003). In particular, combining altered flow with rising salinity can have a severe impact on invertebrates and food webs (e.g. South Lagoon in the Coorong).

**Vegetation**

There have been significant changes to vegetation communities in the MDB due to a combination of pressures including flow, land use (including clearing and grazing changes: Jurskis 2009), introduced species and increases in salinity.

Changes to flood regimes will have an effect on communities including diversity even when they are used to variability (Capon 2003). This will also affect vegetation and reduce resilience (Colloff & Baldwin 2010).

**Submerged aquatic vegetation**

One of the significant changes in vegetation is declines in submerged aquatic vegetation. Anecdotally there is evidence to suggest that submerged macrophytes have declined in rivers (J. Hawking pers. Comm.) with beds of plants like *Vallisneria* now only found immediately downstream of impoundments or in weir pools (the Broken River is an exception). There is also palaeolimonological evidence of a decline in submerged plants in billabongs (Reid et al. 2007). The decline may be partially due to changes in turbidity as *Vallisneria* do not grow new leaves if light is reduced by 20% and growth ceased if light is reduced by 80% (Blanch et al. 1998).
The decline of submerged vegetation is of significance due to both changes in patterns of productivity and habitat. Invertebrates utilise macrophytes for a variety of purposes including food (e.g. the moth caterpillars Parapoynx nitens and P. polydectalis), case construction (e.g. the caddisfly Triaenodes spp), protection (e.g. damselfly larvae including Austroagrion watsoni and Ischnura aurora) or as a place to deposit eggs (e.g. the dragonflies Adversaeschna brevistyla and Hemianax papuensis).

**Trees**

There has been a significant decline in the condition of floodplain trees in the MDB. Mapping the initiation of the change and its trajectory is difficult due to up to 65% of trees having been cleared (Walker et al. 1993) and that some areas have experienced expansion of the range of red gums at the expense of other vegetation types (e.g. Bren 1992). In the early 1990s, up to 40% of the South Australian floodplain was salinised with effects on vegetation condition (Taylor et al. 1996). By 2002, there was a clear decline in condition that extended from SA into Victoria and NSW with a survey reporting that 51% of trees were unhealthy and this increased to 75% of trees by 2004 (Lane & Associates 2005). A further, more comprehensive survey in 2007 found only 30% of the area containing river red gum stands is currently in good condition and that there is a downstream decline in stand condition, which is related to more extreme declines in flooding, due to water harvesting and drier climate found in the Lower Murray region (Cunningham et al. 2007). The declines are not surprising given the habitat requirements of red gum and black box adult health and germination (summarised in Figure 3 and 4; Table 6 and 7). As an example, the maximum inter-flood period that can be tolerated is two to three years for red gums and seven to 10 years for black box (Table 6) (Johns et al. 2009; Rogers & Ralph 2010). In SA, floodplains that would historically have been inundated once every three years are now only inundated once every 11 years thereby rendering them as unsuitable habitat for either red gum or black box. As a consequence, flow regulation was sufficient to significantly modify tree habitat in some regions of the MDB and the drought has merely pushed the trees beyond their capacity to survive. The latest assessment suggests that current watering regimes (rainfall and flooding) below the Yarrawonga Weir are insufficient to maintain the majority of river red gum stands in good condition (Cunningham et al. 2007). Of longer term concern is that flow regimes may be inadequate to support black box breeding and marginal for red gum breeding in many areas where populations currently exist (George et al. 2005).
Figure 3: Conceptual model summarising the main relationships between flooding regime characteristics and tree growth and health. Yellow boxes are modifying factors, blue boxes indicate flooding regime characteristics, light blue hexagons are primary controls, green boxes are response components and brown ovals are potential stressors. Taken from (Johns et al. 2009).
Table 6: Summary of species flooding requirements for maintenance of growth and health. Taken from Johns et al. (2009).

<table>
<thead>
<tr>
<th>Species</th>
<th>Ideal flood timing</th>
<th>Ideal flood depth</th>
<th>Maximum flood depth</th>
<th>Ideal flood duration</th>
<th>Maximum flood duration</th>
<th>Ideal flood frequency</th>
<th>Maximum flood frequency</th>
<th>Ideal inter-flood dry period</th>
<th>Maximum inter-flood dry period</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Eucalyptus camaldulensis</em></td>
<td>'Winter-spring'</td>
<td>No direct impact</td>
<td>No direct impact</td>
<td>'2-8 months'</td>
<td>'2-4 years'</td>
<td>'1-3 years'</td>
<td>'Variable'</td>
<td>'5-15 months'</td>
<td>'2-3 years'</td>
<td>³Flood timing is more critical for reproduction and seed set than for tree growth and survival. ²Varies according to other aspects of flooding regime, tree health and site factors (soils, geomorphology, rainfall, salinity, etc).</td>
</tr>
<tr>
<td><em>Eucalyptus largiflorens</em></td>
<td>'Winter-spring'</td>
<td>No direct impact</td>
<td>No direct impact</td>
<td>'&gt;4 months'</td>
<td>'2-5 years'</td>
<td>'Variable'</td>
<td>'Variable'</td>
<td>'7-10 years'</td>
<td></td>
<td>³Flood timing is more critical for reproduction and seed set than for tree growth and survival. ²Varies according to other aspects of flooding regime, tree health and site factors (soils, geomorphology, rainfall, salinity, etc).</td>
</tr>
<tr>
<td><em>Acacia stenophylla</em></td>
<td>Not known</td>
<td>Not known</td>
<td>Not known</td>
<td>Not known</td>
<td>Not known</td>
<td>Not known</td>
<td>Not known</td>
<td>Not known</td>
<td>Not known</td>
<td></td>
</tr>
<tr>
<td>Species</td>
<td>Year round</td>
<td>Shallow</td>
<td>Not known</td>
<td>Permanent</td>
<td>Permanent</td>
<td>Continuous</td>
<td>Continuous</td>
<td>None</td>
<td>Variable</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>------------</td>
<td>---------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
<td>------------</td>
<td>------------</td>
<td>------</td>
<td>----------</td>
<td></td>
</tr>
<tr>
<td>Salix spp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Require continuous access to shallow groundwater, but does not tolerate permanent inundation of the root crown.
2. Likely to vary between species and with flood duration.
3. Tolerance to drying may vary between species.
Figure 4. Conceptual model summarising the main relationships between flooding regime characteristics and germination. Blue boxes indicate flooding regime characteristics, hexagons are primary controls, yellow boxes are modifying factors, green boxes are response components and brown ovals are potential stressors. Taken from (Johns et al. 2009).
Table 3. Summary of species flooding requirements for germination. Taken from (Johns et al. 2009).

<table>
<thead>
<tr>
<th>Species</th>
<th>Ideal flood timing</th>
<th>Ideal flood depth</th>
<th>Maximum flood depth</th>
<th>Ideal flood duration</th>
<th>Maximum flood duration</th>
<th>Ideal flood frequency</th>
<th>Maximum flood frequency</th>
<th>Ideal inter-flood dry period</th>
<th>Maximum inter-flood dry period</th>
<th>Notes</th>
</tr>
</thead>
</table>
| Eucalyptus camaldulensis | Receding in spring-early summer | Moist soil         | 'No direct impact'  | No direct impact      | 'No direct impact'     | No direct impact       | No direct impact         | No direct impact             | No direct impact             | Germination success is primarily controlled by seed availability and moisture availability after seed dispersal, with most seeds germinating within 10 days of watering.  
1/Depth does not affect germination because seeds of this species will germinate while floating. However, depth will affect subsequent seedling survival and establishment, as will the other aspects of flooding regime. |
<p>| Eucalyptus largiflorens | Receding in spring-early summer | Moist soil         | 'No direct impact'  | No direct impact      | 'No direct impact'     | No direct impact       | No direct impact         | No direct impact             | No direct impact             | 1/As above. Seeds may germinate underwater but are unlikely to survive prolonged immersion. |
| Acacia stenophylla    | Not known                      | Moist soil         | Not known            | Not known             | Not known              | Not known             | Not known             | Not known                  | Not known                  |                                                                                 |</p>
<table>
<thead>
<tr>
<th>Salix spp.</th>
<th>2 October-November</th>
<th>Moist soil</th>
<th>No direct impact</th>
<th>No direct impact</th>
<th>No direct impact</th>
<th>No direct impact</th>
<th>No direct impact</th>
<th>No direct impact</th>
</tr>
</thead>
</table>

\(^1\) Willow seeds are viable for a short time only (1-9 weeks) after dispersal in spring. During this time seeds will germinate rapidly (typically within 1-2 days) in response to high moisture availability. Seeds will germinate while floating or underwater, however, seedlings will not grow further unless exposed to air within 1 month.

\(^2\) As above.
Fish

Native fish are among the best understood biotic groups and significant effort has gone into their restoration (MDBC 2003). Native fish populations are estimated to be less than 10% of what they were prior to European settlement (Phillips 2003). In addition, the population status of some populations is tenuous with little evidence of recruitment (Humphries et al. 2008). While early declines may be attributed to overexploitation (Humphries & Winemiller 2009) there was a significant decline in the period from 1955 to 1980 in Murray cod, silver perch and freshwater catfish (*Tandanus tandanus*: Reid et al. 1997). In response to significant declines in the abundance of key species the MDBC initiated a Native Fish Strategy that assembled information about the status of native fish (Table 7).

The Native Fish Strategy identified eight discrete pressures that had contributed to the decline in native fish which were:

- flow regulation
- habitat degradation
- lowered water quality
- barriers
- alien species
- exploitation
- diseases
- translocation and stocking.

Given the pressures inflicted on native fish, it is perhaps not surprising that the native fish community has undergone significant modification. The rest of this section focuses on a few of the better known species.

Table 7. Status of native fish in the MDB adapted from the MDBC Native Fish Strategy (MDBC 2003); (Lintermans 2007).

<table>
<thead>
<tr>
<th>Common name</th>
<th>Status and distribution</th>
<th>State and Commonwealth listings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-headed lamprey</td>
<td>Lower MDB</td>
<td>Qld – Extinct in wild</td>
</tr>
<tr>
<td>Pouched lamprey</td>
<td>Lower MDB, rare</td>
<td></td>
</tr>
<tr>
<td>Short-finned eel</td>
<td>Lower MDB, rare</td>
<td></td>
</tr>
<tr>
<td>Long-finned eel</td>
<td>Condamine drainage, Qld</td>
<td></td>
</tr>
<tr>
<td>River blackfish</td>
<td>Lower Murray-Darling Basin and cooler regions, declining Contracted to Mt Lofty Ranges (SA)</td>
<td>SA – Protected (endangered)</td>
</tr>
<tr>
<td>Two-spined blackfish</td>
<td>Upland species, southern MDB</td>
<td>ACT - Vulnerable</td>
</tr>
<tr>
<td>Common galaxias</td>
<td>Lower Murray River only</td>
<td></td>
</tr>
<tr>
<td>Climbing galaxias</td>
<td>Recently introduced into MDB</td>
<td></td>
</tr>
<tr>
<td>Spotted galaxias</td>
<td>Recently introduced into MDB</td>
<td></td>
</tr>
<tr>
<td>Flat-headed galaxias</td>
<td>Threatened species, lowland and lower Basin</td>
<td></td>
</tr>
<tr>
<td>Fish Name</td>
<td>Habitat/Population Status</td>
<td>Conservation Status/Location</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>Mountain galaxias</td>
<td>Upland areas and slopes, reduced due to interactions with trout</td>
<td></td>
</tr>
<tr>
<td>Barred galaxias</td>
<td>Threatened species, upland, lower MDB. 20 known populations in upper Goulburn River</td>
<td>Vic - Critically endangered, listed under FFG Act</td>
</tr>
<tr>
<td>Tupong/congoli</td>
<td>Restricted to lower River Murray, declining Once formed large migrations</td>
<td></td>
</tr>
<tr>
<td>Murray cod</td>
<td>Fragmented and in low abundance</td>
<td>Vic - Vulnerable, listed under FFG Act Commonwealth – Vulnerable listed under EPBC Act</td>
</tr>
<tr>
<td>Trout cod</td>
<td>Threatened species, three known populations, two of which are translocated (Cataract Dam and Sevens Creek)</td>
<td>ACT - Endangered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vic - Critically endangered, listed under FFG Act</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NSW - Endangered and a protected species</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SA – Protected</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Commonwealth – Endangered species listed under EPBC Act</td>
</tr>
<tr>
<td>Golden perch</td>
<td>Widespread and common</td>
<td></td>
</tr>
<tr>
<td>Macquarie perch</td>
<td>Threatened species, restricted, fragmented distribution, but locally abundant in upper Murrumbidgee and Goulburn River systems</td>
<td>ACT – Endangered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vic – Endangered, listed under FFG Act</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NSW – Vulnerable and a protected species</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SA – Protected</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Commonwealth – Endangered species listed under EPBC Act</td>
</tr>
<tr>
<td>Estuary perch</td>
<td>Uncommon, lower River Murray only</td>
<td></td>
</tr>
<tr>
<td>Silver perch</td>
<td>Threatened species, declining</td>
<td>ACT – Endangered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vic – Critically endangered, listed under FFG Act</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NSW – Vulnerable, protected from commercial catch</td>
</tr>
</tbody>
</table>
| Southern pygmy perch | Southern MDB  
Significantly reduced distribution in NSW                                      | NSW – Vulnerable             |
<p>|                   |                                                                                       | SA - Protected               |
| Yarra pygmy perch | Highly restricted to lower River Murray                                                | SA – Protected               |
|                   |                                                                                       | Commonwealth – Vulnerable species listed under EPBC Act |
| Australian smelt  | Widespread                                                                              |                             |
| Freshwater catfish | Declining since 1970s, was widespread                                                  | Vic- vulnerable, listed under FFG Act |
|                   |                                                                                       | NSW – Protected from commercial catch |
|                   |                                                                                       | SA – Protected               |
| Bony herring      | Widespread in mid-reaches                                                              |                             |
| Hyrtl’s tandan    | Northern MDB                                                                            |                             |
| Rendahl’s tandan  | Condamine and Balonne drainages only                                                    |                             |</p>
<table>
<thead>
<tr>
<th>Species</th>
<th>Status and Habitat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern purple spotted-gudgeon</td>
<td>Threatened species, once widespread</td>
</tr>
<tr>
<td>Western carp gudgeon</td>
<td>Widespread</td>
</tr>
<tr>
<td>Midgely’s carp gudgeon</td>
<td>Taxonomy complex</td>
</tr>
<tr>
<td>Spangled perch</td>
<td>Common, mid to upper MDB</td>
</tr>
<tr>
<td>Flat-headed gudgeon</td>
<td>Lower MDB and Murrumbidgee and Murray Rivers Declined in upland reaches</td>
</tr>
<tr>
<td>Dwarf flat-headed gudgeon</td>
<td>Patchy</td>
</tr>
<tr>
<td>Murray-Darling rainbowfish</td>
<td>Widespread, but major declines in Murray region</td>
</tr>
<tr>
<td>Desert rainbowfish</td>
<td>Widespread in Paroo and Warrego Rivers</td>
</tr>
<tr>
<td>Darling River hardyhead</td>
<td>Threatened species, restricted distribution</td>
</tr>
<tr>
<td>Fly-specked hardyhead</td>
<td>Widespread, declining, particularly in southern MDB</td>
</tr>
<tr>
<td>Murray hardyhead</td>
<td>Threatened species, restricted distribution. Only one individual recorded in NSW since 2000</td>
</tr>
<tr>
<td>Olive perchlet</td>
<td>Threatened species, extinct in SA (1983) and Vic.</td>
</tr>
</tbody>
</table>

**Trout cod (Maccullochella macquariensis)**

The trout cod is a moderately large freshwater fish endemic to the southern MDB. They are a riverine species, inhabiting a variety of flowing waters in the mid to upper reaches of rivers and streams with cover in the form of woody debris or boulders. The mid reaches of the Murray River and its tributaries, particularly in Victoria, and the Murrumbidgee River in NSW seem to have been the centre of its distribution. Up until 1950 at least, trout cod were present in the Murray River from Mildura to upstream of Yarrawonga (Cadwallader 1977; Lake 1971), although the species was considered rare downstream from Echuca, but more common upstream (J.O. Langtry, in Cadwallader 1977). There are records of trout cod occurring in the Murray, Murrumbidgee, Macquarie, Goulburn, Broken, Campaspe, Ovens, King, Buffalo and Mitta Mitta Rivers (Lintemans 2007).

Trout cod have suffered a catastrophic decline in range and abundance, apparently in just the last few decades. Currently just one natural population remains in the wild with a further two self sustaining translocated populations (Cataract Dam and Sevens Creek). As a consequence they are listed as endangered under the Australian Government *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).
The reasons for the decline of trout cod are not clear, but it appears likely that a combination of factors may have played a role. The pressures that have been suggested include de-snagging, flow modification, barriers to movement, declines in water quality, siltation, invasive species, overexploitation, disease and low genetic diversity (Trout Cod Recovery Team 2008).

**Murray cod (Maccullochella peeli peeli)**
Initial declines in the numbers of Murray cod are almost certainly due to overexploitation (Faragher & Harris 1993; Humphries & Winemiller 2009). Between 1940 and 1951, cod still represented 42 to 65% of the inland fishery; however, the catch continued to decline so that by the time commercial fishing was ceased Murray cod represented only 10% (Rowland 1988 cited in Faragher & Harris 1993). It appears likely that the further declines were caused by declines in recruitment of young fish through to adulthood. Murray cod breed at a fixed time every year (Humphries 2005) but it would appear that the survival of the larval fish is influenced by flow through its effect on either food or physical habitat abundance (Faragher & Harris 1993; Humphries et al. 2008). As an example, the Barmah-Millewa environmental allocation in 2005/2006 resulted in increased spawning activity (golden perch, silver perch), increased abundances of young fish (Murray cod, trout cod and pygmy perch) or changes in the timing of breeding (flathead gudgeon and unspecked hardyhead) (King et al. 2010).

**Macquarie perch (Macquaria australasica)**
Macquarie perch are a moderate sized predatory fish that were formally widespread throughout the southern MDB (Cadwallader 1981; Harris & Rowland 1996), in rivers ranging from small upland streams to larger deeper rivers but they are also known to inhabit reservoirs. Breeding occurs in upland streams where eggs are laid into the water upstream of riffles (Ingram et al. 2000). The species has undergone significant decline and the current distribution is fragmented into small discrete populations. Within the MDB, Macquarie perch are restricted to the upper reaches of a limited number of rivers, including the Mitta Mitta River system above Dartmouth Dam, and the Goulburn, Murrumbidgee and Lachlan River systems (Harris & Rowland 1996; Ingram et al. 1990). It is believed that the decline is due to a combination of factors including flow modification, decreases in water quality, sedimentation, over-exploitation and the impacts of introduced species (Ingram et al. 2000).

**Murray hardyhead (Craterocephalus fluviatilis)**
Hardyheads are small, silvery, omnivorous fish that usually have a long golden, reddish or black stripe running along the body. They can form very large schools and are probably important in the diet of larger fish and waterbirds. They are an annual species that need to breed every year with eggs dependent on aquatic plants (Allen et al. 2002). The Murray hardyhead is most commonly found in slightly to moderately saline waters (Ebner & Raadik 2001).

The Murray hardyhead was formerly widespread and common in the mid to lower Murray-Darling River system. It has suffered a substantial decline in range and abundance, especially in the upstream part of its range. In NSW, there has only been one record in the last 20 years, there are no recent confirmed records from the Murrumbidgee River and none from the Darling River (Backhouse et al. 2008).
Prior to the 2010-2011 floods there were only a few remaining isolated populations known to exist in western Victoria and SA. While the fish can withstand quite high salinities, it is vulnerable to increases in salinity that effect the aquatic plants that it requires to breed and the invertebrates on which it feeds. The effects of the floods on the species are unknown.

Murray hardyhead are listed as vulnerable under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). However, because of their having undergone a greater than 80% reduction in population size and a number of the remaining populations are expected to be lost due to their isolated nature and vulnerability to increasing salinity - they are classified as critically endangered (Backhouse et al. 2008).

In 2008, Victorian populations were limited to four isolated wetlands; two near Mildura (a segregated section of Cardross Basin 1 and Lake Hawthorn) and two near Swan Hill (Round and Woorinen North Lakes). Lake Hawthorn has not received environmental water since 2007 and all fish species including *C. fluviatilis* have now perished due to lake drying. In South Australia, two populations survive near Berri (Berri Evaporation Basin and Disher’s Creek), while one wetland near Murray Bridge (Rocky Gully) and at least one within the Lower Lakes region of the Murray River (Boggy Creek) survived in 2010.

Murray hardyhead appear to have higher salinity tolerances than other similar native fish and this has enabled them to out-compete other species in slightly saline habitats, but they may be incapable of persisting where they do not have this advantage. As a consequence, Murray hardyheads may have declined due to a combination of changes in flow regime which isolated populations and provided no opportunity for dispersal to wetlands after drying and also improvements in irrigation and drainage practices that have reduced the number of saline wetlands (Wedderburn et al. 2008).

The loss of the species from Lake Hawthorn and from most wetlands in the Cardross Lakes system highlights the critical importance of creating and maintaining suitable alternative habitat in selected translocation sites for Murray hardyhead. A captive management and translocation program containing sub-populations of Murray hardyhead from the Cardross Lakes and Lake Hawthorn was established at the MDFRC in 2007. Two additional captive populations of Murray hardyhead from Victorian wetlands (Woorinen North Lake and Round Lake near Swan Hill), as well as four captive populations from South Australian sites (Boggy Creek, Rocky Gully, Berri Evaporation Basin and Disher’s Creek) have since been established at the MDFRC in Mildura.

The first translocation site in Victoria to receive environmental water in order to establish a translocated population of Murray hardyhead was a drainage basin near Mildura. A release of Murray hardyhead took place in November 2009 and subsequent monitoring indicates the species has successfully bred in the new site. A second translocation site near Merbein in Victoria has recently been filled with environmental water and it appears likely to provide suitable habitat for translocated Murray hardyhead.
In May 2010, Murray hardyhead originally salvaged from Hindmarsh Island and maintained at the MDFRC were successfully released into a refuge dam in the Adelaide Hills. Finally, translocation of 140 Murray hardyhead, consisting of fish originally salvaged from sites near Berri in South Australia, were released into an established translocation site near Berri in October 2010.

**Purple spotted gudgeon (Mogurnda adspersa)**
Purple spotted gudgeons are a small attractive fish that ambushes its prey that include invertebrates small fish and tadpoles (Linternans 2007). Purple spotted gudgeons were once widespread in the MDB but have undergone a dramatic decline to the point that they are believed to be extinct in Vic and with only one translocated population in SA. The *Stressed Rivers Survey in NSW* (Harris & Gehrke 1997) failed to record their presence in NSW; however, there are believed to be isolated populations in northern NSW and are locally abundant in the Border Rivers, Moonie River and Condamine-Balonne system in Qld. (Linternans 2007).

The decline in numbers has been ascribed to interactions with introduced species such as gambusia and redfin (Larson & Hoese 1996) or the loss of macrophytes (Harris & Gehrke 1997). Dispersal of male fish is a characteristic of the species and abundance is influenced by current speed and pool size (Boxall et al. 2002), so it is possible that fragmentation and flow modification have also played a role.

**Catfish (Tandanus tandanus)**
This catfish was once widespread and common throughout the Murray-Darling Basin, found generally in the lower, slow-flowing rivers. It is a relatively sedentary species that builds a nest in which to lay its eggs. Most riverine populations have declined significantly since the late 1970s/early 1980s and the species is no longer common in many areas where it was formerly abundant.

**Silver perch (Bidyanus bidyanus)**
Silver perch were once an abundant species in lowland rivers and were commercially harvested. The number of fish moving through the Euston Weir declined by 93% between 1940 and 1990 (Mallen-Cooper and Brand, 1992 cited in Faragher & Harris 1993) which corresponds with declines in the commercial catch over the same period (Reid et al. 1997). The first two rounds of the SRA have recorded only 20 individuals despite having sampled 351 sites across the MDB. The major pressures appear to be flow regulation and fragmentation as silver perch are known to undertake an upstream migration prior to spawning and spawning intensity is heavily influenced by floods (Linternans 2007).
Birds

Sources:


Diversity and distribution
About 10% of the land surface area of the Murray–Darling Basin is covered by the eastern Australian waterbird survey, including some extensive floodplain wetlands. Aerial survey data have been collected each year (1983-2010) on waterbird distribution and abundance. Currently, these data have only been analysed for the entire area of eastern Australia, not just the Murray-Darling Basin (Kingsford & Porter 2009a; Kingsford et al. 1999). These have indicated long-term declines in waterbird numbers (Figure 5). Such impacts have also affected migratory and resident shorebird species where impacts appear to be higher on regulated wetlands in the Murray-Darling Basin (Nebel et al. 2008). This includes regulated lakes (Kingsford et al. 2004) as well as large wetlands such as the Macquarie Marshes (Kingsford & Thomas 1995) and Lowbidgee Wetlands (Kingsford & Thomas 2004). A decrease in the numbers of waterbirds has occurred, coinciding with decreased flooding and extent of wetlands in the Murray-Darling Basin.

The Macquarie Marshes are listed as a wetland of international importance under the Ramsar Convention and the abundance of waterbirds and number of species declined as flows to the area were reduced and the size of the wetland decreased by at least 40–50% (Kingsford & Thomas 1995). Separation of groups of waterbirds into guilds, recorded about an 80% decline in total abundance but also in abundances of guilds on the Lowbidgee Floodplain (Kingsford & Thomas 2004). The Lowbidgee Floodplain was ranked third in all wetlands surveyed over the period of 25 years across eastern Australia, despite its significant degradation. Its ranking has declined further with each year as species richness and abundance on the wetland continue to decline (Kingsford & Thomas 2004). Long-term data from aerial surveys of waterbirds demonstrated that this significantly affected the composition and density of the waterbird community (Kingsford et al. 2004). Combining data from such regulated lakes with unregulated lakes, the aerial surveys showed that a variable flooding regime with natural flooding and drying cycles provided for the full range of waterbirds at high densities. As the waterbird community could be divided into foraging guilds, changes to the waterbird community implied changes to the distribution and abundance of other organisms (e.g. piscivores and fish species) and the ecosystem itself. This extended understanding of the potential impacts of river regulation on the suite of organisms in wetlands with relevance to river management.
Colonial waterbird breeding

Many of Australia’s river systems, particularly in the Murray-Darling Basin (Kingsford 2000b), are impacted by water resource development with diversions of water mainly for irrigated agriculture (NLWRA 2001). This has resulted in a loss or decline in the ecological integrity of many wetland and river systems (CSIRO 2008a), including those used by colonial waterbirds for breeding (Kingsford & Thomas 1995; Driver et al. 2004; Kingsford & Johnson 1998; Kingsford & Thomas 2004; Kingsford et al. 2004; Leslie 2001). The breeding of colonial waterbirds is primarily driven by large scale flooding events which occur on highly variable dryland river systems.

In the Murray-Darling Basin, water resource development has changed the natural flow regimes of many river systems affecting colonial waterbird breeding, reducing the frequency of breeding opportunities, and impacting on reproductive success (Driver et al. 2004; Kingsford & Johnson 1998; Leslie 2001). In species that are nomadic and opportunistic and breed on relatively few wetlands, this may have significant implications for continental waterbird populations.

Impacts from water resource development have been recorded at several key breeding sites in the Murray-Darling Basin. In the Macquarie Marshes, colony sizes, species abundance, species diversity and breeding frequency have all been reduced following reductions in flows (Kingsford & Thomas 1995; Kingsford & Johnson 1998). Similar impacts have also been reported in the Lowbidgee (Kingsford & Thomas 2004) and the Barmah-Millewa Forest (Leslie 2001).

The key wetland sites in Australia for colonial waterbird breeding, based on frequency of use, species diversity and colony sizes were Narran Lakes (16 years with breeding; eight breeding species, five events >10 000 birds), and the Macquarie Marshes (13 years with breeding; eight breeding species, eight events >10 000 birds); many of these have declined with river regulation. Other important sites included Booligal and Second Reedy Lake. All the major sites for breeding waterbirds in the Murray-Darling Basin are threatened by water resource development.
Figure 5. Total waterbird abundance (1983-2010) recorded during annual Eastern Australian Waterbird Surveys.
References


Frogs
There are more than 50 frog species supported in the Murray-Darling Basin, they can be present in all temporary, permanent waterholes and wetlands across the Basin and some species are even present in forests and wetlands of the Great Dividing Range (Scott 2001b; Wassens 2010). All the frog species present in the MDB need standing water for reproduction and tadpole larvae development (Wassens 2010). Some frog populations in the MDB, in line with world-wide trends, have been declining with several species listed nationally as vulnerable or endangered under the Environment Protection and Biodiversity Conservation Act (EPBC Act, 1999; Mahony 1996; see papers in Campbell 1999), Table 8). Anthropogenic impacts that have potentially contributed to frog population declines have been summarised by Tyler (1994) which includes; chemical use in agricultural areas (e.g. aerial spraying), habitat loss by wetland drainage (which can result in a loss of breeding habitats), using temporary ponds as dams for stock use (resulting in the destruction of suitable habitat by cattle) and the introduction of the mosquitofish, Gambusia holbrooki, which can prey on tadpoles and eggs. Furthermore, flow regulation has also been implicated as a cause of decline in some frog species due to most frogs in floodplain areas requiring flooding in spring or summer to initiate breeding cycles (e.g. southern bell frog (Scott 2001b; Wassens 2010)). In addition, a major cause of some frog declines is the amphibian disease Chytrid fungus which is a water-borne pathogen responsible for Chytridiomycosis (an infectious disease which affects amphibians globally). This disease is widespread in frog populations in eastern Australia and is a significant cause of population decline for some frog species (Berger et al. 1998). To further illustrate these frog declines in the MDB, two species will be further discussed that are listed nationally as vulnerable or endangered under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) - the booroolong frog (Litoria booroolongensis) and the southern bell frog (Litoria raniformis) (Table 8).

Booroolong frog
The booroolong frog (Litoria booroolongensis) is listed as endangered under the Environment Protection Biodiversity Conservation Act 1999 and is distributed in NSW and NE Victoria, occurring mainly along western-flowing streams and the headwaters of the Great Dividing Range, from 200 to 1300 m asl (DSE 2001). It has now disappeared from much of the Northern Tablelands and is considered to be rare throughout its range (DSE 2001; NSW Scientific Committee 2005). An estimate of the total number of adults present in the species entire range is 5001 to 10 000 individuals and the size of the geographic area over which the taxon is distributed: 80 001 to 1 000 000 km² (up to 12% of the area of Australia) and the area occupied by this species has declined by 25 to 74% (Frog Australia Network 2005). In the 1980s, this species was considered to be abundant in northern NSW, whereas in the last 15 years, there have been very few records of this species (Gillespie & Hines 1999; Heatwole et al. 1995). There are several key threats which may have contributed to the decline of this species such as grazing by cattle, timber harvesting and land clearance (these can either destroy/degrade suitable habitat), which have occurred within the vicinity of streams of the booroolong frog range (DSE 2001).
Furthermore, weed invasion has been prevalent including willows in SE Australia which can modify riparian habitat and potentially make it unsuitable for frog habitat (Hunter & Gillespie 1999). Flow regimes (irrigation, hydro-electric power generation) have also been altered along with impoundments on streams in the range of the booroolong frog which may lead to the decline of this species via the inundation of suitable habitat and the changing of flow conditions downstream (Bevitt et al. 1998). The booroolong frog’s eggs, tadpoles and adult stages may also suffer from predation from introduced fish (e.g. mosquito fish Gambusia holbrooki, european carp Cyprinus carpio etc) and foxes and cats in its range (DSE 2001; Gillespie & Hero 1999).

Climate change may also be another potential reason for the decline of the booroolong frog. Since from the early 1980s, when severe droughts occurred in south eastern Australia, very few booroolong frog have been reported (DSE 2001). The increased use of herbicides, which can be toxic to frogs and tadpoles, over the last 20 years may also be a contributing factor for the decline of the booroolong frog (DSE 2001; Tyler 1989). In addition, the chytrid fungus may also be affecting booroolong frog populations; however, in the wild the fungus has never been discovered on this species but has been found in populations of other frog species that share the same range (DSE 2001).

**Southern bell frog**
The southern bell frog (*Litoria raniformis*) is listed as vulnerable under the *Environment Protection and Biodiversity Conservation Act 1999* and is a wetland specialist. Southern bell frogs were historically common along the Murray and Murrumbidgee Rivers, their tributaries and other areas of south-eastern Australia (Pyke 2002; Wassens 2010). Currently, it has declined in abundance and distribution throughout much of its range which has resulted in fragmented distributions ((Clemann & Gillespie 2010; Wassens 2010), Table 8). An estimate of the total number of adults present in the species entire range is >50 000 individuals, the size of the geographic area over which the taxon is distributed is >1 000 000 km² and the area occupied by this species has declined by 25 to 74% (Frog Australia Network 2005). There are two biogeographically distinct groups which differ in terms of their ecology and biology. For the populations in NSW, Vic and SA which line the Murray River, breeding and movement is found to be initiated by flooding events of ephemeral wetlands, swamps and billabongs during spring or summer (Wassens 2010; Wassens et al. 2008). The second population distributed in south-eastern NSW, including areas of Vic and south-eastern SA and Tas, is found to breed in summer and spring and is not as reliant on flooding events (White & Pyke 1999).

Key threats which have implicated in the decline of the southern bell frog include loss and fragmentation of habitat through draining of wetlands and drought, predation on eggs and tadpoles by introduced fish species, infection by pathogens (particularly Chytrid fungus) and degradation of habitat from pollution, salinisation and chemical use (Clemann & Gillespie 2010).

<table>
<thead>
<tr>
<th>Scientific name</th>
<th>Common name</th>
<th>Conservation status</th>
<th>Population*</th>
<th>Range size estimate*</th>
<th>Distribution trend estimate*+</th>
<th>Distribution in Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Litoria booroolongensis</em></td>
<td>Booroolong frog</td>
<td>Endangered</td>
<td>5001-10,000</td>
<td>80,001-1,000,000 km²</td>
<td>declined by 25-74%</td>
<td>NSW, Vic</td>
</tr>
<tr>
<td><em>Litoria castanea</em></td>
<td>Yellow spotted tree frog</td>
<td>Endangered</td>
<td>0-1000</td>
<td>1001-80,000 km²</td>
<td>declined by 75-100%</td>
<td>NSW</td>
</tr>
<tr>
<td><em>Litoria spenceri</em></td>
<td>Spotted frog</td>
<td>Endangered</td>
<td>1000-5000</td>
<td>1001-80,000 km²</td>
<td>declined by 25-74%</td>
<td>NSW, Vic</td>
</tr>
<tr>
<td><em>Mixophyes fleayi</em></td>
<td>Fleay's frog</td>
<td>Endangered</td>
<td>5001-10,000</td>
<td>101-1000 km²</td>
<td>declined by &lt; 25%</td>
<td>Qld</td>
</tr>
<tr>
<td><em>Mixophyes iterates</em></td>
<td>Southern barred frog</td>
<td>Endangered</td>
<td>5001-10,000</td>
<td>1001-80,000 km²</td>
<td>decline, if any, unknown</td>
<td>Qld</td>
</tr>
<tr>
<td><em>Pseudophryne corroboree</em></td>
<td>Southern corroboree frog</td>
<td>Endangered</td>
<td>0-1000</td>
<td>&lt; 100 km²</td>
<td>declined by 75-100%</td>
<td>NSW (alpine)</td>
</tr>
<tr>
<td><em>Heleioporus australiacus</em></td>
<td>Giant burrowing frog</td>
<td>Vulnerable</td>
<td>10,001-50,000</td>
<td>1,01-80,000 km²</td>
<td>decline, if any, unknown</td>
<td>NSW, Vic</td>
</tr>
<tr>
<td><em>Litoria aurea</em></td>
<td>Green and golden bell frog</td>
<td>Vulnerable</td>
<td>10,001-50,000</td>
<td>80,001-1,000,000 km²</td>
<td>declined by 75-100%</td>
<td>NSW, Vic</td>
</tr>
<tr>
<td><em>Litoria littlejohni</em></td>
<td>Littlejohn's tree frog, Heath frog</td>
<td>Vulnerable</td>
<td>10,001-50,000</td>
<td></td>
<td></td>
<td>NSW, Vic</td>
</tr>
<tr>
<td><em>Litoria raniformis</em></td>
<td>Southern bell frog, Growling grass frog</td>
<td>Vulnerable</td>
<td>&gt;50,000</td>
<td>&gt; 1,000,000 km²</td>
<td>declined by 25-74%</td>
<td>NSW, Vic, SA</td>
</tr>
<tr>
<td><em>Litoria verreauxii alpina</em></td>
<td>Alpine tree frog, Verreaux's alpine tree frog</td>
<td>Vulnerable</td>
<td>1000-5000</td>
<td>3500 km²</td>
<td>declined by 75-100%</td>
<td>NSW, Vic (alpine)</td>
</tr>
<tr>
<td><em>Mixophyes balbus</em></td>
<td>Stuttering frog</td>
<td>Vulnerable</td>
<td>5001-10,000</td>
<td>110,000 km²</td>
<td>25-74%</td>
<td>NSW, Vic (?)</td>
</tr>
<tr>
<td><em>Pseudophryne pengilleyi</em></td>
<td>Northern corroboree frog; Northern brood frog</td>
<td>Vulnerable</td>
<td>1000-5000</td>
<td>101-1000 km²</td>
<td>declined by 25-74%</td>
<td>NSW (alpine)</td>
</tr>
</tbody>
</table>

* (Frog Australia Network 2005) + This is an estimate of change in the portion of the total range that is occupied or utilised; it may not equal the change in total range.

**Reptiles in the Murray-Darling Basin**

Reptiles are found throughout the MDB with some relying explicitly on the waterways such as tortoises, while others such as snakes and lizards do not depend solely on aquatic environments, but can use these habitats for foraging, sheltering sites and to exploit the rich food sources of these riverine-floodplain habitats (Michael & Lindenmayer 2010; Scott 2001b). The Murray Catchment supports 80 species of reptiles from nine families and one-quarter have an extremely restricted distribution (in one or two locations) (Michael & Lindenmayer 2010). In the Darling Basin, there is a total of 126 lizards and 52 species of snakes (Ayers et al. 2004). Despite no reptile species being known to have become extinct since European settlement, there has been evidence of decline in reptiles in the MDB (Ayers et al. 2004; Michael & Lindenmayer 2010; Table 9). Some species of reptiles that are vulnerable are endemic to the Basin such as the five-clawed worm-skink (*Anomalopus mackayi*).
Reptiles have declined in the MDB due to factors such as loss of habitat, altered fire regimes, livestock overgrazing, large scale crop cultivation, chemical pesticides, weed invasion and predation by introduced predators (e.g. red fox and feral cats) (for a comprehensive review see (Ayers et al. 2004; Michael & Lindenmayer 2010)). In addition, flow regimes in the Murray-Darling Basin have been altered by changes in timing, duration and magnitude of floods (Walker 1985). The effects of these widespread system changes on reptiles of riverine-floodplain habitats are not well understood (Sadlier & Pressey 1994). To further illustrate these reptile declines in response to the condition of the MDB, two species will be further discussed that are listed nationally as vulnerable under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act), the five-clawed worm-skink (Anomalopus mackayi) and the Bell’s turtle (Elseya belli) (Table 9).

**Five-clawed worm-skink**
The five-clawed worm-skink (Anomalopus mackayi) is listed as vulnerable under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). The five-clawed worm-skink is distributed along the western slopes of the Great Dividing Range ranging from south-eastern Queensland to north-eastern NSW (Sadlier et al. 1996; Swan 1990; Wilson & Knowles 1988), Table 9). This species has a restricted distribution which appears to have declined in NSW with evidence from museum records (Cogger et al. 1993; Sadlier & Pressey 1994). This species was only known in NSW from eight specimens, the most recent collected approximately 15-30 years ago (Sadlier & Pressey 1994). This species is vulnerable as it has a restricted distribution and specialised habitat requirements, as it requires loose soil or existing soil hollows for burrowing to escape detection and potentially to move (Sadlier & Pressey 1994). Key threats to the five-clawed worm-skink summarised previously by (Cogger et al. 1993), (Sadlier & Pressey 1994) and (Ayers et al. 1996) include habitat loss through clearance of land and conversion to agriculture (wheat and cotton are grown extensively within the range of this species); habitat degradation from grazing of cattle (which compact the soil and causes erosion which affects the burrowing of this species), removal of habitat and sheltering sites (e.g. fallen logs, ground litter etc.), predation by introduced species (e.g. foxes and cats) and usage of chemicals (e.g. spraying of herbicides).

**Bell’s turtle**
The Bell’s turtle (Elseya belli) is listed as vulnerable under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). This species is restricted to the upper headwaters of the Namoi, Gwydir and MacDonald Rivers in NSW ((DERM 2010; NSW Scientific Committee 1997), Table 9). In NSW, it has been found at only a handful of sites, though where it does occur it is abundant (NSW Scientific Committee 1997). There is also a separate population in south-east Queensland. This species inhabits narrow sections of rivers and prefers to inhabit pools less than 3m deep with rocky or sandy substrate and vegetation (NSW DEC 2005). Key threats to Bell’s turtle include pollution and sedimentation of river habitat, changes to the natural flow regime, predation on eggs by introduced predators (e.g. foxes), habitat degradation via trampling by stock, or modification of riparian habitat by weeds (e.g. willows). In addition, disease (which causes blindness in Bell’s turtle) can contribute to the decline in the population (NSW DEC 2005). Climate change and drought conditions may also impact on Bell’s turtle populations (Threatened Species Scientific Committee 2008).

<table>
<thead>
<tr>
<th>Scientific name</th>
<th>Common name(s)</th>
<th>Conservation status</th>
<th>Population size</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Cyclodomorphus praetaltus</em></td>
<td>Alpine she-oak skink</td>
<td>Endangered</td>
<td>Insufficient data</td>
<td>NSW/Vic (alpine)</td>
</tr>
<tr>
<td><em>Tymanocryptis pinguicolla</em></td>
<td>Grassland earless dragon</td>
<td>Endangered</td>
<td>Three isolated populations</td>
<td>NSW/Vic/Qld</td>
</tr>
<tr>
<td><em>Anomalopus mackayi</em></td>
<td>Five-clawed worm-skink, Long-legged worm-skink</td>
<td>Vulnerable</td>
<td>Restricted and possibly declined</td>
<td>NSW/Qld</td>
</tr>
<tr>
<td><em>Aprasia parapulchella</em></td>
<td>Pink-tailed worm-lizard</td>
<td>Vulnerable</td>
<td>Restricted, four known locations</td>
<td>NSW/Vic</td>
</tr>
<tr>
<td><em>Delma impar</em></td>
<td>Striped legless lizard</td>
<td>Vulnerable</td>
<td>&gt;1000 individuals?</td>
<td>SA/NSW/Vic</td>
</tr>
<tr>
<td><em>Delma torquata</em></td>
<td>Collared delma</td>
<td>Vulnerable</td>
<td>Four known locations</td>
<td>Qld</td>
</tr>
<tr>
<td><em>Egernia rugosa</em></td>
<td>Yakka skink</td>
<td>Vulnerable</td>
<td>Restricted, Namoi and Gwydir headwaters</td>
<td>Qld/Qld</td>
</tr>
<tr>
<td><em>Elseya belli</em></td>
<td>Bell's turtle, Namoi River turtle, Bell's saw-shelled turtle</td>
<td>Vulnerable</td>
<td>Restricted, Namoi and Gwydir headwaters</td>
<td>Qld/Qld</td>
</tr>
<tr>
<td><em>Furina dunmalli</em></td>
<td>Dunmall's snake</td>
<td>Vulnerable</td>
<td>Restricted</td>
<td>Qld/QNSW</td>
</tr>
<tr>
<td><em>Paradelma orientalis</em></td>
<td>Brigalow scaly-foot</td>
<td>Vulnerable</td>
<td>Restricted</td>
<td>Qld</td>
</tr>
<tr>
<td><em>Underwoodisaurus sphyurus</em></td>
<td>Border thick-tailed gecko</td>
<td>Vulnerable</td>
<td>Restricted</td>
<td>NSW/Qld</td>
</tr>
<tr>
<td><em>Hoplocephalus bungaroides</em></td>
<td>Broad-headed snake</td>
<td>Vulnerable</td>
<td>Restricted</td>
<td>NSW</td>
</tr>
</tbody>
</table>

Implications

The WDEs of the MDB are a complex system comprised of a mosaic of interconnected components, including river channels, floodplain wetlands, floodplains, estuaries and groundwater aquifers linked together through the exchange of sediment, nutrients, energy and organisms. In order to achieve the objectives of the *Water Act 2007* (Australia 2007) the MDBA is required to manage WDEs to protect biodiversity (as required by international agreements) and protect, restore and provide for the ecological values and ecosystem services of the Murray-Darling Basin. This section will apply both our current knowledge of WDEs and their condition to describe some of the implications for achievement of the *Water Act*‘s objectives.
Under natural conditions, WDEs sustain biodiversity and provide a range of ecosystem services through a diversity of environmental and climatic conditions. As WDEs are modified, biodiversity is reduced and the delivery of services, on which MDB communities are reliant, changes. Due to the nature of complex systems, the changes are unlikely to be a gradual change in average conditions, rather the system is more likely to either;

- Cross thresholds that will lead to step changes in the condition of the system and/or delivery of services, or;
- Exhibit less stability as resilience declines resulting in greater variation in the condition of the system and delivery of services which may result in increases in the magnitude or severity of extreme events.

As noted earlier, our capacity to predict the behavior of WDEs is, and may always be, relatively limited; however, it is possible to make some general predictions based on the following characteristics of WDEs in the MDB.

- The MDB’s WDEs are naturally characterised by a high degree of disturbance (e.g. flood, drought, fire).
- Natural disturbances and anthropogenic pressures tend to interact to increase pressure on the system or decrease resilience.
- River floodplain ecosystems are a network of interconnected or interdependent components (e.g. habitats or assets).
- There can be significant delays between the implementation of a change and the system achieving a new state.
- There are likely to be feedback mechanisms that may reinforce and amplify change.
- Extinctions are often driven by synergistic, feedback processes or stochastic events that either occur or have a greater impact due to the state of the system.

The following paragraphs will explore the implications of these characteristics given the current condition of WDEs in the MDB.

Water dependent ecosystems are characterised by their disturbance regime. This has benefits for management as it means that WDE are highly resilient and will often respond well to rehabilitation. There are however, a number of downsides to this characteristic. The first is that disturbances tend to make WDE more vulnerable to invasion. It appears likely that the MDB will continue to experience further invasions that will have a detrimental effect on the natural biota. It is likely that our modification of the system, through the creation of novel habitats and reducing the capacity of native competitors and predators to interact with the invader will promote the success of invading species. Further, it is likely that the effects of the invading species will interact with other modifications of the system to further degrade the values of the system.
A second issue associated with disturbance is that major disturbances are rare and unpredictable, but can cast a long shadow. In a modified system, the response of the system to these rare events may be quite different to the response that would have occurred under natural conditions. This may be due to the remaining species being more susceptible to the disturbance due to either reduced resistance (e.g. red gums that are already stressed) or resilience (e.g. small bird populations dominated by old individuals). Alternatively, the disturbance may produce novel stresses or combinations of stresses on the system. An example of this would be the early floods that interacted with cleared catchments that resulted in the deposition of large amounts of sand in small low gradient streams that continue to affect the streams.

A final implication of the disturbance issue is that bad things tend to happen to all components of the system at some stage, it is just a matter of when. Under natural conditions, resilience was underpinned by maintenance of a large number of populations in interconnected habitats so that recovery of a population was achieved by dispersal of organisms from nearby populations. Given the dramatically reduced and fragmented distribution of some species and the fragmentation of the landscape, recovery of some populations is likely to be problematic. As a consequence, ongoing declines of species are almost inevitable as populations are extirpated, unless there is dramatic and costly intervention.

Delivery of ecosystem services relies on the organisms, biotic communities and ecosystem components that trap sediment and sequester, and process nutrients and carbon through the food web. Sustaining the delivery of ecosystem services requires that the organisms, communities and components are able to sustain themselves and fulfill their role. A decline in the condition of the biotic community in one part of the system will affect the way in which material is processed in that area and that will mean that the material exported from that area will be different. In some instances this may not matter or may provide some benefit to other connected components of the system. There will of course be times when it will have significant detrimental effects. We have already witnessed some spectacular examples with the clearing of vegetation leading to increases in sediment supply and it might be hoped that the lesson has been learnt.

There is however, a more subtle problem that emerges from this characteristic and that is that the integrity of iconic assets is reliant on the condition of the system in which they are imbedded. There are two reasons for this; first, the disturbed nature of MDB WDE means that sooner or later other sites will be needed to provide colonists. Second, if the rest of the system is degraded and this means that the flux of material into the icon is different in some way, then this may lead to a change in the character of the icon system. The most obvious example is water, but the movement of sediment, salt, nutrients, seeds or animals from a degraded system may all lead to significant character alterations. The implication of this is that attempts to manage assets as isolated landscape fragments have very little chance of success in the long-term.
The effects of water resource development on WDE in the MDB are still emerging. For example, river channels are still changing shape. A further example is the decline in the condition of trees. The full effects of water resource development did not become apparent until the effects of water resource development interacted with the millennium drought. This is only one example of this type of interaction. The interaction between sand slugs and resilience to drying events and the acidification of wetlands (salinity interacting with flow change) are others. This type of interaction appears obvious in hindsight; however, we cannot be sure that as the system continues to adjust to modifications that further interactions won’t manifest. In a healthy system, these interactions may not represent a major issue; however, the evidence suggests that the system’s capacity to respond to stress is diminished and the threat increases.

The other area where interactions become important is the issue of feedback loops. The idea is well established in freshwater ecology where some lakes are known to have two alternative stable states; one characterised by macrophyte dominance and clear water, the other by floating algae and poor water quality. Both states are stable because the biota modify the environment to facilitate their persistence. This type of behavior is a common feature of complex systems. It is possible that the degradation of WDE will initiate a feedback that will promote further degradation. One possible example is that flow change leads to a loss of trees, leading to a decline in soil condition which then reduces the capacity of trees to become established (Colloff & Baldwin 2010). A further possible example is that flow changes lead to a decline in water quality during floods that affect vegetation communities which reduces the community’s capacity to capture sediment, thereby further reducing water quality. It is possible to think of a number of scenarios, none of which are particularly helpful, except to make the point that this type of system behavior is predicted by an understanding of complex systems and ought to be considered in any evaluation of risk.

So, what is an appropriate response given the degraded nature of WDE in the MDB and some fairly vague predictions about future risks? There is, of course, a spectrum of choices confronting managers. At one extreme is the continuation of current management practices which run the risk that as the effects of our management decisions mature, synergies among stresses will emerge or stochastic events (e.g. fire and drought) will cause additional degradation, further undermining the integrity of the system and increasing the likelihood of ongoing decline.

Given our understanding of how WDE function, the likely outcome from this option is that, over the long-term, protection of key environmental assets will become increasingly difficult as the influences of the system in which they are imbedded, and on which they depend, becomes increasingly degraded. As the system and its component assets become degraded so the system will struggle to deliver ecosystem services. The deterioration is unlikely to manifest as a gradual change but is more likely to be an increase in the magnitude or frequency of adverse events such as high salinity, turbidity (e.g. Ovens River: (Lyon & O’Connor 2008)), blackwater events or a precipitous change of character as some environmental threshold is exceeded.
The alternate option is to intervene to attempt to protect and restore the system. There are inevitable arguments about the identity of the major stress on the system and the way the system may be restored. This paper illustrates that MDB WDE have been subjected to a variety of interacting stressors, so there will be questions about both whether flow is the major stress and whether there is any point addressing flow when some of the other degrading stressors remain.

Arguing about which stress is the most important represents a failure to understand the nature of WDE. If a person was asked to nominate which vital organ - heart, lungs or brain, they would like to do without, they would have trouble answering. Similarly, thinking about flow in isolation of the other drivers of WDE condition is similarly futile. What can be said with a great deal of certainty is that without addressing flow issues, any other attempt to protect and restore the environmental, social and economic values of MDB WDE will be futile.

Addressing the issue of flow restoration makes sense from a management perspective because;

- Flow has been identified as a key habitat characteristic for many biota and it is likely that we do not yet know all the ways in which flow influences the persistence of species.
- Flow is a critical connection among components, facilitating the exchange of sediment, nutrients, organic material and organisms.
- Flow restoration will provide the system with an opportunity that has existed in the system’s evolutionary history and that the system will be able to respond to. Addressing other drivers of system change without addressing flow are likely to both end in failure and be incredibly expensive, while restoring flow provides the opportunity to harness the system’s natural resilience to sustain the values articulated in the Water Act.

Advocating flow restoration does not imply that other forms of rehabilitation will not be necessary. The broad scale of the degradation and the presence of introduced species will present challenges but these provide an opportunity for landholders and communities to collaborate in the achievement of a shared vision for the future.
References


Cook R (1999). The effect of shading on biofilm biomass, macroinvertebrate density and macroinvertebrate community structure in the Murray and Darling Rivers at Wentworth Unpublished Honours, La Trobe University, Albury-Wodonga


Geddes MC (1987) Changes In Salinity And In The Distribution Of Macrophytes Macrobenthos And Fish In The Coorong Lagoons South Australia Following A Period Of River Murray Flow. Transactions of the Royal Society of South Australia, 111(3-4): 173-182


Harrington B, and Hale J (in prep) Ecological Character Description for NSW Central Murray Ramsar Site. *A Report to SEWPaC*


Kingsford RT (2000b) Protecting rivers in arid regions or pumping them dry? *Hydrobiologia* Vol.427p1-11 including figures and maps


Lake JS (1971) Freshwater fishes and rivers of Australia. Melbourne: Thomas Nelson & Sons Ltd.


Reid DD, Harris JH, and Chapman DJ (1997) NSW inland commercial fishery data analysis. FRDC project no. 94/027. NSW Fisheries and Cooperative Research Centre for Freshwater Ecology, Cronulla.


Attachment A. Chronology of significant steps in addressing environmental degradation


1975 – River Murray Working Party report to Ministerial Steering Committee, which proposed changes to the River Murray Waters Agreement to take account of water quality.

1979 - Report to River Murray Commission Murray Valley Salinity and Drainage, which developed and costed a plan for coordinated action to address salinisation.

1982 – Amendment of River Murray Waters Agreement to take account of water quality.

1985 – Meeting of 12 Ministers representing water, land and environment in the Commonwealth, NSW, Vic and SA in Adelaide in response to the need for coordinated action to address the Basin’s problems, establishing the MDB Ministerial Council.

1986 – The former Australian Water Research Advisory Council establishes the MDFRC, together with contributing partners.

1987 – Report to Council MDB Environmental Resources Study, which documents key resource and management issues leading to Council agreeing to the preparation of an overarching framework for coordinating action.

1987 – Council decision to amend River Murray Waters Agreement to establish the Murray-Darling Basin Commission.

1987 – Council releases the draft Salinity and Drainage Strategy and background papers for public consultation, proposing saline drainage returns offset by investment in interception schemes.

1988 – Council adopts the Salinity and Drainage Strategy and makes formal agreements between the States for its implementation.

1989 – Report to Council Background Papers of the Natural Resources Management Strategy, which described the joint action required for the Basin’s resources to complement regional community action.

1990 – Release of Council’s Natural Resources Management Strategy, which set the framework for coordinated action and provided funding to on-ground works and to knowledge based activities such as research, investigations, monitoring and education.

1990 – SA Minister’s presentation to Council on Nutrient Management in the MDB, leading to the adoption of a MDB Water Quality Policy to maintain and improve existing quality.


1992 - SA Minister’s presentation to Council on an Environment Policy for the MDB. Council agrees to the development of an environmental policy and notes the preparation of a Nutrient Management Strategy is underway by the Commission.


1993 – SA Minister’s presentation to Council on the need to cease further regulations and diversions that exacerbate deteriorating flow regimes.

1993 – Council noted the Barmah-Millewa Forest Water Management Plan and agreed to allocate 100 GL to meet the water needs of the forest ecosystem.

1993 – Council agreed to the release of the draft Algal Management Strategy and adopts the Environment Policy.

1994 – Council released the Irrigation Management Strategy to achieve an economically and environmentally sustainable irrigation industry.


1994 – Council agreed to a Regional Economic Development Policy to ensure the incorporation of economic development goals in MDB programs.

1995 – Council considered an audit of water use in the Basin and agreed to place an immediate moratorium on further increases in diversions.

1996 – Council agreed to a pilot project for interstate trading of property rights and to extend the moratorium on diversions.

1997 – Council endorsed the preparation of an Interim Flow Management Plan for the River Murray to ensure an appropriate level of environmental quality of the river and its floodplain while meeting the needs of other users. Scientific Panels assess river operation options to improve river environment.

1998 – Council released the Floodplain Wetlands Management Strategy for the Murray-Darling Basin, to guide and coordinate actions and research to improve their condition.

1999 – Release of Council’s report The Salinity Audit of the MDB: a 100 year perspective, which documented Basin-wide the extent and trend of salinisation and announced the development of a Basin Salinity Management Strategy.

2000 – Council noted the apparent decline in migratory bird numbers in the vicinity of the Coorong.

2000 - Council agreed the release of the draft Basin Salinity Management Strategy for public comment and agreed cost sharing arrangements for the salt interception schemes.
2000 – Council agreed the proposal for a Sustainable Rivers Audit using the CRCFE scope as a guide.

2000 – Within the Review of the Operation of the Cap, Council received a report on the Ecological Sustainability of Rivers (by the CRCFE) confirming the need for continuing restriction of diversions.

2001 – Council adopted the Basin Salinity Management Strategy and agreed the program of joint works for salt interception.

2001 – Council adopted the vision and objectives of phase 1 of the Environmental Flows and Water Quality Objectives project and approved immediate implementation of the Sea to Hume fishway program, the investigation of thermal mitigation options at Hume Dam, operating rules for the Barmah-Millewa Forest EWA and a review of the operating procedures of the Commission’s weirs and barrages to improve the effectiveness of watering ecosystems.

2001 – Council Chair requested an interim snapshot assessment of river health to aid Council decisions on the allocation and management of environmental flows. The resultant Snapshot of the Murray-Darling Basin River Condition (by CRCFE and CSIRO, using NLWRA’s Assessment of River Condition), together with advice from the ISRAG, reveals that the current state of ecological health is less than what is required for ecological sustainability.

2002 – Council endorsed the release of the draft Native Fish Strategy, aiming to restore fish populations to 60% or pre-European condition over next 50 years.

2003 – Council received a presentation from the Chair of the Living Murray Scientific Reference Panel on the science and modeling underpinning the options for water recovery and approved the release of the final Native Fish Strategy.

2003 – Council agreed the First Step Decision for the Living Murray, identifying six icon sites, 500 GL water recovery under the $500M COAG investment and the establishment of an environmental water account. Council also agreed, in the light of a pilot, to implement the Sustainable Rivers Audit.
Attachment B. Additional references on the condition of WDE in the MDB sourced from Richard Kingsford’s WISE database


Adamson CM (1975) A simple method for determining rainfall intensities for the riverina and southern soil conservation districts.


Affairs NSWDoU, and Planning. (1999). Kosciusko Regional Environmental Plan 1988 - (Snowy River) (pp. 27 pages).


Anderson J (1992) Hydrogeological Assessment of the Dryland Salinisation of the Snake Creek Catchment Mumbil, NSW.


anon. Yass Valley Soil Conservation Project.

anon. (1927). Yanco irrigation area, embracing Leeton and Yanco (pp. npr).


anon. (1982). Discover the Lachlan Area: the Newell, more than just a highway (pp. 32 pages).


Apps E (2003) Archaeological survey of proposed subdivision on Lot 2 Mirrong Street Cooma NSW.

Apps E (2003) Archaeological survey of proposed subdivision on Lot 2, Alira Lane, Cooma NSW.


Assembly NSWL (1906) Barren Jack storage reservoir and northern Murrumbidgee Irrigation Scheme.


Australia RBo (1968) Lachlan Region of New South Wales: rural valuation information.


Authority BR-GCM. Biodiversity: icon threatened species (pp. 2 pages).

Authority M-DB. Flora and fauna of the Murray-Darling Basin (pp. 1).

Authority M-DB. Stickers of flora/ fauna of Murray-Darling Basin (pp. 3).

Authority M-DB. The Living Murray planned works (pp. 4).

Authority SMH-E (1953) The Snowy Mountains Scheme: water and power for the development of Australia.

Authority SM. (1964) Irrigation in the Murrumbidgee Valley (pp. 9 pages).

Authority SMH-E (1964) Soil conservation on the Snowy Mountains Scheme.


Authority SMH-e (1972) Sediment records of the Snowy Mountains Region, Australia (No. ISBN 0642951594).

Authority SM. (1973) History of the Snowy Mountains Scheme and notes on electricity generation and irrigation aspects (pp. 19 pages).


Authority NSWEP. (1994) Preliminary Regional Environment Improvement Plan: Southern Tablelands (pp. 73 pages).


Authority NSWEP. (1997) Proposed interim environmental objectives for NSW waters: Lachlan Catchment (pp. 20 pages).


Authority NSWEP. (1999) Water quality and river flow interim environmental objectives: Gwydir River Catchment (pp. 40 pages).


Authority NSWEP. (1999) Water quality and river flow interim environmental objectives guidelines for river, groundwater and water management committees Barwon-Darling and Far Western catchments (pp. 40 pages).


Authority NSWEP (2002) Monbeef Pty Limited, Monbeef meat processing plant, Carlaminda Road, Cooma NSW - final compliance audit report.


Authority BR-GCM. (2008). Regent Honeyeater: icon threatened species (pp. 2 pages).


Authority BR-GCM. (2008). Brolga: icon threatened species (pp. 2 pages).

Authority BR-GCM. (2008). Salinity: balancing your water use efficiently (pp. 4 pages).

Authority BR-GCM. (2008). Our Catchment: making a difference (pp. 4 pages).


Authority M-DB. (2008). Murray-Darling Basin Authority - transition water for the future (pp. 2).

Authority MCM. (2009). The Living Murray planned works in the Koondrook-Perricoota Forest (pp. 2).

Authority M-DB. (2009). Native fish of the Murray-Darling Basin (pp. 1).

Authority M-DB. (2009). Frogs of the Murray-Darling Basin (pp. 1).


Authority M-DB. (2009) Fact sheet 2: the Barmah Choke study - investigations phase (pp. 2).

Authority M-DB. (2009) Fact sheet: the Living Murray program (pp. 2).


Authority MDB. (2009) Basin plan fact sheet 3: Sustainable Diversion Limits (SDLs) and the impacts of environmental water purchases (pp. 4).


Authority MDB (2009) Fact Sheet: the Basin Plan Concept Statement introducing the key elements and approach being taken to develop the Basin Plan (No. ISBN N/A).

Authority MDB. (2009) Fact sheet: the basin plan concept statement. Introducing the key elements and approach being taken to develop the basin plan (pp. 2).


Authority MDB. (2009) Fact sheet 4: Basin Community Committee introducing the members of the Murray-Darling Basin - Authority Basin Community Committee (pp. 4).


Authority M-DB. (2010) The Living Murray planned works in the Gunbower Forest (pp. 4).

Authority M-DB. (2010) The Living Murray planned works on Mulcra Island (pp. 4).


Baker-Gabb D. (1993). Managing native grassland to maintain biodiversity and conserve the plains-wanderer (pp. 8 pages).


Barrett J. (2009). Native fish strategy highlights - the first five years.


Basinski JJ (1960) Water resources of the Young Valley and their present and potential use.


Bayley WA (1965) Down the Lachlan Years Ago: History of Condobolin New South Wales.


Beale JG. (1970). Address on the Proposal for a Dam on the Cudgegong River near Windamere (pp. 18 pages + maps).


Bennett KH (1891) Notes on the disappearance - total or partial - of a certain species of birds in the Lower Lachlan District. *Australian Museum Record Vol.1*p107-109


Benning NJ (1979) Evans Plains Creek Catchment Area.


Bish S (2002) Groundwater management areas within NSW.


Board CWM. (2003). Central West Catchment Blueprint (pp. 50 pages).

Board MCM. (2003). Integrated catchment management plan for the Murrumbidgee Catchment 2003, also known as the Murrumbidgee Catchment blueprint (pp. 78 pages).


Bowen PF, and Pressey RL (1993) Localities and Habitats of Plants with Restricted Distributions in the Western Division of New South Wales.


Bowmer K. (2000). *Research needs for the management of the Murrumbidgee River: we need information for your river management plan!*


Bradd JM, and Gates GWB (1993) Dryland salinity in the Williams Creek catchment - a hydrological perspective.


Bradd J, and Gates G. (1995). *The progression from site investigation to GIS analysis to map dryland salinity hazards in NSW.*


Brayshaw H (1985) Archaeological survey of a quarry site 10km north east of Yass, NSW.


Bridle J (1979) My mountain country, Talbingo.


Briggs SS, J., and Doyle S (2002) Surveys of Vegetation and Birds in the Warrengong Catchment, NSW.


Butler BE (1952) A theory of prior streams as a causal factor of soil occurrence in the Riverine Plain of south-eastern Australia. *Australian Jour Agric Res,* 1((3)): 231-252


Cadwallader PL (1986) Fish of the Murray-Darling system.


Chessman BC (1999) Predicting the macroinvertebrate faunas of rivers by multiple regression of biological and environmental differences. *Freshwater Biology Vol.41p747-757*


Churton I (1981). Plant species-area relationships and the planning of nature reserves on the Southern Tablelands of N.S.W.


Commission M-DB. Discovering the Murray-Darling Basin.

Commission M-DB. Ladders for fish.

Commission M-DB. Fish for the future.

Commission M-DB. Artesian water.

Commission M-DB. Floods.

Commission M-DB. Wetlands.
Commission M-DB. Introduction - gold.

Commission M-DB. Wetlands - wonderlands not wastelands.

Commission M-DB. River Red Gums.

Commission NSWWR Guidelines for floodplain development Gwydir River - Moree area (Carole Creek to Brageen Crossing).

Commission NSWWR Water resources inventory.


Commission NSWWR Waters of change: irrigation in the Murrumbidgee Valley.


Commission NSWWR Murrumbidgee River Investigation.


Commission NCD (1975) Water resources strategy planning for the Upper Murrumbidgee Basin.


Commission NSWWR (1977) Burrinjuck Dam flood mitigation investigation.


Commission NCD (1984) The ecological resources of the ACT.


Committee N-WCM. Draft strategy plan: North West Catchment Management Committee (pp. 34 pages).

Committee NWCM. Draft catchment management strategy (pp. 34 pages).

Committee JP (1957) Regional research and extension study, Southern Tablelands, N.S.W.: Report no. 1: Outline of the project.


Committee JP (1958) Regional research and extension study, Southern Tablelands, N.S.W.: Report no. 4: Climate of the Yass River Valley.


Committee MotJP (1958) The water resources of the Yass River Valley.

Committee LRD (1972) Lachlan Region, N.S.W: a record of action taken by the Lachlan Regional Development Committee towards implementation of recommendations of the Datex report.

Committee UoNEWRMR. (1981). Water for the Future (pp. p5-8 + figures + pictures).


Committee N-WCM (1992) Our plan for the regions natural resources.


Committee MCM (1994) Natural resource management strategy for the Murrumbidgee catchment.


Committee CWCM. (1996). Strategic Plan 1997-2000, Central West Catchment Management Committee (pp. 5 pages).


Committee NLBRV. (2002). Draft regional vegetation management plan for the North Lachlan - Bogan Region (pp. 38 pages + appendices).


Conservation NSWDo, and Management L. Detecting dryland salinity on the Southern Tablelands of New South Wales (pp. 6 pages).

Conservation NSWDo, and Management L. Yass salinity abatement demonstration program (pp. 6 pages).

Conservation NSWW, and Commission I Coleambally Irrigation Area.


Conservation NSWW, and Commission I (1974) Report on a proposal by the Snowy Mountains Council that the carrying capacity of the Tumut River be increased.


Cooper B, and Riley GT. (1996). *Storm transport of pollutants from dryland agriculture*.

Cooper BW, and Brooks AJ (1997) Distribution and environmental impact of endosulfan in a cotton growing area in New South Wales, Australia. *Land Contamination and Reclamation Vol.5 No.4 p307-312*

Corbett CCH, C.G., and Bowmaker EW (1956) Report on the committee appointed by the Minister for Conservation to advise on the extent and location of lands and the form of production which would offer most benefit to the state by development.


Council LRA Water management in the Lachlan Valley, balancing riverhealth and regional prosperity.

Council QC. (1986). Queanbeyan's sewage plant (pp. 4 pages).


Council M-DBM. (1994). The algal management strategy summary (pp. 5 pages).


Crouch RJG, C. Broughton, A. Bradd, J., and Young R. A program of agronomic and hydrogeologic research into rising water tables and increasing salinity in the Liverpool Plains Catchment.

CSIRO Water availability in the Namoi. A report to the Australian Government from the CSIRO Murray-Darling Basin sustainable yields project (No. ISSN N./A.).


CSIRO. (2008). Water availability in the Campaspe: Campaspe fact sheet Murray-Darling basin sustainable yields project (pp. 2).


Cunningham GM (1973) Aboriginal waterholes in the Cobar area. *Australian Natural History vol. 17 no. 11* p365-369


Dahlstrom T (1932) River red gum forests in Victoria. *Skogen*, 19((3)): 53-56


Dare HH. (1917). The engineering work of the Murrumbidgee Irrigation Scheme (pp. 15 pages).


Date R (1999) A fond memory. *International Water Power and Dam Construction, October* p18-20


Department NSWP (1949) The Murrumbidgee region: a preliminary survey of resources.


Division NSWDWR (1989) Responses to review of water distribution operations in irrigation areas and districts of N.S.W. Volumes 1 and 2.


Donaldson S Gwydir River catchment. Land management proposals for the integrated treatment and prevention of land degradation.


Downes RG, and Sleeman JR (1955) Soils of the Macquarie region, New South Wales.


DPI, and Melbourne Uo (2003) The Living Murray creating markets for the environment: a report to the MDBC from the Economics Branch (DPI) and the Economic Theory Centre (University of Melbourne) (No. ISSN N./A.).


Dudley N The integration of wetlands water supply and demand management in a market environment using capacity sharing.


Education NSWDo. (1986). The high country (pp. various).


Emery KA (1970) An erosional survey of the Molonglo River area within the New South Wales section of the catchment area of Lake Burley Griffin.


Favaloro N (1944) The white-breasted sea-eagle along the Murray Valley. *Emu*, 43((4)): 233-242


Fitzgerald BJ. (1975). *A key station approach to rural and urban flood frequencies in the A.C.T.*

Fitzgerald B (1989) Lachlan Region - effect of conversion of 15 000ml normal security licenses to high security and of permanent transfer factors on system reliability.


FitzSimon JM (1983). The effect varying fire regimes have on the hydrolysable nitrogen fraction in a sub-alpine woodland soil in the Brindabella Range, A.C.T.


Foster N, and Fulford T. NSW Department of Land and Water Conservation, Tamworth, pictures collection.

Foundation HVR (1968) Lachlan Region NSW: A Regional Study with Conclusions and Recommendations on Economic Growth Vol 1, 2 and 3.


Furness GO (1977) Apparent failure of 2 Parasites Anarhopus-Sydneyensis Hymenoptera Encyrtidae And Hungariella-Peregrina Hymenoptera Pteromalidae to establish on field populations of Pseudococcus-Longispinus Hemiptera Heteroptera Coccidae In South Australia. *Journal of the Australian Entomological Society*, 16(1): 111-112


German P. *Wildlife Images Pictures Collection.*


Gilligan DM (2005) Fish communities of the Murrumbidgee catchment: status and trends NSW Department of Primary Industries.


Gippel CJ (2006) Scoping study of operational changes to reduce river and storage losses along the River Murray system (No. ISBN 1-921038-84-5).


Government A. (2003). Think water, act water - Volume 3: draft state of the ACT’s water resources and catchment (pp. 75 pages).


Griffin WB. (1915). The town of Leeton (pp. 3 pages).

Griffin RJ (1959). The geology of the Lake Cargelligo - Rankin's Springs district with special reference to underground water resources.

Grose J, and Holics M (1995) Natural resources of the Murrumbidgee Irrigation Area, Tabbita and Benerembah Irrigation Districts.

Group KVL Kyeamba Valley soil management and salinity control program: final project report.


Gutteridge H, Davey Pty Ltd. AAPL, Coopers, and Scott LW (1989) Water distribution operations in irrigation areas and districts of NSW.


Haddad E (1994). Estimated leakage rates in the shallow and deep aquifers in the Coleambally Irrigation Area, NSW, Australia.

Haeusler TM (1987). Recent sediment yield and environmental change at the Ginninderra Experimental Station, A.C.T.


Harris JH (1986) Fish passage in Australia.


Harris JH. (1994). *Carp in Australia: The Role of Research.*


Harris JH, and Mallen-Cooper M (1994) Fish-passage development in the rehabilitation of fisheries in mainland south-eastern Australia.


Hawkins LV (1960). The application of geophysics to the investigation of foundation conditions at sites for proposed engineering construction in the A.C.T.


Heweston PF, and Daniell TM. (1988). HYDSYS - the ACT water administration hydrometric archiving system.


Hodge H (1964) The Hill End story. Volume 1, 2 and 3.


Holmes M. The Namoi: a catchment to talk about. In Grogan A (Ed.) (pp. 21 pages).


Hood MNM (1989). Factors influencing vegetation in saline areas of the Yass Valley, N.S.W.


Hooper B. (1995). *Results of a study of the adoption of salinity management in the Goran catchment (N.S.W.) and the Tragowel Plains (Vic.)*.


Howling GM. (1997). Remnant vegetation strategy for the Central West Catchment (pp. 50 pages).


Hudson K (1997) Bidgee bridge to bridge bank care project report: an assessment of the Murrumbidgee River and banks within the City of Wagga Wagga.


Hunter JT (2000) Vegetation and floristics of Mt Conobolas State Recreation Area.


Ingwersen F (2001). """Sundry nameless ranges""": the landscape ecology of the Naas-Gudgenby catchment".


Ivey ATP The Current Cost of Dryland Salinity to Agricultural Landholders in Selected Victorian and New South Wales Catchments.


Jackson P. (2009). *Demonstration reaches - where to now?*


Jacobs TA. (1989). *Regulation of the Murray-Darling river system*.


Jenkins BR (1993) Soil landscapes of the Michelago 1:100 000 sheet (Captains Flat, Jerangle, Bredbo, Tharwa).


Jenkins K, and Briggs S (1997) Wetland invertebrates and flood frequency on lakes along Teryaweinya Creek.


Johnston TH, and Cleland ER (1938) Larval trematodes from Australian freshwater molluscs. IV. *Trans Roy Soc S Australia, 62*(1)): 127-131

Johnston TH, and Angel LM (1939) Larval trematodes from Australian fresh-water molluscs. VI. *Trans Roy Soc S Australia, 63*(2)): 200-203

Johnston TH, and Simpson ER (1939) Larval trematodes from Australian freshwater molluscs. V. *Trans Roy Soc S Australia, 63*(1)): 63-68

Johnston TH, and Angel LM (1941) Life cycle of the trematode, Diplostomum murrayense J and C. *Trans Boy Soc S Australia, 65*(1)): 140-144


Jolly ID (1989) Investigation into the potential for increased stream salinisation in the Darling Basin.


Jones HA (2007) The influence of hydrology on freshwater mussel (Bivalvia : Hyriidae) distributions in a semi-arid river system, the Barwon-Darling River and Intersecting Streams.


King A. (2009). *How successful are environmental flows for enhancing fish populations?*


A Review of River Ecosystem Condition in the Murray-Darling Basin

Kingsford R (1990) Back of Bourke - not just red dust and kangaroos but home for thousands of waterbirds. *Australian Ranger Bulletin Vol.5 No.4* p18-19


Klaver J (1987). Old ovens are soon hot: a study of function and location of Aboriginal mounds in the Upper Murrumbidgee Region.


Koehn JD, and Harrington DJ (2006) Environmental conditions and timing for the spawning of Murray cod (Maccullochella peeli peeli) and the endangered trout cod (Maccullochella macquariensis) in southeastern Australian rivers. *River Research and Applications*, 22(3): 327-342


Lake JS Principal fishes of the Murray-Darling River system.

Lake JS Freshwater fish of the Murray-Darling River system. The native and introduced fish species.

Lake JS (1963) Fish on the Murray river system Australia. *Victoria S Resources, 5*(1)): 12-13


Land NSWDo, Conservation W, and Board MCM. (2003). Integrated catchment management plan for the Murray Catchment 2003, also known as the Murray Catchment Blueprint (pp. 61 pages).


Lawrence BW. (1991). Fish management plan (pp. 48 pages).


Lindenmayer DBC, R.B., and Pope ML (1999) A large-scale "experiment" to examine the effects of landscape context and habitat fragmentation on mammals. Biological Conservation Vol.88p387-403


Lloyd LN, and Walker KF. (1989). *Management of snags (woody debris) and river and floodplain vegetation for native fish in the Murray-Darling River system.*


Ltd AASCP (1997) An archaeological investigation of the Haberechts Gravel Pit near Wagga Wagga, NSW.


Ltd RFMP, and Resources NSWDoW (1990) Environmental Impact Assessment for the establishment of a feedlot and associated feedmill complex at Rockdale and Boree Plain, Yanco, N.S.W.


MacRae GP (1989) Geology of the Lachlan Downs: 1:100 000 sheet 8033 (No. ISSN 07289901).


Maher P (1988) Threatened Avifauna of Western New South Wales with Special Reference to Plant Communities. *National Parks Journal Vol.32 No.4p11-16* + figures + pictures + maps


Maher MT, and Braithwaite LW (1992) Patterns of waterbird use in wetlands of the Paroo - a river system of inland Australia. *Rangeland Journal 14 (2)p128-142*


Mallen-Cooper M (1992) Fish migration and vertical-slot fishways in south-eastern Australia.


Mallen-Cooper M, and Thorncraft GA (1992) Fish passage and fish abundance at Brewarrina Weir following a bloom of blue-green algae.


Management L (1986) Natural Regions of Western New South Wales and their Major Vegetation Communities.


McCosker RO, and Duggin JA (1992) Gingham watercourse resource management issues, Gwydir River basin, Moree NSW.


McIntyre S (1987) Archaeological survey of the proposed Wagga to Darlington Point 132kV transmission line.

A Review of River Ecosystem Condition in the Murray-Darling Basin


McKay RT. (1907). The utilisation of the Murrumbidgee Waters (pp. 14 pages).


McMinn A (1992) Quaternary coastal evolution and vegetation history of northern New South Wales, Australia, based on dinoflagellates and pollen. *Quaternary Research (Orlando)*, 38(3): 347-358


McPherson AA (2003). Salt sources and development of the regolith salt store in the upper Billabong Creek catchment, southeast NSW.


Mein RG, and Turner AK (1968) A study of the drainage of irrigated sand dunes using an electrical resistance analogue.


A Review of River Ecosystem Condition in the Murray-Darling Basin 233


Meteorology CBo (Cartographer). (1910). *Map showing rainfall and temperature statistics of the proposed site for the Federal Capital and the surrounding district.*


Middleton A, and Beresford Maning F (1978) Bathurst and western district directory and tourist guide and gazetteer.


Mills JRA, C.R. Purdie, R.W., and McDonald WJF (1990) Western Arid Region Land Use Study Part III (No. ISSN 0811 9007).


Mulholland CSJ (1940) Geology and underground water resources of the East Darling district.


Murphy GP. (1983). Griffin's other towns: a paper read to the Canberra and District Historical Society (pp. 24 pages).


Nagy J (1997). The use of remotely sensed imagery to delineate and classify dryland salinity near Cowra, NSW.


Navin K (1993) Archaeological survey for Aboriginal sites - CSR Readymix Cooma Road Quarry, Queanbeyan NSW.


New South Wales Department of Water Resources TSD, Macquarie Western Region. (1992). Revised groundwater allocation policy for the alluvial groundwater resources of the Macquarie Valley downstream of Narromine (pp. 7 pages + figures).


Nguyen M (2002). The effects of fire on hydrological processes in the upper Cotter River catchment, ACT.


A Review of River Ecosystem Condition in the Murray-Darling Basin

NSW SCSo. Yass Valley Soil Conservation Project (pp. 16 pages).


Oxley J (1820) Journal of the two expeditions into the interior of New South Wales, undertaken by order of the British Government in the years 1817-18.


Pearce GW. (1985). *Border Rivers Agreements and Interstate Waters*.


Pels S (1968) Geology and Groundwater Hydrology.


Penny N. (2007). Namoi Catchment Management Authority: where are our wetlands?

Pepperell JG (1975). Effects of DDT on birds and fish.

Perkins AJ (1927) Statistical data relative to the reclamation of a salt-impregnated area in a River Murray orchard. *Jour Dept Agric South Australia, 30*(6): 626-637


Phillips B. (2009). Where to next for habitat management areas?


Philp D (1985) Phosphorus removal at the Lower Molonglo Water Quality Control Centre. *Journal of the Water Pollution Control Federation Vol.57 No.8* p841-846


Pickard J (1992) Artesian Springs in the Western Division of New South Wales.


Pigram J (1968) The development and potential of the Namoi Valley cotton industry.


Porteners MF (2001) Vegetation Survey of Woggoon and Tollingo NRs (Central West Region of NSW): report for the NSW NPWS.


Preston BL, and Jones RN. (2008) Screening climatic and non-climatic risks to Australian catchments. *Geographical Research* 258-274.


_Journal of Fish Diseases_, 12(3): 205-222


_Environmental Software Vo.11 No.1-3_ p135-142


Quayle W (2003) Reaching for a positive chemical equation. _CSIRO Land and Water Link, April_ p10-11

Queensland Department of Primary Industries DoLU (1974) Western Arid Region Land Use Study Part I.


Reconstruction NSWDo, and Development (1952) The Namoi region: preliminary survey of resources.


Reid J. (1992). Land degradation in the arid zone: "Rabbits, Rabbits, Rabbits." Don't be fooled - its not just the rabbits (pp. p8-9,11).


Reid DD, and Harris JH (1997) Estimation of total abundance of fish populations: the calibration experiments.


Resources NDoW Water Resources of the Gwydir Valley.

Resources NSWDoW. Water for the Gwydir Valley (pp. 6 pages).

Resources NSWDoW Benerembah Surface Drainage Scheme.

Resources NSWDoW Hydrological study - Griffith: drainage channel "R".

Resources NSWDoW Hydrological study - Griffith: drainage channel "Collina" and drainage channel 1690-J.


Resources NSWDoW (1983) Bore licensing policy.


Resources DoW (1987) Licensing Policy for High-Yield Bores and Wells in the Cudgegong Valley, NSW.


Resources NSWDoW (1989) Benerembah Surface Drainage Scheme, re: project proposal and works schedule.


Resources NDoW (1990) Gwydir Valley dams studies report on second stage investigations.


Resources NDoW (1991) Gwydir Valley dam studies summary report on second stage investigations.


Resources NSWDoW (1991)...doing more with water.


Resources NSWDoW (1991) Tumut River background study to a management strategy - draft.


Resources NSWDoW (1992) Queanbeyan flood study report.


Resources NSWDoW (1993) Irrigation potential of lands in the Wah Wah stock and domestic district.


Resources NSWDoW (1994) Revised groundwater allocation policy for the alluvial groundwater resources of the upper Namoi valley, Mooki valley, and Coxs Creek, New South Wales. Discussion Paper.


Resources NSWDoW (1995) Benerembah Surface Drainage Scheme: review of environmental factors for Stage IIIA.


Resources NSWDoW (1996) Bulk water review - analysis of economic impacts in the Murrumbidgee Irrigation Area and the Gwydir Region.


Riley SJ (1988) Secular change in the annual flows of streams in the NSW section of the Murray-Darling Basin.


Ring S Contract to record and assess gold mining remains in the Macquarie/Turon goldfields. Volume 1.

Ring PJ. (1982). *Cudgegong Valley computer simulation studies.*


Roberts J (1994) Riverbanks, plants and water management.


Robinson SE (1983). The effects of ruralization and urbanization on the recreational fishery in the upper Murrumbidgee River with an analysis of changes in hydrological characteristics and their potential impact on fish populations.


Roshier DA, Klomp NI, and Asmus M. (2006). Movements of a nomadic waterfowl, Grey Teal Anas gracilis, across inland Australia – results from satellite telemetry spanning fifteen months. 16


Ross J, and Jeffery L (1991) Ground subsidence and bore collapse associated with groundwater withdrawals - Namoi Valley NSW.


Rutherford DA (1979) One hundred years of local government in Molong 1879-1978.


Ryan JG (1968) Economics of the development of large area farms on the Coleambally Irrigation Area.


Sander Y (1996) Towns and villages utilising groundwater in NSW.


Sauti Australia Pty Ltd. CE Report on feasibility studies for the further development of the Lachlan and Shoalhaven Valleys. (4 volumes).

Saxon D (1988) The gateway to the M.I.A., a history of Yanco N.S.W.


Schmitz B (2002) Sound production in Crustacea with special reference to the Alpheidae.


Schroder DH, M. Smith, M., and Lunney D. The Liverpool Plains tree link (pp. 4 pages).

Schumm SA. (1968). River adjustment to altered hydrologic regimen - Murrumbidgee River and paleochannels, Australia (pp. 65 pages).


Scown JT (2001) Hillas catchment: an integrated project to assess land use and catchment condition in the Murrumbidgee catchment.


Seddon JT, S., and Briggs S (1997) An Inventory of Lakes in the Western Division of New South Wales.


Sewell R (1998) Salinity assessment and electromagnetic (EM31) survey results for the Murrumbateman, Bushes Lane area (No. ISSN 0734751516).


A Review of River Ecosystem Condition in the Murray-Darling Basin 263


Shepheard M (1992) Flooding frequency and Eucalyptus largiflorens (Black Box) wetland health in the Wah Wah District.


Shiel RJ (1980) Billabongs of the Murray-Darling system.

Shiel RJ (1983) The Genus Brachionus Rotifera Brachionidae In Australia With A Description Of

Shiel RJ (1986) Zooplankton of the Murray-Darling system.

AUSTRALIA. Australian Journal of Marine and Freshwater Research, 33(2): 301-328

Shiel RJ, Green JD, and Nielsen DL (1998) Floodplain biodiversity: Why are there so many species?
Hydrobiologia, 387-388(0): 39-46

planning approach to the determination of environmental needs. Water Science Technology Vol.45
No.11 p241-249


Journal of Environmental Science and Health Part B Pesticides Food Contaminants and Agricultural
Wastes, 40(5): 711-720

Shorebird conservation conserving shorebird habitat: The Fivebough and Tuckerbil Swamp Wetland

Short GI (1986) Total catchment management - the development of a strategy concept. Journal of Soil
Conservation (42) 1p72-74

River Murray, South Australia. River Research and Applications 765-774

River Murray, South Australia. River Research and Applications, 20(7): 765-774

Simmons CT, and Narayan KA (1998) Modelling density-dependent flow and solute transport at the Lake
Tutchewop saline disposal complex, Victoria. Journal of Hydrology (Amsterdam), 206(3-4): 219-236

at the Mourquong saline-water disposal basin, Murray Basin, Southeastern Australia. Hydrogeology
Journal 278-295

Simpson KNG (1973) Amphibians Reptiles And Mammals Of The Murray River Region Between Mildura
And Renmark Australia. Memoirs of the National Museum of Victoria(34): 275-279


Sivertsen D, and Metcalfe L (1994) Natural vegetation of the southern wheat-belt (Forbes and Cargelligo 1:250 000 map sheets). *Cunninghamia Vol.4* p103-129 + maps


Stannard ME (1968) Physiography.

Stannard ME (1978) Irrigation in the Murrumbidgee Region of New South Wales.

Stannard AE (1987) Total Catchment Management in the Murray-Darling Basin - its practical application in the northern region (No. ISSN 1030 - 5092).


Surveys A, and Ltd RP (2000) The report of the archaeological investigation of the Mine Site and sites of Associated Ancillary Infrastructure for the Syerston nickel-cobalt project, Condobolin/Fifield Area, Western NSW.


Swales S (1994) Streamflow requirements of native fish in NSW rivers- the role and importance of flushing flows.


Talyor G (1930) Agricultural regions of Australia - Installment II. *Economic Geography Vol.6 No.3* p213-242

Taylor AC (1956) A soil conservation survey of the upper Burринjuck Catchment.


Timms BV, and Boulton AJ (2001) Typology of arid-zone floodplain wetlands of the Paroo River (inland Australia) and the influence of water regime, turbidity, and salinity on their aquatic invertebrate assemblages. *Archiv fuer Hydrobiologie*, 153(1): 1-27


Tuckson M (1994) Salinity, piezometers and landuse: a report for the Simmons Creek sub-group of the Alma Park-Pleasant Hills Landcare group.

Tuckson M (1994) History, landscapes and phalaris: understanding salinity in the Upper Burkes Creek landcare area.


Turner GWR, R.M.C., and Roberts MW (1996) Extent and Environmental Significance of Vegetation Clearance in the Nymagee-Cargelligo Area, Western New South Wales. *Australian Geographer* Vol.27 No.1p87-100


van der Lelij A Cause and effect of deep percolation losses in the Murrumbidgee Region.

van der Lelij A (1972) The groundwater hydrology of the Coleambally Irrigation Area.


van der Lely A (1995) Murrumbidgee Irrigation: Groundwater conditions in the MIA.


various. Qld Parks and Wildlife Service pictures collection.

various. Qld Environmental Protection Agency pictures collection.

various. WISE (NSW National Parks and Wildlife Service) pictures collection.

various. Charleville Historical Society Pictures Collection.

various. NSW National Parks and Wildlife Service, Photo Library Collection.

various. Moree and District Historical Society Pictures Collection.

various. Geography Teachers Association of NSW Pictures Collection.


Wade LAB (1905) Murrumbidgee Irrigation Barren Jack Scheme.

Wade LAB (1914) New South Wales, The Murrumbidgee Irrigation Scheme.


Wales SPAoNS (1965) Coleambally, a new town in the making.


Wales SCSoNS (1972) Soil conservation projects on the Queanbeyan-Molonglo River system in New South Wales: inspection - Commonwealth Inter-Departmental Committee on Soil Conservation, 18th August 1972.
Wales SCSoNS (1973) Barraba district technical manual.
Wales SCSoNS (1979) Square Knob Project: a proposed valley type project for the Riverina area.


Walter Hoder DoWR. (1994). *Managing Urban Streams - Important Natural Ecosystems or Drains?*


Ward WT. (1987). *Role of sheet erosion in landscape development on sandstone at Edgeroi, N.S.W.*


Wedderburn SD, Walker KF, and Zampatti BP (2007) Habitat separation of Craterocephalus (Atherinidae) species and populations in off-channel areas of the lower River Murray, Australia. *Ecology of Freshwater Fish*, 16(3): 442-449.10.1111/j.1600-0633.2007.00243.x


Whitten SM, and Bennett JW (1999) Wetland ecosystems and landuse in the Murrumbidgee catchment - Wagga Wagga to Hay and including Mirrool Creek (No. ISSN 14412136).


Whitten SM, and Bennett JW (2000) Farmer perceptions of wetlands and wetland management on the Murrumbidgee River between Wagga Wagga and Hay including Mirrool Creek (No. ISSN 14412136).


Williams RM (1983) Hydrogeology and hydrochemistry of the young granodiorite in the vicinity of the Young township, N.S.W.

Williams RM (1985) Hydrochemistry of the groundwater of the unconsolidated sediments associated with the Murrumbidgee River west of Narrandera (No. ISSN 0727968X).

Williams RM (1990) Groundwater conditions in the Young (Scenic Road) Land Care Group Area.


Williams AR (2007) Puccinellia (Poaceae) in Western Australia. *Nuytsia*, 16(2): 435-467


Williamson WH. (1964). *The development of ground-water resources of alluvial formation*.


Wong V (2001). The effect of tree health on soil physical and chemistry properties in Kyeamba Valley, NSW.

Wood BSC Outline of the present salinity situation in the southern N.S.W. irrigated areas and districts.


Woolley DR (1998) Assessment of possible impact of proposed increased pumping from artesian bores in Moree.


Works Do, Housing, and Reconstruction P-w (1947) Report on proposals to divert the Snowy River into the Murrumbidgee and the Murray Rivers.


Zare M (1986). A simulation approach to the operation of a multiple reservoir and aquifer water resource system.

Zare M, and Howell DT. (1983). Conjunctive use of surface and ground water.


