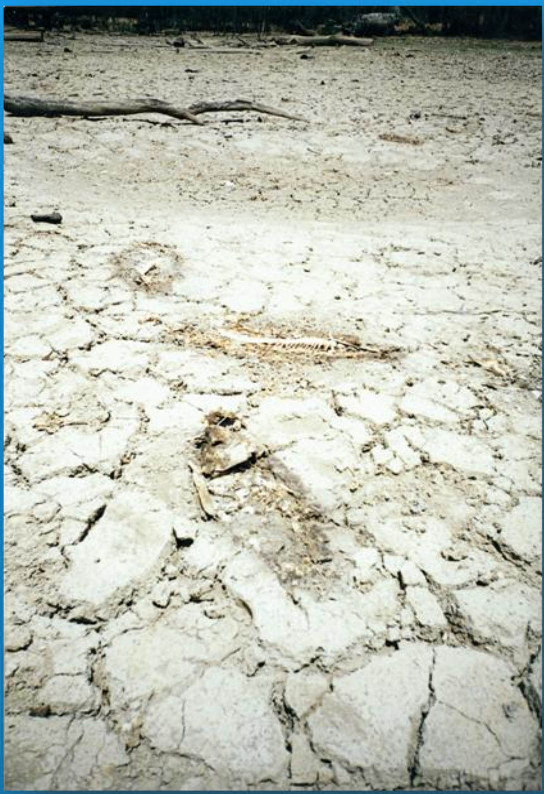
Inland Waters & Catchment Ecology

The Protection of Drought Refuges for Native Fish in the Murray-Darling Basin



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SARDI Aquatic Sciences
PO Box 120 Henley Beach SA 5022

April 2013

A report to the Murray-Darling Basin Authority

Government of South Australia

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LIST OF ACRONYMS

ACT: Australian Capital Territory

ARI: Arthur Rylah Institute (DSE Victoria)

CMA: Catchment Management Authorities

CRC: Co-operative Research Centre

DEEDI: Department of Employment, Economic Development and Innovation

DERM: Department of Environment and Resource Management (previously Queensland Department of Natural Resource Management)

DICP: Dry Inflow Contingency Plans

DPI: Department of Primary Industries

DSE: Department of Sustainability and Environment (Victoria)

EFAP: Environmental Flows Assessment Program MDB: Murray-Darling Basin

EPBC Act: *Environment Protection and Biodiversity Conservation Act 1999 (Commonwealth)* (EPBC Act 1999)

FFG Act: *Flora and Fauna Guarantee Act 1988 (Vic*) (FFG Act 1988)

IUCN Redlist: *International Union for Conservation of Nature and Natural Resources (ICUN) Red list of threatened species*. Version 2010.4 (ICUN 2010)

ISC: Index of Stream Conditions

MDBA: Murray-Darling Basin Authority (previously the MDBC: Murray-Darling Basin Commission)

NCA QLD: *Queensland Nature Conservation Act 1992 (Reprint No 6G)* (NCA QLD 1992)

NFS: Native Fish Strategy

NRM: Natural Resource Management

NRSWS: Northern Rivers Sustainable Water Strategy

NSW FM Act: *Fisheries Management Act 1994 No. 38* (FM Act NSW 1979)

NSW: New South Wales

QLD: Queensland

ROP: Queensland Resource Operation Plan

RRHS: Regional River Health Strategies

SA FM Act: *South Australian Fisheries Management Act 2007* (FM Act SA 2007)

SA: South Australia

SARDI: South Australian Research and Development Institute

SEAP: Stream and Estuary Assessment Program

SRA: Sustainable Rivers Audit

TSC Act (NSW): *Threatened Species Conservation Act 1995 No 101* (TSC Act (NSW) 1995)

Vic: Victoria

WRP: Water Resource Plans.

GLOSSARY

Attributes: the specific ecological components that make up the broader refuge characteristics, components that allow refuges to function e.g. “things that refuges have”, intact riparian zones, permanence of water, lateral connectivity, etc.

Characteristics: are the broad concepts that are critical for maintaining healthy and resilient refuge habitats e.g. physical habitat, hydrology, biological integrity, connectivity.

Functions: provide ecological services and/or processes (alone or in combination) that are essential for maintaining attributes at a sustainable or adequate level e.g. “things that refuges do”, e.g. ground cover (vegetation, leaf litter and woody habitat) present (providing stability and nutrient exchange, preventing erosion).

Governance: includes Federal (e.g. MDBA), State (DSE Vic) and regional (Goulburn Broken CMA) legislative and policy bodies. Additionally, Federal, State and Sub-ordinate legislation (e.g. *EPBC Act 1999; Flora and Fauna Guarantee Act 1988; Victorian Regional River Health Strategies*) and policy frameworks.

Legislation: refers to laws which serve to legally prohibit certain actions and ensure others are carried out.

Policy: plans of action which guide towards making sure legislation is complied with.

Pressures: high level descriptors of the activities that generate the threats (often anthropogenic driven impacts) e.g. catchment management/mismanagement, water resource management, introduced species and fisheries management.

Refuge(s): This report will follow the terminology outlined by Lake (In Press), therefore the term refuge(s) will be used instead of ‘refugium’ or ‘refugia’. …*To resist the stresses of drought and to strengthen resilience, biota may use refuges. This step is taken to distinguish refugia in a palaeoecological and evolutionary sense, such as places where biota survived ice ages, from refuges in a more immediate ecological sense, such as places where biota survived floods, droughts and wildfires”…* (from Lake In Press).

Resilience: the ability to recover and rebuild populations following disturbance impacts. Largely, these are factors that generally support the maintenance of robust and viable populations across their geographic range.

Resistance: the ability for biota to survive (through physiological and behavioural mechanisms) direct and indirect impacts of a disturbance (e.g. drought) involving deteriorating and unfavourable conditions.

Threats: activities that threaten the refuge attributes and refuge functions e.g. sedimentation, diversion of water, waterhole pumping, and lack of riparian structure.

Values: aspects of the fish or sites that are identified as important to protect or restore. This may be an individual species, a community, a habitat, etc.

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EXECUTIVE SUMMARY (NON-TECHNICAL)

Following record low inflows into the Murray-Darling Basin in 2006, the Native Fish Strategy under the Murray-Darling Basin Commission (now the Murray-Darling Basin Authority or MDBA) commissioned an expert panel to investigate the impact of drought on freshwater fish populations and to outline an approach for protecting key populations from drought-related impacts (Lintermans and Cottingham 2007). Amongst the high priority actions recommended by the expert panel was a need to identify, catalogue and protect drought refuges and to develop drought action plans to assist regional agencies and jurisdictions to protect key refuges in the Murray-Darling Basin (MDB). Subsequently, the current project was developed to advance the high priority actions. The broad aims of the project were to: 1) explore the current status and management of drought refuges in the MDB; and 2) develop an approach to identify and protect drought refuges for native fish that can be implemented across the MDB.

The current status and management of refuges were explored using a number of techniques including questionnaires, an expert/management workshop and a review of relevant literature and management programs. This process identified the types of habitats that serve as drought refuges across the MDB, the key native fish species that have been targeted for protection under drought response programs, key threats and the current management responses/actions undertaken for refuge protection. In order to catalogue refuge sites, a preliminary list of critical sites was developed in collaboration with managers and experts.

Of the 14 different habitats identified as critical refuge habitats, unregulated and regulated streams and rivers were the most common; constituting a combined 64% of habitats. The largest suite of critical refuge habitats identified (37%) were associated with unregulated streams and rivers. Regulated streams and rivers made up 27% of the identified critical refuge sites. While current management tends to focus on *resistance* (i.e. the ability to persist), often through emergency water management programs, it is necessary to incorporate drought response activities that build *resilience* (i.e. the ability to recover) into aquatic ecosystem networks and biotic populations with long-term, large-scale programs.

An approach to identify and protect refuges was developed in conjunction with regional agencies and jurisdictions from two *pilot valleys*: the Goulburn Broken catchment in northern Victoria and the Moonie catchment in south-eastern Queensland. These two jurisdictions were specifically chosen for more detailed attention as they offered contrasting contexts in which to test the ideas of drought refuge management, in terms of their policy drivers, challenges and key differences in ecosystem characteristics. Under this phase of the project, definitions and criteria for identifying and prioritising refuges were developed in conjunction with management agencies. A management tool was developed for collating refuge values and habitat attributes, as well as threats to the maintenance and improvement of these important characteristics. This approach may be used for the prioritisation of interventions based on key management principles, including: threatened species, protection of habitat biodiversity, water allocation, catchment management actions, fisheries management actions and restoration.

Based on the information elicited from the pilot valley analyses, a template was produced that outlines a process for approaching refuge identification and management across the MDB. This template documents a process that can be integrated into regional natural resource management frameworks across the MDB, acknowledging that different states and regions are subject to various legislative and policy environments and possess varying levels of information, data, planning structures and intervention opportunities that relate to aquatic habitat protection.

It is a key recommendation that this template and management tool is trialled at regional and catchment scales across the MDB to assist managers in collating relevant information and data, identifying critical local refuges and capturing regional conservation priorities and species of concern. This process can then be used to build a comprehensive spatial database that captures the location and characteristics of key refuges that can be utilised by the MDBA and other relevant agencies to prioritise NRM investment and water for the protection of drought refuges across the MDB.

A summary of key recommendations provided from this report are:

- Develop co-ordinated drought response groups that can objectively gather and collate information and prioritise resources for protecting key attributes and functions of aquatic refuges that support viable native fish populations (or other aquatic-dependent populations) in the MDB. These groups must have the ability and capacity to influence the delivery of water and catchment management resources under an objective, well informed priority process.
- Develop a common policy framework for refuge protection in the MDB within which regional scale management plans can be developed.
- Implement long-term (including non-drought periods) spatially expansive programs to restore and maintain populations and connective pathways to build resilience and viability into native fish populations at the appropriate scale.
- Develop and implement catchment, regional or local scale refuge management plans (using outputs outlined in this report). The information provided through these plans can then be used to build a spatial information database for the MDB that supports drought response prioritisation and co-ordinates resources and investments that are critical for protecting native fish values and populations. This should be integrated with ongoing catchment planning and investment to maintain and build resilience into native fish populations and refuges across the MDB.
- Co-ordinate resources and investment to support on-ground works and drought response management options, particularly through state natural resource management and fisheries agencies, which are responsible for protecting native fish communities and aquatic ecosystems and conducting critical intervention programs.
- Monitoring is the primary mechanism for identifying high risk refuges during drought. A co-ordinated monitoring program incorporating state agencies and research institutions should be considered at the onset of drought to provide a baseline of knowledge for response planning and prioritisation. Early warnings can be provided only if appropriate monitoring programs are ongoing and able to detect impacts, threatened species and refuges with enough lead time to inform management direction. Monitoring programs require careful design, analysis and effective reporting of results; particularly as this step is often poorly developed or implemented, especially with respect to programs dealing with fish ecology and management. Remote sensing and spatial technologies, modelling frameworks and the integration of existing datasets, would also facilitate the rapid assessment of high risk

systems and critical refuge areas for protection under future drought or climatic drying scenarios.

1. GENERAL INTRODUCTION AND BACKGROUND

1.1 The impact of drought on the Murray-Darling Basin

From 1996 to 2009, the Murray-Darling Basin (MDB) experienced severe drought conditions (the 'millennium drought') (Murphy and Timbal 2007; Ummenhofer *et al.* 2009), the likes of which have only been recorded on one prior occasion in the 20th century (from 1936-1945, see Potter *et al.* 2010). Between 1996 and 2007, mean annual rainfall and run-off were approximately 16 and 39% lower (respectively) than the long-term average, from 1895 to 2006 (Murphy and Timbal 2008; Potter *et al.* 2008). Subsequently, inflows to the River Murray system over the 1996-2007 decade were approximately 42% below average; an amount roughly comparable to inflows recorded during earlier extended droughts in the 1900's and 1940's (Timbal and Murphy 2007; Post *et al.* 2009). The unprecedented reductions in run-off appear to be due to a combination of factors relating to: low annual rainfall, increased temperatures, increased potential evaporation, decreased autumn and winter rainfall (in a region with largely winter-dominated runoff) and decreased inter-annual variability of rainfall (Potter *et al.* 2008). These lower rainfall and runoff averages, while detectable in the north-east region, were mostly concentrated in the southern most regions of the MDB. Overall, the extended drought conditions were particularly noticeable in parts of South Australia and Victoria that typically experience a winter rainfall peak (May to October) (Timbal and Jones 2008).

As the impacts of the millennium drought worsened and waterways, wetlands and water storages began to dry significantly, the need for improved and co-ordinated management responses became increasingly important to protect key ecological assets and critical aquatic habitats and ecosystems. Management of the MDB's water, aquatic ecosystems and native biota falls across five jurisdictions, namely the Australian Capital Territory, Queensland, New South Wales, Victoria and South Australia and subsequently, management programs for the protection of aquatic environments, including drought refuges, can differ significantly depending on various state and regional management priorities and different legislative, policy and planning frameworks.

1.2 Drought impacts

Droughts decrease water availability and consequently disrupt key ecological processes; which may result in both direct and indirect effects on aquatic-dependent biota (Lake 2003). The early phases of drought are characterised by reduced rainfall and runoff, leading to the overall drying of catchments (Jones *et al.* 2002; Dahm *et al.* 2003; Lake 2003; Matthews and Marsh-Matthews 2003; Bond *et al.* 2008). As drought increases, shallower waterbodies, or habitats with porous substrate, dry out, so that only deeper, retentive or spring-fed pools remain (Wiens 1977; Sparks *et al.* 1990; Ostrand and Wilde 2001; McNeil 2004; Closs *et al.* 2006).

As the effects of desiccation continue, there is often a progressive disconnection of remnant waterbodies both longitudinally (e.g. upstream to downstream) and laterally (e.g. river to floodplain) (Bond *et al.* 2008; Gawne and Gigney 2008); reducing the quantity and quality of available habitat for aquatic biota and limiting movement between habitats. Restricted access to floodplain wetlands, limited longitudinal connectivity and increasingly shrinking habitats with poor habitat complexity/quality may restrict fish movements and/or successful spawning and recruitment.

In general, as individual waterbodies dry out and become isolated, numerous physical and physico-chemical changes occur (Balcombe and Closs 2004; McNeil 2004; Arthington *et al.* 2005; Closs *et al.* 2006; Patra *et al.* 2007). While the nature and magnitude will vary depending on the type of waterbody (Wood and Pfitzer 1960), impacts include:

- a reduction in water depth and surface area,
- decreased availability, complexity and variety of hydraulic and structural habitat, and
- physicochemical changes in water quality (e.g. increased water temperatures, hypoxia, salinity, organic loading and toxicity).

As environmental conditions deteriorate, the resistance mechanisms aquatic biota possess to tolerate or avoid these impacts become critical for survival (Lake 2003; McNeil 2004). In temperate freshwater systems where seasonal drought tends to be a relatively frequent and predictable occurrence, the associated aquatic biota are often well-adapted to increasing desiccation, disconnection and isolation (Lake 2003). Survival of freshwater fishes subjected to these events is, therefore, largely dependent on the individual's intrinsic capacity to resist drought (Magoulick and Kobza 2003; Matthews and Marsh-Matthews 2003; Marques *et al.* 2007; Geissler and Gzik 2008) and on the extent of harshness of the drought impacts that define each episode (e.g. drought timing, frequency, duration and magnitude) (Wood and Pfitzer 1960). If systems are subjected to *supra-seasonal droughts* (spanning decades to centuries) there may be critical population losses, or local extinctions (Boulton 2003; Magalhaes *et al.* 2007). As a result there is valid concern that the ongoing threat of drought could seriously reduce and simplify fish assemblages; threatening conservation of fish diversity (Magalhaes *et al.* 2002; Magalhaes *et al.* 2007).

Although it is possible for ecosystems to recover once drought has ended (Caruso 2002), there is a lack of data relating to the resilience of ecosystems during drought and the responses of fish assemblages to drought and the use of drought refuges (Closs and Lake 1996; Humphries and Baldwin 2003; King *et al.* 2003; Arthington *et al.* 2005; Magalhaes *et al.* 2007) Within the MDB it is uncertain whether an adequate network of drought refuges (e.g. flowing perennial river reaches, deep waterholes) remains to preserve native fish species/populations. This is particularly important given the historical pressures of human development and anthropogenic disturbance, which have resulted in significant loss of lateral and longitudinal connectivity throughout the MDB (Closs *et al*. 2006).

There are two phases in the response of fish to drought impacts; firstly, there is a period of increasingly harsh environmental impact where the survival or *resistance* potential of fish is critical to enable them to persist through deteriorating and unfavourable conditions. The second phase involves the alleviation of drought conditions when fish must rebuild populations to a level that ensures *resilience* to future disturbance impacts. These notions and the integration of resistance and resilience traits into conceptual and empirical models of drought impact require further exploration. A report under a sister project (MD1086) focuses more explicitly upon these issues of resistance, resilience and the responses of native fish to drought disturbance (McNeil *et al.* In prep).

1.3 The role of drought refuges for native fish

Drought acts as a serious disturbance to freshwater biota from which individuals and populations must recover to survive. Central to the issue of native fish and drought is the role that persistent aquatic habitats play in protecting aquatic life during drought, essentially serving as refuges for aquatic biota, protecting them from the various impacts of drought disturbance. The concept of biotic refuges pertains to habitats where biota can escape the impacts of disturbance events, which could threaten individual fitness or population size (Lancaster and Belyea 1997). Furthermore, the ability of biota to utilise refuge habitats requires the evolution of particular mechanisms to respond to drought stressors (Lancaster and Belyea 1997). Lancaster and Belyea (1997) define biotic refuges as places:

'In which individuals or populations can avoid the negative effects of disturbance, or where these impacts are lower than surrounding areas (or times), and where viable source populations can survive disturbance to repopulate non refuge areas following disturbance'.

Under this definition, drought refuges protect organisms from the impacts of drought disturbance; increasing survival (resistance) during drought and facilitating resilience (population recovery) when drought breaks (Sedell *et al.* 1990; Lake 2003; Robson *et al.* 2008).

In freshwater ecosystems, the habitats that serve as refuges for native fish are likely to be diverse in terms of structure and characteristics. Both large and small habitats may potentially serve as refuges and as such, refuges may exhibit differing degrees of isolation and connectedness, which may vary seasonally and/or inter-annually. In general, as refuge habitats become fewer and/or more isolated, the more resistant species will persist, whilst others will be extirpated, and post-drought recovery rates, even for the most resilient species will decrease dramatically, increasing the risk of permanent population loss (Crook *et al.* 2010b). The concept of aquatic drought refuges for freshwater fish relates to habitats that allow a source population to persist, then potentially recolonise formerly desiccated and/or impacted habitats and thus rebuild viable populations (e.g. Chapman and Chapman 1998; Rosenberger and Chapman 2000; Magoulick and Kobza 2003). It is important to emphasise that the success, or otherwise, of a refuge in protecting native fish populations cannot be ascertained until both resistance and resilience requirements have been adequately documented, and moreover these outcomes are likely to differ at a given location depending on the length, severity and frequency of drought events.

The key characteristics of refuges, such as scale, physical habitat features, biological integrity, hydrology and connectivity, will influence the survival and recovery of fish populations during drought (Crook *et al.* 2010b; McNeil *et al.* In prep; Lake In Press). It is also critical to consider potential threats to the key characteristics that make refuge habitats valuable, especially since the number of available refuge habitats tends to decrease or become increasingly isolated as drought increases (Bunn and Arthington 2002; Balcombe *et al.* 2006a; Balcombe and Arthington 2009), potentially risking permanent population losses (Lancaster and Belyea 1997).

The role of aquatic refuges in protecting freshwater biota from the ramping disturbance impacts caused by increasing drought and climatic harshness has recently come to the attention of scientists and natural resource managers (Chapman and Chapman 1998; Rosenberger and Chapman 2000; Magoulick and Kobza 2003; Morrongiello *et al.* 2006; Lintermans and Cottingham 2007; Lake *et al.* 2008; Crook *et al.* 2010a). However, there are still many significant knowledge gaps in relation to defining, identifying and prioritising drought refuges, and the management of these refuges to increase the resilience of fish populations and to maximise survival and diversity within the MDB.

1.4 Project background and objectives

In response to persistent and increasing impacts under the Millennium Drought, the Murray-Darling Basin Commission (now the Murray-Darling Basin Authority or MDBA), convened a Drought Expert Panel workshop under the Native Fish Strategy (NFS) to examine drought impacts on native fish populations. The panel outlined a number of high priority actions to be considered by the Authority, including the need to identify, catalogue and protect critical drought refuges through drought action plans and threatened species recovery plans that focus on regional agencies and jurisdictions within the MDB (Lintermans and Cottingham 2007).

Following the recommendations of the Drought Expert Panel, the NFS commissioned two studies to:

1. Improve understanding of the relationship between native fish resilience and the impacts of drought (MD1086).

2. Investigate drought management processes in the MDB and to develop plans for the protection of drought refuges (MD1087).

The focus of this report (MD1087) outlines a number of project components, each with a specific aim to progress the management of drought refuges within the MDB. The broad aims of the project were to: a) define, identify and explore the current status and management of drought refuges in the MDB (Section 2) and b) develop guidelines and an approach to identify, prioritise and protect drought refuges for native fish that can be implemented across the MDB (Section 3). The current status and management of drought refuges have been investigated using a number of techniques including questionnaires, phone interviews, a workshop and the review of relevant literature and management programs. This process was expanded to identify and prioritise refuge characteristics, functions, attributes and threats/pressures. A template was produced that outlines a process for approaching refuge identification and management across the MDB. This was then linked to a tool for collating and possibly prioritising refuge characteristics, functions, attributes and threats. Overall, this report aims to provide information and background regarding the current perception and management of drought refuges for native fish in the MDB, and to develop an effective process, supporting information and tools for identifying and protecting important refuge habitats into the future.

2. THE CURRENT STATUS AND MANAGEMENT OF DROUGHT REFUGES FOR FISH IN THE MURRAY-DARLING BASIN

This section details approaches to protecting aquatic drought refuges that are currently utilised across the MDB. Specifically, it collates current knowledge regarding refuge habitat types and key native fish species that require management protection. Finally, key threats and appropriate management options for threat amelioration are addressed, with the aim of capturing current management practices, expert opinion, knowledge and management mechanisms that are useful in protecting native fish under drought conditions.

2.1 Methodology

It is necessary to determine the kinds of habitats considered important as drought refuges for native fish and the current status of such habitats throughout the MDB. Furthermore, it is critical to identify the key threats to refuge habitats (both generally and specific to drought) and the management actions available to address these threats to protect refuge habitats and threatened fish populations. To address these questions a workshop was held with environmental managers and experts from across the MDB, preceded by a questionnaire, with the intention to identify and define priority drought refuge sites within the MDB (Appendix 6.1). The questionnaire was sent out to more than 80 representatives from a range of state and regional affiliations, agencies and research institutions (Appendix 6.2). In this questionnaire, no specific definitions of refuges were provided; allowing any locations considered important refuges by the recipient to be listed regardless of defining terms. Participants were asked to consider a number of key questions relating to drought refuges in their management areas. Sixteen surveys were returned, with thirteen follow up phone interviews being conducted with participants to expand on answers and clarify comments. While a low percentage, the returned surveys covered a number of regions across all states in the MDB (Appendix 6.1). Phone calls were also made to all individuals in an attempt to increase the number of respondents and ensure that all completed surveys were returned.

The results from this questionnaire were presented and discussed at '*A Native Fish Drought Refuge Management Workshop'*, co-hosted by the MDBA and Victoria's DSE (Melbourne; 24 and 25th of November 2008), which aimed to refine understanding of refuges status and management. The workshop was attended by representatives from almost all catchment management regions in the MDB as well as various researchers and state agency staff (Appendix 6.2). The results of the survey were combined with the workshop outputs and summarised rather than being presented independently.

The objectives of the workshop were to:

- Explore definitions of refuges used for management.
- Identify habitats that provide refuge to aquatic fauna during drought and explore criteria used to:
    - List critical refuges sites within jurisdictions.
    - Define habitat types.
    - List what species drive the listing.
- Identify any key threats to refuges.

- Outline management options for protecting drought refuges.
    - List management actions.
- List regional priorities for immediate protection.
- Identify knowledge gaps and barriers to the implementation of protection strategies.

Workshop participants were given a series of presentations outlining scientific, state policy and regional departmental approaches to drought and refuge management and undertook a series of discussion sessions to identify what current working definitions of drought refuges might include. Throughout these sessions participants were asked to consider the workshop objectives. Participants were not restricted in the spatial scale of their selection and instead defined the refuge at spatial scales they considered appropriate (e.g. individual pools or entire rivers). Similarly, selection of fish species, assemblages or general populations was not restricted. Threats could be either specific to that refuge habitat (e.g. road works or a pump site) or more generally applicable (e.g. flow regulation or invasive species). Management options included any interventions that could be used, in both the short- and long-term, to protect and/or enhance refuge habitats.

A comprehensive search of published and unpublished government and scientific literature was undertaken by the project team and a number of smaller team workshops were held to develop the ideas and themes generated through project outputs. These sessions were also used to build definitions and criteria for managing drought refuges and discuss and collate information to be used in the development of management tools and templates.

2.2 Workshop outcomes and literature review

A strict definition of refuges was not provided explicitly to workshop participants, however through discussions, the definition of refuges explored in the previous section was agreed to by participants. Two distinct approaches to defining and identifying refuges (through habitat and through species) were incorporated into a standard approach for selecting critical refuge sites.

1. The first was to use important aquatic habitats where ecology and habitat conditions were perceived to be relatively intact. These sites were often identified through listings such as Ramsar sites, Wetlands of National Significance, and Endangered Ecological Community listings, through management processes such as Victoria's Regional River Health Strategies (RRHS) and through monitoring and information sources such as the Sustainable Rivers Audit (SRA) and Index of Stream Conditions (ISC). These information sources were combined with local knowledge and processes undertaken during regional management planning such as CMA Catchment Action Plans and investment strategies.

2. The second approach was through the identification of priority fish species for management and protection. Often, known populations of threatened species are targeted for protection under legislation and these are reflected in regional management plans and investment strategies. Participants acknowledged that this approach was more a 'bottom up' process, whereby local knowledge and results from monitoring programs (e.g. SRA, ISC and regional monitoring), were used to determine populations and species that warranted protection during drought. In particular, drying habitats within known ranges of threatened species were targeted for management protection without

any process available for assessing the distribution and status of those species throughout the region.

Once species and habitat types were identified, participants were able to identify threats and management actions for protecting those assets in the short term (i.e. the immediate summer) (Figure 1).

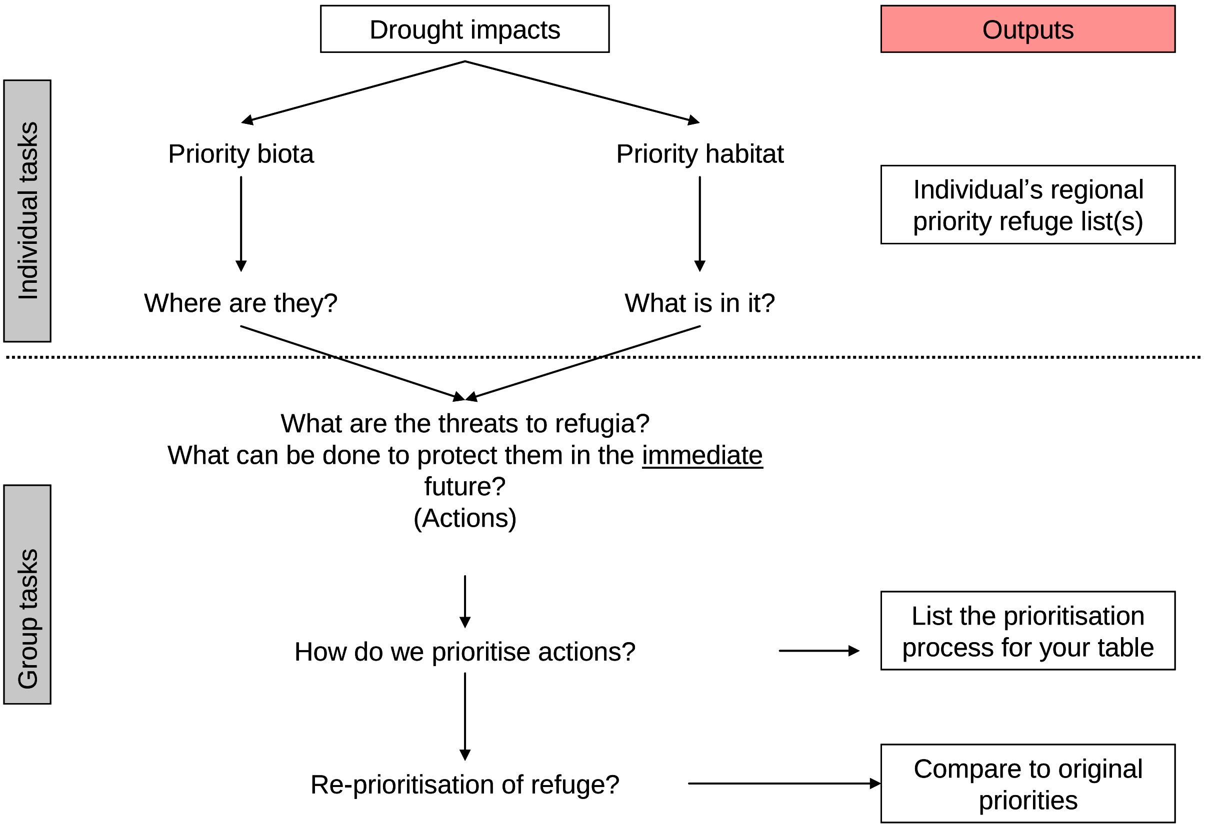


Figure 1. Workshop process for defining and identifying refuges either through species or habitats before combining information into a common framework for identifying threats and management options.

2.2.1 Drought refuge habitats

Participants identified 25 potential drought refuge habitat types (Table 1) and highlighted the importance of considering both natural and man-made refuge types, including captive refuges, such as aquaria in fisheries centres or the ornamental fish industry (although such *ex situ* refuge types were controversial and not seen as consistent with *in situ* refuges). The majority of refuges identified (14 types) were naturally occurring waterways, however, six types of man-made waterways (such as weir pools, reservoirs and constructed wetlands) were also identified as important. While of lesser value to native fish in the MDB, sediments and damp microhabitats, such as leaf litter, intact riparian vegetation and intact floodplains, were also highlighted as important aquatic refuges for the maintenance of functioning aquatic ecosystems. Furthermore, these habitats are important as they may support native fish populations through functional food webs and trophic processes.

Participants recognised the varying importance of the range of refuge habitats and were asked to assign and agree upon ecological value ratings (high, medium or low value). Ecological value was defined as direct habitat value for native fish, acknowledging that some refuge types are also critical refuges for other fauna essential for supporting native fish populations. In general, natural refuge types had the highest ecological value for native fish, while man-made refuges were generally seen as moderate quality refuges (Table 1). While regulation of waterways was seen as an impediment to protection of ecological values, regulated waterways may represent a critical refuge type and hold significant ecological values for several native fishes.

Some refuge habitats, such as farm dams and constructed wetlands, may increase in importance with conservation stocking of threatened fish translocated from impacted natural refuge habitats (Hammer *et al.* 2009). In addition, the ecological values of captive refuges are highly dependent on a range of factors such as genetic structure, presence of disease and adaptability of captive bred individuals for release into the wild. The ornamental fish industry may play an important role as repositories and captive breeding centres for some threatened fish species, with hobbyists potentially able to hold and increase captive stocks of seriously threatened fishes during drought disturbances. Again, there are significant limitations on the value of these types of refuges.

Participants were also asked to determine a permanence rating for each habitat type (Table 1) to identify those refuge habitats likely to persist during the most extreme or prolonged climatic disturbances. In contrast to the ecological value ratings, participants scored man-made refuges consistently higher than many of the natural refuge habitat types. Habitats that scored high for both ecological value and permanence were all natural habitats.

Groundwater fed streams and pools, flowing anabranches and river sections (hydrological refuges), chain of ponds, lakes and the Murray Estuary were all identified as possessing both high ecological and permanence values and all are examples (except groundwater fed streams and chain of ponds) of highly regulated habitats in the MDB. The degree of flow and water quality in these habitats is often linked strongly with the extraction of water for human uses. Interestingly, captive refuges also scored high on both ecological and permanence rankings (given habitat and criteria for selecting captive sites) reinforcing the need to consider the roles of these refuges carefully, especially given the dependence on continuous and detailed human management programs and systems.

Table 1. Refuge habitats identified through survey and workshop outputs noting broad definitions of natural, human constructed, moisture dependent terrestrial and captive refuges. (*) indicates habitats that may increase in ecological value as recipients of conservation/rescue stocking. Bold type represents habitats rated with high ecological values and high permanence.

Refuge Types	Refuge habitats	Ecological Value (for Native Fish in MDB)	Permanence
Naturally Occurring Refuges	Waterholes in intermittent rivers/streams	High	Moderate
	Wetlands	High	Moderate
	Groundwater fed streams and pools	**High**	**High**
	Flowing anabranches (regulated)	**High**	**High**
	Estuary	**High**	**High**
	Floodplains (billabongs anabranches and lagoons)	High	Moderate
	Flowing rivers/sections (hydrological refuges)	**High**	**High**
	Large Lakes	**Moderate/High**	**Moderate/High**
	Chain of ponds	**Moderate/high**	**High**
	Permanent regulated river	Moderate	High
	Salinity/evaporation basins	Moderate*	Moderate
	Upland wetlands	Low	High
	Artesian basin springs	Low*	High
Human Constructed Refuges	In-channel weirs	Moderate	High
	Constructed wetlands/urban	Moderate*	High
	Drains	Moderate	High
	Large reservoirs	Moderate/Low	High
	Irrigation channels/dams	Moderate/Low*	High
	Farm dams	Low*	High
Moisture Dependent/ terrestrial	Riparian areas	N/A	N/A
	Crayfish burrows	Low	N/A
	Sediments and substrate	N/A	N/A
	Moisture under instream debris	Low	N/A
Captive Refuges	**Captive breeding populations**	**High**	**High**
	Aquariums (Industry)	Unknown*	High

2.2.2 Drought refuge sites and locations in the MDB

Participants identified 111 critical drought refuge sites across the MDB (Appendix 6.4). A total of 16 sites were identified in South Australia (SA), 27 in Victoria (Vic), 49 in New South Wales (NSW)/Australian Capital Territory (ACT) and 19 in Queensland (QLD) (Table 2). The outputs of this component of the workshop were collated as a preliminary listing of critical refuges for management attention, outlining the location, habitat type, refugee (native fish) species, key threats and management interventions available for each site (Appendix 6-4). This details each refuge site by state, catchment and region, and includes data on the refuge habitat type, the native fish species believed to be important to management objectives and the key threats that present management issues for each site (where known). The list of critical refuges (Appendix 6-4) developed from this process should not be perceived as an exhaustive, nor definitive list of critical refuge sites for fish within the MDB.

Within the 111 refuges identified (Appendix 6-4), ten key habitat types were determined (Table 2). While larger numbers of habitat types were identified as potential refuges in Table 1, the ten key habitat types taken from the critical refuge list (Table 2) combine those types into more defined management units, reflecting the spatial scale of refuge habitats, existing management issues or avenues for management actions and prioritisation of resources for protection. The spatial scale of refuge habitats varied greatly from river reaches (where minimal detail regarding specific locations of importance within each reach was available) through to spatially explicit site locations, such as individual pools or drains.

Table 2. Total number of physical habitat types identified as high priority refuges for each state (SA: South Australia, Vic: Victoria, NSW/ACT: New South Wales & Australian Capital Territory and Qld: Queensland) of the Murray-Darling Basin. Percentages for MDB totals are shown in parentheses.

Refuge Habitat Type	Descriptor	SA	Vic	NSW & ACT	QLD	MDB total
1	Unregulated waterways (streams and creeks)	5	8	16	12	41 (37%)
2	Regulated waterways (lowland river and stream reaches)	1	10	15	4	30 (27%)
3	Lake	3	5	3	0	11 (10%)
4	Wetland	2	0	6	2	10 (9%)
5	Upland wetland	0	0	3	0	3(3%)
6	Floodplain (billabongs and lagoons)	0	2	2	1	5 (5%)
7	Weir pool	0	1	3	0	4(4%)
8	Channel/drain	3	0	0	0	3(3%)
9	Flowing Anabranch	1	1	0	0	2 (2%)
10	Estuary	1	0	0	0	1(1%)
	Total number of refuges per state by habitat type	**16**	**27**	**48**	**19**	**110**

Across the MDB, unregulated rivers (those where the majority of flow is determined by catchment rainfall and run-off rather than human management), streams and creeks were the dominant refuge habitat type, holding ~37% of refuges identified. Regulated rivers, streams and creeks were the second most common refuge habitat type (27%). Off channel lakes, wetlands and floodplain habitats made up a further 24%, while other habitat types made up the remaining 12% (Table 2). Of the dominant refuge habitats, unregulated systems were predominately identified in SA and QLD, while unregulated and regulated systems were listed equally in Victoria and NSW/ACT.

The distinction between regulated and unregulated waterways was identified as being critical to the management of refuges. Critical refuge habitats most commonly occur within unregulated waterways, often in tributaries of larger regulated systems, including upland streams and pools. While unregulated streams and creeks exhibit more natural flow regimes, the inability to regulate water means drought impacts on groundwater expression, snow melt and tributary inputs are directly expressed through reduced surface water flows. Drought, therefore, leads to the contraction of flowing reaches, frequently into a series of isolated pools, where water quality impacts such as temperature can become extreme.

Unregulated waterways provide a major challenge to managers of aquatic ecosystems, largely due to the inability to maintain these habitats through allocation of water. Drought response actions in these systems are therefore complex and difficult to co-ordinate, fund and carry out. Unregulated waterways, in particular, require long-term investment through catchment and landscape management programs, focussing on restoration of catchment and stream processes, physical habitat, riparian vegetation structure, soil health and water holding capacity, spring flows and rainfall runoff patterns, farm dam design, land use practises and local riparian water extraction and stock watering points. During extreme drought, refuges in unregulated waterways may also require more local management interventions such as emergency rescue, or direct provision of water (e.g. trucking) and water quality, particularly where priority populations of threatened species are present in individual pools or reaches (Bice *et al.* 2010).

Regulated waterways (lowland river and stream reaches) are often the most permanent habitats within the MDB, as water resources are heavily managed for consumptive and agricultural use. Accordingly these sites are potentially the last remaining refuges for some freshwater species under extreme drought conditions. However, many regulated waterways tend to have low native biodiversity, increased presence of introduced fishes, poor trophic food-webs and limited habitat availability (Gehrke and Harris 2001), and are further subjected by threats of increasing water resource development (e.g. abstraction, diversions). During drought, however, regulated river reaches may be subject to significantly reduced water levels, leading to the formation of isolated refuge pools, water quality deterioration and increased angling pressure. While many of these impacts are similar to unregulated reaches, water delivery may be available as a management intervention.

Lakes and wetlands (including upland wetlands) were identified as important drought refuges across the MDB, and recent reports have focussed closely on the delivery of water to key wetland habitats to protect against drought impacts (Meredith and Beesley 2009). These habitats can be either regulated or unregulated; for instance many lakes and wetlands in the MDB are in lowland sections of large river catchments and are dependant on regulated flows for filling. Although they were perhaps the most permanent aquatic habitats in the western MDB historically, the allocation of water away from the environment has seen many lakes and wetlands in the MDB shut off to inflows in response to drought. Almost all of the wetland refuges listed are under threat from drought impacts, the over allocation of water upstream, or the disconnection of wetland and lake channels for the preservation of channel flows.

Floodplain refuges, including billabongs and lagoons, vary in degree of regulation throughout the MDB and were identified as critical refuges in Victoria, NSW and Queensland. These habitats differ from many lakes and wetlands due to their need for quite large water volumes. These large volumes of flow are rarely available as managed environmental flows and therefore, floodplain inundation has been greatly reduced from historic levels (Closs *et al.* 2006). The water requirements for maintenance of floodplain refuges are therefore relatively high, but this is balanced by high ecological and biodiversity values. These floodplain systems are key refuges for several native fish species that are not well adapted to in-channel refuges (McNeil 2004; Closs *et al.* 2006). Floodplain habitats are often heavily impacted by agricultural practices (e.g. grazing, cropping) which are exacerbated during drought periods, leading to further declines in habitat and water quality following subsequent re-inundation (Closs *et al.* 2006).

Weir pools are an artefact of river regulation and are typically characterised by limited connectivity, poor habitat value and comparatively static water levels. Nonetheless, as artificially deepened river sections, they may be the most persistent bodies of water, even within larger regulated systems and subsequently, weir pools may be more important fish refuges than previously considered, especially during drought when normally higher quality habitats have dried up. Weir pools were identified as important refuges for large fish, such as Murray cod (*Maccullochella peelii peelii*).

Small drains and channels were not commonly listed but may be extremely important as final critical refuges for highly impacted species that are on the verge of local extinction. Drains and channels are particularly important in South Australia's Lower Lakes area where they may represent one of the last remaining, if low quality, refuges for littoral or wetland fish communities.

Two flowing anabranch systems (Chowilla and Lindsay-Wallpolla) were identified as critical refuge habitats for species adapted to lotic environments, in particular Murray cod. Although flow in these systems is artificially maintained through regulation, the flowing anabranch systems represent the only remnant permanently lotic environments within the highly regulated lower River Murray, particularly under millennium drought conditions.

The Coorong and Murray Mouth region represents the single estuarine refuge habitat area in the MDB. The region has been significantly impacted since the mid 20th century when the Murray Barrages were constructed, largely disconnecting marine, estuarine (the Coorong) and freshwater (Lake Alexandrina) habitats. Furthermore, reduced freshwater inflows due to over-allocation of water threaten the sustainability of estuarine conditions in the region. Recent reports highlight that disconnection between these habitats and increasingly marine-like conditions due to reduced freshwater inflows, have led to reductions in species diversity, changes in fish assemblage structure and reduced abundance of several diadromous species (Zampatti *et al.* 2010).

Longitudinal connectivity, whilst important throughout the MDB, is of particularly importance to the diadromous fish species of the Lower Lakes, Coorong and Murray Mouth region, for whom movement between freshwater and estuarine/marine environments represents an obligate stage of their lifecycle (Jennings *et al.* 2008). Thus, prolonged disconnection of the Lower Lakes and Coorong may lead to localised extinctions of some fish populations, as many key life stages are kept from accessing drought refuges.

2.2.3 Native fish in drought refuges

Different approaches to identifying native fish dependent on critical refuges were identified among states. While South Australia predominantly identified critical refuges through the conservation of single native species (60% single species approach) (Table 3), other states tended towards multi-species approaches, with Victoria and NSW identifying ~60% and Queensland ~88% of critical refuges using multiple species. This varied approach is reflected somewhat by the varying severity of drought across south-eastern Australia (Box 1).

Table 3. Single versus multiple species approaches used to identify critical refuges in the MDB.

State	Single Species	Multiple Species	Percent single species approach
SA	6	10	60%
VIC	8	20	40%
NSW/ACT	13	34	38%
QLD	2	17	12%

Refuges were frequently defined based on the presence of important or threatened fishes and other iconic aquatic fauna, such as the Murray cray (*Euastacus armatus*). Thirty-three native fish species were listed as being important in defining and managing critical drought refuges, of which twenty have a high conservation status under state or federal lists (Table 4). Although the species identified differed across states, there was a common pattern in the total number of native fish species recognised as important, with all states listing between 16 and 18 species (Appendix 6-5).

Seventeen of the critical refuges identified (12 in NSW and five in Victoria) did not have any fish species identified (Appendix 6-5). These sites are believed to represent either a lack of knowledge regarding the fish species present or a disconnection between the participating management agencies and local knowledge of native fish distributions.

If refuges are to be defined by their importance for protection of a single species (or small group of species) the conservation status of those species must be comprehensive and up-to-date. Use of a single species to identify refuges has the potential to overlook critical areas or species as the listed status may not necessarily reflect the local or population level status. For example, in SA a state specific document by Hammer *et al.* (2009) has provided an advisory listing of

Box 1. Management frameworks and drought impacts directing refuge protection planning.

No Species Loss: South Australia's no species loss policy has driven actions under the Drought Action Plan to protect *individual refuge populations* of threatened species, rather than integrating spatial networks or scattered remnant populations of threatened fish. This is a response to extreme drought where protection under state policy is directed towards the protection of species from extinction at the state scale.

The **Pressure-Stressor-Response (PSR)** approach in Queensland's policy and programs is currently designed to incorporate a range of habitat, landscape and biodiversity values in prioritising regions for protection. This approach leads to a broader scale, catchment and/or reach based focus encompassing *fish assemblages* rather than individual sites and species. This may reflect the relatively lower impact of drought in the northern MDB, where individual refuges are not as critical in preventing local scale species extinctions.

species using local biological information and the framework provided in the national “Action Plan for Australian Freshwater Fish” (Wager and Jackson 1993). These advisory listings highlight that a number of previously ‘unlisted’ species (both state and nationally/internationally) should have a declared and recognised conservation status within SA (Hammer *et al.* 2009).

In general, the international, national and state listings of fish species are inconsistent (see Table 4). The international and national listings are the most confined as species are ranked as being at risk at a global or national level (EPBC Act 1999; IUCN 2010), while the state listings (FM Act NSW 1979; FFG Act 1988; NCA QLD 1992; TSC Act (NSW) 1995; FM Act SA 2007) provide a more accurate, and up to date, interpretation at a local scale. A species may require a conservation listing within one state, while being common elsewhere, simply due to regional population patterns and threats. The listing methods also vary; the international, national and NSW listings utilise a tiered system (i.e. extinct, endangered, vulnerable, rare), while the SA and Victorian listings are limited to protected or threatened categories, respectively. Additionally, the EPBC, FFG and TSC Act (NSW) also list regions, populations, or assemblages of species that may require conservation status (FFG Act 1988; TSC Act (NSW) 1995; EPBC Act 1999).

The issue of whether to approach conservation planning from a single species, multi-species/ community or landscape/ecosystem level has received considerable attention globally (Franklin 1993, 1994; Tracy and Brussard 1994; Lambeck 1997; Bennett *et al.* 2009). The single species approach has been successfully employed for management and restoration of habitats through conservation of threatened species (Tracy and Brussard 1994). These species approaches (single and multi/community) have been criticised for not providing a whole of landscape solution, occurring within an adequate time frame and for monopolising a disproportionate amount of funding (Franklin 1993; Lambeck 1997). Franklin (1994) stated that landscapes managed around the needs of a single species are likely to overlook other critical elements of the ecosystems in which they occur. However, those in favour of single species approaches highlight that it is necessary to identify umbrella species (or groups of species), which allow for the needs of a community or ecosystem to be managed while efforts are focused on maintaining a defined ‘asset’ (Tracy and Brussard 1994; Lambeck 1997). Arguably, management at the ecosystem or landscape level is a preferred long-term solution, as this allows ecological processes that sustain species, populations, communities and landscapes to be maintained (Franklin 1993, 1994; Bennett *et al.* 2009). While this is clearly the longer-term solution, in extreme cases where threat mitigation must be undertaken immediately to prevent the loss of important species, the single or multi-species approach is warranted and indeed required.

2.2.3.1 Drought management groups

Assessment of the key species identified five broad groups of native fish species based on their biology and vulnerability to drought impacts.

Group 1: The most commonly identified species for prioritising drought refuges were large-bodied species. Group 1 represents fishes of high conservation value due to their declining numbers, but may still be commonly found in river and stream reaches, pools and weir pools. These are relatively widespread across the MDB, but not necessarily abundant and are conservation listed only within the southern MDB (Table 4). This list includes Murray cod, freshwater catfish (*Tandanus tandanus*), golden perch (*Macquaria ambigua*) and Murray cray, which were all important for the commercial fishing industry (now closed) and remain popular recreational species.

Group 2: Less commonly identified for critical refuges were those species that are widespread, but very patchily distributed across the MDB; often existing within increasingly isolated and threatened populations (Table 4). Group 2 is likely to represent the highest conservation priority species, as all species within this group are listed as having conservation concerns in the MDBA. Consequently, management decisions based on fish conservation may target this group when prioritising refuges, as is reflected by protection activities undertaken during the most recent drought.

Group 3: Although not nationally listed, these species were often confined to very specific habitats and/or geographical locations and were present in only a few refuge sites and often have state conservation listings (Table 4). Group 3 includes diadromous species, such as, congolli (*Pseudaphritis urvillii*), pouched lamprey (*Geotria australis*) and shortheaded lamprey (*Mordacia mordax*) [although lampreys have been recorded as far upstream as Yarrawonga], short-finned eel (*Anguilla australis*) and common galaxias (*Galaxias maculatus*) which are largely restricted to the Lower River Murray in SA. Estuarine species, such as black bream (*Acanthopagrus butcheri*), mulloway (*Argyrosomus hololepidotus*) and estuary perch (*Macquaria colonorum*), are not listed as conservation concerns, but are highly threatened under the millennium drought due to the deterioration of the Lower Lakes, Coorong and Murray Mouth (Jennings *et al.* 2008; Noell *et al.* 2009; Bice *et al.* 2010; Zampatti *et al.* 2010). Additional species were restricted to refuges in the northern MDB [e.g. Rendahl's tandan (*Porochilus rendahli*) and Hyrtl's tandan (*Neosilurus hyrtlii*)], or cooler, upland regions [e.g. mountain galaxias (*Galaxias olidus*)] (Lintermans 2007). This group is therefore likely to be under threat from very localised or specific impacts of drought and/or management during drought, requiring immediate action to protect existing refuge populations and reduce the risk of localised extinctions.

Group 4: Fishes that are restricted in distribution and/or abundance and are subsequently of conservation concern within regions where they persist (Table 4). This group includes nationally endangered species which were listed in only single refuge sites or within a couple of key drought refuges. Group 4 therefore represents extremely high priorities for immediate action to prevent drought destroying their final refuges. Two of these species, barred galaxias (*Galaxias fuscus*) and two-spined blackfish (*Gadopsis bispinosus*), are greatly restricted to cool water streams in the upper catchments of the MDB. Flatheaded galaxias is a cryptic species that very little is known about, but appears to be largely confined to wetland and floodplain habitats in Victoria and NSW. Yarra pygmy perch, a nationally listed species, are found solely within Lake Alexandrina in the lower Murray in SA in littoral lake habitats which have predominantly disappeared during the millennium drought.

Group 5: This group includes species which are common and widespread, and despite their use of refuge habitats, are unlikely to be heavily impacted by drought at the MDB scale (Table 4). These species were not listed for single species interventions, but were listed as part of broader native fish communities at critical refuge sites. While the resilience of these species is unlikely to depend on specific management strategies within individual refuges, they deserve consideration in planning and execution as they are important constituent fauna, and are often key trophic level species, supporting a range of large-bodied fish and birds. Longer term management actions are likely to be important in preserving the abundance and resilience of these species rather than short term drought response interventions.

Table 4. Drought management guilds for target fish species used to identify priority drought refuges in the Murray-Darling Basin across states (SA: South Australia; Vic: Victoria; NSW: New South Wales, Qld: Queensland), and comparison of current legislated [advisory] conservation status. Note: EX – extinct; CR – Critically endangered; EN – endangered; VU - vulnerable; RA – rare; P – protected; T-threatened; POP – population.([1] International - International Union for Conservation of Nature and Natural Resources (IUCN) Red List (IUCN 2010); [2] National - Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act 1999);[3]SA - Fisheries Management Act 2007 (SA) (FM Act SA 2007) and [Advisory listing - Action plan for South Australian Freshwater Fishes (Hammer *et al.* 2009)]; [4]Vic - Flora and Fauna Guarantee Act 1988 (Vic) (FFG Act 1988); [5] NSW - Fisheries Management Act 1994 (NSW) (FM Act NSW 1979) and Threatened Species Conservation Act 1995 NSW (TSC Act (NSW) 1995), [LL] proposed status at May 2007 (Lintermans 2007); and [6] QLD - Queensland Nature Conservation Act 1992 (NCA QLD 1992)).

Group	Species	Common Name	Distribution in MDB	Listed in MDB	International[1]	National[2]	SA[3]	VIC[4]	NSW[5]	QLD[6]	ACT	Emergency Intervention Conducted
1	*Euastacus armatus*	Murray cray	VIC, NSW	Y	-	-	P [EX]	T	-	-	-	N
	Maccullochella peelii peelii	Murray cod	SA, VIC, NSW, QLD	Y	-	VU	[EN]	T	-	-	-	Y
	Macquaria ambigua	Golden perch	SA, NSW, QLD	N	-	-	-	-	-	-	-	N
	Tandanus tandanus	Freshwater catfish	SA, VIC, NSW, QLD	Y	-	-	P [EN]	T	-	-	-	N
2	*Ambassis agassizii*	Olive perchlet	NSW, QLD	Y	-	-	P [CR]	T	EN POP	-	-	Y
	Bidyanus bidyanus	Silver perch	SA, VIC, NSW, QLD	Y	VU	-	P [EN]	T	VU	-	EN	Y
	Craterocephalus fluviatilis	Murray hardyhead	SA, VIC, NSW	Y	EN	VU	[CR]	T	EN	-	-	Y
	Gadopsis marmoratus	River blackfish	SA, VIC, NSW, QLD	Y	-	-	P [EN]	-	-	-	-	Y
	Maccullochella macquariensis	Trout cod	VIC, NSW, QLD	Y	EN	EN	P [EX]	T	EN	-	EN	N
	Macquaria australasica	Macquarie perch	VIC, NSW	Y	-	EN	[EX]	T	VU	-	EN	Y
	Mogurnda adspersa	Purple-spotted gudgeon	SA, VIC, NSW, QLD	Y	-	-	P [CR]	T	EN POP	-	-	Y
	Nannoperca australis	Southern pygmy perch	SA, VIC, NSW	Y	-	-	P [EN]	T	VU [EN]	-	-	Y

Group	Species	Common Name	Distribution in MDB	Listed in MDB	International[1]	National[2]	SA[3]	VIC[4]	NSW[5]	QLD[6]	ACT	Emergency Intervention Conducted
3	*Acanthopagrus butcheri*	Black bream	SA	N	-	-	-	-	-	-	-	N
	Anguilla australis	Short finned eel	SA	N	-	-	[RA]	-	-	-	-	N
	Argyrosomus hololepidotus	Mulloway	SA	N	-	-	-	-	-	-	-	N
	Galaxias maculatus	Common galaxias	SA	N	-	-	-	-	-	-	-	N
	Galaxias olidus	Mountain galaxias	SA, VIC, NSW, QLD	Y	-	-	[VU]	-	-	-	-	N
	Geotra australis	Pouched lamprey	SA	Y	-	-	[EN]	-	-	-	-	N
	Leipotherapon unicolour	Spangled perch	NSW, QLD	N	-	-	-	-	-	-	-	N
	Macquaria colonorum	Estuary perch	SA	Y	-	-	[EN]	-	-	-	-	N
	Mordacia morax	Short-headed lamprey	SA	Y	-	-	[EN]	-	-	-	-	N
	Neosilurus hyrtlii	Hyrtl's tandan	NSW, QLD	N	-	-	-	-	-	-	-	N
	Porochilus rendahli	Rendahl's tandan	NSW	N	-	-	-	-	-	-	-	N
	Pseudaphritis urvillii	Congolli	SA	N	-	-	[VU]	-	-	-	-	N
4	*Gadopsis bispinosus*	Two-spined blackfish	VIC, NSW	Y	-	-	-	-	-	-	VU	N
	Galaxias fuscus	Barred galaxias	VIC	Y	-	-	-	T	-	-	-	Y
	Galaxias rostratus	Flat-headed galaxias	VIC, NSW	N	VU	-	[EX]	-	-	-	-	N
	Nannoperca obscura	Yarra pygmy perch	SA	Y	VU	VU	P [CR]	-	-	-	-	Y

Group	Species	Common Name	Distribution in MDB	Listed in MDB	International[1]	National[2]	SA[3]	VIC[4]	NSW[5]	QLD[6]	ACT	Emergency Intervention Conducted
5	*Craterocephalus stercusmuscarum*	Unspecked hardyhead	SA, VIC, NSW, QLD	Y	-	-	-	T	-	-	-	N
	Melanotaenia fluviatilis	Murray rainbowfish	SA, VIC, NSW, QLD	N	-	-	-	T	-	-	-	N
	Nematalosa erebi	Bony herring	SA, VIC, NSW, QLD	N	-	-	-	-	-	-	-	N
	Philypnodon macrostomus	Dwarf flat-headed gudgeon	SA, VIC, NSW, QLD	N	-	-	-	-	-	-	-	N
	Retropinna semoni	Australian smelt	SA, VIC, NSW, QLD	N	-	-	-	-	-	-	-	N

2.2.3.2 Native fish and refuge habitat types

Understanding the habitat preferences of native fish is important for the selection of refuge sites at the onset of drought response planning. The majority of habitat types identified were associated with a wide range of species, as opposed to single target species (Table 5). This is likely to be an artefact of the lack of habitat specificity shown by many of the MDB fish species (Table 6; Closs *et al.* 2006) and provides opportunities to target a wide range of species through protection activities carried out across habitat types.

A few habitat types were, however, associated with only a small number of fish species. For example, flowing anabranches (e.g. Lindsay/Wallpolla creeks and Chowilla anabranch) were identified as critical refuge habitats for Murray cod. Hydrological diversity is seen as critical for survival during drought, and for spawning and recruitment, maintaining resilience (Meredith and Conallin 2006; Leigh *et al.* 2008). Upland wetlands were largely seen as refuges for biota other than fish, but a single population of purple-spotted gudgeon was listed as potentially inhabiting an upland wetland in southern Queensland. Drains/channels and the Murray Estuary were critical habitat for diadromous and estuarine species and threatened populations of southern pygmy perch (*Nannoperca australis*), Yarra pygmy perch (*Nannoperca obscura*) and Murray hardyhead (*Craterocephalus fluviatilis*) in the Lower Lakes region of SA. Wetland refuges were identified for a range of small bodied species, most of which are of conservation concern, such as, olive perchlet (*Ambassis agassizii*), purple-spotted gudgeon (*Mogurnda adspersa*), Murray hardyhead and flat-headed galaxias (*Galaxias rostratus*) and suggest that wetlands need to be managed carefully as critical refuge habitats for sensitive native fish species. Additionally, this group of species was also commonly listed in floodplain and lake habitats and may represent an "off-channel group" that could be targeted through monitoring and protection activities based around lentic refuges.

2.2.4 Key threats to drought refuges in the MDB

A list of general threats to refuges was generated by workshop participants, including threats to fish survival during drought and to the overall resilience of fish populations. Five general threat categories were identified: 1) direct threats, 2) flow regulation and water, 3) catchment processes, 4) barriers and connectivity and 5) fisheries (Table 6). These threats were considered applicable to drought refuges regardless of habitat type or fish species present. Specific threats, however, were collated from the critical refuges tables and provide more focussed threat identification for the various refuge types (Figure 2). There were no habitat types where all identified threats were considered important, and some refuge types were subject to very few specific threats.

Table 5. Numbers of refuge habitat types identified by workshop participants where native fish species were identified as target species or known inhabitants. Each species is also classified into Drought Management Groups based on their identification as priority species for various refuges.

Fish Species	Drought Management Group	Unregulated Waterways	Regulated Waterways	Lake	Wetland	Floodplain	Weir pool	Drains/ channel	Estuary	Flowing Anabranch	Upland Wetland	Total
Golden perch	1	6	12	1	1	1	1					**22**
Murray catfish	1	8	11	2	2		1					**24**
Murray cod	1	10	17	2	1					2		**32**
Murray cray	1	1	4									**5**
Macquarie perch	2	8	5									**13**
Murray hardyhead	2	1		6	2			3				**12**
Olive perchlet	2	10	3		2	2	2					**19**
Purple-spotted gudgeon	2	4		1	2		1				1	**9**
River blackfish	2	13	5			1						**19**
Silver perch	2	6	10	1								**17**
Southern pygmy perch	2	8	1	1	1	2	1	2				**16**
Trout cod	2	5	7				1					**14**
Common galaxias	3		1	1				1	1			**4**
Congolli	3	1	1	1				1	1			**5**
Estuarine community	3								1			**1**

Fish Species	Drought Management Group	Unregulated Waterways	Regulated Waterways	Lake	Wetland	Floodplain	Weir pool	Drains/ channel	Estuary	Flowing Anabranch	Upland Wetland	Total
Hyrtl's tandan	3	3	1			1						**5**
Mountain galaxias	3	8	4									**13**
Rendahl's tandan	3	1	1			1						**3**
2 spined blackfish	4		2									**2**
Barred galaxias	4	1										**1**
Flat-headed galaxias	4				1	2	1					**4**
Yarra pygmy perch	4			1								**1**
Bony herring	5				1							**1**
Flat-headed gudgeon	5			1		1						**2**
Pouched lamprey	5			1					1			**2**
Short-headed lamprey	5			1					1			**2**
Smelt	5	2	1			1						**4**
Short-finned eel	5		1	1					1			**3**
Spangled perch	5				1							**1**
Unspecked hardyhead	5	6	3									**9**
Total		**103**	**90**	**21**	**14**	**12**	**8**	**7**	**6**	**2**	**1**	

Unregulated and regulated waterways were identified with the highest number of specific threats (14 and 9 respectively). Importantly, angling in refuge pools, stocking of hatchery fish, groundwater abstraction and sedimentation were identified as key threats in these habitats exclusively. Pumping from refuge pools and lack of knowledge (regarding the location and importance of refuge sites) were only identified for unregulated waterways, while invasive species and bushfire were identified for unregulated waterways and upland wetlands, even though these impacts are widely considered to be highly relevant across habitat types.

Other critical habitats were associated with between two and four threat types. The allocation and diversion of water resources away from the environment was identified as a threat to all refuge types, with the exception of drains and mound springs. Floodplain and flowing anabranch refuges were largely threatened by changed flow regime and reduced flooding, while threats to weir pools and the Coorong estuary were associated with water allocation impacts and loss of connectivity (namely through the presence of weirs and barrages). Desiccation under drought conditions was identified as a key threat for unregulated and regulated waterways, lakes and channels/drains. Climate change was only identified as a specific threat to upland wetlands.

Identifying the most significant threat types is essential in developing interventions and protective actions for refuges; it is a critical step in the development of recovery plans for individual species and in river restoration. To further assist with this process, the total number of occurrences of each specific threat type was matched with the field of management that is predominantly responsible for addressing each of the key threat types (Figure 2). Allocation of water away from refuge habitats (i.e. diversion and abstraction) was a key threat to refuges in the MDB, with over 50% of critical drought refuges under threat from this practice (Figure 3). Across the MDB, 27% of critical refuges were impacted by urbanisation and agriculture (including grazing and vegetation clearance), with 20% being effected by sedimentation and loss of deep waterholes. Actual habitat desiccation under drought conditions and disconnection of refuge habitats from water supply were also commonly identified (12% of critical refuges).

Only one of the six most commonly listed threats (poor water quality) is actually a direct impact of drought. The other major threats are consequences of water management practices or catchment and land management disturbances to riparian and aquatic environments. Fisheries management and general impacts (lack of knowledge and climate change) were identified for very few critical refuges (Figure 3). Of note is the failure of managers to identify critical population scale impacts such as the development of genetic bottlenecks through increasing isolation of populations across the landscape.

Table 6. A summary of some of the general threats to refuges identified by catchment managers and experts through survey and workshop methods.

Direct Threats	Flow Regulation and Water	Catchment Processes	Barriers and Connectivity	Fisheries
Disease/pathogens	Prioritisation and diversion of water away from the environment. Includes diverting water for stock and domestic, irrigation, urban community and industry.	Erosion and incision, lowering stream beds and destroying refuge pools.	Barriers to migration/recolonisation	Exploitation -Angling – illegal and legal
Higher risk of agricultural herbicide – contamination – accidental or deliberate	Change in flow regimes due to regulation. Mechanisms – volumes, timing and duration of flows leads to: reduction in fecundity and recruitment with extended drought and increased exotic plant and animal impacts	Maintenance of too few refuges in localised areas or loss of refuge types (i.e. need to maintain wetlands, floodplains, springs and rivers	Lack of connectivity between sea, estuary and freshwater. Lack of estuarine habitat (Murray River)	Pest plant and animal impacts
Predation	Direct flow regulation reducing anabranch flows (Mullaroo, Chowilla).	Terrestrialisation of wetlands and floodplains	Isolation leads to more susceptibity to natural disasters (fires etc)	Translocation and stocking of hatchery fish
Fire related impacts	Loss of high flows between droughts	De-snagging and floodplain wood harvesting	Genetic bottlenecks through isolation that can lead to regional extinctions	
Saline ground water intrusion	Ground water extraction and management	Forestry		
Poor Water Quality.	Lower flows rivers shut down as they fill up with in stream vegetation – sedimentation – sand slugs	Catchment scale modification for land use - agriculture and urbanisation		
	Water recovery and efficiency on farms – efficiency may impact environmental flows due to lower dependence on river transfers.	Sedimentation and sand slugs		
	Loss of low and medium flooding flows leading to the desiccation of floodplain habitats.	Morphological modification to maintain waterhole duration including deepening of beds for pumping water		
	Capping of Bores – loss of habitat	Urban and road development.		
	Emergency water extractions – bushfires etc	Riparian clearing		
	Flood plain harvesting	Stock impacts - grazing, erosion, nutrification		
	Direct waterhole pumping			

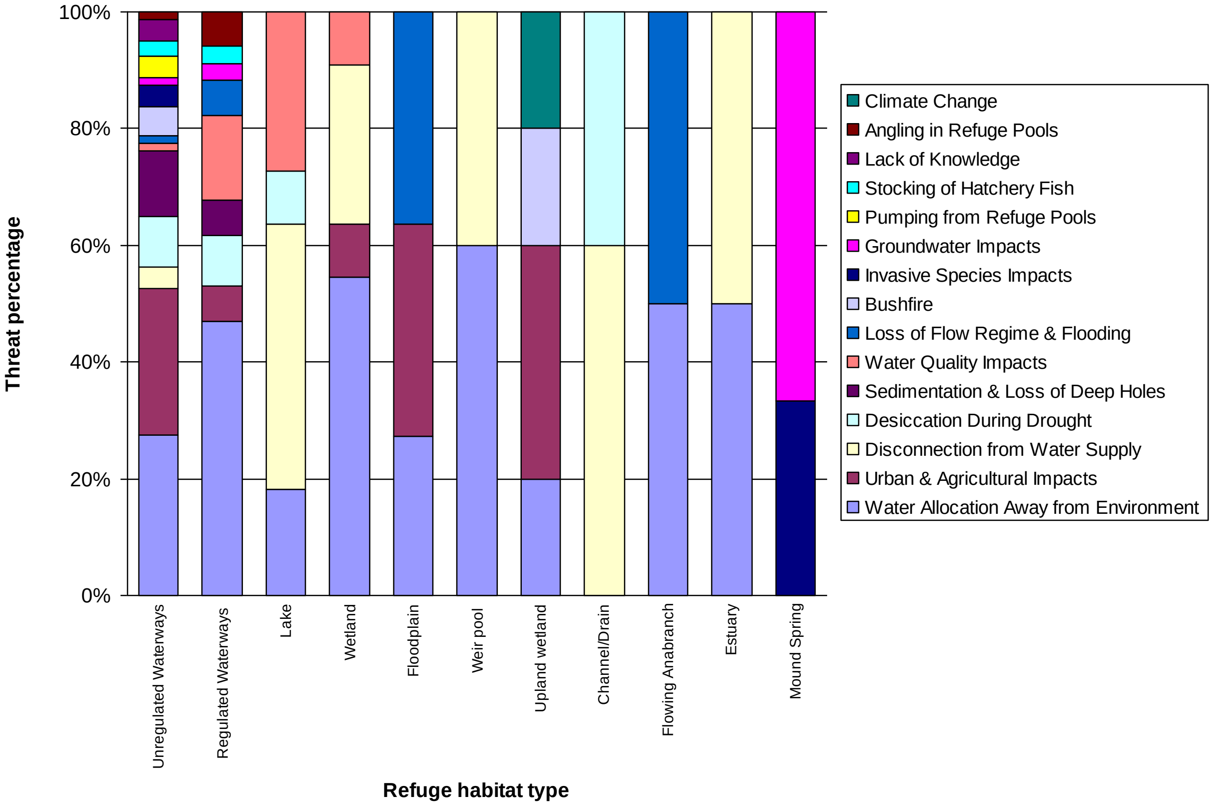


Figure 2. Specific threat types were identified for each of the refuge habitat groups identified during workshop sessions. This figure shows the proportion of habitats within each grouping that were associated with the various threat types and allows specific threats to be identified for each refuge habitat type.

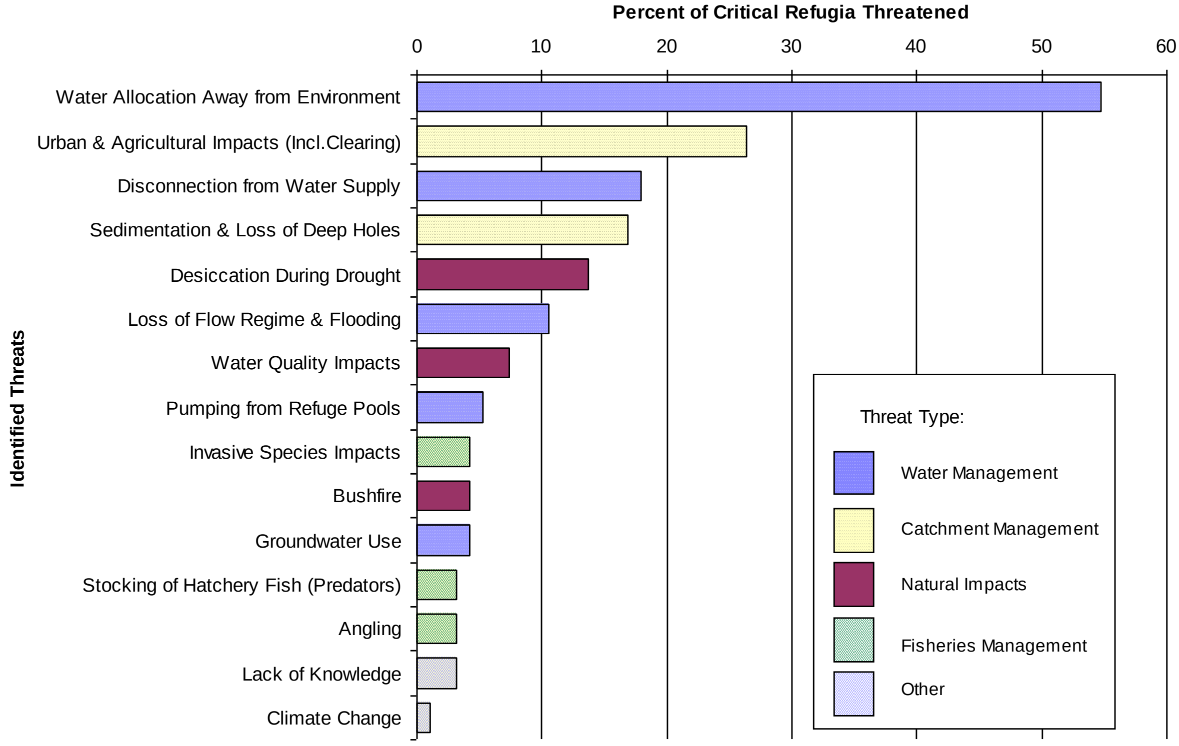


Figure 3. Each of the identified threat types were classified into management units outlining the general jurisdiction of Natural Resource Management responsible for addressing threats and related pressures on refuge habitats.

2.2.4.1 Addressing threats to drought refuges

The direct impacts of drought on aquatic refuges may be secondary in importance to the response of management jurisdictions that can determine what water is delivered to various habitats during drought periods (Box 2). The long-term reduction of threats to drought refuges may therefore best be focussed towards water and catchment management practises, closely linked with fisheries management agencies as the principle agency responsible for managing fish populations (Figure 3). Dedicated, long-term management approaches are required, even during non-drought periods, to ensure that threat impacts can be reduced over time and population resilience assured (Bond *et al.* 2008).

Box 2. Setting aside water for the environment during drought.

The delivery of water to Victoria's northern Murray Lakes to preserve threatened Murray hardyhead was achieved through co-operation of diverse groups and regional authorities. Water was delivered to Cardross, Hawthorn, Round, and Wooreinen North Lakes as outlined by DSE in a recovery plan for that species.

The **Commonwealth Environmental Water Holder** is responsible for delivering environmental water within the MDB and delivers water in line with the Environmental Watering Plan being developed under the MDBA's new Basin Plan (currently under development). The new arrangement will change the way water can be delivered to the environment, including the protection of drought refuges.

2.2.5 Protecting refuges and native fish: water resources, unregulated waterways and fisheries management

2.2.5.1 Protecting refuges through water resource regulation

The major threat to refuge persistence was the allocation of water away from refuge habitats (Figure 3). In addition, the alteration of flow regime and the loss of flooding (especially smaller floods), physical disconnection from water supply, the pumping of water from refuge pools and the extraction of groundwater were all identified as threats to critical refuges. The direct impacts of desiccation and water quality deterioration may also be addressed through the management of water. Management interventions require the planning, allocation and delivery of water back to the environment for the protection of critical refuges (Box 3; Box 4).

Box 3. Delivering water to protect refuges: case studies.

Wakool River, NSW: Monitoring of threatened species populations by NSW Department of Industry and Investment (DII) identified declining water levels, drying pools and refuge water quality as a threat to major populations of EPBC listed Murray cod. Subsequently, water provisions were delivered through the MDBA Living Murray Program (~30GL) and supplemented with NSW State Water provisions (~7GL).

Rocky Gully Wetland, SA: Disconnected from the River Murray in 2007, water quality declined steadily threatening native fish including the EPBC listed Murray hardyhead. Water quality thresholds for salinity, oxygen and pH had been set under the South Australian Drought Action Plan, by the SA Department of Environment and Natural Resources (DENR; formerly DEH). Emergency Water Allocations (~80ML) were delivered by the SA River Murray Environmental Manager. Funding was also provided by the MDBA to facilitate pumping and infrastructure works for water delivery. As a result, salinity levels were reduced from ~60,000EC to ~ 20,000EC, restoring appropriate refuge water quality conditions to support native fish through the short term.

In all cases, deliveries of water provisions were accompanied by other interventions including the physical removal of fish from high risk refuges and either the captive storage or translocation of refugee fish into higher quality refuges.

Source: Pritchard *et al.* (2009), Arkellah Hall (SA DENR-pers com), Allan Lugg & Luke Pearce (NSW DII-pers com)

The ability of jurisdictions to directly manipulate water differs between regulated and unregulated waterways. Regulated waterways provide an option for the delivery of water to protect refuges from drought impacts, consequently water resource related impacts are the principal threats to refuges in regulated waterways, lakes, wetlands, floodplains, weir pools, drains/channels, flowing anabranches and the Murray Estuary (see Table 6 and Box 4). Management interventions that can utilise water regulation to deliver flows to threatened critical refuges are therefore likely to be the most effective refuge protection tool across the majority of critical refuge habitats. In addition, the legislative and policy framework under which water might be allocated to refuge protection activities is highly dependent on state and regional legislative and policy frameworks (Table 7).

Box 4. Planning for water allocation and delivery during drought

Moonie River Refuge Depth Thresholds: A collaborative project between the Queensland Department of Environmental and Resource Management (DERM) and the e-Water Co-operative Research Centre was developed at the onset of the millennium drought to identify the role of refuges for native fish and assess the effect of a number of stressors (water abstraction, sedimentation, habitat quality thresholds).

NSW Water Sharing Plans (WSP) were developed under the Water Management Act (2000), with built-in environmental protection measures to protect threatened fish species and Endangered Ecological Communities (EEC) listed under the Fisheries management Act (2000). At the onset of severe drought, however, WSP were shut off with no additional water set aside for environmental provisions. As a result, threatened populations such as those in the Lower Lachlan River EEC, including the state listed olive perchlet, were left without a mechanism for the delivery of water as a refuge protection measure.

Victorian legislation qualifies the environment is a bonafide water user and is able to receive emergency water provisions under the Water Act (1989). This enables government to purchase water to meet critical environmental needs including the protection of critical refuge habitats for aquatic biota. Water was delivered successfully to a number of Murray Lakes during the millennium drought to ensure water quality standards for EPBC listed Murray hardyhead.

Table 7. Legislation and policy context for flow regulation and water management in aquatic refuge protection in each jurisdiction.

Jurisdiction	Acts	Subordinate Legislation	Agencies Responsible
Commonwealth	Water Act 2007		Commonwealth Environmental Water Holder
NSW	Water Management Act 2000	Water Sharing Plans	State Water
	Water Act 1912		
Queensland	Water Act 2000	Water Resource Plan, Resource Operations Plans	DERM
South Australia	River Murray Act 2003	Water Allocation Plans	SA Water
	Natural Resources Management Act 2004		
Victoria	Water Act 1989	Our Water Our Future	DSE, Regional Water Authorities, CMAs.
		Environmental Water Reserves	
		Sustainable Water Strategies	

2.2.5.2 Protecting refuges in unregulated waterways

Unregulated waterways were the most commonly identified refuge habitat type, and had the widest range of specific threats and impacts. Unregulated waterways were threatened to a greater extent than other critical refuge habitats by catchment management (or mismanagement) and other non-water resource related threats, such as urban and agricultural impacts, sedimentation, pumping from refuge pools, invasive species impacts, stocking of hatchery fish, farm dams and the impacts of bushfire.

> **Box 5. Coppabella Creek: rescue, survey and management**
>
> Threatened populations of southern pygmy perch (*Nannoperca australis*) were identified in drying pools in the Coppabella Creek, an unregulated tributary of the Murray River above Lake Hume, by regional Murray CMA staff during 2007/08. NSW DII staff undertook a survey to establish the population size and risk of drying and embarked on a rescue operation. Southern pygmy perch were rescued just prior to the pools drying and were stored at Narrandera Fisheries Centre.
>
> A follow up survey of the region was then conducted by DII staff to determine the regional significance of the rescued population and of Macquarie perch populations in the stream. Other refuge populations were discovered elsewhere in the stream so follow-up rescue operations were not required. The Murray CMA immediately developed a catchment restoration strategy to reduce future impacts of land use on the survival of pygmy and Macquarie perch during drought periods and to increase the persistence of refuge pools in the creek.
>
> Source: Gilligan *et al.* (2010)

Developing management strategies to protect unregulated waterways is likely to be difficult and require a wide range of interventions at much broader spatio-temporal scales than the delivery of water to specific refuge sites. Urban and agricultural land use encompasses a wide range of impacts and threats. These include clearing of vegetation in the catchment, riparian zone and waterways, structural works to divert and store water, cropping and stock impacts. Accordingly, management interventions are therefore equally as diverse and complex.

The required management interventions require long-term commitment at catchment scales, consistent with current Catchment Management Authority (CMA) structures (Box 5; Box 6). The key role in adapting catchment management programs towards refuge protection is likely to sit with CMA's, NRM Boards and other regional management groups. Solutions such as riparian restoration (fencing and revegetation), provision of off-channel watering points, promotion of low impact farming technologies and direct habitat restoration activities within waterways, wetlands and other refuges, are all standard components of catchment management plans and investment strategies across the MDB (e.g. NSW CMA Catchment Action Plans, Victorian Regional River Health strategies). Management interventions targeted towards protecting refuges in unregulated waterways will therefore best be served by assisting catchment managers to redirect investment towards protecting critical refuge areas, including the surrounding or contributing catchment areas.

> **Box 6**. The **Condamine Catchment Alliance** in partnership with SMEC and Queensland DPI carried out drought response surveys around the catchment to identify key refuges for Native fish. Key populations of Murray cod and other valuable species were located in areas subject to historical de-snagging and sedimentation resulting in the infilling of the deep refuge holes where cod live**.**
>
> With support from the MDBAs Demonstration Reach program and local recreational fishing clubs, key refuge sites in the river were re-snagged and in-stream scouring structures constructed to recreate deeper habitat and improve refuge values for cod.

Water resource issues, especially the allocation of water away from the environment, loss of smaller floods and disconnection from water supplies still threaten many drought refuges. In unregulated systems these threats were primarily evident through the capture of water in farm dams or in-channel storages, or the pumping of water out of channels and refuge pools, largely for agriculture, riparian rights and stock and domestic allowances. The management interventions identified for unregulated water often revolved around the cessation of water extraction during low flow periods and/or periods of extended drought.

Interestingly, lack of knowledge was highlighted as a significant threat to refuges in unregulated waterways. This was linked to a perceived focus of research in the MDB around managed water, rather than on aquatic ecosystems in general. An understanding of the environmental water requirements and ecology of native fish in unregulated systems were identified as key knowledge gaps in the protection of unregulated systems during drought. The legislative and policy framework through which natural resource and catchment management activities are carried out are far broader than those that underpin water resource use for protecting refuges (Table 8). A wide range of water, conservation and natural resource legislation exists and can be used to direct catchment management and NRM based actions. This framework is discussed in more detail in Peters and McNeil (2011).

Table 8. Legislation and policy context for catchment and fisheries management in aquatic refuge protection

Jurisdiction	Catchment Issues	Acts	Subordinate Legislation	Agencies Involved
Commonwealth	Instream and Riparian Habitat Degradation	Environment Protection and Biodiversity Conservation Act 1999		SEWPC, MDBA, DAFF, ISC
	Lowered Water Quality		National Water Quality Management Strategy	SEWPC, MDBA, ISC, CCEE
			Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000)	
			National Water Initiative	
	Barriers			MDBA, SEWPC, DAFF, IISC
NSW	Instream and Riparian Habitat Degradation	Fisheries Management Act 1994	Key Threatening Processes	CMAs, DII, DECCW, DNRW
		Native Vegetation Act 2003	Threat Abatement Plans	
		Crown Lands Act 1989		
	Lowered Water Quality	Water Management Act 2000	NSW Water Quality Objectives	DECCW (EPA)
		Protection of the Environment Operations Act 1997	State Water Management Outcomes Plan	
	Barriers	Fisheries Management Act 1994	NSW Weirs Policy	CMA's, DII
Queensland	Instream and Riparian Habitat Degradation	Fisheries Act 1994	Fish Habitat Areas	DEEDI (formerly DPI), DERM, NRM Bodies (non-statutory)
		Vegetation Management Act 1999	Regional Vegetation Management Codes	
		Land Act 1994		
		Water Act 2000		
		Nature Conservation Act 1992		
	Lowered Water Quality	Environment Protection Act 1994	Environment Protection (Water) Policy 2009	DERM (EPA)
			Queensland Water Quality Guidelines 2009	
	Barriers	Fisheries Act 1994	Waterway Barrier Works Approvals and Fishway Assessments	NRM Bodies, DPI
South Australia	Instream and Riparian Habitat Degradation	River Murray Act 2003		DENR, NRM Boards, EPA, DfW
		Natural Resources Management Act 2004		
		Native Vegetation Act 1991		
	Lowered Water Quality	Environment Protection Act 1993	Environmental Protection (Water Quality) Policy	EPA
	Barriers	River Murray Act 2003	River Murray Regulations 2003	PIRSA, NRM Boards
		Natural Resources Management Act 2004		
Victoria	Instream and Riparian Habitat Degradation	Flora and Fauna Guarantee Act 1988	Waterways Protection By-Laws	DSE, DPI , EPA, CMA's, Regional Water Authorities
		Crown Land (Reserves) Act 1978	Planning Schemes	
		Fisheries Act 1995		
		Heritage Rivers Act 1992		
		Water Act 1989		
		Planning and Environment Act 1987		
	Lowered Water Quality	Environment Protection Act 1970	State Environment Protection Policy (SEPP) (Waters of Victoria)	EPA
			SEPP (Groundwaters of Victoria)	
	Barriers	Fisheries Act 1995	Waterways Protection By-Law	DPI, DSE, CMAs
		Water Act 1989		
		Flora and Fauna Act 1988		

2.2.5.3 Protecting native fishes in refuges: fisheries management

Three of the key threats identified in the workshop fall within the realm of fisheries management agencies; 1) the impact of alien species, 2) angling and removal of native fish trapped in refuge pools and 3) the stocking of hatchery-reared fish. These represent potential impacts for native fish that typically increase during drought periods. Angling for large native fish, particularly Murray cod, was identified as a significant risk in regulated and unregulated waterways, with large fish becoming increasingly susceptible to capture in shrinking refuge habitats, particularly when limited natural food resources may also increase the likelihood of catching fish. It was suggested that fisheries legislation and policy may be modified to regulate fishing during periods of extended drought, particularly in habitats identified as likely refuges for Murray cod.

Similarly, the impacts of alien aquatic and terrestrial pest species may be magnified during drought, particularly in unregulated waterways. The impacts of terrestrial pests may be mediated through catchment management programs such as fencing off of critical refuges. Aquatic pests, in particular piscivorous fish such as redfin perch (*Perca fluviatilis*), rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*), and species that exert competitive and habitat impacts on native fishes such as carp (*Cyprinus carpio*) and eastern gambusia (*Gambusia holbrooki*) need to be considered by fisheries managers. The presence of introduced competitors and predators within refuge habitats is likely to pose an increased threat to the survival of native fish, particularly small-bodied species (McNeil 2004), during drought when space, habitat and resources may be limited. Control programs, targeted towards the removal of introduced species from critical refuge habitats, may need to be considered during drought periods, particularly where highly threatened or susceptible native species are likely to be present.

The stocking of native and introduced fish is also conducted by state fisheries agencies within the MDB. This is usually focussed on large-bodied threatened or native angling species, such as Murray cod, trout cod (*Maccullochella macquariensis*), golden perch, silver perch (*Bidyanus bidyanus*), or introduced brown trout and rainbow trout. These fish are predominantly large piscivores and are likely to have a substantial impact on native fishes within refuge habitats, particularly where threatened, small bodied fish species are present. It was suggested that stocking programs be directed away from critical refuges during and immediately following drought periods to prevent additional impacts on refuge species and allow populations of susceptible species to recover.

In addition, fisheries managers were identified as key stakeholders in the protection of key native fish species from other drought impacts such as refuge pool desiccation, deterioration of water quality, pumping of refuge pools and the isolation of wetland, lake and floodplain refuges and other habitat impacts during drought. It was acknowledged that all refuge protection processes involving native fish must consider close involvement of fisheries agencies including monitoring of drought refuges and fish status. A number of key roles in protecting drought refuges is dependent on fisheries and environmental agencies and associated research and management groups.

Firstly, these agencies are responsible for determining conservation status listing, monitoring and assessment of native fish populations and identification of threatened species distributions and locations. These roles are crucial to forecasting the potential sites of drought impacts and informing risk assessments during the onset of drought. In addition, these agencies are crucial in providing field assessment of population status and implementing rescue and captive breeding programs where key populations are threatened by drought impacts. Rescue and captive breeding are not considered optimal management solutions, but became necessary as 'last resorts' to save priority populations of threatened fish during the millennium drought (Box 7)

There is a range of specific legislative and policy drivers for protecting refuges through fisheries management (Table 8). In addition, fisheries managers work within the framework of water resource, conservation catchment management and NRM policy and legislation, as the protection of threatened native species, populations, habitats and water are covered across these levels of jurisdiction.

2.2.5.4 Protecting native fishes: beyond refuge protection

When *in situ* refuge management options are unavailable or when pre-drought planning and preparatory works have been insufficient to protect vital refuge attributes (e.g. water quality), the physical removal of threatened native fish populations may be required. This situation occurred across the MDB during the drought and the MDBA has provided supporting funds for a number of rescue interventions (Box 7). While these rescued populations are protected in the short term, several issues threaten the successful return of these rescued fish to the wild, including diseases, inbreeding and risks of releasing genetically modified fish into the wild (Box 7).

Box 7. Emergency fish rescues

In South Australia's Eastern Mount Lofty Ranges and lower River Murray, isolated catchment populations of river blackfish, southern and Yarra pygmy perch, Murray hardyhead and southern purple-spotted gudgeon were taken from drying refuge habitats and transferred to aquarium facilities at Aquasave and the South Australian Research and Development Institute Aquatic Sciences Centre in Adelaide and the Murray-Darling Freshwater Research Centre in Mildura. Captive breeding programs are being developed in the hope that re-introduction and re-establishment of these species will occur once the drought eases. Diseases and in-breeding can develop during captive rearing and genetic investigations are being undertaken by SA DENR and Flinders University to evaluate the best adult pairings to mitigate the threat of inbreeding and loss of genetic vitality during captive programs, and the risks of returning genetically modified captive fish to the wild. DENR and Aquasave have also embarked on a program for locating alternative natural storage facilities such as dams and ponds where captive populations may be less exposed to impacts of aquarium life. Yarra pygmy perch have been released into two such dams with great success to date.

Similar rescues have occurred in NSW for southern pygmy perch in Coppabella creek and olive perchlet from the mid-Lachlan River with rescued fish stored at Narrandera Research Station.

In north-eastern Victoria, threatened populations of Macquarie perch and barred galaxias have been transferred to the Snobs creek hatchery and a purpose built facility at the Arthur Rylah Institute where cold-water conditions can be maintained for galaxiids.

Sources: (Backhouse *et al.* 2008; Pritchard *et al.* 2009).

To develop a common strategic process for fish rescue operations during the drought, a 'Fish Rescue Workshop' was held in 2007 by the MDBC. It is recommended that the proceedings from this workshop be updated and released to assist managers with this aspect of refuge management.

2.3 Conclusions

The process of questionnaires, interviews and workshop sessions successfully collated a wide range of information regarding the perceptions and priorities of managers and experts regarding aquatic drought refuges in the MDB. Refuges were defined as any habitat within which fish are able to survive the impacts of drought (resistance) and provide a source of individuals from which populations can be expanded and rebuilt during climatically benign periods intervening drought periods (resilience). As such, a range of aquatic habitat types was identified as providing refuge to native fish, including regulated and unregulated waterways, as well as a range of off-channel habitats such as lakes, wetlands and floodplain habitats, and a range of smaller scale habitats such as channels/drains, springs, weir pools and estuarine habitats. A diversity of native fish were identified as being important species for the identification of refuges, with threatened species and iconic or valuable species being the primary drivers of refuge identification and protection. Native fish within refuges are faced with a range of threats during drought periods, which differ according to refuge type. However, many of the threats to native fish in refuges relate not specifically to drought impacts but to the management of water and the broader environmental condition of catchments.

Whilst drought responses tended to focus upon the protection of fish from the impacts of drought, existing management rarely focusses on building the resilience of ecosystems and aquatic populations to withstand climatic impacts such as drought. Management actions that are most effective at protecting refuges occur over large temporal and spatial scales. Actions should not be specific to drought periods or refuge habitats but instead be implemented on an ongoing basis to improve the overall condition of aquatic habitats and to secure water (Bond *et al.* 2008; Crook *et al.* 2010b). To maintain viable fish populations, connectivity across the landscape (which allows recolonisation and population mixing) needs to be a key focus for management. This applies to a) the identification of refuge areas, and b) to the identification, protection and restoration of connective pathways. Without maintaining large scale connectivity; resistance and resilience are likely to decrease under future drought conditions.

Crook *et al.* (2010b) presented a conceptual framework to guide management of fish populations during drought that included a number of approaches for maintaining this management scope. Their approach included quantifying spatial variation in the severity of drought impacts on particular habitats (rivers, wetlands etc.), assembling information on drought sensitivities of regionally important species, identifying high risk areas (based on species sensitivity and drought severity), determining and implementing appropriate management actions (pre-emptive, responsive) and monitoring outcomes and disseminating information on outcomes.

During drought periods, short term intervention responses to protect refuges are often dependent on the actions of fisheries and NRM agencies responsible for protecting threatened and valuable native fishes. However, to protect refuges, there is a need to develop structured strategies for obtaining and delivering water (pre-drought) that would assist in decreasing the need for emergency response/intervention flows (during drought) . The dearth of legislation, the fragmentation of agencies and the uncertainity surrounding responsibilities, is a major hurdle to cohesive planning and actions regarding in relation to the protection of refuges.

The process of questioning, assessing and collating a range of expert opinions regarding critical refuge sites proved challenging since there were some perceptible differences in terminology and characterisation of particular refuge types. In addition, managers tended not to be highly trained ecologists (i.e. with post-graduate qualifications), which may represent a gap in the ability for identifying and comprehending local ecological issues and priorities at the local scale. For instance, a key outcome of the workshop was the recognition that 'lack of knowledge' poses a significant threat to refuges. It should be acknowledged that there is a general lack of detailed knowledge about the impacts of climate change and flow on effects of drought on aquatic systems (Lake 2003, McInnes *et al.* 2003; Lake *et al.* 2008; Dai 2011). Equally, ecologists often do not understand the complexities involved in managing natural resources (which requires not only consideration of the science, but also the political, social and economic impacts). These issues highlight the need for cohesive linkages between research scientists and managers for the protection of drought refuges (beyond personal contacts) and a more strategic approach for integrating research, monitoring and scientific expertise with management activities (as will be discussed in more detail later).

The list of critical refuges (Appendix 6-4) developed from this process should not be perceived as an exhaustive, nor definitive list of critical refuge sites for fish within the MDB. It is recommended that this be treated as a preliminary listing and that more effort is made to develop the detail and knowledge of these sites drawing upon specific catchment based knowledge, information and resources. It is a key recommendation of this report that refuge identification and protection plans be developed exhaustively for each catchment within the MDB, taking into account local management frameworks and information sources.

In order to support this approach, a process was undertaken by the project team to develop a set of criteria capturing key assets, threats and management interventions and developing a spreadsheet based tool for collating information on individual refuges. This tool was to be incorporated into refuge management plans and developed into a spatial database to collate refuge information and data layers across the MDB. In this way key knowledge about refuge habitats could be captured and utilised to improve the management of drought impacts across the MDB.

3. DEVELOPING AN APPROACH TO PROTECTING DROUGHT REFUGES IN THE MURRAY-DARLING BASIN

To develop a consistent planning approach for identifying and protecting refuges across the MDB, it is necessary to explore mechanisms that enhance or maintain resistance and resilience of native fish and refuges. Section 2 focussed on the status of refuges and outlined management approaches undertaken to-date. This section will outline how the development of management interventions at local and regional scales requires an understanding of specific values, characteristics, attributes, functions, threats/pressures and management options for native fish and refuges. In addition, a framework for collating data and knowledge to assist managers in prioritising refuge habitats for protection during drought and for building management programs to improve the resilience of refuge populations during non-drought periods was developed.

This report is largely focussed on freshwater fish, however, the approach developed for fish may act as a surrogate for a wide range of biota and indeed for aquatic ecosystems and communities (MDBA 2010). As native fishes in the MDB possess no adaptations to survive without surface water, they are more sensitive to the impacts of drought than many other aquatic biota that possess additional mechanisms for surviving during drought periods. For example, many species of zooplankton and aquatic plants possess desiccation resistant life stages than can persist during dry periods and many others can burrow into moist soils or simply move to another habitat to avoid these impacts (Lake 2003). Whilst native fish largely remain the focus of this report, other aquatic biota should also be considered when forming refuge management plans.

3.1 Pilot valleys

An approach to identify and protect refuges was developed in conjunction with regional agencies and jurisdictions from two *pilot valleys*, the Goulburn Broken (GB) catchment in northern Victoria and the Moonie catchment in south-eastern Queensland. These two catchments were chosen as they represent upland and lowland examples, and extremes of climate and drought intensity across the MDB. Furthermore, they offered contrasting contexts in which to test the ideas of drought refuge management, both in terms of their policy drivers, challenges and key differences in ecosystem characteristics.

3.1.1 Pilot valley governance frameworks

The following section explores the governance frameworks within which each of the pilot valleys operate, and which must be considered before refuge management plans can be effectively integrated into relevant governance and policy frameworks. For each pilot valley, the state governance context will be explored, followed by the regional framework for integrating refuge protection plans.

3.1.1.1 Victorian refuge governance framework

> **Box 8. Environmental Water Reserve (EWR)**
>
> The amendments to the *Water Act 1989* made in 2005 provide legislated protection to environmental water in Victorian river systems. This *Environmental Water Reserve (EWR)* outlines the amount of environmental flow that each of Victoria's rivers must receive by law.
>
> From an operational perspective, the EWR includes two types of water:
>
> - Water that is held in storage and actively managed to meet specific environmental needs (environmental entitlements); and
> - Water that is available as a result of rules on consumptive use (conditions on bulk entitlements and water licences, management plans and caps on water use).

The management of riverine health and protection of aquatic habitats in Victoria, while not focussing directly on protection of refuges, provides a broader focus on improving and maintaining habitat quality during drought and non-drought conditions. The process and legislation for governance of the MDB aquatic habitats and resources in Victoria are advanced and well structured. The Victorian Department of Sustainability and Environment (DSE) oversees the protection of aquatic resources by utilising amendments made in 2005 to the *Water Act 1989* (Water Act (Victoria) 1989); where *Environmental Water Reserves* (Box 8) and regional sustainable water strategies are legislated documents. The responsibility for coordinated catchment management is vested in 10 Catchment Management Authorities (CMA's). These regional organisations, established under the *Catchment and Land Protection Act 1994*, effectively undertake the role of 'caretaker of river health'.

The governance framework for Victorian rivers is clearly articulated in the Northern Rivers Sustainable Water Strategy, and is linked to conservation listings in the *Flora and Fauna Guarantee Act (1998)*(FFG Act 1988) and *Fisheries Act (1995) (Fisheries Act (Vic) 1995)* (NRSWS; see examples in Box 9) (DSE 2009), Our Environment, Our Future: Victoria's Environmental Sustainability Framework (DSE 2005) and Victorian River Health strategy (DNRE 2002). Underpinning these state-wide documents are the Regional River Health Strategies and the Regional Dry Inflow Contingency Plans (Box 10) (e.g. GBCMA 2005, 2008) that identify rivers of high community value, establish objectives for river systems and river reaches, and action plans to achieve them. Reaches are defined as high priority based on a number of criteria, including presence of threatened species, ecological condition, social value, and significant sites (i.e. GBCMA 2005). However, there are also site specific, fish community and species specific projects run within this broader framework (GBCMA 2005, 2008; DSE 2009).

> **Box 9. Northern Region Sustainable Water Strategy (2009)**
>
> The Northern Regions Sustainable Water Strategy of Victoria aims to:
>
> - identify and understand threats to water availability and quality, including the implications of climate change;
> - assist regional communities to adjust to reduced water availability;
> - ensure entitlements for towns, industry and the environment are secure;
> - encourage economically viable and sustainable agriculture;
> - improve choice and flexibility for entitlement-holders to manage the risks imposed by drought and climate change;
> - protect and, where possible, improve the health of rivers, wetlands and aquifers from the impacts of drought, climate change and other risks; and
> - recognise and respond to indigenous and other cultural and heritage values associated with the region's rivers and catchment areas
>
> Source: DSE 2009.

Goulburn Broken: regional governance framework

The GB catchment comprises the catchments of the Goulburn and Broken Rivers and a small part of the Murray Valley, upstream of Echuca, covering a total 10.5% of Victoria's total land area. Terrain varies from the high ranges with an altitude greater than 1200 m to the Murray Plain with an altitude of around 100 m, while the northern half of the catchment is relatively flat. Consequently, the GB catchment consists of a combination of upland unregulated headwater streams, a heavily regulated mid region (regulated rivers, water storages and abstractions) and a lowland heavily regulated region that supports agriculture. A number of the Goulburn rivers major tributaries rise on the northern slopes of the Great Dividing Range. Rainfall varies substantially throughout the catchment; in the south east high country there are cool winters with persistent snow and an average annual rainfall greater than 1600 mm, while in the far north of the catchment average annual rainfall is less than 450 mm, only accounting for one third of the annual evaporation in that area. The hydrology within the GB catchment is driven by a combination of rainfall-runoff, ground water and snow melt. Within the catchment the Goulburn river is one of the most highly regulated major rivers in Victoria, if not Australia (CRC for Catchment Hydrology 2004). The GB region has been significantly impacted by drought through reduced stream flows, which have been exacerbated by catastrophic bushfires (Hames and Tennant 2009).

Box 10. Dry Inflow Contingency Plans (DICPs)

DICPs provide Victorian CMA's with the basis and direction for the management of significant rivers and associated wetlands, floodplains, flora and fauna if lower than average flows are experienced. Typical management objectives within the plans aim to:

- avoid local extinction of priority species and communities;
- maintain geographic distribution of priority species and communities to facilitate their recovery;
- avoid catastrophic events such as fish deaths;
- maintain the values and functions of Ecologically Healthy Rivers;
- avoid loss of priority areas where significant past ecological investment has occurred;
- minimise impacts on human health; and
- maintain the ecological values and functions of priority streams and wetlands.

Source: GBCMA 2005, 2008

The governance of the GB catchment emanates from state and regional agencies. The over-arching guidelines are set within the state level legislations which are then adapted by the regional Goulburn Broken Catchment Management Authority (GB CMA) through initiatives such as the Goulburn Broken Regional River Health Strategies (GB RRHS) and Goulburn Broken Dry Inflow Contingency Plans (GB DICP) (GBCMA 2005, 2008). GB RRHS and GB DICP operate with the overall intention to enhance and protect high priority rivers, maintain ecologically healthy rivers, improve habitat quality and prevent damage during low flow conditions The CMA provides strategic direction, direct investment and NRM programs towards the protection of refuges within the catchment. Both the GB RRHS and GC DICP cost the actions required, and provide a clear alignment of management objectives with the investment objectives, including alignment within flagship areas for state funding through the Victorian Investment Program (VIP) (GBCMA 2005, 2008).

The GB DICP focuses on protection of aquatic habitats within the GB catchment during drought conditions and specifically addresses the threats, risks and actions for reaches under a range of lower than average flows throughout the catchment (GBCMA 2008). The GB DICP highlights the annual environmental water entitlements available, which are allocated through the *Environmental Water Reserve* (Box 8). This indicates a clear ability to deliver water to drought refuges for the maintenance of assets identified in the DICP.

3.1.1.2 Queensland refuge governance framework

In Queensland (QLD) the governance of freshwater aquatic resources is spread across three main groups: Queensland's Department of Environment and Resource Management (DERM), Fisheries Queensland, which operates under the Department of Employment, Economic Development and Innovation (DEEDI) and the CMA/NRM Alliance groups. DERM is primarily responsible for the management of water delivery and aquatic resources at a state wide and catchment scale. Fisheries Queensland is responsible for management and monitoring of fish and the regional CMA/NRM Alliance groups conduct on-ground monitoring and restoration at regional scales. While project consultation often includes representatives from each of these groups, there are relatively few collaborative projects. There is a range of legislation within Queensland that provide for the protection of water and riverine habitats, including the *Water Act 2000, Wild Rivers Act 2005, Fisheries Act 1994* and *Nature Conservation Act 1992*. In addition there are a range of subordinate legislations including the Water Resource Plans (WRP's; Box 10), Resource Operation Plans (ROP's) and Fish Habitat Areas (Peters and McNeil 2011).

Box 11. Water Resource Plans (WRP)

Under Section 38 of the *Water Act 2000*, the Minister may prepare a Water Resource Plan for any part of Queensland to advance the sustainable management of water.

Water Resource Plans represent the first legal provision for addressing the importance of adequate water flows for maintaining the health of freshwater ecosystems (Phillips B. (compiler), 2003).

The purposes of Water Resource Plans are:

- to define the availability of water in the plan area;
- to provide a framework for sustainably managing water and the taking of water;
- to identify priorities and mechanisms for dealing with future water requirements;
- to provide a framework for establishing water allocations;
- to provide a framework for reversing, where practicable, degradation that has occurred in natural ecosystems, including, for example, stressed rivers; and,
- to regulate the taking of overland flow water.

DERM is legislatively driven by the *Water Act 2000, Environmental Protection Act 1994* and *Nature Conservations Act 1992* and is responsible for the implementation of the Stream and Estuary Assessment Program (SEAP) and the Environmental Flows Assessment Program (EFAP; Box 12). These programs assess and report on aquatic condition and the provision of water in QLD (DERM 2010b). The SEAP program monitors ecological condition of waterways, using a Pressure-Stressor-Response (PSR; Box 13) framework and is designed to investigate, prioritise and assess the effect of human activity (e.g. flow management) on aquatic systems and identify potential causes of ecosystem condition decline (DERM 2010b, 2011).

The EFAP program was established to assess the effectiveness of the WRP's and ROP's by defining and monitoring ecological assets within each WRP area. Assets were defined as a species, biological function or place of value for which water is known to be critical. (DERM 2010b). WRP's have been developed for most catchments areas within QLD.

Box 12. Environmental Flows Assessment Program (EFAP)

The EFAP assesses the environmental performance of flow management strategies implemented through the WRPs and ROPs. Development of WRP/ROP for a specific catchment must precede the EFAP. EFAPs have three stages:

1. Identification and prioritisation of ecological assets that are dependent on the provision of critical flow related conditions.
2. Ecological asset monitoring and assessment.
3. WRP review: information gathered in step 3 is used within an environmental assessment component of the WRP review. A risk assessment framework assesses the effectiveness of the current plan.

Fisheries Queensland's primary legislative responsibility is sustainable fisheries management, policy and habitat protection as prescribed under the Queensland *Fisheries Act 1994* (DEEDI 2009). However, the *Nature Conservation Act 1992* is responsible for the protection of threatened species; once a species is listed as threatened, it is no longer covered by the *Fisheries Act 1994* and the responsibility moves to DERM. As yet, no MDB fish species in QLD are listed under the *Nature Conservation Act 1992*. The *Fish Habitat Areas* is a subordinate legislation that allows for an area to be a 'Declared Fish Habitat Area' which offers protection to areas from alteration and degradation, although most areas recognised are coastal regions and none exist within the QLD MDB.

Box 13. Pressure-Stressor-Response (PSR) conceptual framework.

- *Pressures* are human activities in the landscapes that have the potential to adversely influence aquatic ecosystems.
- *Stressors* are physical, chemical and biological attributes of the aquatic ecosystem which are controlled by *natural drivers* and when altered by *pressures* become threats to the ecosystem and elicit an ecological response.
- *Responses* are the changes in ecosystem structure and function which occur due to exposure to *pressures* and *stressors*.
- *Natural drivers* can include climate, topography, vegetation, soils, geology and geomorphology. These create landscape variability and will underlie the design of most ecosystem research and monitoring.
- *Management controls* are the processes and activities that natural resource managers use to ensure *pressures* are environmentally sustainable. Controls are applied to *pressures* and in some cases *stressors*.

For example, a *pressure* could be vegetation clearing for intensive agriculture. An associated *stressor* would be increased sediment washing into the waterway. The in-stream biological *response* may include loss of a submerged macrophyte species because of the limited light availability.

Source: (DERM 2011)

QLD CMA/NRM Alliance groups are non legislative organisations that sit completely independent from DERM. Funding is mostly provided through external commonwealth funding bodies such as the MDBA. CMA/NRM Alliance groups work in close collaboration with Fisheries Queensland, often providing funding, monitoring and survey projects.

Moonie: Regional Governance Framework

The Moonie Catchment is a mostly unregulated, lowland system in the headwaters of the MDB. There are substantial inter-annual variations in rainfall and temperature throughout the catchment. The climate is semi-arid with average annual rainfall of less than 600 mm per year, while the average annual evaporation is considerably greater, ranging from 1800 to 2200 mm (Sternberg et al. 2008). The hydrology of the Moonie River is dependent on rainfall-runoff, as opposed to groundwater or base-flows. Rainfall through the region generally occurs as sporadic large-scale events, shaping the hydrology of the river to a system dominated by periods of low/no flow, and inconsistent well defined flows and floods (Sternberg et al. 2008). Therefore, there are natural periods where the river becomes a series of disconnected waterholes which provide refuge habitats (DNRW 2007a).

The Moonie River is subject to moderate water regulation, with several weirs and off-channel storages. There is also a significant number of sites where water is pumped for unregulated stock and domestic use (Sternberg et al. 2008). The catchment was less impacted by the recent drought than some regions downstream.

Box 14. Refugial Waterholes Project

Intended to fill knowledge gaps regarding the persistence, quality and connectivity of refuges by assessing:

- The persistence time of waterholes in the Moonie catchment.
- Parameters that could be used to estimate persistence.
- The influence of sedimentation and changing morphology on persistence.
- If changing food availability influences body condition of resident biota, and whether feeding preferences change.
- The depth threshold before the habitat quality is reduced.
- The spatial extent of connectivity among aquatic populations in the Moonie.

Outcomes identified that a predictive relationship between depth and persistence time in waterholes existed and could be used as a parameter for persistence. Waterhole quality was identified to be temporally and spatially variable, however, inherent resilience and resistance traits exhibited by fish allowed them to persist with changed conditions. Connectivity within the Moonie was identified as high, which allows for the fish to persist in the system by enabling migration to areas with better habitat, food and spawning conditions.

Source: (DERM 2010b)

While the Moonie catchment does not have a specific plan for the management of aquatic resources during drought, the Moonie River WRP identifies a key prioritised asset to be ‘waterholes as refuges’. Consequently the Moonie River was highlighted as a focus catchment for DERM’s Refugial Waterholes Project conducted in collaboration with Griffith University (Box 14) (DERM 2010b). Modelling suggested that in the absence of flows, the persistence time of these refuges can be determined using waterhole depth profiling (DERM 2010b).

Given that a reduced water depth decreases the persistence of waterholes during drought conditions, sedimentation was identified as a key threat to waterhole persistence. While a re-snagging project to mediate the threat of sedimentation was undertaken in the Condamine River (conducted by the Condamine Alliance group), no such action has been undertaken for the Moonie River Catchment.

3.1.2 Pilot valley workshops

The pilot valley studies were designed to trial the development of a refuge management planning process in collaboration between NRM management groups and the project team and to develop a template for identifying and protecting drought refuges at a local or regional scale throughout the MDB. The project team developed a general refuge management approach that set out to establish definitions and criteria for refuge identification and management. This was summarised in a short paper (Appendix 6-8) that included an approach for collecting information that could be built into a management plan for refuge protection. Based on the criteria and approach outlined in this discussion paper, science providers and managers in both the GB CMA and DERM were asked to develop an approach for developing drought refuge management plans. Rather than be overly prescriptive, it was believed that, at least at the initial stages, each pilot valley region should be free to develop a planning approach that best aligned with their own management needs and frameworks. Given that neither catchment had a specific process for the identification and protection of refuges, each was asked to consider how they would structure a management planning approach, preferentially based on the criteria and management document provided (Appendix 6-7). The resulting workshops provided significant modifications to the guidelines for refuge management and format of criteria matrices.

The specific aims of the pilot valley process were to:

- Develop refuge management criteria and explore approaches for identifying and prioritising refuge habitats, values, attributes, threats and management options.
- Develop a consistent approach (template) for refuge management planning that can serve as a template for implementation across the MDB.
- Capture existing mechanisms for protecting refuges within the pilot valley catchments and explore the legislative and policy framework within which drought management plans could be developed.
- Identify the linkages in management planning approaches that would facilitate the integration of refuge management plans into existing management frameworks.
- Trial the application of this approach to current management in pilot valley catchments.

Goulburn Broken Workshop

As a first approach, a workshop was conducted with available staff from GB CMA (17th December 2009, Shepparton) to provide an assessment of the applicability of available information and data sources to identify, categorise and prioritise refuge habitats at the valley-scale. Workshop attendees were asked to assist in the identification of indicators that could be used to define key drought refuge attributes and assets, threats and management options within the broad criteria pertaining to refuge values: hydrology, physical habitat, spatial connectivity and biological integrity.

Outcomes from this workshop revealed that multiple indicators with specific measures are needed to prioritise refuges for management or interventions. The GB CMA felt that they had sufficient data (e.g. sand slugs, significant fauna, fish deaths, loss of instream habitat, proximity of barriers, risk of algal blooms and risk of poor water quality) at the site scale to begin assessing individual refuges.

Moonie Workshop

In the Moonie catchment, protecting individual refuges was not deemed adequate for the protection of the system, because the processes within this system function at broader, landscape-scales. The approach for the Moonie was to assemble a workshop of stakeholders, experts and individuals who have an interest in native fish management within the Moonie catchment. A workshop was held on the 17th of March 2010 (at Griffith University, Brisbane) with workshop attendees representing the following organisations: Griffith University, Department of Natural Resource Management (now DERM), Department of Primary Industries (now DEEDI, QLD Fisheries), Condamine Alliance, Queensland Murray-Darling Committee and South West NRM Ltd (Regional NRM bodies). The aim of this workshop was to develop a 'process' (with the assistance of DERM and Griffith University) that could be used to identify what sort of information is needed to develop a management plan for the protection of native fish values that are supported by drought refuges within the Moonie Catchment at adequate broader, landscape scales that can also be transferrable to similar catchments. The workshop drew heavily on collaborative research by Griffith University and DERM funded by the eWater CRC, and from an Honours Thesis by David Sternberg, Griffith University (Sternberg et al. 2008). The approach used could be applied at smaller scales as the focus is on the functional role of refuges in supporting values associated with native fish.

The process utilised (Appendix 6-9) encapsulated the PSR conceptual framework (DERM 2011). The process was heavily influenced by existing DERM programs (e.g. SEAP, EFAP and Coal Seam Gas Risk Assessment), which have used PSR type approaches successfully. The method used in the workshop identifies:

- the ecological values of the Moonie catchment system (in particular those linked to fish) and the current status of these,
- how drought refuges support these values, including the supporting attributes of refuges and the relevant spatial and temporal scales over which they operate,
- the potential stressors/specific threats to these values, and
- what human activities (pressures) result in the stressors identified.

The information gathered was used to link the pressures/stressors to drought refuge attributes and ecological values. Throughout the process, aspects were scored and ranked according to their importance, influence and/or current status.

By doing this, threatening processes were prioritised, which would inform the selection of appropriate and effective management responses. Prioritisation could then be considered for each value, across all values weighted equally, or across all values weighted by their perceived importance in the Moonie River. In order to identify potential target locations for implementation of on-ground restoration/protection activities, information on known refuge pools in the Moonie was compiled following the methodology developed in the GB workshop. Therefore, the process provided useful information to inform and prioritise the management of threats to refuges in order to protect values associated with native fish.

The information gained from these workshops (when combined with results from section 2), was used to develop a consistent, yet flexible, set of criteria for inclusion within the drought refuges management template.

3.2 Criteria for refuge management

Refuge management can be broadly separated into six essential criteria: values, characteristics, attributes, functions, threats and pressures and management strategies (refer to Glossary).

3.2.1 Refuge values

Values are the aspects of refugia that are identified as important to protect or restore. This may be an individual species, a community or a habitat. Based on the existing management approaches outlined in earlier sections, it is important to highlight that values can relate to habitats (i.e. individual sites, reaches, catchments), or biota (biodiversity or threatened or valued fauna). Alternatively, values can also apply to human aspects such as cultural, aesthetic or recreational values. Management values may be identified for individual, localised sites, as well as for larger areas such as river reaches and catchments. The wide range of physical habitats identified as critical refuges highlights the diverse scales at which refuges exist and operate. Furthermore, spatial and temporal scales of refuge management vary in relation to the defined management values (Appendix 6-8).

Scale is one of the most important determinants of refuge value (Ross *et al.* 1985). Aquatic refuges may span large reaches of main river channels (including artificially constructed habitats) or streams (perennial and intermittent), through to off-channel lakes, lagoons, waterholes, wetlands, anabranches, and billabongs (Arthington *et al.* 2005; Closs *et al.* 2006; Bond *et al.* 2008). At larger spatial scales, important refuge values will undoubtedly reflect a greater heterogeneity of physical refuge habitat types, thereby serving to protect and maintain a greater diversity of fish species (Arthington *et al.* 2005; Bond *et al.* 2008). Ultimately, it is important to protect and maintain refuge habitats at the stream and/or river reach scale (Bond *et al.* 2008). However, droughts progress, refuges dry out and the number of critically important refuges (often those protecting the last members of fish populations or species) decrease; therefore, identification and protection of refuges at local scales (e.g. individual waterbodies) becomes increasingly important.

3.2.2 Characteristics

Refuge characteristics are defined as the broad concepts critical for maintaining healthy and resilient refuge habitats. Refuge characteristics will differ within and between individual refuges, across catchments, regions and states; however, defining, identifying and prioritising the key characteristics relevant to the management area is critical to the planning process. There are several governance frameworks already developed for identifying refuge characteristics such as Queensland's AquaBAMM (DERM 2010a) and Victoria's Regional River Health Strategy (DNRE 2002). The development of refuge characteristics is likely therefore to represent such local approaches and in some cases, these existing frameworks can drive or inform refuge criteria identification. The refuge characteristics are often complex, albeit simply stated, and underpinned by a number of attributes and functions that are important to maintain in order to support the broader characteristics.

Four broad characteristics were identified:

- physical habitat.
- hydrological processes.
- spatial connectivity (networks).
- biological integrity.

Physical habitat outlines the structural nature of refuges; providing healthy, functioning ecosystems that support resistance and resilience of native fish. Physical habitat includes the presence/absence or quality of: deep pools, instream habitat (macrophyte beds, woody habitat, cobbles and interstices, spawning and nesting substrates, riparian vegetation, roots and bank structure) and water physico-chemistry. For example, the presence of deep waterholes is particularly important to the physical habitat of drought refuges providing relatively permanent refuge conditions for large and small-bodied fishes (Balcombe *et al.* 2006b; Arthington *et al.* 2010).

Hydrological processes consider the persistence and behaviour of surface water. Important hydrological processes may include: reliable groundwater levels and connections (e.g. headwater springs, some wetlands), maintenance of lotic habitats for dependent species, and flow regimes that are close to natural and meet the environmental water, flow and water quality requirements of native fish and aquatic ecosystems. The presence of permanent higher flow levels may be important for cool water or flow-dependent species, or for maintaining spawning and recruitment for flow dependent spawners. Alternatively, flushing flows may be required to scour organic materials or dissipate poor quality water that can build up during drought.

Spatial connectivity (i.e. hydrological connectivity) between refuges and other aquatic habitats is highly important, facilitating ecological or population connectivity that is essential for maintaining resilient and viable populations of aquatic biota as well as ecosystem processes. Desiccation drives a progressive disconnection between remnant waterbodies and increases the potential number of barriers to fish movement. Prolonged disconnection of refuges may have significant impacts, such as preventing spawning, feeding, predator avoidance and dispersal movements and therefore may threaten recruitment and re-colonisation. Additionally, the loss of individual refuges will be of varying consequence to native fish populations depending on the nature of refuge 'networks' and the dispersal traits of the species, wherein other connected refuges may persist to serve as a source population to lost refuges upon the resumption of connecting flows. Some specific connections are crucial for native fishes, especially connections to wetland and floodplain habitats for small bodied wetland species, and connections to marine systems for diadromous and estuarine species that periodically utilise freshwater habitats. These connections may by especially important following drought to facilitate recolonisation and population mixing over previously denuded or isolated regions.

Biological integrity of refuges is crucial, since refuges are not always guaranteed sanctuaries for fish and other aquatic biota. Refuges must provide adequate shelter, food and habitat and support population dynamics for short lived species that may be trapped in refuges for longer than an individual's life span. The threat of parasitism and disease typically increases as conditions in refuges, and the health and immune strength of fish, deteriorates due to reduced resources and water quality. The presence of predators or competitors, especially introduced species, can also threaten the survival of fish species within refuge habitats. Intact trophic processes and food webs are important for sustaining fish over long-term drought periods. Even in healthy and intact refuges, these processes are likely to be heavily impacted by drought. Greater inherent natural biological and ecological integrity within a refuge will allow for a greater likelihood that it can support a more natural composition of native fish.

3.2.3 Attributes

Attributes are defined as specific ecological assets of refuges that make up the broader refuge characteristics. These attributes are likely to differ very little across refuges or regions as they form the basis of aquatic ecosystem values commonly acknowledged to maintain freshwater ecosystem health. Attributes are often the specific target of management actions for catchment, water and biodiversity managers. For example, intact and well structured riparian, aquatic and catchment vegetation communities, permanency of water, the maintenance of deep holes, appropriate water quality and trophic processes, and diverse biotic assemblages are all attributes of aquatic habitats that are likely to be critical to the refuge value.

Loss of attributes may lead to a decline in the quality of refuges and a loss of the refuge characteristics and functions that they support. It is likely that desirable attributes will be added or removed based on the objectives of individual managers and sites, but it is hoped that the following list provides a basis for identifying key attributes. Within identified refuge characteristics, key attributes include:

- Physical habitat:
    - Intact riparian zones
    - Presence of deep holes
    - Substrate quality and variability (i.e. presence of rocky substrates)
    - In stream structure (i.e. presence of woody habitat, aquatic vegetation)
    - Range of depths
- Hydrological processes:
    - Permanence of water
    - Groundwater Inputs (not saline)
    - Natural flow regime
    - Permanent flow
    - Presence of flow regulation infrastructure
- Spatial connectivity (networks):
    - Lateral connectivity (wetlands, lakes, floodplains)
    - Longitudinal connectivity (connectivity to up- and downstream habitats including marine systems)
- Biological integrity:
    - Intact ecological processes
    - Diverse and abundant/intact riparian vegetation
    - Diverse and abundant/intact macrophytes
    - Diverse and abundant invertebrate assemblages

3.2.4 Functions

Refuge functions provide ecological services and/or processes (alone or in combination) that are essential for maintaining attributes at a sustainable or adequate level. The specific functions that are important for individual refuges are likely to vary significantly depending on the nature of each individual refuge habitat. Hence managers will need to integrate a high degree of local knowledge and experience into the identification of appropriate functions. For example, diverse and abundant/intact riparian vegetation is a key attribute of refuge waterholes and provides a range of ecological functions. A dense layer of groundcover provides bank stability and intercepts sediment moving from adjacent catchment areas as well as providing habitat for invertebrates that may be essential components of foodwebs and inputs from terrestrial food sources. Upper riparian layers may serve additional functions such as the provision of leaf litter that drive ecosystem processes (Reid *et al.* 2008) and shade streams maintaining lower water temperatures and evaporation rates. In deteriorated systems the functions provided by refuges are often reduced, causing a range of flow on effects. As a result, the improvement or restoration of key functions is often the desired outcome of many restoration activities. For example, restoring riparian vegetation communities through fencing, stock removal, planting and off- channel watering points will assist with the restoration of stream ecosystem processes necessary to improve fish habitat. NRM monitoring programs may be directed towards measuring improvement to functions by sampling water quality, fish populations or invertebrate densities.

3.2.5 Threats and pressures

The approach taken here to identifying threats to values, characteristics, attributes and functions of refugia is consistent with current PSR approaches to resource management (DERM 2011). The identification and amelioration of key threatening processes and related impacts are extremely important in refuge management. Threats (direct impacts), such as sedimentation, diversion of water, waterhole pumping, and lack of riparian structure or de-snagging, have a direct impact upon the desirable attributes that refuges provide. In turn, these threats impact on the overall fish values supported by refuge habitats through the deterioration of key attributes. Threats are likely to differ across the MDB and will need to be identified by managers based on local processes and stressors.

It is important to identify the pressures, often indirect anthropogenic impacts, that relate to various management fields such as catchment management (e.g. land use, sedimentation etc.), water resource management and introduced species and fisheries management, which address threats and allows identification of management pathways for ameliorating processes through Natural Resource Management strategies and programs. These are similar to the threat management groups identified in section 2.2.4 and represent the scale at which Natural Resource Management programs are developed as it reflects the broad processes or areas of human concern that relate to the natural environment. Therefore, identifying the management scale at which specific threats can be addressed will help to develop actions and interventions for managers to protect and restore refuge quality.

3.2.6 Management strategies

Management strategies should mitigate threats and pressures, and also maintain and protect refuge characteristics, functions, attributes and values. Management strategies will be vastly different across refuges, often with a small number of management strategies available for individual refuges. These strategies are often developed by Natural Resource, Water, Catchment and Fisheries Management agencies and identified and prioritised through various catchment plans (NSW), regional river health strategies (Victoria), Water Resource Plans (WRPs) and NRM plans (SA and Queensland). The difficulties posed for environmental managers in developing sound management options are considerable. For example, in unregulated waterways the range of management options may be limited by factors such as investment, NRM/CMA board and local/federal government priorities, accessibility, stakeholder relationships/agreements, or the simple inability to deliver or redirect water during drought.

3.3 Refuge Management Template

In order to develop holistic, long-term refuge management plans and monitoring strategies, a *Refuge Management Template* was developed. The template incorporates the criteria described in Section 3.2 to strategically direct refuge management, by defining the values, characteristics of and threats to refuges. The template is intended to increase understanding of the role that refuges provide in supporting the resistance and resilience of aquatic biota and habitats at the relevant scales.

The proposed Refuge Management Template outlines a strategic process that fits within three phases: (1) *Defining*, (2) *Analysing* and (3) *Implementation*, which presents six key questions to address the criteria defined for refuge management (Figure 4). Working through these phases provides a strategic process that allows managers to begin to: 1) define values, management objectives, scales, refuge characteristics, attributes and functions; 2) analyse threats and pressures, and 3) implement adaptive management strategies and monitoring. The template also highlights how *research* and *governance* (refer to Glossary) interact throughout the process and assist in addressing the relevant questions (Figure 4).

The flow of information through phases may follow three pathways: 1) strategic direction, 2) information and 3) actions. These pathways generally flow bi-directionally through all phases, but there are instances where the pathways are more direct (Figure 4). Overall, flow pathways illustrate how the system is in constant flux (i.e. new information is gathered, management priorities change).

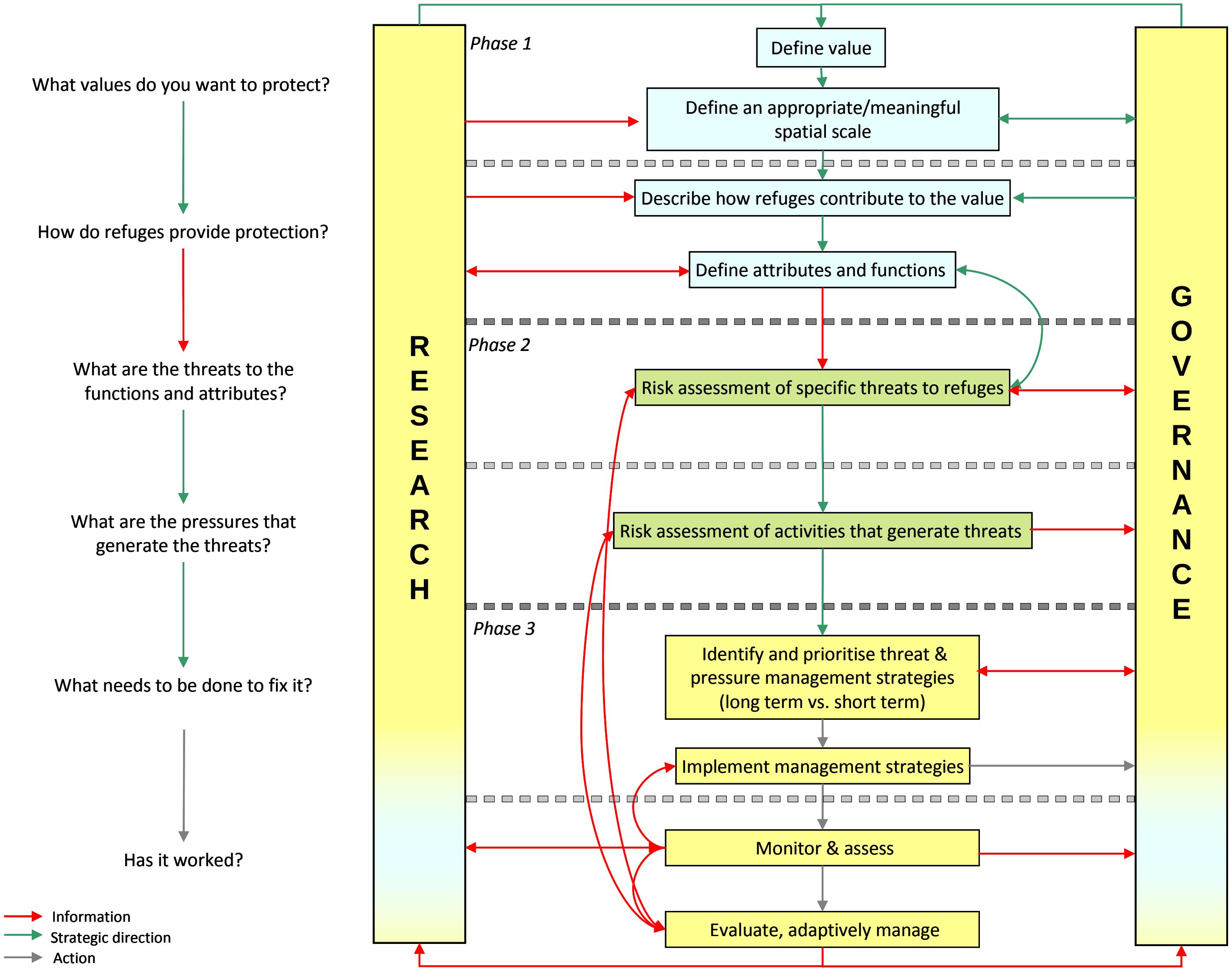


Figure 4. A schematic diagram illustrating the essential strategic directions, information and action pathways that are involved in planning for the protection of drought refuges.

3.3.1 Phase 1 - Defining

What values do you want to protect?

Define value(s):

Values may encompass the need to protect or restore species, populations, communities, individual habitats and/or river reaches (see section 3.2.1). Refuges may be identified based on the presence of fish or other aquatic biota of conservation, recreational or cultural significance, or as sites of cultural significance. While research and governance bodies may highlight the particular value of a refuge, governance may also provide leverage through legislation and policy frameworks at Federal, State and regional levels (refer to Glossary). Careful assessment of values minimises the risk of omitting species and/or refuges; and also refines the analysis of threats/pressures and the implementation of efficient monitoring and assessment programs.

Define appropriate management scale:

In this step, it is critical to consider the spatial scale that will best support the defined value(s). This may range from landscape (i.e. whole river-reach) to local scales (i.e. individual refuge pools). Consideration of scientific research and governance re-emphasises the importance of considering the spatial scale of all impacts on refuge habitats when identifying refuge management approaches. Furthermore, identification and protection of local scale refuges may assist in directing regional governance (e.g. CMA's and NRM boards), restoration (e.g. Landcare and Greening Australia) and community groups.

Investments may be sought and projects commissioned to protect the refuge values at the appropriate scale. Engagement and communication must be sought to fit within the framework of partner and stakeholder responsibilities. Similarly, linkages to broader policy, management targets and legislative responsibilities need to be identified and met.

How do refuges provide protection?

How refuges contribute to the value(s):

The essential aim of refuge management is to protect organisms; and hence increase their resistance during drought and facilitate resilience. Therefore, it is important to consider how the selected refuge(s) contribute to protecting or enhancing resistance and resilience requirements for target species. Characteristics (see section 3.2.2) that support resistance and resilience are often complex, even if simply stated, and are underpinned by a number of attributes and functions.

Define attributes and functions:

Research bodies may assist in providing data sources to identify attributes and functions (see sections 3.2.3 and 3.2.4). This step will also ensure that ancillary data sources, such as rainfall and climate data, geology, land use, vegetation mapping (and so on) are included; thereby maximising the application of the refuge databases. Acquiring and collating data provides a means for lobbying those who may be responsible for the protection of refuges. Depending on the availability and sources of data the information derived from this step is likely to differ between catchments/regions, as will the application of these data sets to individual refuges. Indeed, knowledge gaps derived from database development will help to develop holistic, long-term management plans, providing information and strategic direction for Phase 2.

3.3.2 Phase 2 - Analysing

What are the threats to the functions and attributes?

What are the pressures that generate the threats?

Risk assessment of specific threats and pressures to refuges:

The identification of threats and pressures (see sections 2.2.4 and 3.2.5) is an integral step in developing risk assessments; which provide a process for analysing and evaluating the likelihood and consequence of selected threats. Utilising a risk analysis matrix allows for prioritisation of threats; with highest priority given to threats/pressures with major-catastrophic consequence rankings and likely-very likely likelihood rankings (resulting in extreme risk levels) (Table 9). In addition to analysing direct threats and pressures to refuges, the risk associated of 'taking no action' must be evaluated. Consideration of the relevant governance responsible for targeting water resource allocation, natural resource, catchment and fisheries management also need to be considered.

Table 9. Generic example of an environmental risk assessment matrix. The matrix requires that the user ranks the consequence and likelihood levels for each threat. The table can then be used to obtain the risk level for each threat (e.g. MAJOR consequence + UNLIKELY likelihood = MEDIUM threat).

		Likelihood ranking			
		Unlikely *(and might happen only rarely)*	**Possible** *(unlikely but could happen at some time)*	**Likely** *(and will probably happen at some time)*	**Very likely** *(and will almost certainly happen)*
Consequence ranking	**Catastrophic** *(Destruction of protected wildlife/plants and habitat)*	MEDIUM	HIGH	EXTREME	EXTREME
	Major *(Severely effecting protected wildlife/ plants or habitat, long term)*	MEDIUM	MEDIUM	HIGH	EXTREME
	Moderate *(Environmental impact on wildlife/ plants or habitat, short term)*	LOW	MEDIUM	MEDIUM	HIGH
	Minor *(Concern for environmental impact)*	LOW	LOW	MEDIUM	MEDIUM

3.3.3 Phase 3 - Implementing

What needs to be done to fix it?

Identify, prioritise and implement threat and pressure management strategies (long-term vs. short-term)

The mitigation of threats and pressures to refuges may be hindered through management interventions directed towards allocating and delivering water and restoring critical habitat components and processes (e.g. sections 2.2.4 and 2.2.5). There is a need for developing a process to begin prioritising and listing the management strategies that can be realistically achieved within program and funding constraints. This process of identifying and prioritising management strategies should be implemented into management and restoration plans.

Has it worked?

Monitor, assess, evaluate and adaptively manage

One of the most important and often overlooked processes of intervention and management programs is to determine the outcomes. Targeted monitoring is needed to assess and evaluate whether the actions taken are adequately protecting refuges. This includes developing: a) condition baseline monitoring programs to detect trends and b) question driven, long-term monitoring programs to evaluate the effectiveness of management options.

Baseline monitoring is essential because it provides a basis upon which changes or extremes can be evaluated (Lindenmayer and Likens 2010). Pre-existing and/or baseline data may be required to address key questions and provide ecological and/or biological information on key target species (e.g. thresholds and/or trigger points). Pre-existing/baseline data may also provide a means of determining which areas may be suitable for "control and/or reference" sites, or which sites are suitable for post-drought recovery assessments.

Similarly, when based on well-defined and scientifically rigorous hypotheses, targeted monitoring programs can provide key information about the mechanisms and processes occurring within drought refuges (Lindenmayer and Likens 2010). These programs are most valuable when conducted over long time scales (≥ 10 years) and at local spatial scales because they are well-suited for providing in-depth perspectives which are vital for developing, understanding and initiating management strategies. They are also flexible enough to ensure that the scale of monitoring matches the spatial and temporal dimensions of the question being addressed.

Therefore, a robust monitoring strategy needs to:

a) address threats and pressures to refuges,

b) collate and maintain knowledge of key aquatic-dependent species status and population sustainability and

c) critically assess outcomes of specific management actions.

Conducting on-ground monitoring is integral to drought refuge management and must feed information and strategic direction directly back into all preceding phases. If monitoring strategies are well designed and outcomes are well documented and widely available, this will provide a critical tool for informing future decisions and management plans (Boys *et al.* 2008). Through adaptive management, targeted monitoring programs may provide a means of assessing the efficacy of existing management strategies and guide future management strategies that are likely to vary considerably over time, allowing new information to guide future actions and further refine values and management strategies. Consultation between on-ground staff and relevant partners, stakeholders and agencies is imperative. It is integral that monitoring strategies do not further impact already stressed populations or sites and adequately address threats and pressures. It is probable that monitoring and management strategies will need to be vastly different across refuges based on site specific values, attributes, functions and threats/pressures, and therefore may need to be tailored for each region and possibly each individual refuge.

3.3.4 Scoring refuge criteria for management prioritisation

Criteria for refuge management (Section 3.2) can be used to assess specific attributes, functions, threats and pressures *within* and *between* sites. The relevant criteria for specific sites or values can be assessed, allowing the relative quality of refuges to be compared and also providing a process for determining the highest priorities for management strategies.

Criteria that support site values and improve characteristics are those that increase attribute/function scores. For example, a desirable attribute may be the maintenance of ‘intact riparian zone’ or ‘instream structure’; however, to achieve a high score for these attributes, a number of functions must also be maintained, maximised, restored or protected (e.g. Table 10). Similarly, scoring threats and pressures for each site (or value) will aid in directing management strategies (e.g. stock access, riparian clearance, the provision of adequate/natural flow) to improve the characteristics, attributes and functions of refuges. Threats and pressures that impact heavily on values, characteristics, attributes and function will also receive a higher score (e.g. Table 10). In combination, the scores for attributes/functions and threats/pressures can be used to identify sites where priority habitats are at greatest risk due to drought.

These criteria were developed into the Critical Refuge Assessment Process using an Excel workbook (Figure 5) as an example of how a systematic scoring process may assist managers (or relevant agencies/bodies) in their development of drought refuge management plans. This process would ideally be conducted within Phase 1 and 2 of the Drought Refuge Management Template (Section 3.3.1 and Section 3.3.2). Accordingly the first step in this process is to define the value(s) of the selected refuge. While examples of some typical values for refuge protection/management are provided within the Critical Refuge Assessment Process (by selecting the associated drop down box), there is also the option to add site specific values, if needed. Additionally, in those instances where an individual site is considered to have multiple values, another column may be simply added for that site and then scored for each value. Hence, within every site/value column an individual score for each criterion is allocated based on best available knowledge/information. A description associated with each attribute/function and threat/pressure score can be provided in the Critical Refuge Assessment Process (e.g. Table 10). If a particular criterion is absent and/or irrelevant to that site; then it may be excluded from the analysis (or alternatively given a zero score). Hence the final assessment allows a standardised way of comparing and prioritising within and between refuges. Once the values for refuges are defined and the criteria scored, the process of scoring and/or ranking values may help to identify threats and pressures. Relevant triggers for management strategies (including site-scale interventions) that target the enhancement of specific attributes/functions or mitigate threats/pressures, may then be identified and prioritised.

Table 10. An example of how attributes, functions, threats and pressures may be identified, recorded and scored for the 'physical habitat' characteristics: 'intact riparian zone' and 'instream structure', in drought refuges.

Characteristic	Attributes	Function	Attribute/ Function Score		Threat /pressure	Threat / Pressure Score	
Physical Habitat	Intact Riparian Zone	*Ground cover (vegetation, leaf litter and woody habitat) present (providing stability and nutrient exchange, preventing erosion)*	0	Absent/Not relevant	*Local stock access (sediment compaction and vegetation loss)*	0	Absent/Not relevant
			1	Low stability		1	Minimal direct stock access
			2	Low-moderate stability		2	Low – moderate direct stock access
			3	Moderate stability		3	Moderate direct stock access
			4	Moderate-high stability		4	Moderate – high direct stock access
			5	Stable banks		5	High level of direct stock access
		Canopy cover (e.g. trees, shrubs) present (providing shade)	0	Absent/Not relevant	*Riparian clearance (vegetation loss)*	0	Absent/Not relevant
			1	Minimal cover		1	Minimal riparian clearance
			2	Low – moderate cover		2	Low-moderate riparian clearance
			3	Moderate cover		5	Moderate riparian clearance
			4	Moderate – high cover		4	Moderate-high riparian clearance
			5	High cover		5	Major riparian clearance
	Instream structure	*Woody habitat (providing micro habitat)*	0	Absent/Not relevant	*De-snagging of river and stream channels*	0	Absent/Not relevant
			1	Not representative of natural state		1	Minimal de-snagging
			2	Low – moderate natural state		2	Low-moderate de-snagging
			3	Moderate natural state		3	Moderate de-snagging
			4	Near natural state		4	Moderate-high de-snagging
			5	Natural state		5	Major de-snagging
		Intact macrophytes (providing micro habitat)	0	Absent/Not relevant	*Alteration to natural water regime (e.g. high or low static water levels)*	0	Absent/Not relevant
			1	Not representative of natural diversity		1	Natural/near natural water regime
			2	Low – moderate natural diversity		2	Low – moderate alteration
			3	Moderate natural diversity		3	Moderate alteration
			4	Near natural diversity		4	Moderate – high alteration
			5	Natural diversity		5	Major alteration

Refuge Assesment	Site Evaluation #1	Site Evaluation #2
Refuge Name	Snakes	Ladders
Catchment Name	Far far away	Woop woop
Catchment Location	lowland	mid-catchment
Latitude/Longitude		
Refuge Type	weir pool	pools in river
Values	diverse native freshwater fish assemblage	Populations of conservation priority species

Can insert different values that have been defined for the management and protection of a particular refuge.

Select using following scale:
Score 0 = absent/not relevant or inclusive values up to
Score 5 = abundant leaf litter and diverse small and large sized woody debris present

Attributes/Function

Characteristic	*Attribute*	*Function*	*Site 1 Score*	*Site 2 Score*
Physical habitat	Range of depths	*Not applicable*	0	5
	Deep pools present	*Not applicable*	3	0
	Instream structure	Woody debris	4	2
		Intact macrophytes		
	Substrate quality and i	Bedrock substrate		
		Cobbles		
	Intact riparian zone	Stable banks		
		Ground cover	5	2
		Canopy cover	5	0
Hydrological Processes	Permanence of water	*Not applicable*	0	0
	Flow	Permanence	1	0
		Natural regime	0	0
	Groundwater inputs	Local source	0	0
		Upstream source	0	1
	Flow regulation infrastr	Lateral	2	5
		Longitudinal	5	1
Spatial connectivity	Lateral	Wetlands	0	0
		Lakes	1	3
		Floodplain	1	3
	Longitudinal	*Not applicable*	3	1
Biological integrity	Intact ecological proce	*Not applicable*	3	1
	Intact macrophytes	Native biodiversity	5	5
	Intact fauna assembla	Native biodiversity	4	3
		Threatened species	5	1
		Total attribute score	***61***	***41***

Threats/Pressures

Characteristic	*Threat/pressure*	*Sub-threat/pressure*	*Score*	*Score*
Physical habitat	Sedimentation	*Not applicable*	2	5
	De-snagging	*Not applicable*	0	0
	Riparian clearance	*Not applicable*	0	2
	Water quality	Dissolved Oxygen	0	1
		Salinity	0	0
		Temperature	0	0
		Turbidity	0	0
Hydrological processes	Farm dams	*Not applicable*	0	0
	Local flow regulation	Extraction	0	2
		Diversions	0	0
		Inputs	0	0
	Non-local flow regulation	Impoundments	0	0
		Extractions	0	0
		Lateral	0	0
		Longitudinal	0	2
Spatial connectivity	Barriers	Lateral	0	0
		Longitudinal	2	1
	Floodplain inundation possibility	*Not applicable*	0	0
Biological integrity	Stock access	Local access	2	5
		Upstream access	1	1
		Adjacent access	0	0
	Invasive species threat	*Not applicable*	2	4
		Total threat/pressure score	***9***	***23***

Total scores may provide a relative comparison within and between sites. Analysis of these criteria shows the Snakes site scores a slighly higher attribute/function score than theLadders site relating to: more intact instream structures and intact riparian zone and presence of high conservation species (for example).

Total threat/pressure scores may provide a relative comparison within and between sites, which may help in the prioritisation process and assist in targeting management strategies

Figure 5. Screenshot of applicability of the Critical Refuge Assessment Process for defining, identifying and prioritising site-scale drought refuges values, attributes and threats.

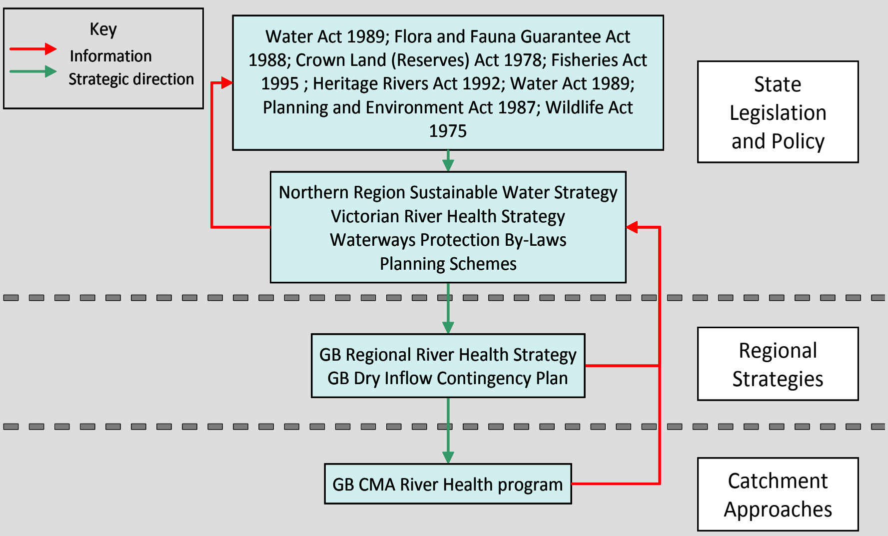
3.3.5 Feasibility of refuge management template and scoring process to pilot valleys

The Refuge Management Template was developed with the intention that it could be applied to refuge protection and management throughout the MDB. The template is also intended to increase understanding of the role that refuges provide in supporting the resistance and resilience of aquatic biota and habitats at the relevant scales. The feasibility of the template and scoring process was assessed against the approaches to refuge management currently undertaken in the pilot valleys.

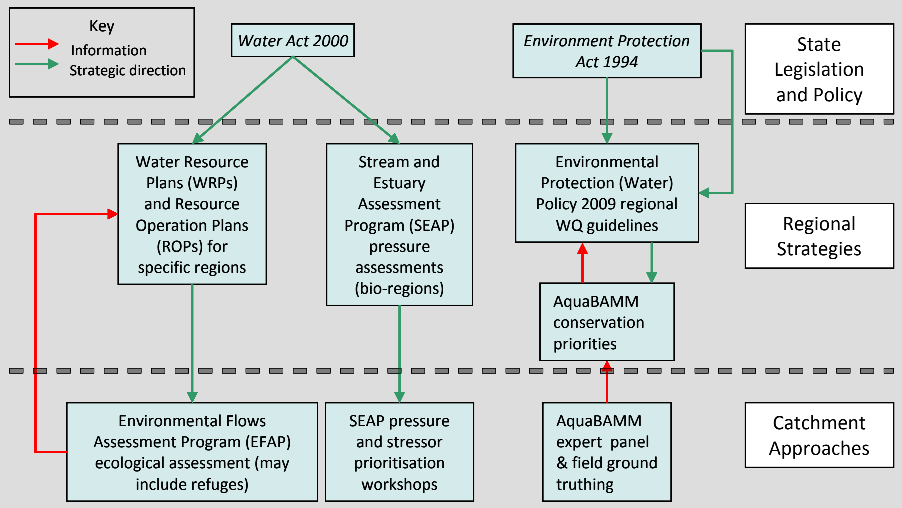
While the GB and the Moonie catchment approaches (current programs and/or projects, including the Moonie WRP, EFAP, GB RRHS, DICP) were able to be adapted within the proposed template structure (Table 11), neither has a defined process specifically aimed at managing or protecting aquatic refuges. However, in both instances the approaches aim to maintain, improve or restore aquatic habitats (Table 11). Hence, through these approaches, refuges may be a) categorised as an asset and b) enhanced or protected, which may support resilience within the system (e.g. the Moonie WRP specifically recognised waterholes as refuge habitats, and modelling has been conducted to determine potential threats to their persistence during drought.).

The governance structures of the pilot valleys also vary (see Section 3.1). In particular the GB legislative framework functions as a top heavy, top down process, where various commonwealth and state policies and legislations filter down to sub-ordinate state and regional strategies (Box 15; Table 11). For instance, through the GB RRHS and GB DICP, the GB CMA is maximising funding and leverage available through policy and legislation, and the framework and processes outlined provide a dynamically structured program (Box 15). In contrast, the Moonie legislative framework functions disjointedly through several state level agencies that operate more autonomously, representative of the silo concept (Box 16). Within these silos, primary state legislation and policies provide over arching policy for the regional strategies, which flow into the catchment-scale approaches (Box 16; Table 11). However, if drought conditions became critical, a management plan that holistically provides stronger linkages to plan and deliver refuge protection and coordinates state, regional and catchment-scale management, would be required.

Box 15. An example of the governance approach and legislative framework in the Goulburn-Broken catchment.



Box 16. An example of the governance approach and legislative framework utilised by DERM in the Moonie catchment.



In terms of defining values and how refuges contribute to protecting these values, the GB and the Moonie Catchments' approaches may identify refuges as valuable assets within the overarching objectives of their relevant programs, therefore refuges areas may be inadvertently protected under the broader value of habitat condition protection (Table 11). While the proposed refuge management template allows values to be defined based on habitat, it also encompasses the ability to define values associated with the needs of aquatic dependent biota (e.g. the protection of native fish, or threatened species). The consideration of these values may also mean that key refuges are not neglected for protection and management. Furthermore, the scale at which habitats are protected differs, with the current approach in the GB being more reflective of the need for reach-site scale interventions that may be required for refuges during drought, whereas the Moonie operates at a much broader reach-scale (Table 11). The need to define values at a finer resolution may become increasingly relevant during severe drought conditions where it is no longer sustainable or feasible to operate at a broader scale. For example, severe drought conditions may identify an immediate need for active interventions (e.g. water delivery) to protect specific biota at short temporal and smaller spatial scales, and not necessarily at broader regional-catchment scales (Bond and Lake 2003; Crook *et al.* 2010b). However, outside of severe drought conditions focussing at such a fine level may be ineffectual if small-scale interventions are superseded by broader-scale threats and pressures (e.g. altered flow regimes).

Under the current approaches, defining attributes and functions within both the GB and Moonie would need to be expanded to fit within the proposed template structure to specifically manage refuges. For example, in the Moonie WRP, 'waterholes as refuges' were identified as an ecological asset for which persistence, connectivity and 'quality' were defined as attributes and asset functions and attributes were assessed with regard to flows, under the EFAP Ecological assets process (Table 11). The GB RRHS identifies attributes and functions as environmental, social or economic assets (Table 11). Under the GB approach, environmental assets are most analogous to the attributes/functions defined for refuge management in the proposed template. So far, the approaches in the GB and the Moonie do not take into account the full suite and diversity of attributes specifically tailored for refuge management, nor is scoring of attributes and functions performed to prioritise significance. The feasibility of the finer-scale Critical Refuge Assessment Process is dependent on the regional management structure. Furthermore a key requirement is a comprehensive source of site-scale data, which will not only supply information for identifying refuge and dependent biota values, but also provide a means to score characteristics and attributes/functions. For instance, the GB CMA currently has a well-structured, data-rich, adaptive management process (e.g. CMA program, catchment map and species) that would benefit from the scoring process to collate and prioritise all the available data sources. The utilisation of this fine-scale scoring process in the Moonie would not be as effective under the PSR framework used by DERM (Box 13). However, Moonie CMA/NRM Alliance groups (which manage on-ground interventions) may find the scoring process a useful application for directing management actions and prioritising site interventions for refuge management.

In regards to threat and pressure assessments, the Moonie operates under the EFAP and SEAP PSR framework (Box 13), which identifies stressors, pressures and management controls, to determine the risks to selected ecological assets and evaluate whether ecological outcomes are likely to be met under current management strategies. Importantly, the only pressure considered under the current approach was water resource development, thus for refuge management a wider range of pressures may need to be taken in consideration (Table 11). Nevertheless, the QLD PSR framework (Box 13) provides an excellent platform that could be readily applied to refuge management. For the GB, the RRHS and DICP identify impacts (analogous to pressures) and stresses (or threats: physical, flow, water quality and, biological), conduct risk-based assessments and identifies adverse management strategies at priority reach scales (Table 11). This risk-based analysis is expressed as a function of “consequence” and “likelihood”, which in combination provide a risk rating and a measure of probability as a means of evaluating the level of impact on the asset. As a result, the GB approach evaluates current and proposed management actions and identifies new actions and management arrangements by defining agencies roles and responsibilities. Overall, threat/pressure risk assessments and the application of risk management strategies are well defined in the GB and Moonie and follow similar approaches to those outlined in the Refuge Management Template, although for refuge management they would need to be specifically directed at protecting refuges.

At present, the GB has reach-scale and site-scale management strategies, and site-scale interventions that manage for both resistance and resilience; however the Moonie only manages resilience at the reach-scale. For example, the GB CMA is responsible for implementation of the Regional Catchment Strategy and through their River Health Program conduct in-house projects and additionally contracts other agencies to provide on ground monitoring and evaluation. Conversely, in the Moonie, DERM in collaboration with Griffith University and the University of Queensland, conducts the Moonie Refugial Waterholes program, which is focussed on reach scale connectivity, persistence and resilience of waterholes. Management of refuges requires specific on ground projects that are focussed at supporting resistance during drought periods and also building resistance into the system during non-drought, which requires a more direct approach to the management and restoration of drought refuges throughout the MDB.

Table 11. Comparison of the current approaches to refuge management undertaken in the Moonie River and Goulburn Broken pilot valley catchments in relation to the proposed refuge management template.

	Moonie River Catchment		Goulburn-Broken Catchment	
Descriptor	**Program**	**Action**	**Program**	**Action**
Define refuge value	State: *Water Act 2000:* Moonie WRP Ecological Outcomes. *Environment Protection Act 1994:* Environmental Protection (Water) Policy 2009	*Water Act 2000* provides over arching legislation and policy for the WRP's. WRP Ecological outcomes help to define values (valued ecosystem components). *Environment Protection Act 1994* provides over arching legislation for the EPP (Water) which identifies ecological water values. 'Waterholes as refuges' were identified as assets under the Moonie WRP	State: W*ater Act 1989; Flora and Fauna Guarantee Act 1988; Crown Land (Reserves) Act 1978; Fisheries Act 1995 ; Heritage Rivers Act 1992; Water Act 1989; Planning and Environment Act 1987; Wildlife Act 1975.* NRSWS; RRHS, DICP	Various commonwealth and state policy and legislations filter down to provide sub-ordinate state and regional strategies (NRSWS, RRHS, DICP) which identify values: to enhance and protect high priority waterways, maintain ecologically healthy rivers, improve habitat quality and prevent damage during low flow conditions
Define an appropriate/meaningful spatial scale	WRP	WRP's operates at the catchment- reach scale. EPP operates at state to catchment scale	GB RRHS & GB DICP	GB RRHS and GB DICP's operate at the catchment- reach -site scale.
Describe how refuges contribute to the value	EFAP Ecological Assets	An environmental flows assessment program to assess the ecological performance of each water resource plan in meeting its stated ecological outcomes.	GB RRHS & GB DICP	GB RRHS and GB DICP's follow a process where priority waterways may be defined as an asset. High priority waterways are defined as: • heritage rivers, • reaches with international or nationally significant wetlands, • environmental sites of significance, • regional representative rivers, • reaches with records of water dependent nationally listed endangered flora and fauna, • reaches of high environmental significance, • high social value and, • high economic value.
Define attributes and functions	WRP; EFAP Ecological Assets	Under the 'Waterholes as refuges' persistence was defined as an attribute. An assessment of assets functions and attributes with regard to flows.	GB RRHS & GB DICP	GB RRHS and DICP's list assets: • environmental (rarity, naturalness or representativeness), • social and, • economic

	Moonie River Catchment		Goulburn-Broken Catchment	
Descriptor	**Program**	**Action**	**Program**	**Action**
Risk assessment of specific threats to refuges	EFAP and SEAP (PSR)	To determine the risk to selected ecological assets and evaluate if ecological outcomes are likely to be met under current flow management strategies. SEAP stressor models (consider all stressors to stream health. Risk assessment and prioritisation may identify threats to refuges.	GB RRHS & GB DICP	GB RRHS and DICP's identify threats (stresses) and conduct risk-based assessment at priority reach scale for: • physical, • flow, • water quality and, • biological.
Risk assessment of activities (pressures) that generate threats	WRP and SEAP (PSR)	Water resource development only pressure considered. SEAP PSR pressure assessment and risk assessment.	GB RRHS & GB DICP	GB RRHS and DICP's identify impacts (pressures) and conduct risk-based assessment at priority reach scale. The risk-based analysis is expressed as a function of "consequence" and "likelihood". This combination of consequence and likelihood provides a risk rating which represents a measure of the probability that a threat will have a serious impact on the asset.
Identify and prioritise threat and pressure management strategies (long-term vs. short term)	WRP	Choice of WRP scenario and establishment of flow rules for ecological outcomes.	GB RRHS & GB DICP	GB RRHS and DICP's identify current and proposed management actions; identify new actions, plan monitoring and evaluation at the priority reach scale. Identifies on-ground actions and targets, agencies responsible and costing.
Implement management strategies (reach vs. site and long-term vs. short term)			GB CMA	GB RRHS: Identifies agencies roles and responsibilities, management arrangements (based on the VRHS), implements monitoring and evaluation
Monitor and assess	Moonie Refugial Waterholes DERM; Griffith University	EFAP monitoring; Monitoring of SEAP pressures, stressors and ecological responses; AquaBAMM conservation assessment (includes refuges).	GB CMA River Health program.	The GB CMA is responsible for implementation of the Regional Catchment Strategy, which conduct and contract other agencies for on going monitoring and evaluation.
Evaluate and adaptively manage	WRP	10 year WRP review cycle.	GB RRHS & GB DICP	Adaptively manage

3.3.6 Example for native fish

Given the primary focus of this report is on native fish in the MDB, the following is an example of the refuge management process utilising the template and approach outlined. The values used, are commonly associated with native fish management and in particular reflect values developed within pilot valley projects.

3.3.6.1 Identifying values

The first step involves identifying the values related to refuges and native fish and may prioritise sites or include the identification of relevant management strategies and management groups. Two contrasting examples include 1) protection of a site for recreational fishing values versus 2) protection of a site for fish conservation values. In the first example, a site may be more highly valued where recreational/angling target species, such as Murray cod, are present. Therefore, this site would be a management priority, requiring engagement with fisheries management stakeholders (e.g. state fisheries departments and recreational angling clubs/groups). In the second example, a site where small-bodied threatened species are present (especially in refuge areas where populations are isolated) would be a high conservation priority. Protection of this site would potentially require involvement with catchment management boards and state and federal departments committed to wildlife conservation. Management strategies are likely to differ based on the selected native fish values. For example, conservation of threatened species may require site scale emergency actions, while maintenance of recreational/angling species or sites, may require overarching large scale and long-term investment (e.g. restoration and/or stocking to build resilience into populations). Table 12 selects one such value (i.e. native fish conservation) and illustrates the scoring process and how the information can be recorded to assist with prioritisation, stakeholder engagement and identification of possible management strategies.

Table 12. An example of a scoring system for native fish values using a conservation value and identification of management triggers and strategies.

Native fish values		Score	Descriptor	Triggers	Management Strategies
Native Fish Conservation	**Diverse and abundant native fish assemblage**	0	Poor assemblage known	Scores of 1, 2 & 4 triggers fish monitoring actions.	• Management actions are likely to focus on maintaining refuge quality across a range of habitats to maximise biodiversity values. • Largely water and catchment management operations.
		1	Unknown fish assemblage		
		2	Moderate assemblage diversity likely, but unconfirmed		
		3	Known moderate diversity		
		4	High likelihood of diverse assemblage, but unconfirmed		
		5	Diverse fish assemblage known		
	Presence of conservation listed threatened species	0	Known absence of threatened species	Scores of 1, 2 3 & 4 triggers fish monitoring actions. A score of 5 should lead to detailed population assessment and scoping of emergency intervention measures.	• Management actions are likely to involve *in situ* management interventions and possibly emergency rescue operations to protect conservation priorities. • Largely fisheries operations with water management and NRM support.
		1	Low likelihood of threatened species		
		2	Moderate likelihood of threatened species		
		3	High likelihood of threatened species		
		4	Known habitat for threatened species		
		5	Identified significant population of threatened species		
	Presence of recreational or commercial species	0	Angling species known to be absent	Scores of 1, 2 & 4 triggers fish monitoring action. Scores of 4 & 5 Trigger possible fishery closure measures during drought.	• Management actions are likely to focus on maintaining refuge quality across a range of habitats to maximise biodiversity values. Protection of fish from exploitation when fish are concentrated in refuge habitats with low food reserves and therefore increasingly susceptible to overfishing. Extreme cases may lead to water management operations, usually large scale. • Largely fisheries operations with water management and NRM support.
		1	Low likelihood of angling species		
		2	Moderate likelihood of angling species		
		3	Likely habitat for large angling species		
		4	Known refuge for large angling species		
		5	Known refuge for large angling species of conservation concern		

3.3.6.2 Traits and status of native fishes

Native fish species inherently have different requirements associated with various refuge characteristics, attributes and functions. The dynamics of physical habitat, hydrology, connectivity and biological integrity are important, particularly during drought periods when specialist requirements may not be met under changed and often declining conditions within refuges. As refuge habitats dry and shrink, over-crowding increases intra- and inter- specific competition and decreases water quality which may increase susceptibility to disease and parasitism (Ostrand and Wilde 2001; McNeil *et al.* 2009). Further desiccation of individual waterbodies may push physicochemical parameters to extremes, forcing organisms to retreat to microhabitats (Matthews 1998; Gomez and Lunt 2006; Anjos *et al.* 2008). Fish with greater physicochemical tolerances may consequently seek microhabitat patches with poorer water quality to escape predation (Rosenberger and Chapman 2000; McNeil 2004; Chapman *et al.* 2006; Anjos *et al.* 2008). Food resources may become extremely limited or confined to intolerable microhabitats, such as hypoxic depths, and fish may need to use these intermittently to meet energetic requirements (Rahel and Nutzman 1994). Hence, a decline in the physical habitat quality of refuge attributes (e.g. woody habitat, flow volume, microhabitat quality) may potentially reduce species' resilience during drought periods (King 2002). Drying of pools often leads to the mortality of large numbers of individuals; yet the survival of some individuals is critical through drought conditions for populations to persist.

As a result, different species or groups of species may need to be assessed independently to determine the refuge values and characteristics/assets that will support populations. More detailed assessments of the native fish habitat, flow and ecological requirements are summarised elsewhere (Reynolds 1983; SKM 2003; Pusey *et al.* 2004; McNeil *et al.* In prep) but a brief summary of the interaction of refuge characteristics and life history strategies is provided (see Appendix 6-10).

Table 13 provides an example of the development of a matrix of relevant attributes and functions, and threats/pressures relating to the specific characteristics of refuges that support native fish values. Furthermore, some examples of management strategies directly related to the identified threats/pressures for maintenance of the characteristics, attributes and functions have been included. This may assist with identifying important aspects for refuge protection and prioritisation for particular species or assemblages (Table 13).

Table 13. An example of a summary matrix of characteristics, attributes, functions, threats and pressures and management strategies relating to protecting specific aquatic refuge sites during drought.

<table>
<tr><th rowspan="2">Characteristics</th><th rowspan="2">Attributes</th><th rowspan="2">Functions</th><th rowspan="2">Examples for Attribute Scoring</th><th colspan="2">Threats and Pressures</th><th rowspan="2">Examples for Threat Scoring</th><th colspan="2">Management Strategy</th></tr>
<tr><th>Threats</th><th>Related Pressures</th><th>Management Fields</th><th>Management Strategy Examples</th></tr>
<tr><td rowspan="10">Connectivity</td><td rowspan="4">Lateral connectivity</td><td rowspan="4">• Access to off-channel wetlands, lakes and floodplain habitats and resources
• Population and genetic connectivity between off-channel habitats and rivers
• Access to off channel spawning sites
• Inputs of nutrients and food to support riverine processes</td><td rowspan="4">Potentially connected off channel habitats are present</td><td>Lack of over bank or commence to fill flows.</td><td>Flow regulation</td><td>Upstream abstraction of water</td><td>Water Management</td><td>Maximise delivery of overbank flows, medium and small floods utilising other flow delivery requirements where possible.</td></tr>
<tr><td rowspan="3">Presence of barriers to lateral connectivity.</td><td rowspan="3">Infrastructure and Irrigation</td><td rowspan="3">Presence of lateral barriers (i.e. Regulators, levees, roads)</td><td>Fisheries Management</td><td>Provide fish passage into and out of all floodplain and off channel areas.</td></tr>
<tr><td>Catchment Management</td><td>Remove levees and structures inhibiting lateral fish movement, modify road/bridge designs.</td></tr>
<tr><td>Water Management</td><td>Integrate fish passage into infrastructure designs.</td></tr>
<tr><td rowspan="6">Longitudinal connectivity</td><td rowspan="6">• Migrational pathways
• Access to spawning partners and sites
• Movement of eggs, larvae and recruits to juvenile and adult habitats
• Recolonisation after drought
• Retreat to refuges</td><td rowspan="6">• Presence of migrating or diadromous species.
• Presence of nearby reaches relying on the refuge as a source population.
• Presence of flow spawners raises refuge value.</td><td rowspan="2">Presence of instream barriers; weirs, dams etc.</td><td rowspan="2">Infrastructure and Water Storage</td><td rowspan="2">Presence of instream barriers</td><td>Water Management</td><td>Develop plans for delivering connecting "resilience building" flows at the end of drought periods to facilitate recolonisation and access to spawning sites and habitats.</td></tr>
<tr><td>Fisheries Management</td><td>Provide fish passage at all weirs and barriers for all size ranges of native fish.</td></tr>
<tr><td>Insufficient flows to connect spawning sites to adult habitats.</td><td rowspan="3">Flow regulation</td><td rowspan="4">• Upstream abstraction of water
• Absence of effective e-flow program
• Ability to regulate flows
• Lack of competing water resource users</td><td rowspan="4">Water Management</td><td>Ensure regular connectivity to the marine environment to maintain diadromous populations throughout drought.</td></tr>
<tr><td>Flow regime doesn't trigger spawning cues or inundate spawning habitats.</td><td>Utilise fish passage structures to capture and remove migrating invasive fish such as carp.</td></tr>
<tr><td>Rapid drawdown of water levels.</td><td rowspan="2">Design flow delivery to maximise opportunities for fish movement and to minimise stranding due to rapid draw-downs during drought onset.</td></tr>
<tr><td>Insufficient flows to connect refuges.</td><td>Natural Climate Flow regulation</td></tr>
</table>

Characteristics	Attributes	Functions	Examples for Attribute Scoring	Threats and Pressures		Examples for Threat Scoring	Management Strategy	
				Threats	**Related Pressures**		**Management Fields**	**Management Strategy Examples**
Biological Integrity	Diverse and abundant macrophytes	• Provides diverse and adequate food • Increased macro- and micro - habitat complexity • Buffering against adverse water quality • Protection from predators • Relief from competition	Macrophyte diversity and abundance	Cattle grazing and trampling.	Land use	• Access of cattle to refuges • Presence of cropping in dry waterways or river banks • Known use of agricultural pollutants	Catchment Management	Reduce agricultural impacts on areas with high macrophyte values, prevent cattle access and prevent pollution with agro-chemicals.
				Cropping of habitats when dry (i.e. planting in wetlands or lake beds).				Limit agricultural impacts (cropping, overgrazing) on dry habitats where seedbank and rhizome refuges are maintained.
				Introduced macrophytes.	Invasive Species	• Presence of invasive macrophyte species	Invasive Species	Monitor for and develop control programs for aquatic and riparian weeds and invasive pest biota.
				Loss of shallower areas where macrophytes establish.	Flow regulation	Maintained stable and/or high water levels	Water Management	Maximise natural flow regime, wetting and drying, to promote growth and health of aquatic plants communities.
				Flow regime preventing drying requirements for macrophytes.				Protect refuge habitats such as wetlands as a source of macrophyte colonists following drought.
	Diverse and intact riparian vegetation	• Organic inputs supporting food web dynamics and ecological processes • Adult insect habitat maintaining larval food sources • Reduced water quality impacts through shading and run-off interception • Protection against salinity through watertable regulation • Bank stabilisation, sediment transfer and erosion control.	Intact and diverse riparian vegetation (native)	Clearing of riparian vegetation.	Land Use	• Denuded or cleared riparian areas • Access of stock to refuges • Presence of clear ground and/or eroded areas in riparian zone	Catchment Management	Target riparian restoration activities (fencing, revegetation, bank stabilisation) to key refuge habitat areas.
			Connected riparian and catchment vegetation	Disconnection of riparian and catchment vegetation.				Restrict agricultural use (e.g. cropping) in riparian zones.
				Stock impacts; grazing and trampling of riparian areas.				Install off channel watering points for stock.
				Erosion of unvegetated and unstable river banks.				
				Riparian weeds (e.g. Willows, Blackberry).	Invasive Species	• Introduced riparian weeds	Invasive Species	Identify and remove infestations of riparian weeds and replace with appropriate native species.

Characteristics	Attributes	Functions	Examples for Attribute Scoring	Threats and Pressures: Threats	Threats and Pressures: Related Pressures	Examples for Threat Scoring	Management Strategy: Management Fields	Management Strategy: Management Strategy Examples
Biological Integrity Cntd…	Diverse and abundant invertebrate assemblage	• Food resources for a range of native fish species. • Maintenance of trophic structure	Invertebrate diversity	Riparian clearance and disconnection with catchment vegetation.	Land Use	• Presence of highly modified riparian and instream vegetation • Turbidity and upstream erosion and deposition impacts • Absence of macrophyte beds from shallower areas	Catchment Management	Maintain aquatic and riparian vegetation structure.
				Sedimentation and smothering of substrates.				Maintain habitat and substrate diversity within refuge areas.
								Reduce sedimentary processes upstream of key refuge areas.
				Macrophyte loss.				Manage for biodiversity protection around refuge areas, linking biota across riverine and catchment landscapes.
				Competition for food resources from introduced species.	Invasive Species	Invasive fish present	Invasive Species	Identify and remove introduced predators such as trout that decimate invertebrate resources.
	Intact ecological processes	• Trophic structure and foodweb components in balance • Top down and bottom up ecological processes are functioning sustainably	Intact primary production, primary, secondary and apex consumers	Loss of any trophic level or imbalance of top down and bottom up processes.	Land Use Flow regulation Invasive Species	Imbalance of any trophic levels, often evident via algal blooms or low biodiversity	Land Use	Protect or restore trophic structure through habitat restoration.
			Presence of diverse algae, plants, insect larvae, zooplankton, fish and other aquatic biota increase refuge value	Decline in water quality (including pollutants), habitat, nutrient loads. Changes to competitive and predatory interactions.			Water Management	Protect or restore trophic structure through maintenance of natural water regimes.
							Invasive Species	Control introduced plants and animals.

Characteristics	Attributes	Functions	Examples for Attribute Scoring	Threats and Pressures: Threats	Threats and Pressures: Related Pressures	Examples for Threat Scoring	Management Strategy: Management Fields	Management Strategy: Management Strategy Examples
Physical Habitat features	**Deep holes or pools**	• Provide habitat for large-bodied fish • Provide open water habitats for pelagic species • Provide more permanent habit during dry periods • Maintain cooler water temperatures during hot periods • Cause drop out of invertebrate drift	• Presence of deep holes (relative to catchment and appropriate foe species) add to refuge value • Bedrock substrates increase permanence and adds to refuge value • Presence of woody habitat (i.e. leaf litter, tree roots, fallen logs and trees) increase refuge value	Sedimentation	Land Use	• Upstream erosion, sand slugs or sedimentation of substrates locally • Presence of pumps or irrigation off-takes, utilisation for road works, council projects	Catchment Management	Target upstream sediment mobilisation points
				Direct Pumping				Arrest progress and stabilise upstream and tributary sand slugs
				Reduced flows, increased cease to flow periods	Flow Regulation	• Upstream regulation and abstraction • Detectable increases in salinity, temperature, oxygen, DOC, pH (monitoring required) • Planned summer water allocations (post Christmas).	Water Management	Implement in-stream scouring structures such as snags and rock bars to maintain bed diversity
				Declining water quality				Ensure flushing and scouring flows are provided regularly to maintain bed diversity and reduce organic loads
				Poorly delivered flows during or following drought (blackwater events)				Deliver environmental water before hot summer conditions begin and in sufficient volumes to flush organic matter out of dry channels and deep pools.
				Angling of large fish from deep pools	Fisheries Manageme nt	Presence of large angling species (e.g. Murray cod) and access by roads, facilities	Fisheries Management	Identify key refuge waterholes likely to hold target angling species; implement local or general fishing bans during extreme dry periods and drought.

Characteristics	Attributes	Functions	Examples for Attribute Scoring	Threats and Pressures		Examples for Threat Scoring	Management Strategy	
				Threats	**Related Pressures**		**Management Fields**	**Management Strategy Examples**
Physical Habitat features Cntd…	Intact substrates	• Bedrock substrates increase permanence and cause groundwater upwelling improving spring expression • Cobbles and rocky substrates provide interstices for larval and juvenile fish and invertebrate prey items • Stable sediment substrates provide spawning habitats for some native fish species • Rocky riffles increase fish passage and increase connectivity values.	• Presence of bedrock • Rocky interstices in pools and riffles • Large rocks and gravel bars • Riffle areas present with rocky substrates	Sedimentation.	Land use	Presence of sediments mobilised through upstream land use impacts Upstream erosion sources or sand slugs	Catchment Management	Identification and targeted works to prevent upstream erosion and arrest sediment movement.
				algal smothering due to nitrification.				Installation of scouring instream structures to maintain hydraulic sediment movement out of pools.
				Absence of scouring flows under water regulation.	Flow Regulation	Stock access (local and upstream)	Water Management	Integration of flushing flows into environmental or other flow management regimes.
				Low flows drying riffles unseasonably.		Identified nutrient sources from agriculture or urban runoff		
	Intact riparian zones	• Stream shading • Organic inputs (leaf litter, etc) • Woody habitat inputs • Reduced sediment and nutrient inputs fro catchment • Habitat for adult life stages of invertebrate food species • Bank stabilisation • Increased habitat diversity	Dense riparian over story	Clearing of riparian vegetation.	Land use	• Vegetation clearing, grazing or poor health of over story trees • De-snagging, riparian clearing or presence of young riparian vegetation community • Absence of perennial groundcover in the riparian zone • Disconnected or cleared riparian and catchment vegetation communities • Stock access	Catchment Management	Undertake riparian protection and restoration programs targeted towards refuge habitats and associated catchment areas.
			Riparian age structure including large trees for snag creation, hollow logs and complex branch structures	Grazing and stock access to riparian areas.				Ensure diversity in riparian revegetation programs including groundcover, shrubs and trees linking where possible to floodplain and catchment vegetation.
			Presence of dense groundcover in riparian zone	Ploughing and agricultural use of riparian areas.				Fence out stock and provide off-channel watering points around key refuge habitats.
			Well connected and dense native riparian and catchment vegetation	Disconnection of catchment and riparian vegetation communities.				

Characteristics	Attributes	Functions	Examples for Attribute Scoring	Threats and Pressures		Examples for Threat Scoring	Management Strategy	
				Threats	**Related Pressures**		**Management Fields**	**Management Strategy Examples**
Physical Habitat features Cntd…	Intact Riparian Zone cntd…	(see above)	Groundcover on banks and dense root matts	Regulation of flows causing high or low stable water levels for extended periods.	Water Manageme nt	Water level regulation (leading to bank collapse)	Water Management	Avoid long-term inundation or desiccation of riparian and floodplain areas to prevent drowning or desiccation related vegetation deaths.
								Maintenance of high flows to inundate riparian and floodplain areas, watering vegetation communities.
								Manage flow regimes to prevent bank instability (i.e. avoid sudden increases/decreases in flow volume).
			Riparian vegetation structure	Invasion and establishment of weeds and exotic trees/shrubs.	Invasive species	Presence of exotic riparian vegetation	Invasive species	Targeted removal of high impact riparian weeds (e.g. willows) around refuge habitats. Replacement with appropriate native vegetation.
Hydrological Factors	Permanence of waterholes	• Provides an opportunity for permanent refuge habitat • Sustains fish populations (providing adequate resources and conditions are present) • Reduces dependence on permanent surface flows for refuge maintenance	• Persistence record (failure to dry out) Impermeable • substrates increase refuge value • Provision of flow inputs	Pumping from waterholes.	Flow Regulation	• Presence of pumps or access to roadwork's etc • Upstream storage and abstraction of water • Extended cease to flow periods • Absence of environmental flow management plans or Inability to regulate water resource delivery	Water Management	Organise alternative water collection sites for road works and local councils uses during drought periods.
				Allocation of flow away from waterholes.				Provide alternative watering sources for landholders with pumps in or adjacent to refuges.
								Integrate minimum cease to flow periods into environmental flow regimes to ensure waterhole persistence throughout summer and autumn periods.
								Manage local groundwater use to protect spring flow inputs to refuge waterholes and to upstream and catchment areas.
				Sedimentation filling up waterholes	Land Use	Sedimentation	Land Use	Address sedimentation issues to prevent loss off waterhole depth.
								Exclude stock to minimise access related impacts on sediments and banks.

Characteristics	Attributes	Functions	Examples for Attribute Scoring	Threats and Pressures		Examples for Threat Scoring	Management Strategy	
				Threats	**Related Pressures**		**Management Fields**	**Management Strategy Examples**
Hydrological Factors Cntd…	Permanence of waterholes Cntd…	See above		Loss of surface waters.	Flow regulation Natural Climate & Land Use	• Presence of threatened biota • Importance of habitat for biodiversity	Fisheries Management	Rescue operations to remove highly threatened conservation listed populations and species. Translocation to safer refuges, or into captive storage and breeding facilities with the aim of re-introduction to the wild following alleviation of drought impacts.
								Monitoring programs during drought onset to identify refuges at high risk of desiccation containing valuable or threatened populations of native fish. Make recommendations, advise and drive water and catchment management responses.
	Reliable groundwater inputs (local and upstream)	• Maintains water level in the absence of surface flows • Increases permanence • Provides fresh water inputs to maintain water quality (dependent on local groundwater characteristics) • Maintains water temperatures • Sustains riparian and wetland vegetation communities	• Presence of groundwater inputs • High groundwater inflows (springs)	Over use of groundwater (drawdown of aquifer).	Water Manageme nt	Presence of groundwater extraction in aquifer area	Water Management	Undertake assessments of groundwater dependent ecosystems to identify refuges at risk.
				Natural spring cessation during drought.	Land Use	• Groundwater salinisation upstream (aquifer flow) • diversion of spring flows to dams or for stock and domestic use	Land Use	Develop groundwater resource plans that protect surface expression and spring flow.
				Salinisation of groundwater through land use.				Implement salinity control works in areas around refuge habitats to minimise the flow of saline groundwater into refuge waterbodies.

Characteristics	Attributes	Functions	Examples for Attribute Scoring	Threats and Pressures		Examples for Threat Scoring	Management Strategy	
				Threats	**Related Pressures**		**Management Fields**	**Management Strategy Examples**
Hydrological Factors Cntd…	Natural flow regime (volume, duration and timing)	• Ensures appropriate cues for spawning and migration • Gradual drawdown enables fish to retreat to suitable refuge habitats during decreasing flows • Maintains native ecosystem processes • Provides connectivity for recolonisation following drought • Inundates wetland and floodplain habitats following drought	• Flows increase in autumn and decrease in summer = high value refuge • Hydrograph rises and falls gradually with catchment rainfall and runoff = high value refuge • High levels of rainfall, snowmelt spring flow lead to flow increases = high value refuge • Cease to flow periods matching seasonally drying regime	Delivery of water for unseasonal agriculture.	Flow Regulation	• Presence of upstream storages increases threat level • Presence of floodplains, wetlands and off channel habitats requiring regular high flow inundation • Presence of irrigated agriculture in local area • Presence of human water storages and off takes	Water Management	Undertake environmental flow plans to adhere as closely as possible to natural flow patterns.
				Storage of water after dry periods to recharge reservoirs.				Address processes that remove flow bands to seek alternative water abstraction and storage possibilities.
				Transfer flows during summer.				Plan for critical hydrological components (e.g. connectivity to the sea for diadromous fish, spawning events, floodplain and wetland inundation) at onset of drought
				Loss of medium and small floods.				Ensure that following drought, flow delivery allows resilience building for native fish (i.e. flood pulses, spawning cues, habitat inundation, connectivity).
				Poorly designed or resourced environment flow delivery.				
	Flow delivery infrastructure	• Provides opportunities for water resource delivery to sustain refuges • Provides mechanism for timing flows in regulated stable water systems	Presence of upstream regulators and water sources	Poorly managed flow regulation or delivery of flows can result in catastrophic collapse of water quality and fish kills.	Flow Regulation	• Misuse of flow delivery infrastructure. Flow structures unable to be operated to meet environmental flow requirements.	Water Management	Assess the costs and benefits of installing regulatory structures (e.g. if water is not available to provide adequate flow volumes, investment in a regulator may not be cost effective).
								Ensure that infrastructure does not provide additional duress to native fish by causing additional barriers or impact further on flow regime.

Characteristics	Attributes	Functions	Examples for Attribute Scoring	Threats and Pressures		Examples for Threat Scoring	Management Strategy	
				Threats	**Related Pressures**		**Management Fields**	**Management Strategy Examples**
Hydrological Factors Cntd…	Presence of flow	• Allows the persistence of flow dependent species such as Murray cod (lowland), blackfish and galaxias species (upland) • Flushes accumulated nutrients, organic compounds, salts and poor quality water. • Mobilises sediment deposits and scours substrates • Delivers food resources from upstream sources • Maintains benign water temperatures	• Flows through habitats containing populations of cool water or flow dependent fish species • Creeks, anabranches rivers and streams with permanent flow increase refuge value • Flushing flows delivered most years matching local rainfall events raises refuge	Water abstraction for irrigation, stock and domestic or urban uses.	Flow Regulation	• Dams, reservoirs, weirpools and flow regulating structures upstream increase threat level • Absence of environmental flow management plans	Water Management	Identify permanently flowing reaches and plan water delivery patterns to maintain flow through reaches.
				Poorly managed flow regime and ecological flow requirements.				
				Drought restrictions on environmental water allocations.				Investigate opportunities for innovative water delivery operations to maximise flow through reaches with flow dependent species.

4. DISCUSSION

4.1 Current status of drought refuge management in the MDB

4.1.1 How are refuges characterised?

A wide range of aquatic habitats were considered important as drought refuges, with unregulated waterways the most commonly identified habitat type, and of the greatest concern to managers. Unregulated systems were of concern largely due to the inability to deliver water to maintain refuge habitats and limited requirement for long-term restoration investment within short term (~1-3 years) political and funding cycles.

In some instances, key native fish species (e.g. conservation listed, of recreational and commercial significance) were used to identify particular drought refuges. The protection and/or management of the refuges for these species either followed a 'single species' approach (more common in the drier, southern MDB) or 'multi-species/community' approach (more common in the northern MDB).

Available information on refuges and the extent of drought response planning and projects differed considerably across the jurisdictions. Refuges were defined and identified at larger spatial scales (e.g. catchments and habitat networks) in the northern MDB and at smaller, site-specific scales in the southern MDB. The underlying driver of these different approaches reflects the varying intensity of drought impacts across the MDB. For instance, in the southern MDB where drought impacts were extreme and several populations of highly threatened fish were at considerable risk of localised extinctions and/or population collapse, management responses tended to target individual threatened species populations and their associated habitats for immediate protection. Under these scenarios, species conservation policies (e.g. South Australia's "no species loss" policy) became important levers for the critical development of drought response interventions and planning. In contrast, in the northern MDB, drought impacts were less severe and refuge management targeted the maintenance of biodiversity hot spots and high value ecosystems. In these instances, projects were developed with a less specific focus on protecting individual species and/or sites from drought impacts, and instead used approaches such as AquaBAMM and the Pressure-Stressor-Response process (e.g. SEAP) to identify and prioritise areas for maximising biodiversity and ecological integrity. Approaches that seek to identify refuge habitats either through scale or target species are equally valid in the development of long-term management and protection of drought refuges.

These disparate approaches to the management and protection of drought refuges reflect the different aspects of native fish ecology, in terms of resistance versus resilience. Local scale (i.e. site-specific) and individual species approaches to interventions aim to stabilise and improve resistance of immediately threatened populations, while larger scale and whole assemblage based approaches aim to build and protect resilience in native fish communities so that they are able to withstand and recover from drought impacts (Bond *et al.* 2008). In Victoria, where drought impacts have been particularly severe, this has been reflected in the ongoing, adaptive management process; with resistance scale planning through the use of dry inflow contingency and emergency watering plans (during the peak of drought impacts), followed by an integration of drought actions into Regional River Health Strategies to ensure a long-term focus on resilience management.

4.2 Planning and protecting drought refuges in the MDB

To maintain a holistic approach to drought management, drought refuge protection plans must incorporate enough flexibility to identify and invest in emergency short-term responses during peak drought periods (facilitating the resistance of native fishes). In addition, guidelines need to be provided to build projects over broader spatio-temporal scales to help develop and maintain long-term resilience in native fish populations (and other aquatic dependent species).

The review of the current status of refuge management revealed that there are many management agencies and stakeholders involved in planning and implementing measures for the protection of native fish and drought refuges. However, utilising the specific roles each stakeholder takes in refuge protection needs to be co-ordinated effectively to provide adequate management planning and funding pathways. Coordination of management stakeholders must integrate legislative and planning processes so that water, ecosystem and conservation planning are interconnected. During the millennium drought, some impediments to refuge management were identified. For instance, in many areas water management planning was unable to allocate critical environmental water. Furthermore, the responsibility of native fish protection was at times unclear across jurisdictions, resulting in a heavy reliance on the MDBA to fund many of the emergency drought interventions. To ensure these impediments are minimised in future drought periods, it is highly recommended that a coordinated drought response be developed, if possible through integration into a MDB Plan, as a means of avoiding disjunct and poorly prioritised drought responses.

Drought management cannot be specifically confined to drought periods. The ongoing commitment to protecting drought refuges and building resilience in native fish populations needs to be promoted and maintained at all times (Bond *et al.* 2008; Crook *et al.* 2010b). Programs, such as the Native Fish Strategy, could provide the overarching level of coordination, especially given the recent proposed shifts towards a holistic level of management described in the impending Basin Plan (MDBA 2010). Planning and management of refuges must seek a complementary and coordinated level of involvement from water resource managers, catchment and NRM management groups and state and federal agencies to ensure a consistent approach and accurate prioritisation processes.

An additional impediment to refuge protection is the current focus of management towards regulated waterways, which may result in the loss of many critical refuge habitats in unregulated systems. This project has revealed the extremely high importance of unregulated waterways as critical refuges for native fish and other aquatic biota. MDBA planning should prioritise the consideration of unregulated refuge protection in future management and investment strategies.

A set of criteria was identified to define refuges and refine tools for identifying and collating important refuge information, to support the process of prioritising outcomes for management investment. The management template outlines a process to strategically direct refuge management, by defining the refuge values, characteristics, attributes, functions and threats/pressures. It is anticipated that this approach will serve as a resource for regional managers to develop detailed local refuge management plans in a consistent framework across the MDB. There is, however, a number of key steps that are required to be undertaken before the successful development of a refuge management planning network can be completed for the MDB. Given the scope of information that is required to reliably support the comprehensive identification of drought refuges at the MDB scale, the development of a 'one size fits all' management plan is not feasible. It is, therefore, recommended that regional refuge management plans be developed for the MDB. While the information in this report provides a solid biological, ecological and conceptual grasp of the criteria and possible management pathways for refuge protection, it is also highly recommended that the basic template and tools presented in this report are trialled by each catchment/region to ensure that the final materials produced are locally applicable, across a range of catchments. Thus a series of regional projects should be implemented across the MDB to run regional stakeholders and managers through the template process and to help refine a comprehensive list of local refuge sites, data sets, threats and management opportunities.

The information collated should subsequently be developed into a single spatial database that would facilitate a more objective assessment and prioritisation process for drought refuges in the MDB and focus MDB scale management approaches that complement local scale plans (as with Victoria's regional and state river health strategies). Similarly, while this report outlines an approach and set of tools for informing refuge management, there is scope to further develop "scoring" components using bio-metric or multi-criteria approaches (DNRW 2007b) to allow a consistent approach to prioritisation and to acceptably reflect the priorities of management bodies. It is therefore also recommended that development of prioritisation metrics be incorporated into the implementation phase of drought refuge management planning.

4.3 Conclusions

This report attempted to capture the current status of drought refuge management and develop a process and set of guidelines/tools for consistent refuge management planning in the future. However, the on-ground delivery of comprehensive drought management plans is complex; requiring significant investment and attention to the development of regional/localised refuge management plans that address direct and associated management to protect refuge values. A comprehensive, MDB refuge planning approach will require a complex level of integration into existing management frameworks to ensure that efficiencies are maximised and that state developments are able to complement whole of the MDB approaches to management planning.

All aspects of refuge identification and management rely heavily on the availability of information and data relating to aquatic habitats and biota, and almost all of the successful response programs during the millennium drought have relied heavily on fish monitoring programs and datasets collected by research and environmental agencies. An effective refuge management framework will therefore need to integrate the strategic collection of knowledge and data with a consistent planning approach for identifying, prioritising and facilitating interventions that protect those refuges and the native fish values that they represent.

5. REFERENCES

Anjos M. B., de Oliveira R. R. & Zuanon J. (2008) Hypoxic environments as refuge against predatory fish in the Amazonian floodplains. *Brazilian Journal of Biology* 68, 45-50.

Arthington A. H., Balcombe S. R., Wilson G. A., Thoms M. C. & Marshall J. (2005) Spatial and temporal variation in fish-assemblage structure in isolated waterholes during the 2001 dry season of an arid-zone floodplain river, Cooper Creek, Australia. *Marine and Freshwater Research*, 56, 25-35.

Arthington A. H., Naiman R. J., McClain M. E. & Nilsson G. E. (2010) Preserving the biodiversity and ecological services of rivers: New challenges and research opportunities. *Freshwater Biology*, 55, 1-16.

Backhouse G., Lyon J. & Cant B. (2008) *National recovery plan for the Murray hardyhead Craterocephalus fluviatilis*. State of Victoria Department of Sustainability and Environment, (Melbourne, Victoria).

Balcombe E. R., Arthington A. H., Foster N. D., Thoms M. C., Wilson G. G. & Bunn S. E. (2006a) Fish assemblages of an Australian dryland river: abundance, assemblage structure and recruitment patterns in theWarrego River, Murray–Darling Basin. *Marine and Freshwater Research*, 57, 619 - 633.

Balcombe S. R. & Arthington A. H. (2009) Temporal changes in fish abundance in response to hydrological variability in a dryland floodplain river. *Marine and Freshwater Research*, 60, 146.

Balcombe S. R., Arthington A. H., Foster N. D., Thoms M. C., Wilson G. G. & Bunn S. E. (2006b) Fish assemblage in an Australian dryland river: abundance assemblage structure and recruitment patterns in the Warrego River, Murray-Darling Basin. *Marine and Freshwater Research*, 57, 619-633.

Balcombe S. R. & Closs G. P. (2004) Spatial relationships and temporal variability in a littoral macrophyte fish assemblage. *Marine and Freshwater Research*, 55, 609-617.

Bennett A. F., Haslem A., Cheal D. C., Clarke M. F., Jones R. N., Koehn J. D., Lake P. S., Lumsden L. F., Lunt I. D., Mackey B. G., Nally R. M., Menkhorst P. W., New T. R., Newell G. R., O'Hara T., Quinn G. P., Radford J. Q., Robinson D., Watson J. E. M. & Yen A. L. (2009) Ecological processes: A key element in strategies for nature conservation. *Ecological Management & Restoration*, 10, 192-199. (10.1111/j.1442-8903.2009.00489.x).

Bice C. M., Hammer M., Leigh S. & Zampatti B. P. (2010) *Fish monitoring for the 'Drought Action Plan for South Australian Murray-Darling Basin threatened freshwater fish populations': Summary for 2009/10*. South Australian Research and Devlopment Institute (Aquatic Sciences), SARDI Publication No. F2010/000647-1. SARDI Research Report Series No. 484, (Adelaide).

Bond N. R. & Lake P. S. (2003) Local habitat restoration in streams: constraints on the effectiveness of restoration for stream biota. *Ecological Management & Restoration*, 4, 193-198. (doi: 10.1046/J.1442-8903.2003.00156).

Bond N. R., Lake P. S. & Arthington A. H. (2008) The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia*, 600, 3-16.

Boulton A. J. (2003) Parallels and contrasts in the effects of drought on stream macroinvertebrate assemblages. *Freshwater Biology*, 48, 1173–1185.

Boys C. A., Robinson W., Butcher. A., Zampatti. B. & Lyon J. (2008) *Framework for developing and implementing ecological monitoring and evaluation of aquatic rehabilitation in demonstration reaches*. Murray Darling Basin Commission. , Project No. 43/08.

Bunn S. & Arthington A. H. (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, 30, 492-507.

Caruso B. (2002) Temporal and spatial patterns of extreme summer low flows and effects on steam ecosystems in Otago, New Zealand. *Journal of Hydrology* 257, 115-133.

Chapman C. A., Morgan D. L., Beatty S. J. & Gill H. S. (2006) Variation in life history of land-locked lacustrine and riverine populations of *Galaxias maculatus* (Jenyns 1842) in Western Australia. *Environmental Biology of Fishes*, 77, 21-37.

Chapman L. J. & Chapman C. A. (1998) Hypoxia tolerance of the Mormyrid *Petrocephalus catostoma*: Implications for persistence in swamp refugia. *Copeia*, 1998, 762-768.

Closs G. P., Balcombe S. R., Driver P., McNeil D. G. & Shirley M. J. (2006) The importance of floodplain wetlands to Murray-Darling fish: What's there? What do we know? What do we need to know? In *Native fish and wetlands in the Murray-Darling Basin* Canberra Workshop 7-8 June.

Closs G. P. & Lake P. S. (1996) Drought, differential mortality and the coexistence of a native and an introduced fish species in a south east Australian intermittent stream. *Environmental Biology of Fishes*, 47, 17-26.

CRC for Catchment Hydrology (2004) *Goulburn Broken River*. (<http://www.catchment.crc.org.au/focus_catchments/goulburnriver.html>. Accessed on 01/10/2010.

Crook D. A., Koster W. M., Macdonald J. I., Nicol S. J., Belcher C. A., Dawson D. R., O'Mahony D. J., Lovett D., Walker A. & Bannam L. (2010a) Catadromous migrations by female tupong (*Pseudaphritis urvillii*) in coastal streams in Victoria, Australia. *Marine and Freshwater Research*, 61, 474-483.

Crook D. A., Reich P., Bond N. R., McMaster D., Koehn J. & Lake P. S. (2010b) Using biological information to support proactive strategies for managing freshwater fish during drought. *Marine and Freshwater Research*, 61, 379-387.

Dahm C. N., Baker M. A., Moore D. I. & Thibault J. R. (2003) Coupled biogeochemical and hydrological responses of streams and rivers to drought. *Freshwater Biology*, 48, 1219-1231.

Dai A. (2011) Drought under global warming: a review. *Wiley Interdisciplinary Reviews: Climate Change*, 2, 45-65.

DEEDI (2009) *Your fish. Your future. Queensland Fisheries Strategy 2009–14*. The State of Queensland, Department of Employment, Economic Development and Innovation.

DERM (2010a) *Aquatic Biodiversity Assessment and Mapping Method (AquaBAMM)*. (Department of Environment and Resource Management, Queensland) <http://www.epa.qld.gov.au/wetlandinfo/site/SupportTools/AssessmentMethods/AquaBAMM.html.>. Accessed on 19/01/2010.

DERM (2010b) *Refugial waterholes project: research highlights*. State of Queensland (Department of Environment and Resource Management), (Queensland, Australia).

DERM (2011) *Water Planning Ecology Information Series No. 5: The aquatic ecosystem conceptual framework*. (Queensland Government: Brisbane).

DNRE (2002) *Victorian River Health Strategy*. Department of Natural Resources and Environment (Victoria).

DNRW (2007a) *Annual report 2005–06: Queensland's Water Resource Plans*. Department of Natural Resources and Water, (Brisbane, Australia).

DNRW (2007b) *Far North Queensland Draft Regional Water Supply Strategy*. Department of Natural Resources and Water, Technical Document No. 10: Mutli-Criteria Analysis, (Brisbane, Australia).

DSE (2005) *Our Environment, Our Future: Victoria's Environment Sustainability Framework*. The State of Victoria Department of Sustainability and Environment, (Melbourne, Australia).

DSE (2009) *Northern River Sustainable Water Strategy: Our Water, Our Future*. The State of Victoria Department of Sustainability and Environment, (Melbourne, Australia).

EPBC Act (1999) *Environment Protection and Biodiversity Conservation Act 1999 (Commonwealth)*. Department of the Environment, Water, Heritage and the Arts, (http://www.comlaw.gov.au/Series/C2004A00485: Canberra, Australia).

FFG Act (1988) *Flora and Fauna Guarantee Act 1988. Version No. 035*. Department of Sustainability and Environment, (http://www.legislation.vic.gov.au/Domino/Web_Notes/LDMS/LTObject_Store/LTObjSt2.nsf/DDE300B846EED9C7CA257616000A3571/19DB9EE849989DD7CA257761001F31CA/$FILE/88-47a035.pdf: Melbourne, Australia).

Fisheries Act (Vic) (1995) *Fisheries Act 1995 No. 92 of 1995*. State of Victoria (Melbourne, Victoria).

FM Act NSW (1979) *Fisheries Management Act 1994 No 38 (NSW)*. New South Wales Department of Primary Industries (http://www.legislation.nsw.gov.au/viewtop/inforce/act+38+1994+FIRST+0+N/: Sydney, Australia).

FM Act SA (2007) *Fisheries Management Act 2007 (SA)*. Primary Industries and Resources South Australia, (http://www.legislation.sa.gov.au/LZ/C/A/FISHERIES%20MANAGEMENT%20ACT%202007.aspx: Adelaide, Australia).

Franklin J. F. (1993) Preserving biodiversity: species, ecosystems, or landscapes? *Ecological Applications*, 3, 202-205.

Franklin J. F. (1994) Preserving biodiversity: species in landscapes: response. *Ecological Applications*, 4, 208-209.

Gawne B. & Gigney H. (2008) *The effects of drought on aquatic ecosystems of the Murray-Darling Basin*. Report prepared for Murray-Darling Basin Commission. Murray-Darling Freshwater Research Centre, (Wodonga).

GBCMA (2005) *Regional River Health Strategy 2005-2015*. Goulburn Broken Catchment Management Authority, (Shepparton, Victoria).

GBCMA (2008) *Goulburn Broken Catchment Dry Inflow Contingency Plan 2008-2009*. Goulburn Broken Catchment Management Authority, (Shepparton, Victoria).

Gehrke P. C. & Harris J. H. (2001) Regional-scale effects of flow regulation on lowland riverine fish communities in New South Wales, Australia. *Regulated Rivers: Research and Management*, 17, 369-391.

Geissler K. & Gzik A. (2008) The impact of flooding and drought on seeds of *Cnidium dubium*, *Gratiola officinalis*, and *Juncus atratus*, three endangered perennial river corridor plants of Central European lowlands. *Aquatic Botany*, 89, 283-291.

Gilligan D., Rodgers M., McGarry T., Asmus M. & Pearce L. (2010) *The distribution and abundance of two endangered fish species in the NSW Upper Murray Catchment*. Industry & Investment NSW, Batemans Bay Fisheries Centre, (Batemans Bay, NSW).

Gomez A. & Lunt D. H. (2006) Refugia within refugia: patterns of phylogeographic concordance in the Iberian Peninsula. In *Phylogeography of Southern European Refugia*. (Eds S. Weiss and N. Ferrand) pp. 155-188. (Springer: Netherlands).

Hames F. & Tennant W. (2009) One thousand and one cups of tea and the Native Fish Strategy: engaging with the community. In *Proceedings of the Murray Darling Basin Authority Native Fish Forum* Albury Entertainment Centre. (Ed. J. Pritchard) pp. 36-45. (Murray Darling Basin Authority).

Hammer M., Wedderburn S. D. & van Weenan J. (2009) *Action plan for South Australia: freshwater fishes*. Native Fish Australia (SA) Incorporated and Department for Environment and Heritage, (Adelaide, SA).

Humphries P. & Baldwin D. S. (2003) Drought in aquatic environments. *Freshwater Biology*, 48, 1141-1283.

IUCN (2010) *IUCN Red list of threatened species. Version 2010.4*. International Union for Conservation of Nature and Natural Resources, (http://www.iucnredlist.org27: Downloaded on 27 October 2010. Cambridge, United Kingdom).

Jennings P. R., Zampatti B. P. & Bice C. M. (2008) *Fish movement and recruitment in the Coorong and Lower Lakes*. South Australian Research and Development Institute, Aquatic Sciences, SARDI Aquatic Sciences Publication No. F2007/000555-2, SARDI Research Report Series No. 302, (Adelaide, SA).

Jones R. T., Marhsall J. D., Crowley S. F., Bedford A., Richardson N., Bloemendal J. & Oldfield F. (2002) A high resolution, multiproxy late-glacial record of climate change and intrasystem responses in northwest England. *Journal of Quaternary Science*, 17, 329–340.

King A. J. (2002) *Recruitment ecology of fish in floodplain rivers of the Southern Murray-Darling Basin, Australia*. PhD thesis, Monash University. Melbourne, Australia

King A. J., Humphries P. & Lake P. S. (2003) Fish recruitment on floodplains: the roles of patterns of flooding and life history characteristics. *Canadian Journal of Fish Aquatic sciences*, 60, 773-786.

Lake P. S. (2003) Ecological effects of perturbation by drought in flowing waters. *Freshwater Biology*, 48, 1161-1172.

Lake P. S. (In Press) *Drought and aquatic ecosystems: effects and responses* (Wiley-Blackwell).

Lake P. S., Reich P. & Bond N. R. (2008) An appraisal of studies on the impacts of drought on aquatic ecosystems: gaps and future directions. *Proceedings of the International Association of Theoretical and Applied Limnology* (SIL) 30, 505-509.

Lambeck R. J. (1997) Focal species: a multi-species umbrella for nature conservation. *Conservation Biology*, 11, 849-856. (10.1046/j.1523-1739.1997.96319.x).

Lancaster J. & Belyea L. R. (1997) Nested hierarchies and scale-dependence of mechanisms of flow refugium use. *Journal of the North American Benthological Society*, 16, 221-238.

Leigh S. J., Zampatti B. P. & Nicol J. M. (2008) *Spatial and temporal variation in larval fish assemblage structure in the Chowilla Anabranch system: with reference to water physico-chemistry and stream hydrology*. South Australian Research and Development Institute, Aquatic Sciences, SARDI Aquatic Sciences Publication No: F2008/000051-1; SARDI Research Report Series No. 286, (Adelaide, SA).

Lindenmayer D. B. & Likens G. E. (2010) *Effective ecological monitoring* (CSIRO Publishing and Earthscan: Melbourne and London).

Lintermans M. (2007) *Fishes of the Murray-Darling Basin: an introductory guide*. Murray-Darling Basin Commission, MDBC Publication No. 10/07, (Canberra).

Lintermans M. & Cottingham P. (2007) *Fish out of water: lessons for managing native fish during drought*. Final Report of the Drought Expert Panel. Murray-Darling Basin Commission, (Canberra).

Magalhaes M. F., Beja P., Canas C. & Collares-Pereira J. (2002) Functional heterogeneity of dry-season fish refugia across a Mediterranean catchment: the role of habitat and predation. *Freshwater Biology*, 47, 1919-1934.

Magalhaes M. F., Beja P., Schlossers I. J. & Collares-Pereira J. (2007) Effects of multi-year droughts on fish assemblages of seasonally drying Mediterranean streams. *Freshwater Biology*, 52, 1494-1510.

Magoulick D. D. & Kobza R. M. (2003) The role of refugia for fishes during drought: a review and synthesis. *Freshwater Biology*, 48, 1186–1198.

Marques S. C., Azeiteiro U. M., Martinho F. & Pardal M. A. (2007) Climate variability and planktonic communities: The effect of an extreme event (severe drought) in a southern European estuary. *Estuarine, Coastal and Shelf Science*, 73, 725-734.

Matthews T. G. (1998) Patterns in freshwater fish ecology. Chapter 7. In. (Chapman and Hall New York).

Matthews W. J. & Marsh-Matthews E. (2003) Effects of drought on fish across axes of space, time and ecological complexity. *Freshwater Biology*, 48, 1232-1253.

McInnes K. L., Suppiah R., Whetton P. H., Hennessy K. J. & Jones R. N. (2003) *Climate change in South Australia. Report on: assessment of climate change, impacts and possible adaptation strategies relevant toSouth Australia. Undertaken for the South Australian Government.* . Climate Impact Group, CSIRO Atmospheric Research, (Aspendale, Victoria).

McNeil D. G. (2004) *Ecophysiology and behaviour of Ovens River floodplain fish: hypoxia tolerance and the role of the physicochemical environment in structuring Australian billabong fish communities*. LaTrobe University. Bundoora, Victoria

McNeil D. G., Gehrig S. & Sharpe C. (In prep) *Resistance and resilience of Murray-Darling Basin fishes to drought disturbance*. A report to the Murray-Darling Basin Authority under Native Fish Strategy project MD/1086 "Ecosystem Resilience and The Role of Refugia for Native Fish Communities & Populations". South Australian Research and Development Institute, Aqutics Sciences, (Adelaide, Australia).

McNeil D. G., Wilson P. J., Reid D. F. & Schmarr D. W. (2009) *Sustainability and flow ecology of fishes in the Western Mount Lofty Ranges, South Australia*. South Australian Research and Development Institute, SARDI Reasearch Report Series, (Adelaide).

MDBA (2010) *Guide to the proposed Basin Plan: overview*. Murray-Darling Basin Authority, MDBA Publication No. 60/10, (Canberra, Australia).

Meredith S. & Beesley L. (Eds) (2009) *Watering floodplain wetlands in the Murray–Darling Basin to benefit fish: a discussion with managers*. (Arthur Rylah Institute for Environmental Research Technical Report Series No. 189. Department of Sustainability and Environment: Heidelberg, Victoria).

Meredith S. & Conallin A. (2006) *The influence of flow on lowland river fish communities (Lindsay, Island Victoria)*. Murray-Darling Freshwater Research Centre, Technical Report 3/06, (Mildura, Australia).

Morrongiello J., Elith J. & Crook D. (2006) *Impacts of drought on fish in Victorian rivers and streams*. Arthur Rylah Institute for Environmental Research, (Heidelberg, Victoria).

Murphy B. F. & Timbal B. (2007) A review of recent climate variability and climate change in southeastern Australia. *International Journal of Climatology*, 7, 859-879.

Murphy B. F. & Timbal B. (2008) A review of recent climate variability and climate change in southeastern Australia. *International Journal of Climatology*, 28, 859-879. (doi: 10.1002/joc.1627).

NCA QLD (1992) *Queensland Nature Conservation Act 1992 (Reprint No 6G)*. Queensland Department of Environment and Resource Management (http://www.legislation.qld.gov.au/LEGISLTN/CURRENT/N/NatureConA92.pdf: Brisbane, Australia).

Noell C., Ye Q., Short D. A., Bucater L. B. & Wellman N. R. (2009) *Fish assemblages of the Murray Mouth and Coorong region, South Australia, during an extended drought period.* CSIRO: Water for a healthy Country National Research Flagship and South Australia Research and Development Institute (Aquatic Sciences), Adelaide, (Adelaide, SA).

Ostrand K. G. & Wilde G. R. (2001) Temperature, dissolved oxygen, and salinity tolerances of five prairie stream fishes and their role in explaining fish assemblage patterns. . *Transactions of the American Fisheries Society*, 130, 742-749.

Patra R. W., Chapman J. C., Lim R. P. & Gehrke P. C. (2007) The effects of three organic chemicals on the upper thermal tolerances of four freshwater fishes. *Environmental Toxicology and Chemistry* 26, 1454-1459.

Peters, G. and McNeil, D. G (2011). Legislative and Policy Context for the Protection of Drought Refuges for Native Fish in the Murray-Darling Basin Report to the Murray-Darling Basin Authority, Native Fish Strategy – Project MD1087. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000202-1. SARDI Research Report Series No. 554. 100pp.

Phillips, B. (compiler). (2003). Government overviews and perspectives. *Managing Fish Translocation and Stocking in the Murray-Darling Basin workshop held in Canberra, 25-26 September 2002.* WWF Australia.

Post D., Chiew F., Vaze J., Teng J., Perraud J.-M. & Viney N. R. (2009) *Future runoff projections (~2030) for south-eastern Australia*. South East Climate Change Inititative. CSIRO Land and Water.

Potter N. J., Chiew F. H. S. & Frost A. J. (2010) An assessment of the severity of recent reductions in rainfall and runoff in the Murray-Darling Basin. *Journal of Hydrology*, 381, 52-64. (DOI: 10.1016/j.jhydrol.2009.11.025).

Potter N. J., Chiew F. H. S., Frost A. J., Srikanthan R., McMahon T. A., Peel M. C. & Austin J. M. (2008) *Characterisation of recent rainfall and runoff in the Murray-Darling Basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project*. CSIRO, (Australia).

Pritchard J., Hammer M., Hall A., Lugg A., Pearce L., Kearns J., Hames F. & Lyon J. (2009) Drought and threatened species. In *Proceedings of the Murray Darling Basin Authority Native Fish Forum* Albury Entertainment Centre. (Ed. J. Prtichard) pp. 63-73. (Murray Darling Basin Authority).

Pusey B., Kennard M. & Arthington A. (2004) *Freshwater fishes of north-eastern Australia* (CSIRO Publishing: Collingwood, Victoria).

Rahel J. F. & Nutzman J. W. (1994) Foraging in a lethal environment: fish predation in hypoxic waters of a stratified lake. *Ecology* 75, 1246-1253.

Reid D. J., Quinn G. P., Lake P. S. & Reich P. (2008) Terrestrial detritus supports the food webs in lowlandintermittent streams of south-eastern Australia: a stableisotope study. *Freswater Biology*, 53, 2036-2050.

Reynolds L. (1983) Migration patterns of 5 fish species in the Murray-Darling River system. *Australian journal of marine and freshwater research*, 34, 857-871.

Robson B. J., Chester E. T., Mitchell B. D. & Matthews T. G. (2008) *Identification and management of refuges for aquatic organisms: waterlines report*. Waterlines Report. National Water Commission, (Canberra).

Rosenberger A. E. & Chapman L. J. (2000) Respiratory characters of three species of haplochromine cichlids: implications for the use of swampland refugia. . *Journal of Fish Biology*, 57, 483-501.

Ross S. T., Matthews W. J. & Echelle A. A. (1985) Persistence of stream fish assemblages: effects of environmental change. *The American Naturalist*, 126, 24-40.

Sedell J. R., Reeves G. H., Hauer F. R., Stanford J. A. & Hawkins C. P. (1990) Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems. *Environmental Management*, 14, 711-724.

SKM (2003) *Review of habitat associations of native fish in the Murray-Darling Basin. Murray-Darling Basin Commission Project R2105*. . Sinclair Knight Merz, (Armadale, Victoria).

Sparks R. E., Bayley P. B., Kohler S. L. & Osborne L. L. (1990) Disturbance and recovery of large floodplain rivers. . *Environmental Management*, 14, 699-709.

Sternberg D., Balcombe S., Marshall J. & Lobegeiger J. (2008) Food resource variability in an Australian dryland river: evidence from the diet of two generalist native fish species. *Marine and Freshwater Research*, 59, 137-144. (doi:10.1071/MF07125).

Timbal B. & Jones D. A. (2008) Future projections of winter rainfall in southeast Australia using a statistical downscaling technique. *Climate Change.*, 86, 165-187.

Timbal B. & Murphy B. (2007) *Documenting changes in south-eastern Australian rainfall, temperature, surface humidity and pan evaporation*. South East Climate Change Inititative. CSIRO Land and Water.

Tracy C. R. & Brussard P. F. (1994) Preserving biodiversity: species in landscapes. *Ecological Applications*, 4, 206-207.

TSC Act (NSW) (1995) *Threatened Species Conservation Act 1995 No 101*. New South Wales Department of Environment and Climate Change, (http://www.legislation.nsw.gov.au/viewtop/inforce/act+101+1995+FIRST+0+N: Sydney, Australia).

Ummenhofer C. C., England M. H., McIntosh P. C., Meyers G. A., Pook M. J., Risbey J. S., Sen Gupta A. & Taschetto A. S. (2009) What causes Southeast Australia's worst drought? . *Geophysical Research Letters*, 36. (doi: 10.1029/2008GL036801).

Wager R. & Jackson P. (1993) *The action plan for Australian freshwater fishes* (Environment Australia).

Water Act (Victoria) (1989) *Water Act 1989 (Vic). Version No. 099B*. Office of Water, State Government of Victoria, (http://www.legislation.vic.gov.au/Domino/Web_Notes/LDMS/LTObject_Store/LTObjSt5.nsf/DDE300B846EED9C7CA257616000A3571/F8DBB7E6417A03EDCA2577CB00024075/$FILE/89-80a099B.pdf: Melbourne, Australia).

Wiens J. A. (1977) On competition and variable environments. *American Scientist*, 65, 590-597.

Wood R. & Pfitzer D. W. (1960) Some effects of water-level fluctuations on the fisheries of large impoundments. In *International Union for conservation of nature & natural resources, soil and water conservation*. Brussels pp. 118–138. (IUCN).

Zampatti B. P., Bice C. M. & Jennings P. R. (2010) Temporal variability in fish assemblage structure and recruitment in a freshwater-deprived estuary: The Coorong, Australia. *Marine and Freshwater Research*, 61, 1298-1312.

6. APPENDICES

6.1 Survey questionnaire developed to collate management information regarding drought refuges

Questionnaire: Defining and Managing Aquatic Drought Refuges

Please answer each of the following questions to the best of your ability. Feel free to seek input from other experts in your area prior to the phone survey to help provide comprehensive answers.

All answers will be collected over the phone later this week. Please advise us what time would best suit you for the phone interview.

It may help you to make a list of the refuge types you identify in Q1 as many of the questions ask you to address points for each of these separately.

1. What different types of physical aquatic refuges do you have in your region?
2. Prioritisation: In what order would you prioritise the importance of each of these as aquatic refuges in your region?

For each type of refuge, please address the following in as much detail as possible:

Refuge value:

3. What are the major ecological values of each type of refuge you identified in Q1?
4. For the refuges identified in Q1 please fill out the following:
    4. How would you prioritise each type as refuge?
        i. For vulnerable/threatened fishes?
        ii. For native fish biodiversity?
    5. For extended drought conditions, over what timeframe is each type likely to serve as a refuge?
    6. What are the key fish species that these refuges protect?

Key threats:

5. What are the major factors that threaten the persistence or value of each of these types of refuge?
6. For the refuges identified in Q1, which of these types are most at risk from the impacts of drought?

Management actions:

7. What are the primary management options for protecting each these types?
    a. In the short term?
    b. In the long-term?
8. What projects and/or programs is your region/state currently running that have outcomes for protecting/managing drought refuges?
9. What are the management objectives for these projects/programs?
10. How are the outcomes of these projects/programs assessed?

Resilience following drought:

11. What other ecosystem components are essential for these to allow resilience for aquatic fauna (especially fish) during and following drought?
12. What components of aquatic systems provide a threat to the resilience of native fish following drought?

Fish and critical refuges for immediate protection:

13. What are the key fish species/populations at immediate risk from drought?

14. What are the key refuge types that provide refuges for each of these species?
15. Which are the most critical refuges for immediate management action in your region?
16. Where are they located? (E&N)
17. What species are under threat within these?

One of the team members will collect your answers over the phone later in the week. Please try to get as much as you can fill out prior to the phone interview. All information will be used as the basis for the Melbourne workshop and your input and assistance in this process is greatly appreciated. We hope this process will benefit the consistent and effective protection and management of aquatic refuges in the long-term.

Thanks for your co-operation,

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6.2 List of state and regional affiliations and relevant individuals that contributed to this report through workshop attendance, telephone and written interviews and other inputs.

State	*Institution/Affiliation*	*Invited Participants*	*Survey*	*Workshop*	*Phone Interview*
Federal	Murray-Darling Basin Authority	Janet Pritchard		Janet Pritchard	
	Environment ACT	Lisa Evens, Jason Thiem, Matthew Bietzel			Matthew Bietzel
	University of Canberra	Mark Lintermans, Martin Thoms,			
South Australia	Department of Primary Industries and Resources (PIRSA)	John McPhail, Julia Smith, Louise Searle			
	South Australian Research and Development Institute (SARDI)	Chris Bice, Dale McNeil, Ben Smith, Brenton Zampatti, Qifeng Ye	Brenton Zampatti	Dale McNeil, Qifeng Ye	
	Department of Environment and Heritage	Jason Higham, Arkellah Hall	Jason Higham, Arkellah Hall	Jason Higham, Arkellah Hall	Arkellah Hall
	South Australian Murray-Darling Basin Natural Resource Management Board (SAMDBNRMB)	Adrienne Frears, Brad Hollis, Tracey Steggles, Mardi van der Wielen		Adrienne Frears	Adrienne Frears
	University of Adelaide	Scotte Wedderburn, Anthony Conallin			
	Aquasave Consultants	Michael Hammer			Michael Hammer
Victoria	Department of Sustainability and Environment (DSE)	Paul Bennett, David Crook, Pam Clunie, Fern Hames, John Koehn, Alison King, Jarrod Lyon, Sam Marwood, Jed McDonald, Bill O'Connor, Tarmo Raadik, Steve Saddlier, Zeb Tonkin	John Koehn	Paul Bennett, Bill O'Connor, Sam Marwood, John Koehn, Fern Hames, Andrea Joyce, Michael Jensz	Michael Jensz, Steven Nicol
	Environmental Protection Authority (EPA)	Leon Metzeling	Leon Metzeling	Leon Metzeling	Leon Metzeling
	Department of Primary Industries (DPI VIC)	John Douglas, Wayne Fulton, Fiona Gavine	Fiona Gavine	Fiona Gavine	
	Monash University	Nick Bond, Sam Lake, Damien McMaster, Paul Reich, Kirsten Shelley, Ross		Nick Bond, Sam Lake, Damien McMaster, Paul Reich,	

State	***Institution/Affiliation***	***Invited Participants***	***Survey***	***Workshop***	***Phone Interview***
		Thompson		Kirsten Shelley	
	Latrobe University	Terry Hillman			
	Deakin University	Belinda Robson			
	Wimmera Catchment Management Authority (CMA)	Hugh Christie, Greg Fletcher		Greg Fletcher	
	Mallee CMA	Louise Searle	Louise Searle	Louise Searle	
	North Central CMA	Darren White,		Darren White,	
	Goulbourn-Broken CMA	Wayne Tennant, Keith Ward	Keith Ward	Keith Ward	
	North East CMA	Sarah Daniell, Matthew O'Connell	Sarah Daniell, Matthew O'Connell	Sarah Daniell, Matthew O'Connell	
New South Wales	Department of Primary Industries (DPI)	Craig Boys, Sam Davis, Dean Gilligan, Allan Lugg, Sharon Malloy, Nathan Reynoldson, Adam Vey, Luke Pearce		Allan Lugg	Adam Vey, Allan Lugg, Luke Pearce
	Department of Environment and Climate Change (DECC)	Mike Maher, Neil Saintilan, Peter Terrill			
	Department of Water Resources and Environment	Ivor Growns, Patrick Driver			
	University of New England	Andrew Boulton, Glen Wilson			
	University of New South Wales	Tom Rayner			
	Charles Sturt University	Paul Humphries			
	Lower Murray Darling CMA	Troy Muster, Clayton Sharpe (MDFRC)	Clayton Sharpe (MDFRC)	Clayton Sharpe (MDFRC)	
	Murray CMA	Tracy Brownbill		Tracy Brownbill	
	Murrumbidgee CMA	Pat Murray			
	Lachlan CMA	Alan McGufficke		Alan McGufficke	
	Central West CMA	Shona Whitfield		Shona Whitfield	
	Western CMA	Marita Pearson		Marita Pearson	

State	***Institution/Affiliation***	***Invited Participants***	***Survey***	***Workshop***	***Phone Interview***
	Namoi CMA	Nathan Penny, Stephanie McCaffrey		Nathan Penny, Stephanie McCaffrey	
	Border Rivers/Gwydir CMA	Liz Savage		Liz Savage	
Queensland	Condamine Alliance	Kevin Graham			Kevin Graham
	Department of Primary Industries (QDPI) (now DEEDI)	Adam Butcher, Stephanie Challen, Mark Hutchinson, Greg Ringwood	Stephanie Challen, Greg Ringwood	Stephanie Challen, Greg Ringwood	Greg Ringwood
	Department of Environment and Natural Resources	Charlie Ellway, Jonathan Marshall, Jaye Lobegeiger	Charlie Ellway, Jonathan Marshall, Jaye Lobegeiger	Charlie Ellway, Jonathan Marshall, Jaye Lobegeiger	Charlie Ellway
	Griffith University	Angela Arthington, Stephen Balcombe, Brendan Ebner, Mark Kennard, David Sternberg		Stephen Balcombe	

6.3 Drought refuges: workshop questionnaire

Defining criteria and refuge types:

1. In the table below, please fill in the following:
   a. What different types of physical aquatic refuges do you have in your region? (Tick).
   b. Prioritisation: In what order would you prioritise the importance each of these as aquatic refuges in your region? (Number).

Refuge Types	Presence	Priority of importance
Isolated ephemeral stream pools		
Permanently flowing unregulated lowland streams/rivers		
Permanently flowing upland streams		
Permanently flowing regulated streams/rivers		
Floodplain billabongs and anabranches (ephemeral)		
Permanently Flowing Anabranches		
Estuaries and marine systems		
Off channel lakes and wetlands		
Weir pools		
Other manmade aquatic habitats (please explain)		
Other types (please explain)		

Refuge value: for each type of refuge identified, please address the following in as much detail as possible:

2. What are the major ecological values of each type of refuge?
3. For the table below please fill out the following:
   a. How would you prioritise each type as refuges?
      i. For vulnerable/threatened fishes?
      ii. For native fish biodiversity?
   b. For extended drought conditions, over what timeframe is each type likely to serve as a refuge?
   c. What are the key fish species that these refuges protect?

Refuge Types	Vulnerable and/or Threatened Fish-Priority	Native Fish Biodiversity-Priority	Fish Species	Time-frame
Isolated ephemeral stream pools				
Permanently flowing unregulated lowland streams/rivers				
Permanently flowing upland streams				
Permanently flowing regulated streams/rivers				
Floodplain billabongs and anabranches (ephemeral)				
Permanently Flowing Anabranches				
Estuaries and marine systems				
Off channel lakes and wetlands				
Weir pools				
Other manmade aquatic habitats				
Other types				

Key threats: what are the major factors that threaten the persistence or value of each of these types?

4. For the table below, which of these types are most at risk from the impacts of drought? (Number)

Refuge Types	Risk Priority
Isolated ephemeral stream pools	
Permanently flowing unregulated lowland streams/rivers	
Permanently flowing upland streams	
Permanently flowing regulated streams/rivers	
Floodplain billabongs and anabranches (ephemeral)	
Permanently Flowing Anabranches	
Estuaries and marine systems	
Off channel lakes and wetlands	
Weir pools	
Other manmade aquatic habitats (please explain)	
Other types (please explain)	

Management actions:

5. What are the primary management options for protecting each these types?

   a. In the short term?

   b. In the long-term?

6. What projects and/or programs are your region/state currently running that have outcomes for protecting/managing drought refuges?
7. What were the management objectives for these projects/programs?
8. Which refuge types are <u>not</u> currently addressed by management projects/programs in your region/state? Why aren't these being addressed?

Resilience following drought:

9. What other ecosystem components are essential for these to allow resilience for aquatic fauna (especially fish) during and following drought?
10. What components of aquatic systems provide a threat to the resilience of native fish following drought?

Fish and critical refuges for immediate protection:

11. What are the key fish species/populations at immediate risk from drought?
12. What are the key refuge types that provide refuges for each of these species?
13. Which are the most critical refuges for immediate management action in your region?
14. Where are they located? (E&N)
15. What species are under threat within these?

6.4 Identified priority drought refuge sites for South Australia, Victoria, New South Wales, the Australian Capital Territory and Queensland listed by catchment and/or region from the workshop. Tables also include a list of resident fish species and specific threats. Blank cells represent unknown information.

State	Region	Site	Type	Key fish species	Specific threats
South Australia	Lower Murray	Disher Ck evaporation basin	Lake	Murray hardyhead	Disconnection,
		Chowilla Anabranch	Flowing Anabranch (Regulated)	Murray cod	Cessation of flows, flow regime changes
		Berri evaporation basin	Lake	Murray hardyhead	Disconnection
		Turvey's Drain	Drain/channel	Southern pygmy perch, Murray hardyhead	Desiccation if irrigator stops using drain
		Lake Alexandrina, Goolwa Channel	Lake	Southern pygmy perch, Yarra pygmy perch, galaxias, congolli, lamprey, pouched lamprey, shortfinned eel, Murray hardyhead	Desiccation from disconnection from Lake Alexandrina, acid-sulphate soils
		Coorong and Murray Estuary	Estuary	Congolli, galaxias, estuary perch, lamprey, pouched lamprey, short finned eel Estuarine species : black bream, mulloway	Lack of barrage outflows, connectivity
		Jury Swamp	Wetland	Purple-spotted gudgeon, Murray hardyhead	Water level decrease below lock 1
		Rocky Gully	Wetland	Murray hardyhead	Disconnection from river and rising salinity and nutrient levels
		Main channel below Lock 1	Regulated River (Reach)	Murray cod, freshwater catfish, silver perch, galaxias, congolli, wetland species	Loss of end river flows, upstream allocation of water.
		Mundoo Island	Drain/Channel	Southern pygmy perch, Murray hardyhead, congolli, galaxias	Desiccation from disconnection from Lake Alexandrina
		Boggy Ck, Hindmarsh Island	Drain/Channel	Murray hardyhead	Desiccation from disconnection from Lake Alexandrina
	Mount Lofty Ranges	Marne River	Unregulated stream (pools)	River blackfish, mountain galaxias	Desiccation, upstream water abstraction, loss of flows.
		Rodwell Creek	Unregulated stream (pool)	River blackfish	Desiccation, upstream water abstraction, loss of flows.
		Bremer River	Unregulated stream (pools)	Mountain galaxias, congolli	Desiccation, upstream water abstraction, loss of flows.
		Angas River	Unregulated stream (pools)	River blackfish, southern pygmy perch, mountain galaxias	Desiccation, upstream water abstraction, loss of flows.
		Finniss River/Meadows Creek	Unregulated stream (pools)	Southern pygmy perch, mountain galaxias, Murray hardyhead	Acid sulphate, Desiccation, upstream water abstraction, loss of flows.

State	Region	Site	Type	Key fish species	Specific threats
Victoria	Wimmera	Six pools downstream of Horsham, Wimmera River	Regulated Lowland River (Waterholes)	Freshwater catfish	Desiccation, hyper-salinity downstream in the river. Extraction also has a bearing in some locations
		Upper Mackenzie River (20km downstream of Lake Wartook)	Regulated River Reach	River blackfish, mountain galaxias, southern pygmy perch	Replacing Horsham's supply with groundwater will mean flows could cease
		Fyan's Ck (U/S Lake Bellfield)	Unregulated Creek (pools)	River blackfish, mountain galaxias, southern pygmy perch	Drought related desiccation of pools
		Upper Wimmera River and Mt William Creek (headwaters)	Unregulated Creek (pools)	River blackfish, mountain galaxias, southern pygmy perch	Drought related desiccation of pools
		Mid Wimmera (upstream of Glenorchy)	Regulated River Pools	River blackfish	Drought related desiccation of pools
Victoria (cntd)	Mallee	Lindsay, Wallpolla, Mullaroo	Flowing Anabranch	Murray cod	Flow regulation and regime shift disrupting the hydraulic variability in the system
		Hattah Lakes	Lake	Murray hardyhead, purple-spotted gudgeon?, Murray cod	
		Lake Walla Walla	Lake	Murray cod	
		Lake Cardross	Lake	Murray hardyhead, freshwater catfish, silver perch	
	North Central Victoria	Round and Woorien Lakes	Lake		
		Tullaroop Creek	Regulated River Reach		
		Gunbower	Floodplain	Southern pygmy perch, flat-headed galaxias	
		Lower Campaspe River	Regulated River Reach (pools)		
		Lodden R (Bridgewater -Newstead)	Regulated River Reach		
		Little Lake Boort	Lake		
	Goulbourn Broken	Broken Creek	Regulated River	Murray cod, trout cod, freshwater catfish, Macquarie perch	
		Seven Creeks	Unregulated River	Trout cod, Macquarie perch	
		King Parrot Creek/	Unregulated River	Macquarie perch	Bushfire
		Hughes Creek	Unregulated River	Macquarie perch	Bushfire
		Upper Goulburn R. (Delatite River to Sunday Creek)	Unregulated Streams	Barred galaxias	Complete loss of baseflow due to drought, bushfires and related impacts
	NE Victoria	Lower Ovens Weirpool	Weirpool	Murray cod, trout cod, golden perch, flat-headed galaxias, southern pygmy perch, Murray cray	Lowered water level at Yarrawonga Weir
		Upper Ovens River	Unregulated Streams	River blackfish, mountain galaxias	Loss of snowmelt and spring feeds. Bushfire

State	Region	Site	Type	Key fish species	Specific threats
	Northeastern Victoria (cont..)	Lower Ovens River	Unregulated River	Murray cod, trout cod, golden perch, river blackfish, mountain galaxias, Murray cray, Macquarie perch	Upstream water use, development of storages and reservoirs, recreational fishing from pools
		Lower Ovens Floodplain	Floodplain	Southern pygmy perch, flat-headed galaxias, river blackfish, golden perch, gudgeons, Australian smelt	Loss of small-medium floods,
		Lower Kiewa River	Regulated River	Murray cod, trout cod, golden perch, river blackfish, mountain galaxias, Murray cray, Macquarie perch	Allocation of Water away from reach
		King River	Regulated River	Murray cod, trout cod, golden perch, river blackfish, mountain galaxias, Murray cray, Macquarie perch	Allocation of Water away from reach
		Lower Buffalo River	Regulated River	Murray cod, trout cod, golden perch, River blackfish, mountain galaxias, Murray cray, Macquarie perch	Allocation of Water away from reach
New South Wales and the Australian Capital Territory	Lower Darling	Refuge pools, Darling River downstream of Menindee Lakes	Regulated River (pools)	Murray cod, golden perch, silver perch, freshwater catfish	Allocation of water away from reach, recreational fishing from pools, water quality deterioration.
		Darling River Channel	Regulated River (pools)	Murray cod, golden perch, silver perch, freshwater catfish	Allocation of water away from reach, recreational fishing from pools, water quality deterioration
		Menindee Lakes	Lake	Golden perch	Disconnection, loss of allocations into storage
		Darling Anabranch,	Regulated River	Murray cod, golden perch	Loss of flows into reach,
		Tallywalker Creek Anabranch	Floodplain		Loss of flows into reach,
	Mid-Lower Murray	Murray River Main Channel	Regulated River	Murray cod, golden perch, silver perch, freshwater catfish	Loss of flow variability/regime
		Edward, Wakool River	Regulated River	Murray cod, golden perch, silver perch	Desiccation of pools, loss of inflows
		Lake Euston	Lake	Murray hardyhead	Disconnection and lack of filling
		Washpen Creek	Regulated River	Freshwater catfish	Hyper-salinisation, loss of flow inputs
		Lake Victoria	Lake	Freshwater catfish	Hyper-salinisation, loss of flow inputs
	Mid-Upper Murray	Coppabella Creek (Tumbarumba)	Unregulated Stream	Southern pygmy perch, river blackfish	Desiccation of pools
		Norman's Lagoon (Albury)	Wetland	Southern pygmy perch, flat-headed galaxias	Desiccation and water quality, loss of water inputs for wetland maintenance.
		Tarcutta Creek	Unregulated Stream	Trout cod, southern pygmy perch	Desiccation of pools, loss of inflows
		Mid Murray below Yarrawonga Weir	Regulated River	Trout cod, Murray cod, golden perch, silver perch	Loss of flow variability/regime

State	Region	Site	Type	Key fish species	Specific threats
New South Wales	Murrumbidgee	Montane Peatlands	Upland Wetland		Groundwater drawdown, bushfire, climate change
		Upper Murrumbidgee - Yaouk (near Adaminaby) to Bredbo	Unregulated River	Trout cod, Macquarie perch	Loss of flow (needs e-flows)
		Mid-Upper Murrumbidgee River and tributaries	Regulated River	Murray cray, trout cod, two-spined blackfish,	Extraction of water, loss of flows
		Queanbeyan River	Regulated River		Extraction of water, loss of flows
		Cotter Catchment	Regulated River	Macquarie perch, trout cod, two-spined blackfish	Water abstraction, sedimentation
		Lower Murrumbidgee River	Regulated River	Murray cod, golden perch, freshwater catfish	Loss of flow regime and flooding
	Lachlan	Blakney Creek	Unregulated Creek	Southern pygmy perch	Invasive species, land use & clearing, sedimentation
		Abercrombie River	Unregulated River	Macquarie perch	Loss of instream habitat, sedimentation, riparian vegetation
		Pudman Creek	Unregulated Creek	Southern pygmy perch	Sedimentation, invasive species, land use impacts
		Crookwell River	Unregulated River	Southern pygmy perch	Sedimentation, invasive species, land use impacts
		Upper Lachlan	Unregulated River	Macquarie perch	Sedimentation, loss of instream and riparian habitat, carp.
		Booberoi Creek	Regulated River	Freshwater catfish	Loss of river flows
		Brewster Weir	Weirpool	Olive perchlet, Murray cod	Loss of flows, disconnection of storage
		Burrawang West (Goobang Ck)	Weirpool	Purple-spotted gudgeon	Loss of flow inputs through disconnection of inflow channel
		Willandra Weir	Weirpool	Olive perchlet, Murray cod	Loss of river flows
	Central West NSW	Terminal Wetlands: Castlereagh River	Wetland	Purple-spotted gudgeon, olive perchlet	Loss of river flows, allocation of water away from end of channel targets
		Terminal Wetlands: Bogan River	Wetland		Loss of river flows, allocation of water away from end of channel targets
		Terminal Wetlands: Macquarie River	Wetland		Loss of river flows, allocation of water away from end of channel targets
		Swampy Meadows and Chain of ponds: Castlereagh River	Upland wetland		Land clearance & agriculture, erosion
		Swampy Meadows and Chain of ponds: Macquarie River	Upland wetland		Land clearance & agriculture, erosion

State	Region	Site	Type	Key fish species	Specific threats
New South Wales cont..	Western NSW	Parroo,	Unregulated River (pools)		Water storages, pumping
		Narran Lakes	Wetland	Bony herring, spangled perch	Condamine-Balonne Water Resource Plan (legal extractions / water harvesting
		Warrego-Cuttaburra	Unregulated River (pools)		
		Artesian Mound Springs (Peery Lake)	Mound Spring	Fish or just others?	GAB extractions; feral animal damage
		Culgoa River	Regulated River (pools)??		Condamine-Balonne Water Resource Plan (legal extractions / water harvesting)
		Narran River	Regulated River (pools)		Condamine-Balonne Water Resource Plan (legal extractions / water harvesting)
		Lower Balonne floodplain incl. Culgoa, Birrie, Bokhara and Narran	Floodplain		Loss of small-medium sized flooding flows
		Barwon/Darling (EEC)	Regulated River (system). Pools, floodplain, Wetlands		Allocation of water away from the environment
	Namoi	Upper drainage lines in Great Dividing Range	Unregulated creek	Purple-spotted gudgeon	Lack of knowledge
		Lowland Darling EEC (wetland complex)	Wetland	Golden perch, Murray cod	Loss of flows
		New England Tablelands	Unregulated Streams	Purple-spotted gudgeon	Lack of knowledge
	Border Rivers Gwydir	Severn River	Unregulated Streams	Purple -potted gudgeon, mountain galaxias, River blackfish, silver perch	
		Gwydir River	Unregulated River (including floodplain	Freshwater catfish, Murray cod, unspecked hardyhead	Whole assemblage isolated through barriers, Over-pumping of pools, over-stocking of high-level predators
		Mole River	Unregulated River	Purple-spotted gudgeon, olive perchlet, freshwater catfish, Murray cod, unspecked hardyhead	Landholders pushing block banks over downstream pools, over-pumping of pools
		Dumaresq River	Unregulated River	Purple-spotted gudgeon, olive perchlet, freshwater catfish, Murray cod, unspecked hardyhead, silver perch	Over-pumping of pools, over-stocking of high-level predators
Queensland	South- western QLD	Paroo	Unregulated River	Golden perch	Water Storages

	Southeastern QLD	Warrego	Unregulated River	Golden perch, olive perchlet, Murray cod	Abstraction, weirs at Charleville and Cunnamulla
		Warrego - Cuttaburra Creek (distributary)	Unregulated River (pools)	Golden perch	Extraction
		Moonie	Unregulated River	Golden perch, Murray cod (?), olive perchlet, Hyrtl's tandan	Siltation, extraction
		Weir River	Regulated River	Murray cod, silver perch	Diversions from waterholes
		Macintyre River	Regulated River	Golden perch, Murray cod, olive perchlet, silver perch, unspecked hardyhead, Australian smelt, freshwater catfish	Agricultural development to edge of bank, changed flow regime for irrigation, stock watering causing sedimentary infilling
		Macintyre wetlands	Wetland	Freshwater catfish, olive perchlet	Lack of wetland filling
		Dumaresq River	Regulated River	Purple-spotted gudgeon, olive perchlet, freshwater catfish, Murray cod, unspecked hardyhead, silver perch, flat-headed gudgeon	Over-stocking of predators and overuse of water for irrigation, cold water pollution
		Severn River (Qld)	Unregulated River	Purple-spotted gudgeon, silver perch, freshwater catfish, olive perchlet, Murray rainbowfish	Diversions from waterholes, Loss of flow volumes
		Severn Wetlands	Wetland	Purple-spotted gudgeon, olive perchlet, freshwater catfish, Murray rainbowfish	Lack of filling
		Accommodation Creek	Unregulated stream	Purple-spotted gudgeon, river blackfish, olive perchlet silver perch	
	Condamine (upper)	Upper Condamine tributaries	Unregulated Streams (system)	Purple-spotted gudgeon, river blackfish	
		Condamine River headwaters	Unregulated Streams (pools)	River blackfish, mountain galaxias, freshwater catfish	Clearing of riparian borders for grazing; over-extraction of water; sedimentary infill from stock watering.
	Condamine (Lower)	Canal Creek near Leyburn	Unregulated Creek	Olive perchlet, freshwater catfish, Murray cod, unspecked hardyhead, silver perch	Clearing of riparian borders; sedimentary infill from stock watering.
		Oakey Creek - pools at and below Bowenville Reserve	Unregulated River	Olive perchlet, freshwater catfish, Murray cod, golden perch, unspecked hardyhead, silver perch, Australian smelt	Agricultural development to edge of bank; over-extraction for irrigation; stock watering causing sedimentary infilling.

Queensland cont..	Condamine (Lower) cont..	Lower Myall Creek	Unregulated River (pools)	Olive perchlet, freshwater catfish, Hyrtl's tandan	Urban and agricultural development to edge of bank; over-extraction for irrigation; stock watering causing sedimentary infilling.
		Upper Charlies Creek	Unregulated River (pools)	Olive perchlet, freshwater catfish, unspecked hardyhead, Australian smelt, Hyrtl's tandan, Rendahl's tandan	Urban and agricultural development to edge of bank; over-extraction for irrigation; stock watering causing sedimentary infilling.
		Condamine floodplain (e.g. Caligule, Karreel lagoons)	Floodplain	Olive perchlet, Hyrtl's tandan, Rendahl's tandan	Loss of smaller floods. Urban and agricultural development
		Condamine River - Lowland River	Regulated River (pools)	Olive perchlet, freshwater catfish, Murray cod, golden perch, unspecked hardyhead, silver perch, Australian smelt, Hyrtl's tandan, Rendahl's tandan, dwarf flat-headed gudgeon	Agricultural development to edge of bank; over-extraction for irrigation; stock watering causing sedimentary infilling.

6.5 Number of refuges where target fish species were identified for each state in the MDB.

Species name	Common name	SA	VIC	NSW/ACT	QLD
Retropinna semoni	Australian smelt	0	0	0	4
Galaxias fuscus	Barred galaxias	0	1	0	0
Acanthopagrus butcheri	Black bream	1	0	0	0
Nematalosa erebi	Bony herring	0	0	0	1
Galaxias maculatus	Common galaxias	4	0	0	0
Psuedaphritis urvillii	Congolli	4	0	0	0
Philypnodon macrostomus	Dwarf flat-headed gudgeon	0	0	1	0
Macquaria colonorum	Estuary perch	1	0	0	0
Galaxias rostratus	Flat-headed galaxias	0	3	1	0
Philypnodon spp.	Flat-headed gudgeons	0	1	0	1
Tandanus tandanus	Freshwater catfish	1	4	10	10
Macquaria ambigua	Golden perch	0	6	9	7
Neosilurus hyrtlii	Hyrtl's tandan	0	0	0	5
Macquaria australasica	Macquarie perch	0	8	5	0
Galaxias olidus	Mountain galaxias	4	8	1	0
Argyrosomus japonicus	Mulloway	1	0	0	0
Maccullochella peelii peelii	Murray cod	3	6	13	6
Euasticus armatus	Murray cray	0	5	1	0
Craterocephalus fluviatilis	Murray hardyhead	9	2	1	0
Ambassis agassizii	Olive perchlet	0	0	5	14
Geotria australis	Pouched lamprey	1	0	0	0
Morgunda spp.	Purple-spotted gudgeon	1	1	6	5
Porochilus rendahli	Rendahl's tandan	0	0	0	4
Gadopsis marmoratus	River blackfish	3	10	2	3
Anguilla australis	Short finned eel	2	0	0	0
Mordacia morax	Short headed lamprey	1	0	0	0
Bidyanus bidyanus	Silver perch	1	1	7	8
Nannoperca australis	Southern pygmy perch	5	6	6	0
Leipotherapon unicolour	Spangled perch	0	0	0	1
Maccullochella macquariensis	Trout cod	0	7	6	0
Gadopsis bispinosus	Two-spined blackfish	0	0	2	0
Craterocephalus stercusmuscarum	Unspecked hardyhead	0	0	3	6
Nannoperca obscura	Yarra pygmy perch	1	0	0	0
	Total number of species	**18**	**17**	**17**	**16**

6.6 Workshop outcomes

Presentations, information sessions and discussion groups

A key outcome from the workshop was to stimulate discussion and cross-fertilisation of ideas between managers and experts that may not have the opportunity to discuss drought impacts or refuge management. To stimulate ideas and discussion sessions, a number of presentations were given throughout the workshop by various researchers and management groups. Three major presentations were provided to outline: a) an academic review of the impact of drought on aquatic habitats in Australia, b) State planning responses to the millennium drought in Victoria and c) regional protection of critical threatened populations and drought refuges in the SA MDB. Each presentation was followed by a group discussion session to develop the key themes from each talk and raise issues and experiences from the diverse group of regional representatives.

Presentations:

Professor Sam Lake (Monash University): Drought and drought refuges

Key topics were:

- Definitions of refuges
- Landscape and local scale approaches
- Drought impacts – physico-chemical and water availability
- Human Influences: anthropogenic perturbations exacerbating drought impacts
- Refuge typologies and priorities
- Importance of connectivity and timing of connectivity
- Duration of refuges persistence
- Species approaches versus landscape or system approaches

Paul Bennett (Vic DSE): Response to dry inflows in Victoria

Key topics:

- Lessons from drought
- Adapting River Health Strategies in response to drought
- Dry Inflow Contingency Planning
- Tools for adapting Annual water use – prioritising catchments
- Building longer term resilience for the future
- Diverting water for refuge protection – water losses
- Other interventions: No pumping from pools, off-stream watering points for stock etc
- Re-using water for multiple environmental purposes

Jason Higham and Arkellah Hall (SA DEH): South Australian Response to millennium drought

Key topics:

- Emergency response strategies:
    1. *In-situ* conservation

        2. Translocation

- Triggers for action
- The Drought Action Plan – DAP
- Objectives of DAP
    1. Maintain at least 1 population of each species
    2. Maximise maintenance of genetic diversity of species – maintain each genetic unit
- Prioritisation process - Matrices
    1. Risk
    2. Consequence of no action
    3. Criticality
    4. Species Significance
    5. Feasibility – likelihood of success, ongoing mgt needs, site access etc.…
    6. Value for money – no of threatened species, cost of actions

6.7 Legislative and policy Framework report: Peters and McNeil (2011). Note title page only, can be sourced through supplementary literature or by contacting SARDI Aquatic Sciences.

Legislative and Policy Context for the Protection of Drought Refugia for Native Fish in the Murray-Darling Basin

Report to the Murray-Darling Basin Authority, Native Fish Strategy - Project MD1087

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May 2011

6.8 Principles and criteria for identifying drought refuges for fish in the Murray-Darling Basin

Nick Bond, Paul Reich and Dale McNeil

Summary of key points

- Refuge habitats are defined broadly as areas where the impacts of physical disturbance are reduced, increasing the local survival and/or health of biota. These habitats increase resistance (survival) during drought and facilitate resilience (population recovery) when the drought breaks. In general, as refuge habitats become fewer and/or more isolated, recovery rates will decrease dramatically, and the risk of permanent population loss will increase.
- To protect and maintain populations of native fish, refuge habitats should be identified and managed at the stream or river scale. The range of possible habitat types reported to act as important refuges includes those areas with reliable groundwater connection (e.g. headwater springs, some wetlands), deeper sections of river and stream channels and man-made structures such as weir pools, irrigation diversion channels and farm dams.
- There is a range of possible spatial data sets that could be used for the identification of refuges across broad spatial extents. More research is needed to link remotely sensed data to on-ground refuge identification. In principle there are three key attributes that need to be considered; 1) the physical features associated with refuge habitats, and which can be mapped, 2) the populations or ecological values associated with different refuges and their sensitivity to drought (i.e. in terms of resistance and resilience), and 3) any anthropogenic threats to points 1 and 2.

Drought induced cycling of population decline and recovery area are natural phenomenon, and generally only of major concern where rates of decline or recovery are altered by exacerbating threats associated with anthropogenic activities. In the absence of more complete information on natural patterns of decline and recovery with drought it may be more feasible to focus on known exacerbating threats which are typically well mapped at some scales. By combining information on exacerbating threats and the degree to which individual species rely on resistance or resilience traits to persist through drought, it is possible to develop a risk matrix for individual rivers (or reaches or sites).

Prioritization of refuge habitats should consider the extent to which the inclusion of particular refuge(s) contributes toward protecting the full complement of species being targeted by management. Effective management of drought refuges will include a combination of protection and restoration of key habitats and the mitigation of exacerbating threats.

Background

Since 1996, extreme dry conditions have prevailed across much of the Murray-Darling Basin (MDB) watershed, with record low inflows to the MDB in 2006 (Murphy and Timbal 2007). While dry years are not unprecedented in recorded history of the MDB, this recent 'millennium drought' has been characterised by lower than average rainfall combined with higher than average ambient temperatures, leading to increased evaporation, evapotranspiration, and reduced water availability (Murphy and Timbal 2007).

Due to the combination of ongoing drought and current human demands for water, it will take a number of years before flows and water storages return to pre drought levels, even with a return to average rainfall (Lintermans and Cottingham 2007). In response, the Murray-Darling Basin Commission (MDBC) convened a “Drought Expert Panel” to consider the management of native fishes during drought. The panel charged water and natural resource managers with the task of identifying, categorizing, and protecting drought refuges for fishes, particularly those with substantial depth and volume (including weir pools), high fish diversity, or populations of threatened species (Lintermans and Cottingham 2007). Subsequently, several projects (MD1086-7) were commissioned to better understand the role of refuges in the recovery of native fish from drought, as well as provide information to NRM agencies to assist them with managing refuge habitats.

The present document produced as part of MD1086 provides a concise outline of the general principles together with specific criteria that can be used to identify and manage drought refuges for freshwater fish. In many cases the capacity to identify critical refuges will be constrained by data availability. Therefore, rather than being prescriptive, we have tried to outline an approach that is flexible and capable of being applied at a range of different spatial scales depending on perceived risks and available data. Where perceived risks from drought exist (local populations of endangered species for example), there will be obvious incentives to identify refuges at a finer spatial scale.

Definitions

Refuge habitats are defined broadly as areas where the impacts of physical disturbance are reduced, increasing the local survival and/or health of biota (Sedell et al. 1990). The ecological definition of refuges focuses on the role of these habitats in facilitating population recovery once a disturbance abates. It is worth noting that in some disciplines (e.g. biogeography) refuge habitats are thought of as those containing relictual populations of historically widespread species, with no implicit expectation of population expansion following a disturbance. We warn against confusing these definitions, and emphasize the importance of the former in relation to drought and post drought recovery of fish populations.

Linked to this is the spatial scale over which refuge habitats are maintained and the likely times-scales of post drought population recovery. Lancaster and Belyea (1997) presented a conceptual framework for describing refuges, which distinguished between ‘within’ and ‘between’ habitat refuges; to distinguish, for example, between isolated pools as refuges within a single river and species loss from one catchment but persistence in an adjacent catchment. Depending on the scales over which species disperse these scenarios would likely have very different rates of recovery. In general, as refuge habitats become fewer and/or more isolated, recovery rates will decrease dramatically, and the risk of permanent population loss will increase. Despite some notable exceptions it seems that many native freshwater fish (especially small bodied species) have relatively restricted dispersal between streams, and thus if populations are lost from a stream during drought, recolonisation from neighbouring streams will be unlikely, or at least very slow. Our recommendation therefore is that, as much as possible, NRM groups should seek to protect populations of native fish, and hence maintain refuge habitats, at the stream or river scale. The response of individual species to drought is determined by the interplay between their resistance to drought induced change (e.g. the ability to survive higher temperatures) and their ability to recover at a population level (for example by having high fecundity and dispersal).

Identifying and mapping refuges

Because of spatial and temporal variability in the physical characteristics of rivers and the biota that inhabit them, the habitat characteristics that define a refuge also differ between streams and between species. In many cases however the presence of refuges relies on the persistence of surface water in the channel, although in more upland streams effective refuges may only be provided by perennially flowing stream reaches where temperatures remain low. The range of possible habitat types reported to act as important refuges include those areas with reliable groundwater connection (e.g. headwater springs, some wetlands), deeper sections of river and stream channels and man-made structures such as weir pools, irrigation diversion channels and farm dams. The location of high quality natural refuges in the landscape is likely to coincide with other catchment attributes such as valley confinement, vegetation cover and the degree of surface flow permanency and/or groundwater connection. In all cases there are a range of possible spatial data sets that could be used to the identification of refuges across broad spatial extents (Table 1). It is anticipated that marked increases in the resolution of various spatial data sources as techniques used to gather this information will improve, which will greatly assist in refuge identification.

Given the spatial scales involved in identifying refuges across the MDB approaches are proposed to mapping refuges that can make use of spatial information as much as possible. In principle there are three key attributes that need to be considered; 1) the physical features associated with refuge habitats, and which can be mapped, 2) the populations or ecological values associated with different refuges and their sensitivity to drought (i.e. in terms of resistance and resilience), and 3) any anthropogenic threats to items 1 and 2). However, rather than systematically combining data across all three categories, a slightly different approach based on the premise that drought induced cycles of population decline and recovery are a natural phenomena, and generally only of major concern where rates of decline or recovery are altered by exacerbating threats associated with anthropogenic activities (McNeil et al 2009) is proposed. Under this premise, the focus shifts away from thinking about refuges towards thinking about the spatial distribution of anthropogenic exacerbating threats.

Exacerbating threats can be grouped based on the extent to which they influence four important attributes of streams during drought; habitat quality, hydrologic persistence, connectivity, and biotic interactions (Table 2). For each of the exacerbating threats, the extent to which they are thought to impact on either the resistance or resilience of populations was identified. By combining this with information on the degree to which individual species rely on resistance or resilience traits to persist through drought (McNeil et al. 2009, Fig. 1), it is possible to develop a risk matrix for individual rivers (or reaches or sites) based on the combination of anthropogenic threats and the group of species present in individual reaches.

Table 1. A summary of approaches to mapping drought refuges taking into account the relative advantages/disadvantages of each.

Refuge Mapping Approaches	Advantages	Disadvantages
Ground based mapping	○ Quick start up time ○ Little training required ○ Low initial costs (handheld GPS units etc) ○ Ability to capture anecdotal observations along the way – e.g. the presence of more visible taxa	○ Ongoing labour costs ○ Relatively Slow once started, especially to cover large areas ○ Large practical constraints on the diversity of information that can be reliably collected. ○ Access problems due to terrain, private property etc.
Remote sensing approaches		
Airborne surveys	○ Fast and can cover large areas. ○ Comparatively cheap (per km) if long lengths of stream are to be surveyed. ○ Different options available. Helicopters are relatively cheap (<$1000/hr) and simple to organize when compared to plane mounted electronic sensors, and can be used with relatively untrained staff using hand-held GPS equipment ○ Potential to collect a diverse array of data depending on sensors (e.g. Visual imagery, thermal imagery, channel and floodplain geomorphology (above water surface), IR imagery ○ Data stored and available for future unforeseen uses (e.g. visual data could be used to map a variety of features – erosion, willows etc.)	○ Relatively involved planning means longer start-up time for more sophisticated surveys. ○ Post processing of data may require considerable knowledge and is a significant component of the overall cost ○ Large initial costs for plane based surveys
Satellite based surveys (side-scan radar)	○ Covers very large area ○ Once fully operational may become cheaper than airborne surveys, especially for repeat surveys.	○ Limited availability of satellite imagery at this stage ○ Limited control over flight dates at this stage ○ Resolution may be insufficient for smaller streams? ○ High cost at this point in time

Table 2. Some examples of key exacerbating threats and their putative relative impacts on resistance and resilience traits of freshwater fish.

Refuge Attributes	Desirable characteristics	Specific threats	Mechanism	Impact	
				Resistance	**Resilience**
Physical habitat	Presence of deep pools Instream structure, Intact riparian zone	Sedimentation & erosion	Reduced habitat persistence	High	Medium
		De-snagging	Reduced habitat complexity/ spawning sites	Low	Medium- High
		Riparian clearing	Increased light/temperature	Medium	Low
Hydrology	Springs, Permanent flow, Flow regulation/ water recovery, floodplain inundation	Farm dams	Hydrologic persistence	High	Medium
		Water extraction	Hydrologic persistence	Medium	Medium
	Regular floodplain inundation	Regulation, loss of medium floods	loss of habitat, food resources and nursery areas	High	High
Connectivity	Lateral and longitudinal connectivity unimpeded by human barriers	On-stream dams, weirs and culverts	Prevention of movement, re-colonisation. Access to refuges, spawning & food resources	Medium	High
Biological	Intact macrophytes	Grazing, maintained high water levels		Medium	Medium
	Intact riparian zones	Clearing, Grazing	Reduction of inputs of fine and course organic matter, Food web alteration	Medium	Medium
	Intact species assemblage	Invasive species	Increased predation/ competition	High	High

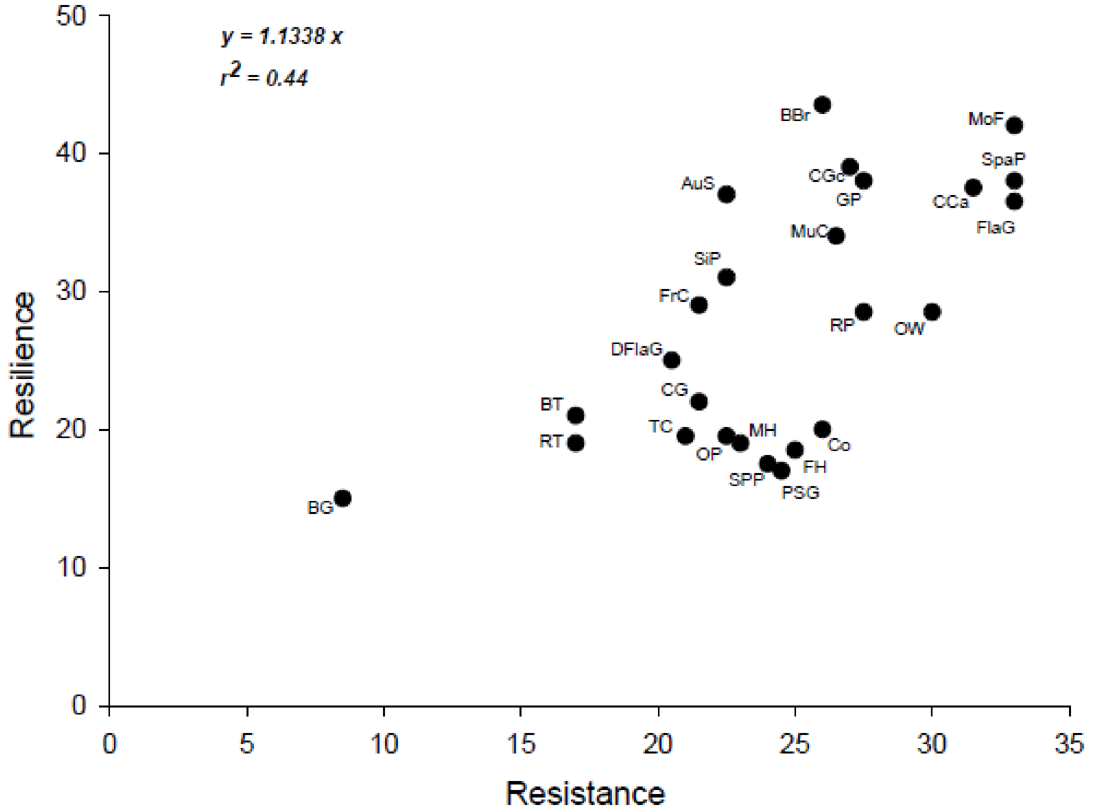

Figure 4. Preliminary plot analysis of resistance versus resilience for each of the 23 Murray-Darling Basin fish species where sufficient data existed to determine total scores based on identified resistance and resilience traits. Species identification follows: BG = barred galaxias, RT = rainbow trout, BT = brown trout, TC = trout cod, OP = olive perchlet, MH = Murray hardyhead, SPP = southern pygmy perch, PSG = purple spotted gudgeon, Co = congolli, DFlaG = dwarf flathead gudgeon, FrC = freshwater catfish, SiP = silver perch, RP = redfin perch, OW = oriental weatherloach, MuC = Murray cod, AuS = Australian smelt, GP = golden perch, CGc = carp gudgeon complex, BBr = bony Herring, CCa = common carp, FlaG = flathead gudgeon, SpaP = spangled perch, MoF = mosquito fish.

Figure 1. Resilience and Resistance factors for some native and invasive fish species from the Murray-Darling Basin. Reproduced from McNeil *et al.* (2009)

Prioritising Management

Prioritisation of refuge habitat should consider the extent to which the inclusion of particular refuges contributes toward protecting the full complement of species being targeted by management. A variety of approaches to prioritising the conservation of remnant habitats are discussed in the scientific literature. At one level the prioritisation of which refuge habitats to protect could be based around conservation principles – for example by considering the likelihood that particular refuge areas might harbor species of conservation significance, and then extending this thinking to ensure that the habitats required to conserve all such species have been identified.

Assuming the aims of drought mitigation strategies extends beyond species specific conservation goals to ensuring the recovery of overall river health, it will be necessary to focus also on the potential contribution that particular habitats make to population, community and ecosystem recovery when the drought breaks. This contribution may be heavily influenced by some of the factors mentioned earlier such as habitat quality, habitat area, and the degree to which habitats are linked to other parts of the river network. As such prioritisation may require additional information on the location of barriers, and importantly will need to ensure that protected refuge areas are sufficiently distributed to ensure recovery occurs throughout the river network. This will depend in part on the dispersal ability and life-history (in particular the timing and location of breeding) of individual taxa. Importantly, the need for refuge habitats in key parts of the river network may place heightened importance on not just high quality areas, but also on degraded refuge habitats that are located in critical parts of the river network.

Table 3. Examples of objectives for the management of drought refuges and some temporal and spatial scales for consideration.

Objective of refuges management	Spatial Scale	Temporal Scale
Threatened species	Local	Immediate
Biodiversity	Regional	Seasonal - Annual
Recreational values	State	Long-term
Ecological processes	National	
Genetic diversity	Population	

Proactive Management

It is essential that refuge habitats are sufficiently robust to physical disturbances (both natural and artificial, present and future) if they are to fulfil their role in drought recovery. In many cases refuge habitats have been degraded by historical disturbances, such as sedimentation infilling pools and reducing their persistence time during drought. Riparian clearing, stock access and direct water extraction further increase water loss rates and contribute to overall declines in habitat quality. Thus, while one outcome prioritization may be the identification of refuge habitats where such threats are minimized, in many cases high priority habitats may be those in which active restoration is needed to improve habitat quality and ensure the refuge performs its expected role. Under both scenarios ensuring that the habitat is resistant to future drought may require active management and restoration – work that can be seen as a proactive step in dealing with future droughts.

Conclusions

Finally, several words of caution; one of the problems with the mapping approaches is that they all provide only a snapshot in time of the presence of particular features. Thus, while particular pools (for example) may have been present on the survey date, these methods provide no inherent reliable means of predicting the longevity or permanence of that habitat. Such prediction is possible but may be relatively data intensive. It may also be possible to identify surrogates (such as surface area) for some of the major controlling factors on longevity/persistence (such as water depth), but this will require validation. Further research investment is therefore required to support mapping, modeling and prioritization for the protection of critical refuge values.

Additionally, this discussion has largely focused on possible physical indicators of refuge habitats. In reality, the true measure of whether an area of habitat acts as a refuge can only be measured by whether that habitat contributed to, or increased the resistance or resilience of the biota – something that to some degree can only be measured after the fact – i.e. once the drought has broken. To this end, present efforts to map drought refuges represent a valuable, but nevertheless reactive response to the current drought. The long-term benefits of this focus on drought refuges may lie not in what these efforts achieve in mitigating impacts from the present drought, but what they provide as a template for predicting and proactively preparing for future droughts, before they occur. Such proactive responses to large scale disturbances, which may include active restoration, and other forms of stream management, will be far more effective than reactive measures often relied upon (Bond *et al*. 2008). Thus, while the effects of the present drought are of great concern, there is also an important opportunity to increase our preparedness for such events in the future.

6.9 Moonie catchment workshop process

Background

The aim of the Moonie workshop was to demonstrate an approach that can be used to identify and compile the information required to develop drought refuge management plans. The approach developed and tested at the workshop was adapted from the indicator selection workshop process used by the Stream and Estuary Assessment Program (SEAP), and utilised the Pressure-Stressor-Response (PSR) framework (DERM 2011). The principles underpinning the process were:

- Clearly-stated ecological values/objectives. These are often forgotten when developing management strategies but are crucial for setting priorities, determining the appropriate spatial and temporal scales, providing relevant management endpoints and monitoring benchmarks, justifying the selection of management actions and setting the context for assessments.
- System understanding. Identification of the physical attributes that support the ecological values/objectives, the threats that may diminish them and the broader pressures that create the threats for the system in question.
- Prioritisation. Ranking and prioritising all aspects of the assessment allows targeted, effective use of limited resources and provides justification for management actions.
- Transparency and repeatability. There is a record of decisions made and the assessment can be updated and adapted over time, for example when new system knowledge becomes available.

Broadly, the Moonie workshop process identified and prioritised the ecological values associated with drought refuges and the attributes of refuges that support them. It then went on to identify threats and human-induced pressures to the refuge attributes and management actions that could mitigate these. Defined links between the values, attributes, threats and pressures enables targeted action and monitoring, and prioritisation at each step will assist managers in deciding how to best allocate resources.

<u>Step 1: Identification of ecological values</u>

Workshop attendees were asked to make a list of the ecological values that they consider are needed for the management of freshwater fish in the Moonie catchment. The resulting list included values such as sustainable and diverse fish populations in the catchment; populations of Tandanus, a conservation-listed species rare in the rest of the MDB and; opportunities for recreational fishing.

Step 2: How much do participants care about each value?

Participants were then asked to assign a rank[1] based on how much each attendee cared about each value (using a simple categorical scale: 1 = do not care, 2 = moderately care, 3 = greatly care). These scores were then averaged out to provide a final score that captured the "care factor" (Table 1).

Step 3: Current condition of values in target catchment

Each workshop attendee was then asked to score the current condition*

[2] of each value (using a simple categorical scale: 1 = condition has been lost or non-existent anymore; 2 = condition is moderately modified; 3 = natural or near-natural condition). Good condition was allocated the highest score as it was decided in this instance that management was best focused on maintaining/protecting those values still in near-natural condition (Table 1). The scoring system could be swapped if restoration of highly-impacted values was the preferred management goal, or this step could be deleted if current condition of values didn't matter to the particular management situation.

Table 1. The fish values identified for the Moonie River catchment, along with the care factor and condition score nominated by workshop participants

• Fish-related values	• Care Factor	• Current Condition
• Sustainable and diverse native freshwater fish assemblage	• 3	• 2
• Low impact of exotics	• 2.5	• 1
• Populations of conservation priority species in the catchment (*Bidyanus, Ambassis, Neosilurus*)	• 2.5	• 2
• Populations of conservation priority species in the catchment (*Tandanus*)	• 2.3	• 3
• Opportunities for recreational fishing (e.g. large-bodied species) in waterholes always	• 1.8	• 2
• Opportunities for indigenous fishing (e.g. large-bodied species) in waterholes always	• 1.6	• 1

Step 4: Prioritisation of values

The scores from steps 2 & 3 could then combined to determine the importance[3] of each those ecological values. In the Moonie workshop, current condition was considered unimportant, so prioritisation was based on Care Factor alone.

Step 5: Identification of refuge attributes that support the values

[1] In this instance, the ranking of the ecological values was a subjective process that was very much dependent on who was present. Therefore it does not necessarily reflect ALL of the wider communities' opinions; however, the process does allow a means of "prioritising" key management values and objectives. This is why the process works best if it is as inclusive as possible.

[2] Assessments of condition were based on attendee's best available knowledge at that time.

[3] Final ranking of the ecological value importance scores were achieved after much discussion and reviewed by workshop attendees to ensure general consensus was met.

Beginning with the ecological value that achieved the highest "importance" score (see Step 4), workshop attendees were then asked to consider each value in terms of the following questions:

How do you believe drought refugia will contribute to the particular value in the Moonie catchment (accounting for resistance and resilience factors)? [4]

Are there key (i.e. critical) areas or places in the Moonie for each value?

For the identified values in the Moonie, persistent waterholes were identified as refuges; however, rather than specific locations, it was the availability of these habitats in general throughout that catchment that was considered important.

The purpose of this step was to provide a means of conceptualising the attributes of drought refugia that would be critical for maintaining each ecological value (in terms of providing either resistance and resilience, or both). For example, workshop attendees determined a list of key attributes of refugia that they believed would best support their most important (i.e. highest ranking) ecological value "*Sustainable and diverse native fish assemblage*" (Table 2). These attributes were divided into those that confer either resistance or resilience to better understand their functional significance to refuge function (Table 2).

Table 2. An example of some of the attributes of drought refugia that are critical for maintaining the ecological value of "sustainable and diverse native fish assemblages" in the Moonie catchment, Qld.

Resistance Attributes	Resilience Attributes
• persistence of water	• connectivity between waterholes
• large waterholes (e.g. Kooroon - most persistent waterhole in the system)	• Multiple waterholes are required
• Habitat heterogeneity	• Minimal distance between refugia (most fish move 15-20 km when waterholes are connected)
• Large Woody habitat (LWD)	• Fish need energy supplies for migration as there may be limited food resources in recently inundated parts of the river
• Bedrock (e.g. basalt substrates)	• Annual connectivity
• Emergent vegetation (e.g. grasses, sedges)	
• Cease to flow <700 days (i.e. critical failure point)	
• shade	

Step 6: Prioritisation of refuge attributes

A final list of the attributes of drought refugia that were believed to contribute to the maintenance of the ecological values (for the Moonie catchment) were then compiled and tabulated into a simple "attribute by value" matrix[5], using an Excel spreadsheet. Each of the attributes in this list were then assigned a score to indicate how important they are for maintaining each value (using simple categorical scale: 0 = not important; 1 = minor importance; 2 = moderate importance; 3 = vital importance). For the example outlined in table 2, 'persistence of water' and 'large woody habitat' were seen as the most important

[4] Attendees were asked to pay particular consideration to spatial and temporal scales.
[5] The purpose of completing this matrix was to identify the "order" of importance of the attributes of drought refugia that are considered by the workshop experts/attendees for maintaining key ecological values in the Moonie.

refuge attributes for maintaining sustainable and diverse fish assemblages (score 3), while 'bedrock substrate' and 'emergent vegetation' were considered unimportant (score 0). Each attribute score was then multiplied by the score for the associated ecological value (from Step 4 above) essentially prioritising those attributes that were most important for maintaining the most important values.

Step 7: Identification of threats to refuge attributes

The next step was to brainstorm a list of stressors and/or threats[6] that currently (or potentially) affect each of the drought refugia attributes that were listed in Step 6. Workshop attendees were then asked to assess the stressors/threats and provide a score for the likelihood that these stressors/threats may occur in the Moonie (using simple categorical scale: 1 = unlikely; 2 = likely; 3 = highly likely). For example, threats to the attribute "waterhole persistence" in the Moonie were identified as sediment infilling, altered rainfall patterns and waterhole pumping.

Step 8: Identification of human pressures

Workshop attendees were then asked to compile a list of pressures[7] (i.e. human activities) that influence each of the stressors/threats in the Moonie catchment and to score each pressure in terms of its influence (using simple categorical scale: 1 = minor influence; 2 = moderate influence; 3 = large influence). This enables the 'root causes' of threats to be identified and managed. This was the final step undertaken at the workshop, with subsequent data interpretation conducted later.

Post-workshop process

Step 9: Synthesis of information

Following the workshop, the information that was gathered from participants was used to link together the pressures/stressors to important attributes of drought refugia and the ecological values they support. (Figure 1). Although the purpose of the workshop was not to actually develop a management plan for Moonie River drought refugia, the information gathered from the workshop could be used for the development of such a plan. For instance:

- the pressures and stressors identified for the Moonie could be added to conceptual models
- the management actions required to deal with the various pressures and stressors could be identified and costed
- available data sources could be identified
- knowledge gaps could be identified and research implemented
- recommendations developed for what data should be collected in the future and where.

[6] The stressors/threats need to be things that directly affect the drought refugia (e.g. sedimentation, waterhole pumping) and not the cause of the stressor (e.g. not grazing).
[7] Pressures may include: grazing, irrigated cropping, stock and domestic water supply, tree clearing, fishing etc

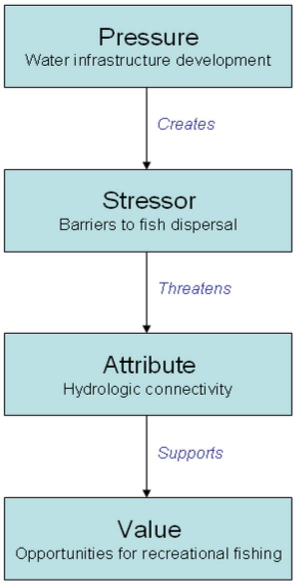

Figure 1. Relationships between the high-priority attributes, stressors and pressures identified for the value "Opportunities for recreational fishing".

<u>Step 10: Application to management</u>

The process presented here informs the selection of management actions, identifying how effort can be used most effectively to deal with the threats and pressures associated with the highest-priority refuge attributes and values. This is important given the often limited resources available.

Depending on the scale (time, area, budget) of the intervention applied, management actions can target prioritised threats immediately and locally, or prioritised pressures in the longer term over large areas. For example, waterhole persistence is an important attribute maintaining sustainable and diverse fish assemblages and is threatened by erosion and sediment deposition (threat) due to grazing in riparian zones (pressure). A local, short-term action might be to address the sedimentation by digging sediment out of a refuge pool. A long-term, broad-scale approach may be to change grazing practices by implementing an education program and subsidising riparian fencing.

Monitoring activities, to determine the effectiveness of management, can also be targeted at high-priority attributes, threats or stressors, depending on the types of changes occurring over time and the information available.

This approach enables managers to justify their actions since they can be clearly linked back to specific ecological values. It also enables critical dependencies to be identified. For instance there may be no improvement expected in the status of a value if habitat in individual waterholes is managed, but barriers to connection between them are not removed.

The outcome of the Moonie workshop was the development of an approach which identifies priority management actions for the protection of fish in drought refugia. The Moonie workshop approach was effective and could be utilised in other catchments. Unlike some parts of the MDB, the nature of the Moonie dictates that there aren't specific places that are current management priorities; rather the processes and habitats required for fish population viability are more generally relevant. However, where a specific value existed (e.g. a particular pool with unusual geomorphology supports a population of a rare fish), the approach could accommodate this by simply including it as one of the priority values.

The approach links actions back to specific ecological values to ensure that they act at appropriate temporal and spatial scales. Knowledge gaps can be identified and the process itself is transparent and repeatable and able to be reviewed and updated over time.

6.10 Some general information regarding the interaction of characteristics and life history strategies of key native fish species (based on McDowall 1996, McNeil and Hammer 2007 and Lintermans 2007).

Key Refuge Fish Species	Physical Habitat	Hydrological	Spatial Connectivity (Networks)	Biological Integrity.
Olive perchlet	Macrophyte beds, lotic habitats, low flow habitats, predator protection.	Low-flow conditions for spawning in spring/summer. Water temperature must exceed ~24C	Slow recolonisers, poor mixing (genetic isolates), good connectivity required, translocation may be necessary.	predation sensitive, invertebrate feeders
Murray hardyhead	Slightly saline off-channel lakes, wetlands, irrigation drains, macrophytes,	Lotic areas large enough for schooling	Patchy distribution, unlikely to recolonise once lost.	zooplankton dependent, predation sensitive
River blackfish	Rivers and streams with mostly rocky substrates (interstitial spaces for juveniles), cool water, low turbidity, woody habitat for spawning and litter	Flows to maintain cool temperature, low salinity, oxygen and flush silt	Recolonise slowly in Victoria following bushfire and drought .	Invertebrate feeders need leaf litter for food webs. Sensitive to trout and redfin predation
Southern pygmy-perch	Lotic habitats in stream pools , floodplain waterholes, irrigation drains. Macrophyte beds for feeding, spawning and predation refuges.	Require reasonable pool depth for water quality and temperature maintenance.	Require regular (<2-3years) lateral floodplain inundation in lowland populations. Recolonisation potential unknown. Spatially isolated floodplain populations likely to exist.	Sensitive to redfin perch predation and trout in some upland regions. Invertebrate feeders require riparian and floodplain vegetation to drive food webs
Murray cod	Deep river pools, woody habitat for adults, macrophyte beds for juveniles	Flowing habitats for maintaining temperature and water quality, flow pulses for spawning in spring, flows to carry eggs downstream	Longitudinal connectivity required for spawning and migration over very long distances. Connectivity and slow drawdown in summer to allow retreat to deeper refuge pools	Apex predator very sensitive to collapse in native food webs. May learn to adapt to feral fish prey (carp)
Mountain galaxias	Smaller order streams, rocky or sandy substrates	Flowing water to maintain water quality and spawning, will persist in refuge pools if regularly connected, winter/spring inundation of spawning habitats.	Local spawning and recruiting require connectivity for distribution and recolonisation. Rapid recolonisers	Very sensitive to trout and redfin predation. Optimal habitats dominated by redfin and trout, persist in smaller tributaries that are likely to be sub-optimal for food webs and diversity.
Pouched & Short -headed lamprey	Sandy substrates required for ammocetes, Marine habitats required for adult life phase	Connecting flows required for diadromy, low flows likely to silt juvenile habitats	Require longitudinal connectivity with the sea in winter/spring for adult spawning migration and juvenile recruitment.	Require fish hosts for marine phase and so depend on marine fish productivity and diversity
Murray crayfish	Large rivers, clay, sand or gravel substrates, woody habitat, redgum root complexes	Extinct in extensively weir pooled lower Murray, flowing conditions possibly required for water quality and to reduce fouling of eggs	Confined mainly to main channels, very slow recolonisers.	Young crays sensitive to redfin predation and carp grazing. Loss of small food items and macrophyte beds may be a problem with juveniles, lack of invertebrate and small fish prey items.

Key Refuge Fish Species	Physical Habitat	Hydrological	Spatial Connectivity (Networks)	Biological Integrity.
Barred galaxias	Rocky and gravel substrates including large rocks for spawning.	Cold water flows required for survival, can survive in summer pools in alpine areas briefly.	Persist in patches of disconnected upper tributaries with low connectivity. Likely to be slow recolonisers. Predators exist between populations forming barriers to movement.	Sensitive to trout predation, persist in pristine natural habitats with high natural diversity. Bushfires have reduced diversity of habitat and food webs resulting in population impacts in refuges.
Two-spined blackfish	Rocky substrates, woody habitat for spawning and juvenile habitats (interstices).	Require constant cool water flows, dependent on snow melt and therefore snowfall in some streams.	Persist in tributaries with possible low connectivity across main rivers where trout predation can be high.	Dependent on invertebrate food webs driven by grazers and leaf litter.
Flat-headed galaxias	Medium and large sized floodplain habitats, wetland vegetation and riparian vegetation important. Lost from the lower Murray for unknown reasons. Persists in mid-upper Murray floodplains.	Regular flood-plain inundation required for habitat and water quality maintenance.	Isolated floodplain habitats likely to have low intermixing, extinction in SA not replenished by NSW and Victorian populations despite floods.	Require intact wetland diversity for prey and aquatic habitat diversity; persist well with other natives but sensitive to redfin perch predation and competition with Gambusia. May require diverse floodplain types to persist allowing refuge from predation and competition as well as water quality impacts.
Trout cod	Larger streams and woody habitat with hollows.	Flowing, cooler water habitats.	Longitudinal connectivity required for recruitment and migration.	Lost to much of its former range since European settlement, likely to be sensitive to loss of habitat and food web diversity. Competition from trout and redfin perch. Angling pressure.
Yarra pygmy-perch	Littoral lake zones and drains in the Lower Murray Lakes, SA. Associated with macrophytes and shallow wetland habitats.	Requires water levels to inundate littoral wetland habitats, larvae sensitive to high salinity.	Extremely isolated populations in the MDB with no apparent colonisation of new habitats.	Depend on invertebrate prey items and wetland diversity for habitat and food.
Silver perch	Larger river channels.	Flowing rivers.		Numbers increasingly lower since European settlement.
Macquarie perch	Medium - large streams and rivers, formerly into lowland areas but now restricted to mid-upland reaches. Rocky and sandy substrates, woody habitat, deep holes and riparian vegetation.	Flows that maintain clear and cooler waters good water quality. Inundation of spawning habitat and connectivity for migration.	Longitudinal migration for spawning and colonisation. Access to refuges from drought and bushfire.	Persist in areas with high natural condition qualities including substrate, woody habitat, riparian structure and depth variability.
Purple spotted gudgeon	Macrophytes, shallower habitats (backwaters, channels) and off-channel habitats (wetlands, floodplains).		Isolated populations exist, mostly in the northern MDB. Slow colonisation ability leading to genetic isolates increases the importance of individual populations.	Extinct over much of the MDB but drivers that have lead to this loss are poorly identified and understood.
Golden perch	Larger rivers, anabranches, lakes and wetlands.	Seasonally timed flow pulses required for spawning and migration.	Longitudinal connectivity required over long distances to access spawning sites and to recruit to adult population.	Reasonably robust to habitat modifications.

Key Refuge Fish Species	Physical Habitat	Hydrological	Spatial Connectivity (Networks)	Biological Integrity.
Freshwater catfish	Large rivers, wetlands and lakes, nesting sites in substrate amongst macrophyte beds. Large lake populations in western NSW lost in recent decades.	low flow conditions required for nesting and egg rearing.	Access to spawning habitats and lateral connectivity between riverine and low flow habitats. Slower colonisers, localised losses lead to isolated populations. Formerly distributed further up-stream than presently (opposite to Macquarie perch), possibly due to barrier construction.	Diversity in flow, vegetation and invertebrate community is essential for good population health. Spawning may be unsuccessful due to carp predation of eggs in nest?
Estuary perch	Confined to the estuary region in SA. Very Rare.	Estuarine conditions and freshwater flows important.	Connectivity between sea and freshwater important but lost in the MDB.	Natural estuarine conditions and ecosystems are important for maintaining this species.
Unspecked hardyhead	Open water in larger streams and rivers.			Dependent on invertebrate prey and biological/nutrient inputs into larger river systems.
Congolli	Confined to the estuary region and lower lakes in SA.	Require connectivity during winter for downstream spawning migrations and connectivity during summer for juvenile upstream migration. Require freshwater inflows.	Diadromous requiring seasonal winter and summer flows to connect freshwater and marine habitats. Spawn in marine environments recruiting into freshwater.	Dependent of freshwater, estuarine and marine ecosystems to support life history aspects.

7. Specific references for Section 6.8

Bond, N. & Cottingham, P. (2007) *Ecology and hydrology of temporary streams: implications for sustainable water management*. A report to the Department of Sustainability and Environment, Victoria. eWater Cooperative Research Centre, Canberra, Australia.

Bond N. R., Lake P. S. & Arthington A. H. (2008) The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia*, **600**, 3-16.

Closs, G.P. & Lake, P.S. (1996) Drought, differential mortality and the coexistence of a native and an introduced fish species in a south east Australian intermittent stream. *Environmental Biology of* Fishes, **47**, 17-26.

Fausch, K.D., Power, M.E. & Murakami, M. (2002) Linkages between stream and forest food webs: Shigeru Nakano's legacy for ecology in Japan. *Trends in Ecology & Evolution*, **17**, 429-434.

Lancaster, L. and Balyea L.R. (2007) Nested hierarchies and scale dependence of mechanisms of flow refugium use. *Journal of the North American Benthological Society*, **16**, 221-238.

Lintermans M. & Cottingham P. (2007) *Fish out of water: lessons for managing native fish during drought*. Final Report of the Drought Expert Panel. Murray-Darling Basin Commission, Canberra

McNeil, D.G., Gehrig S., & Sharpe, C. (2009) *Resistance and Resilience of Murray-Darling Basin Fishes to Drought Disturbance*. Draft report to the Murray-Darling Basin Authority.

Murphy B.F & Timbal, B. (2007) A review of recent climate variability and climate change in south eastern Australia. *International Journal of Climatology*, **7**, 859-879.

Sedell, J.R, Reeves G.H, Hauer, F.R., & Hawkins C.P. (1990) Role of Refuges in recovery from disturbances: modern fragmentation and disconnected river systems. *Environmental Management*, **14**, 711-724.