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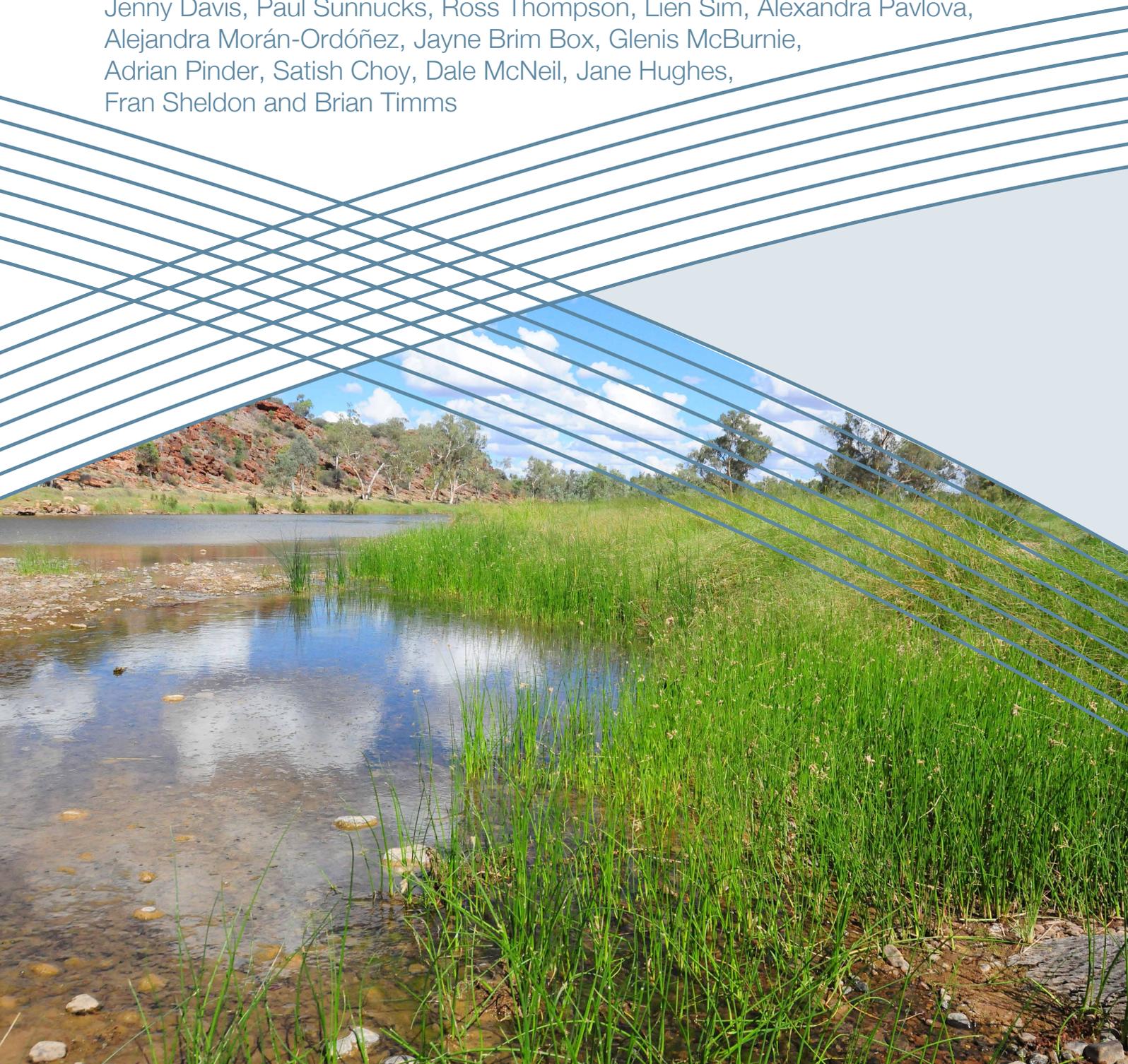
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MONASH University

Climate change adaptation guidelines for arid zone aquatic ecosystems and freshwater biodiversity

Jenny Davis, Paul Sunnucks, Ross Thompson, Lien Sim, Alexandra Pavlova, Alejandra Morán-Ordóñez, Jayne Brim Box, Glenis McBurnie, Adrian Pinder, Satish Choy, Dale McNeil, Jane Hughes, Fran Sheldon and Brian Timms



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TABLE OF CONTENTS

| | |
|--|----|
| Abstract | 1 |
| Executive Summary | 2 |
| 1. Introduction | 5 |
| 2. Climate Scenarios | 7 |
| 3. Geographical Context: the Australian Rangelands and the Arid Biome..... | 8 |
| 4. Historical Context: Past Climatic Changes..... | 9 |
| 5. Key Adaptation Strategies..... | 10 |
| 5.1 Identifying assets: compiling spatial information on the major types of arid zone aquatic ecosystems and the water resources that sustain them | 10 |
| 5.2 Maintaining critical habitats: recognizing evolutionary refugia and ecological refuges as priority sites for arid zone climate adaptation planning and policy..... | 12 |
| 5.3 Maintaining a dynamic matrix of perennial and temporary waters..... | 14 |
| 5.4 Maintaining connectivity and other key processes..... | 17 |
| 5.4.1 Hydrological processes..... | 17 |
| 5.4.2 Ecological processes..... | 17 |
| 5.4.3 Evolutionary and genetic processes..... | 19 |
| 5.5 Vulnerability assessments to determine the climate sensitivity and likely persistence of key habitats..... | 20 |
| 5.6 Reducing risk by reducing existing stressors (especially invasive species)..... | 22 |
| 5.7 Recognising adaptation opportunities – new water and novel ecosystems..... | 24 |
| 5.8 Implementing climate adaptations within in a strategic adaptive management framework..... | 24 |
| 5.9 Supporting indigenous and local community engagement and education | 25 |
| 6. Addressing Knowledge Gaps..... | 27 |
| 7. Summary of Adaptation Options | 29 |
| References | 30 |

LIST OF FIGURES

| | |
|---|----|
| Figure 1. Time series with a five year moving average (continuous line) of: (a) annual maximum temperature; and (b) annual rainfall, Alice Springs, Northern Territory (23.8°S, 133.89°E)..... | 33 |
| Figure 2. Extent of the arid and semi-arid regions comprising the Australian arid biome. | 33 |
| Figure 3. Map showing the location of drainage basins spanning arid and semi-arid zones, watercourses and the Great Artesian Basin..... | 34 |
| Figure 4. Map of the Great Artesian Basin showing recharge zones (shaded), spring supergroups (dotted lines), and flow direction (arrows) | 35 |
| Figure 5. Relict streams in the Central Australian Ranges typically occur in deeply shaded, south-facing gorges, as illustrated by the aerial view of Serpentine Gorge, NT. | 36 |
| Figure 6. Riverine waterholes occur as perennial, temporary and ephemeral systems within dryland rivers. | 37 |
| Figure 7. Many waterholes in the rivers of Lake Eyre Basin, SA, are characterized by high turbidities. | 38 |
| Figure 8. Outcrop springs (top left) occur near the base of ranges and rocky outcrops | 39 |
| Figure 9. Claypans (top) are distinctive shallow basins fed by local rainfall and often that occur throughout the arid zone | 40 |
| Figure 10. The Pilbara region, WA, contains a variety of waterbodies including: spring-fed stream pools (Skull Springs, top left); turbid river pools (Wackilina Creek Pool, top right); temporary wetlands (Fortescue Marsh, bottom left); and claypans (Croyden, bottom right)..... | 41 |
| Figure 11. Stygofauna contain a range of adaptations to a subterranean existence including reduced size, lack of eyes and loss of pigmentation. | 42 |
| Figure 12. Upper box: The different dispersal strategies that are used by organisms in fragmented dryland rivers. Lower box: Conceptual summary of the relationships between refuge types, retreat and recolonisation processes, metapopulation processes and the effects of disturbance..... | 43 |
| Figure 13. Location of sampling sites included in a comparison of aquatic invertebrate assemblages across the arid zone. | 44 |
| Figure 14. Bray-Curtis similarities of aquatic invertebrate assemblages across the Australian arid zone. | 45 |
| Figure 15. Adult dragonflies (top & bottom left, Cowards Springs, SA) are strong, active aerial dispersers, in contrast, adult mayflies (bottom right, Stokes Creek, NT), which are short-lived and small-bodied, are weak aerial dispersers. Isopods (top right, The Bubbler, SA), do not have an aerial dispersal phase, they are aquatic obligates and can only disperse when water is present water. | 46 |
| Figure 16. Differences in occurrence of dispersal traits (as percentages of families) of aquatic invertebrates in regions across the Australian arid zone. | 47 |
| Figure 17. Molecular analysis of a highly dispersive species, the spangled perch, <i>Leiopotherapon unicolor</i> , sampled at sites in the ephemeral rivers of the eastern Lake Eyre Basin, indicates varying levels of connectivity between waterholes. | 48 |

Figure 18. Conceptualisation of the major differences between evolutionary refugia (restricted gene flow but high climatic decoupling) and a range of ecological refuges (high gene flow but exposure to ambient climatic processes).49

Figure 19. Upper box: The Australian Feral Camel Management Program is an important Commonwealth government initiative that addresses one of the greatest threats to arid zone aquatic ecosystems and freshwater biodiversity. Lower box: Traditional owners and indigenous ranger groups are actively involved in monitoring waterhole condition.....50

Figure 20. A simple decision framework for identifying essential climate adaptation actions for arid zone aquatic ecosystems.....51

LIST OF TABLES

Table 1: Major types of arid zone aquatic ecosystems and their water sources.11

Table 2: Refugial importance of arid zone aquatic ecosystems (and associated traits of representative aquatic fauna) in relation to their sensitivity to regional climates (rainfall & temperature).....21

Table 3. Draft threat and risk assessment for aquatic ecosystems in the Qld Lake Eyre Basin based on a questionnaire and workshop.23

ABSTRACT

National climate change adaptation guidelines for arid zone aquatic ecosystems and freshwater biodiversity are proposed which emphasise the protection of habitats and processes that support the persistence of freshwater biota under a changing climate. These guidelines are intended to provide guidance for policy development, planning and on-ground actions. The major goal of these guidelines is to reduce the risk of the loss of aquatic habitats, deteriorating water quality and the extinction of aquatic and water-dependent species. A portfolio of adaptation approaches to maintaining aquatic habitats, the water resources that support them, and the species that depend upon them, is proposed within a framework of strategic adaptive management. This approach best addresses the uncertainty that exists as to how climatic changes will play out across the arid zone with respect to water availability and ecological processes. Recommended climate adaptation actions include: implementing a national mapping program that identifies the major types of arid zone aquatic ecosystems and the surface water and groundwater resources that sustain them; recognising the importance of evolutionary refugia and ecological refuges as priority sites for arid zone climate adaptation planning and policy; protecting a dynamic (spatial and temporal) mosaic of perennial, temporary and ephemeral waterbodies to provide the range of conditions needed support aquatic and water-dependent species with varying life history traits and dispersal abilities; maintaining the integrity of the dry sediments of temporary and ephemeral waters to ensure the persistence of viable seed and egg banks; recognising the importance of key hydrological and ecological processes, particularly connectivity and dispersal; undertaking vulnerability assessments that determine the climate sensitivity and likely persistence of key habitats; reducing the existing stressors on aquatic ecosystems and aquatic biota; identifying new and novel waterbodies created by arid zone industries (e.g. mining, pastoralism) that could provide valuable offsets for aquatic systems lost through climatic drying; implementing climate adaptation actions within a strategic adaptive management framework accompanied by a dedicated program for indigenous and local community engagement and education.

EXECUTIVE SUMMARY

The major goal of climate adaptation for aquatic ecosystems and freshwater biodiversity in the Australian arid zone is to reduce the risk of the loss of aquatic habitats, deteriorating water quality and the extinction of aquatic and water-dependent species. This includes increasing the resilience and, in some cases, the resistance, of the biota of arid zone springs, riverine waterholes, rock holes, lakes and other wetlands to changing water availability, especially increasing water stress. This stress will occur in conjunction with elevated temperatures, an increasing frequency of extreme events and pre-existing environmental impacts, including land degradation and invasive species.

A portfolio of adaptation approaches to maintaining aquatic habitats, the water resources that support them, and the species dependent upon them, is proposed within a framework of strategic adaptive management. This approach best addresses the uncertainty that exists as to how climatic changes will play out with respect to water availability and ecological processes across the arid zone.

Key climate adaptation actions include:

- 1. Identifying key arid zone aquatic assets and assessing vulnerability and risk.**

Spatial information, based on a national mapping program that identifies the major types of arid zone aquatic ecosystems and the surface water and groundwater resources that sustain them, combined with mapping of scenarios of future water availability, is needed to ensure that the locations of vulnerable systems are recognized and the trade-offs between environmental, economic and social water needs and allocations can be accurately assessed. This information will also support development of a national reserve network that adequately represents arid zone wetlands.

- 2. Recognising the importance of evolutionary refugia and ecological refuges as priority sites for arid zone climate adaptation planning and policy**

Evolutionary refugia are freshwater habitats or springs that have supported aquatic species on timescales of millions of years. They are permanent, groundwater-dependent ecosystems (subterranean aquifers, discharge or mound springs and relict streams) that support vicariant relicts (species with ancestral characteristics) and short-range endemics (species that only occur within a very small area). They need to be managed at the aquifer-scale (i.e., the Great Artesian Basin or regional or local aquifers) to ensure that permanent water is maintained. Good water quality and habitat condition needs to be maintained or restored by managing individual sites basis and 'spring-groups' for mound springs.

Ecological refuges are the waterholes that fill and flow after flooding rain. They can vary across space and time depending on the dispersal abilities of their biota. The most important are the perennial waterbodies that support obligate aquatic organisms. These species will persist where suitable habitats are available and dispersal pathways are maintained. Protection of the hydrological and aerial connectivity of ecological refuges needs to occur at a whole of landscape scale. Local, site-scale management (including fencing and

eradication of invasive species) is needed to ensure that good quality habitats, fulfilling a variety of refuge functions, are maintained across the arid zone.

3. Protecting a dynamic (spatial and temporal) mosaic of perennial, temporary and ephemeral waterbodies across the arid zone to support the persistence of aquatic and water-dependent species with varying life history traits and dispersal abilities

The presence of waterbodies of varying type, extent and water regime is fundamentally important to the persistence of arid zone aquatic biota. Protecting the integrity of the sediments (dry lake beds) of temporary and ephemeral waters is critical to the persistence of viable seed and egg banks. These, in turn, confer aquatic invertebrate assemblages with resistance and resilience to prolonged drying.

4. Maintaining connectivity and other key processes

This includes identifying and protecting the critical hydrological (groundwater and surface water) processes that support key arid zone waterbodies. Floods are vitally important for maintaining connectivity in dryland river networks. The dispersal of organisms at local, regional and landscape scales is a key ecological process that enables communities to persist across a range of arid zone sites with varying hydrological regimes. Increasing the understanding of how arid zone waterbodies are connected, based on the genetic structure of representative species of fish and aquatic invertebrates, will provide important information for climate adaptation planning, particularly the prioritization of management and protection efforts. Protecting, restoring and maintaining good quality aquatic habitats is integral to maintaining the key ecological processes that support both fully aquatic and terrestrial water-dependent arid zone biota. Perennial waterbodies provide 'reservoirs' from which species can disperse. Temporary aquatic habitats play important roles as 'stepping stones' between more permanent sites and by providing extra resources that enable populations to increase, reproduce and replenish egg and seed banks during wet phases (booms).

5. Vulnerability assessments that determine the climate sensitivity and likely persistence of key habitats

Determining where local climatic processes are decoupled from regional processes provides important information on the likely persistence of aquatic ecosystems under a drying climate. Evolutionary refugia are the most highly decoupled habitats and so will potentially be the most persistent, however, their endemic taxa are the most vulnerable to extinction. Ecological refuges vary in their exposure to climatic influences. Prioritising the protection and management of evolutionary refugia and perennial aquatic ecological refuges is very important because they offer the only chance for in-situ persistence of poorly dispersed species.

6. Reducing existing stressors (particularly the impact of invasive species) on arid zone aquatic ecosystems and freshwater biota

This will increase the resistance and resilience of arid zone biota to changing and increasingly variable climatic conditions and represents an important 'no-regrets' action. Introduced and invasive species (including camels, goats, pigs and donkeys) have been identified as the greatest threat to arid zone

biodiversity. Ongoing support for the Australian Feral Camel Management Program and the creation of additional programs to address the impacts of other feral species and livestock at arid zone waterholes are important climate adaptation actions.

7. Identifying new and novel waterbodies created by arid zone industries (e.g. mining, pastoralism) that may provide valuable offsets for aquatic systems lost through climatic drying

The opportunities afforded by creation of new waterbodies by various anthropogenic activities need to be recognized but the possible trade-offs for biodiversity need to be clearly articulated and rigorously assessed.

8. Implementing climate adaptation actions within a strategic adaptive management framework

Strategic Adaptive Management (SAM) builds upon adaptive management, often defined as 'learning by doing', by setting desired future objectives and focusing on integration within social, economic and governance processes. Important elements of SAM for the arid zone include: a coordinated national approach to monitoring and evaluating changes in water quantity and quality in surface and groundwater-dependent ecosystems; inclusion of datasets from environmental impact assessments (EIA) and monitoring and rehabilitation programs undertaken by arid zone industries, including the mining and energy production sector.

9. Engaging indigenous groups, local communities and industry (mining, pastoralism and tourism) with climate change adaptation actions and monitoring

Training and equipment is needed to support the management and monitoring of arid zone aquatic assets and biodiversity by people who live and work in the arid zone. This includes indigenous groups, pastoralists, tourism operators, mining companies and school children. A dedicated program is needed to facilitate community engagement with arid zone climate adaptation actions.

1. INTRODUCTION

Climate change adds an over-arching pressure to freshwater systems already experiencing multiple human impacts. Globally, all freshwater ecosystems are considered vulnerable because of their relative isolation and physical fragmentation within terrestrial landscapes. Arid zone freshwater systems are especially vulnerable because of their extreme isolation by deserts and drylands and very low hydrological connectivity. Increasing demands for water for domestic consumption and food production, and the modification of water regimes and water quality by industry, including mineral and energy extraction processes, represent ongoing impacts. The fundamental drivers of environmental change are an expanding world population and increasing global economic development (Millennium Ecosystem Assessment, 2005). Although there is a trend towards decreasing population densities within the Australian arid zone, the impact of global drivers are still present, as exemplified by expanding resource extraction industries.

The major goal of climate change adaptation for aquatic ecosystems and freshwater biodiversity in the Australian arid zone is to reduce the risk of the loss of aquatic habitats, deteriorating water quality and the extinction of aquatic and water-dependent species.

A major objective is to increase the resilience and, in some cases, the resistance of the biota of arid zone springs, waterholes and wetlands to changing water availability, especially increasing water stress. This stress will occur in conjunction with elevated temperatures, an increasing frequency of extreme events and pre-existing environmental impacts, including land degradation and invasive species.

Here resilience refers to the ability of an ecosystem to undergo a certain amount of change in response to environmental change without undergoing a fundamental shift to a different set of processes and structures. Resistance refers to the ability to withstand change, i.e., to not change, despite changing environmental conditions.

In the context of these guidelines,

resilience implies that a system or organism will change when water is scarce or disappears, but it will return to the previous state, when water returns. Aquatic organisms that are highly mobile and can disperse aerially (waterbirds, dragonflies, some beetles and bugs) are highly resilient to changing water availability.

in contrast,

resistance implies the ability to withstand change, despite changing water availability. Obligate aquatic organisms (fish and some aquatic invertebrates), which have a limited ability to persist in the absence of water, often display high resistance to changing local conditions but low resilience.

Planning for adaptation requires strategies to increase resilience and resistance and to reduce vulnerability, exposure and uncertainty. This applies to species and their habitats, and the processes that support them.

These guidelines provide a set of climate adaptation actions that are designed to support policy development, planning and on-ground actions. They are designed for use by policy developers, conservation planners, environmental professionals and community members working in natural resource management. These guidelines suggest actions that will help reduce the risk of the loss of arid zone aquatic habitats,

deteriorating water quality and the extinction of aquatic and water-dependent species. A portfolio of adaptation approaches to maintaining aquatic habitats, the water resources that support them, and the species dependent upon them, is proposed within a framework of strategic adaptive management. This approach best addresses the uncertainty that exists as to how climatic changes will play out with respect to water availability and ecological processes across the arid zone.

Further information on the research undertaken to develop these guidelines is provided in the accompanying scientific report and an open access paper published online in *Global Change Biology* on 18 April, 2013 at [doi: 10.1111/gcb.12203](https://doi.org/10.1111/gcb.12203).

2. CLIMATE SCENARIOS

The Australian arid zone faces the scenario of rising temperatures, changing rainfall patterns and amounts, and an increase in extreme events (floods and droughts). Some of the most rapid climate warming recorded since European colonization of the Australian continent has occurred within the arid zone. Annual maximum temperatures recorded at the Alice Springs meteorological station have increased by 2°C since 1900 while annual rainfall remains highly variable, unpredictable and episodic (Figure 1).

Water availability is the critical factor supporting the persistence not only of freshwater biota but many other arid zone species. A portfolio of adaptation approaches to maintaining water sources, and the species dependent upon them, is needed within a framework of adaptive management. This is important because there is some uncertainty as to how climatic changes will play out across the arid zone with respect to water availability. In the southern regions it is likely that annual rainfall will decrease, while an increase may occur in northern regions.

3. GEOGRAPHICAL CONTEXT: THE AUSTRALIAN RANGELANDS AND THE ARID BIOME

The arid and semi-arid regions characterised by low and unpredictable annual precipitation (100-500 mm/year) and extremely high potential evaporation (2880-4000 mm/year) (Figure 2) make up a distinct biological region, the arid biome. It is the largest biome on the continent, occupying approximately 70% of the landmass (of 7.5 million square kms), and represents one of the largest areas of desert landforms in the world. Arid biomes or drylands cover almost half of the world's land area. The Australian arid zone is a region of low relief (< 300 m above sea level) with the exception of the Pilbara-Hamersley Ranges in Western Australia, the Central Ranges in the Northern Territory and the Flinders Ranges in South Australia.

Most of Australia's wealth is generated in the arid zone through resource extraction (oil, gas and minerals). Pastoralism is also a major source of economic revenue. Tourism is becoming increasingly important and freshwater ecosystems (springs and waterholes) are often visitor focal points within the arid landscape. Important non-market based aspects of Australian culture are also intrinsic to the region, particularly indigenous culture and the notion of the Outback. The arid biome and the Australian rangelands are largely synonymous. The rangelands support sparsely settled communities comprising 2.3 million people, approximately 13 per cent of Australia's total population. Around 18 per cent of the rangelands are in Aboriginal ownership and management (www.lwa.gov.au).

The rangelands are biologically rich. Over 2,000 types of plants and 605 vertebrate animals have been identified. Further surveys are likely to double the number of plant species. The region contains a significant number of endemic species and habitat for rare, threatened and endangered species. It includes five World Heritage sites and 11 per cent of all listings on the Register of the National Estate. Natural resource management issues, attributable largely to inappropriate land management practices and the presence of introduced species, include: soil salinity; accelerated soil erosion; increasing numbers and distribution of weeds and feral animals; reduced water quality; altered hydrology; and decreased biodiversity (www.lwa.gov.au).

4. HISTORICAL CONTEXT: PAST CLIMATIC CHANGES

The Australian continent has had a long history of climatic change associated with its movement northward since the breakup of Gondwana over 90 million years ago. Aridification appears to have been a feature of the Australian landscape for at least 15 million years. Although Australia did not experience the development of large ice sheets associated with glaciation in the Northern Hemisphere, climatic oscillations did occur. Conditions changed between glacial and interglacial periods from cool and dry to warmer and wetter. Widespread and extreme aridity occurred during the Last Glacial Maximum, about 18,000 years ago. This extensive history of aridity and fluctuating climatic conditions means that the plants and animals that occur with the arid zone are well adapted to the dry and highly variable climate. The climatic history since European settlement has been one of long droughts interspersed by major floods (Lake, 2011). It is likely that the more frequent occurrence of extreme events will present unprecedented challenges to arid zone biota.

5. KEY ADAPTATION STRATEGIES

5.1 Identifying assets: compiling spatial information on the major types of arid zone aquatic ecosystems and the water resources that sustain them

Although the arid zone is defined by its low rainfall, a diverse range of aquatic systems occurs within the region. Permanently flowing rivers and deep, freshwater lakes are conspicuously absent (Figure 3) but permanent, or near-permanent waterholes occur within the extensive dryland river networks. Permanent springs and temporary and ephemeral standing waters of varying area and depth are also present.

We developed a simple typology of arid zone waterbodies (see Table 1) as the first step in compiling spatial information. This typology, which builds upon the classification of Fensham *et al.* (2011), is based primarily on hydrological (water source) and geomorphological (landform) attributes. We used these attributes because they are relatively fixed, i.e., much less variable than water quantity or quality.

One of the most important pieces of information needed to determine the vulnerability of arid zone waterbodies to changing water availability is knowing where their water comes from. Groundwater provides a permanent or near-permanent source of water to ecological communities, which, in turn, are dependent on this water supply. Groundwater-fed systems are decoupled from regional rainfall to varying degrees, depending on the size and age of the aquifer and rates of recharge. In contrast, surface water-fed communities are mainly temporary or ephemeral systems. Permanent or near permanent surface-fed waters only exist where waterbodies are deep enough to ensure that annual evaporative losses do not exceed the combined annual input of precipitation, runoff and inflows.

Table 1: Major types of arid zone aquatic ecosystems and their water sources.

GW = groundwater, SW = surface water

| Name | Water Source | Description |
|--|--------------|--|
| Subterranean Aquifers | GW | Shallow, underground carbonate habitats in the central region of WA and in WA palaeo-river channels. Sites within fractured rock aquifers in the Pilbara region. Sites within alluvial aquifers in NE Australia. Characterised by permanent water, no light and therefore no primary production. |
| Discharge (Mound) Springs | GW | Surface expressions of the Great Artesian Basin (GAB). Characterised mainly by permanent and consistent flows and alkaline waters with high concentrations of dissolved solids. Clustered at a range of scales, from individual vents to spring complexes to 13 major 'super-groups.' Discharge springs are also present outside the GAB, eg, Mandora Marsh in NW Australia. |
| Outcrop Springs | GW | Mainly arise from local fractured rock (sandstone, limestone or quartzite) aquifers and usually located near the base of ranges. Slightly acidic and very fresh. Usually permanent although some can contract and sometimes dry completely. |
| Relict Streams | GW | Small, permanently flowing sections of streams in the headwaters of the rivers of the Central Ranges, supported by outcrop springs. Cool, mesic-type habitats, mostly within deeply shaded, south-facing gorges. Called 'relict streams' because they support stream-dwelling insects with Gondwanan affinities. |
| Riverine Waterholes | SW/G W | Permanent, temporary or ephemeral waterbodies present in dryland river networks. Connected when large but infrequent rain events result in high flows or flooding, disconnected and reduced in area and depth when flows cease, except for hyporheic (below surface) flows. Waterholes in the eastern Lake Eyre Basin (LEB) are often turbid, those in the western LEB and the Pilbara are often clear. Often surface water fed but some permanent waterholes may receive groundwater/hyporheic flows. The latter includes the large waterholes on the Finke River (Running Waters and Boggy Hole) and nearly all permanent river pools in the Pilbara region. |
| Stream Pools/Rockholes | SW | Pools or rockholes in small, rocky headwater creeks within arid zone ranges. Fed by local rainfall events they are usually temporary or ephemeral. |
| Isolated Rockholes/Gnammas | SW | Water stored in natural hollows formed by fracturing and weathering of rocky landscapes. Fed by local runoff from infrequent rainfall events. Small and isolated habitats that are widespread, but not abundant, throughout the arid zone. Also called gnammas. Mainly temporary or ephemeral systems. |
| Temporary Lakes, Swamps & Marshes | SW | Isolated, shallow basins, not in watercourses, fed by local runoff after infrequent rain events. These include interdunal systems within desert dune regions and extensive floodplains (eg. in LEB). Hydroperiods are highly variable and unpredictable. The distinction between lakes, swamps and marshes can be arbitrary but the latter two usually refer to vegetated systems. |
| Clay Pans | SW | Temporary, shallow basins with an impervious base fed by local runoff and dominated by evaporative processes. They contain fresh and characteristically turbid water when fed by local runoff after infrequent rain events or left behind as flood waters recede. Hydroperiods are short, highly variable and unpredictable. |
| Salt Lakes/Saline Playas | SW/G W | Temporary, shallow basins fed by SW and/or GW (depending on site). They are characterized by highly episodic hydroperiods, high salinities and clear water. Highly productive systems when water is present. |

The production of national maps of surface water and groundwater dependent arid zone aquatic ecosystems, and listing of important and representative ecological communities under the EPBC Act, is a priority climate adaptation action.

Although many arid zone waterbodies are recognised on local, regional, state and territory maps, few appear on national maps i.e. are mapped at the continental scale. National mapping can be achieved by building upon recent Commonwealth investments in groundwater mapping

<http://www.bom.gov.au/water/groundwater/gde/index.shtml>

and

<http://wetlandinfo.derm.qld.gov.au/wetlands/MappingFandD/WetlandMapsAndData/WetlandMaps.html>

to produce combined maps of arid zone groundwater and surface water resources and dependent aquatic ecosystems. Accessible maps in the form of a web-based atlas are needed to support climate adaptation planning, especially the equitable allocation of environmental water. A web-based GIS platform is needed to provide digital storage and access to the environmental, cultural, social and economic attributes of arid zone aquatic assets.

This information, combined with mapping of scenarios of future water availability, would ensure that the locations of vulnerable systems are recognized and the trade-offs between environmental, economic and social water needs and allocations can be accurately assessed.

Development of an adequate national reserve network that adequately represents arid zone wetlands is also much more easily achieved where there is comprehensive spatial information about wetland diversity and distribution. See:

<http://www.environment.gov.au/water/publications/environmental/ecosystems/ae-toolkit-mod-3.html>.

Threatened species and ecological communities can be listed under the Environment Protection and Biodiversity Conservation (EPBC) Act of 1999. This has been done for: *The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin* (<http://www.environment.gov.au/cgi-bin/sprat/public/publicshowcommunity.pl?id=26&status=Endangered>). Listing of ecological communities representative of the range of aquatic ecosystems listed in Table 1. Examples of the wetland types described in Table 1 are given in Figures 4-10.

5.2 Maintaining critical habitats: recognizing evolutionary refugia and ecological refuges as priority sites for arid zone climate adaptation planning and policy

The importance of refugia and refuges as places that facilitate the survival of plants and animals under adverse conditions has long been recognised. Here we distinguish between evolutionary refugia and ecological refuges because their vulnerability to climate change is very different and they need to be managed accordingly. Our definitions are based on an understanding of the phylogeny (evolutionary history) and ecology of representative species of fish and aquatic invertebrates.

Evolutionary refugia

These are freshwater habitats that have supported aquatic species on timescales of millions of years. They are permanent, groundwater-dependent ecosystems (subterranean aquifers, discharge or mound springs and relict streams) that support

vicariant relicts (species with ancestral characteristics) and short-range endemics (species that only occur within a very small area).

Evolutionary refugia contain populations of species that have very small geographical ranges but relative demographic stability and high levels of genetic diversity. These include crustaceans, molluscs, worms and water beetles in subterranean aquifers (Figure 11), crustaceans, worms, snails and fish (desert gobies) in mound springs and small insects (mayflies, caddisflies and waterpennies) in relict streams.

Evolutionary refugia are ecosystems that show a high degree of resistance, or buffering, to climatic change. The presence of a permanent supply of groundwater has enabled some species to persist through climatic changes spanning thousands to millions of years. These species are very vulnerable to local extinction. If the groundwater or surface water expressions of groundwater that supports them disappears the likelihood of extinction is very high because they do not have good dispersal and recolonisation strategies. Populations cannot be rescued by dispersal from other sites. These systems have a high resistance but very low resilience.

Evolutionary refugia must be managed at the aquifer-scale (the Great Artesian Basin and regional and local aquifers) to ensure that permanent water is maintained. Good water quality and habitat condition needs to be maintained or restored by managing at an individual site basis and by 'spring-groups' for mound springs.

Ecological Refuges

Ecological refuges can vary across space and time depending on the dispersal abilities of their biota. The most important are the perennial waterbodies that support obligate aquatic organisms. They contain biota supported by contemporary demographic and genetic processes, i.e., demogenetic processes, *sensu* Frank *et al.* (2011). These species will persist where suitable habitats are available and dispersal pathways are maintained.

These systems are governed by the expansion & contraction dynamics described by Stanley *et al.* (1997) and the boom and bust dynamics described by Kingsford *et al.* (1999), Bunn *et al.* (2006) and others. Gene flow will occur over a range of scales, depending on the dispersal traits and population sizes of individual taxa and the extent of hydrological connectivity (Bohonak & Jenkins, 2003). Maintaining connectivity by mitigating barriers to dispersal and alterations to the natural flow regime are recommended as important management strategies for arid zone fishes (Faulks *et al.*, 2010). For very mobile taxa (species with an aerial dispersal phase) evolutionary refugia may also act as ecological refuges.

The identification of an ecological refuge varies depending on the dispersal traits of the species of concern. Obligate aquatic organisms (fishes and some aquatic invertebrates) need perennial habitats supported by surface water, groundwater or both, to ensure persistence. Perennial systems are also important for the persistence of waterbirds and a range of terrestrial fauna such as bats and some snakes and amphibians.

Ecological refuges support taxa with a high degree of resilience to climatic variability. They are sources of individuals that contribute to the 'boom and bust' ecosystems that flourish and expand when water is plentiful and decrease and contract when water is scarce. They are vulnerable to changes that affect the ability of species to disperse and to undergo rapid population expansion. Threatening processes include the loss of

connectivity between dryland river waterholes (caused by dams or water extraction) and degradation of aquatic habitats (e.g. fouling by cattle, pigs and camels) that prevent the colonisation and establishment of key species. The impacts of invasive aquatic species, particularly carp and *Gambusia*, are also of concern. On a cautionary note, connectivity may have negative consequences where it enables invasive and exotic fish to colonise and persist.

Three major types of dispersal strategies have been identified in fragmented dryland river landscapes: 'movers', the organisms that have mobile adults and do not require physical flow connectivity to disperse across waterholes (e.g. Odonata, Heteroptera, Coleoptera); 'networkers', the organisms that disperse easily during the high flow through the channel network (e.g. Crustacea, some fish); and 'permanent refugial' organisms (primarily Mollusca) that have limited dispersal abilities even under flow conditions (Figure 12) (Sheldon *et al.*, 2010)

Robson *et al.* (2008) defined five types of refuge based on retreat processes and the biodiversity they support (Figure 12). Ark-type refuges contain an assemblage of species that is representative of aquatic biodiversity at the landscape scale. Polo club-type refuges eventuate where the refuge is suitable for use by only a subset of the regional biodiversity because particular biological and ecological traits are required to persist in the refuge. Casino-type refuges consist of areas that have, by chance, been left untouched by disturbance that affects surrounding areas. These vary in their level of representativeness of local biodiversity. Stepping-stone refuges become vital to an organism when they support some stage in dispersal process that cannot otherwise occur, but their use as a refuge is intermittent or ephemeral. Anthropogenic refuges are provided by artificially created habitat such as drains or farm dams.

Patterns of recolonisation arising from these types of refuges are likely to differ strongly, with Ark-type refuges providing a representative range of colonists and Polo club-type refuges only a subset of the original biodiversity. Chance and the intensity of disturbance determine the contribution made to recolonisation by Casino-type refuges. Stepping stones are likely to be relevant only to single or a few species. Classifying refuges by their ability to accommodate or facilitate local biodiversity, according to the broad spatial and temporal character of disturbances, and taking into account dispersal and population structure of taxa has utility for climate adaptation planning and management because it can provide a basis for prioritization of protection and restoration efforts. However, further work is needed to fully determine the applicability of the Robson *et al.* (2008) classification to arid zone habitats.

Adaptation planning must protect hydrological and aerial connectivity of ecological refuges (especially perennial waters) at a whole of landscape scale. Local, site-scale management (including fencing and eradication of invasive species) is needed to ensure that good quality habitats, fulfilling a variety of refuge functions, are maintained across the arid zone.

5.3 Maintaining a dynamic matrix of perennial and temporary waters

The Australian arid zone often supports very large numbers of waterbirds despite the lack of permanent water (Roshier *et al.* 2001). This is brought about by the availability of temporary wetland habitats in both time and space and the fact that most Australian waterbirds are highly dispersive.

For highly mobile species, the floodplains and lakes of the Lake Eyre Basin provide the greatest concentration of wetland resources within arid Australia. The high ratio of

floodplain area to total catchment area, low flow velocities of floodwaters and long flood transmission times in the two major rivers that drain the upper reaches of the LEB, the Diamantina River and Cooper Creek, combined with spatial variability in topography and hydrology, produce a diverse range of wetland habitats and biotic assemblages that support all functional groups of waterbirds (Roshier *et al.*, 2001).

Landscape analysis has revealed that the wetlands of the Lake Eyre Basin are highly interconnected and linked by broad pathways to wetter parts of south-eastern Australia. The landscape becomes more fragmented during dry periods and wetland connectivity declines. As wetlands fill and dry the landscape provides different resources to waterbirds with differing dispersal abilities. The relationship between wetland connectivity and dispersal distance is considered to be a threshold phenomenon, with small increases in dispersal capability resulting in large increases in wetland connectivity. The dispersal distance at which this threshold is reached changes with the distribution and abundance of wetlands (Roshier *et al.*, 2001). For nomadic species dependent on temporary resources, the distribution of ephemeral habitat patches is likely to be extremely important.

A spatial and temporal mosaic of perennial, temporary and ephemeral waterbodies must be maintained to provide the range of conditions needed for the persistence of arid zone aquatic and water-dependent species.

Arid zone temporary waters are characterized by unpredictable periods of drying, forcing the aquatic biota to either disperse or employ a dormancy strategy (e.g. aestivation or desiccation-resistant eggs) to persist through the disturbance (Williams, 1985). The occurrence of a drying phase should therefore not necessarily be considered 'adverse or catastrophic' for the biota of temporary wetlands (Brock *et al.*, 2003). Invertebrate taxa that persist in temporary wetlands usually do so by reaching a tolerant phase of their development before the wetland dries (Wellborn *et al.*, 1996). Very temporary environments tend to support species with short life cycles, and some of these species rarely occur in more perennial habitats (Wellborn *et al.*, 1996). Mobile invertebrates disperse across the landscape in wetter years, and retract to more reliable habitats when conditions are drier (Wellborn *et al.* 1996). In areas where few perennial waterbodies exist, temporary systems have even greater importance in supporting the survival of species and metapopulations (Williams, 1985).

Wiggins *et al.* (1980) described four groups of invertebrates, found in temporary ponds in southern Ontario, based on their resilience or resistance to drought and their mode of recolonization. These categorizations are useful in a wider range of habitats, including arid zone wetlands. The groups are defined as follows:

- Group 1 – year-round residents incapable of active dispersal. Avoid drying by aestivating as desiccation-resistant cysts or eggs, or by burrowing into wet sediments. Taxa include turbellarians, oligochaetes, cladocerans, copepods, ostracods and gastropods.
- Group 2 – active dispersers that recruit in spring when water is present and dependent on water (or water-dependent vegetation) for oviposition. They must reproduce before the water disappears. These species subsequently survive the dry period as desiccation-resistant eggs and larvae. Taxa include ephemeropterans, coleopterans, dipterans and mites.
- Group 3 – active dispersers that recruit in summer, often laying eggs in damp or dry sediment after the surface water disappears. Survive the dry period as

desiccation-resistant eggs and larvae. Group 3 taxa are often colonizers. Taxa include dipterans, trichopterans and odonatans.

- Group 4 – Active dispersers and migrants that are dependent on water for egg-laying, but adults spend the dry phase in perennial pools, or a series of other temporary pools containing water at different stages (Williams 1985). Many Group 4 taxa are predators. Taxa include odonatans, hemipterans and coleopterans.

The sediments of temporary waters play a very important role in providing the seed and eggbanks from which re-colonisation occurs when water returns, for all but one of the groups listed above.

Maintaining the integrity of the sediments (dry lake beds) of temporary inland waters is critical to the persistence of viable seed and egg banks. These, in turn, confer aquatic invertebrate assemblages with resistance and resilience to prolonged drying.

The ecological and cultural significance of isolated rockholes on granite outcrops, including gnammas, has been described in a comprehensive work by Bayley (2011). Recent work by Brian Timms on gnammas has found that there is a decrease in diversity eastwards and northwards from the central wheatbelt of Western Australia. This is likely the result of drier conditions, resulting in pools drying before life cycles are completed. Even crustaceans with resistant eggs have lower diversity in the drier extremities of the arid zone. A drying climate is likely to result in even lower species richness as the probability of insects colonizing remote waterbodies from a smaller number of distant systems decreases.

Salt lakes represent a special category of temporary inland waters that are often overlooked from a conservation perspective, undoubtedly because they do not contain the freshwater needed for various human activities. Salt lakes are highly resilient, e.g., Lake Torrens had a typical fauna after being dry for 100+ years (Brian Timms, unpublished data). They contain extremophiles, in this case, taxa adapted to very high salt concentrations. Extensive faunal radiations have occurred within Australian salt lake crustaceans. Molecular studies of representative crustacean groups from saline and fresh inland waters have found profound differences in rates of evolution, with halophiles exhibiting greater rates of change than their counterparts from freshwaters (Remigio *et al.*, 2010). A pattern of much higher diversity in crustacean halophiles in Western Australia, compared with eastern Australia has been recorded in the brine shrimp, *Parartemia*, the cladoceran, *Daphniopsis* and the ostracod, *Mytilocypris*. This pattern may be explained by impeded gene flow between lineages of organisms restricted to inland waters when much of the Australia was separated into two subcontinents by an inland sea during the Cretaceous (Remigio *et al.*, 2010). A molecular study of the fairy shrimp genus *Branchinella* (Crustacea, Anostraca), which is found exclusively in temporary aquatic habitats, found both cryptic species and species with substantial physiological plasticity, indicating that they are likely to cope well with environmental change (Pinceel *et al.*, 2012).

East-west differences in the evolution of important arid zone salt lake taxa (crustaceans) indicate the importance of conserving and managing these systems at both the regional and continental scales.

5.4 Maintaining connectivity and other key processes

Identifying and maintaining the core hydrological, ecological and genetic processes that support arid zone aquatic ecosystems is fundamental to reducing the risk of the loss of aquatic habitats, changes in community composition and the extinction of aquatic and water-dependent species. The critical importance of beneficial floods and intact groundwater resources must be recognized.

5.4.1 Hydrological processes

Groundwater-dependent ecosystems

Provision of a permanent supply of water from regional basins, such as the GAB in eastern Australia and the Canning Artesian Basin in Western Australia, and local aquifers, is critical to the persistence of subterranean aquifers, discharge (mound springs), outcrop springs, relict streams and river pools. The Great Artesian Basin Sustainability Initiative (GABSI) (www.environment.gov.au) is an important program supporting the persistence of the GAB mound springs. The extent of local fractured rock aquifers supporting aquatic ecosystems in the Hamersley Ranges, WA; the Central Ranges, NT; and the Flinders Ranges, SA, still needs to be determined. Threats and pressures on these aquifers must be identified and addressed.

Surface water-dependent ecosystems

The critical hydrological processes supporting arid zone surface water dependent ecosystems (SWDEs) are flow variability, good water quality and the maintenance of hydrological connectivity. Activities that threaten hydrological processes include point source discharges, water off-takes and impoundments, which reduce water quantity and flow variability, and barriers (such as dams) that reduce connectivity.

Identifying and maintaining the key hydrological (groundwater and surface water) processes that support the persistence of arid zone aquatic ecosystems and the biodiversity they support is essential. The importance of beneficial floods to dryland rivers and groundwater resources to springs must be recognized.

5.4.2 Ecological processes

Although our knowledge of the factors influencing the distribution, abundance and composition of arid zone aquatic communities is incomplete, enough information exists to identify key ecological processes. Landscape-scale ecological processes (dispersal and connectivity) together with local-scale processes (habitat quality and diversity and biotic interactions) all play a major role in supporting the persistence of species that occupy ecological refuges and temporary waters. In contrast, local-scale ecological processes alone appear to have the most influence on the persistence of the rare, relictual and endemic species found in evolutionary refugia.

Although a national approach to climate adaptation is important, attention must still be paid to regional and local-scale ecological factors. For example, a comparison of the composition of aquatic invertebrate communities at a range of sites (Figure 13) across the arid zone revealed a marked dissimilarity between regions.

A comparison of the ways in which aquatic invertebrates disperse (some examples of taxa with varying dispersal abilities are given in Figure 15) indicates the importance of aerial dispersal in structuring arid zone invertebrate communities (Figure 16).

A large component of the invertebrate fauna at all sites (except the isolated rockholes of the Great Victoria Desert) consisted of species that have adult stages that can fly. The dominance of weak flyers (mayflies, caddisflies and small beetles) suggests good dispersal at local and regional scales but not across the entire arid zone (continental scale). The lack of strong active flyers (dragonflies, beetles and waterbugs) in the smallest and most isolated waterbodies (isolated rockholes in the Great Victoria Desert) suggests that large expanses of desert, and the low probability of finding water, act as a barrier to even the most well-adapted arid zone species.

Some aquatic species that cannot fly, in particular, very small crustaceans, are dispersed across dryland regions by wind or by attachment to mobile species such as waterfowl. This is known as passive dispersal. The dominance of passive dispersers in the rockholes of the Great Victoria Desert (GVD) suggests that this is the most important dispersal mechanism for the fauna of this type of habitat. However, the small number of species recorded in the GVD rockholes suggests that this is a relatively inefficient process.

The importance of the arid zone for indigenous fish species is well recognized (Unmack, 2001). Thirty species have been recorded from the LEB, this is greater than the richness recorded in most southern Australian catchments and only exceeded in some catchments in the tropical north. High richness in the LEB is attributed to the presence of discharge springs and the large area of the Basin. Regional endemism is also high with 42% of species recorded being endemic to the Pilbara region and 40% to the LEB.

All species of arid zone fish are dependent upon water for dispersal (apart from anecdotal records of fish transported by mini-tornadoes). Accordingly, maintaining connectivity throughout stream and river networks so that dispersal can occur during floods is of critical importance to the persistence of arid zone fish. The importance of floods and variable flow regimes, in maintaining dryland river components and processes, especially fish communities, has been well-documented by Leigh et al. (2010), Medeiros and Arthington (2010), Arthington and Balcombe (2011), Balcombe et al. (2011) and Kerezy et al. (2011).

The dispersal of organisms at local, regional and landscape scales is a key ecological process that enables communities to persist across a range of arid zone sites with varying hydrological regimes. Perennial waterbodies provide 'reservoirs' from which species can disperse. Temporary aquatic habitats play important roles as 'stepping stones' between more permanent sites and by providing extra resources that enable populations to increase, reproduce and replenish egg and seed banks during wet phases (booms).

Although the ability to disperse, be it fast/strong, slow/weak or passive, is important, it is not a sufficient condition to ensure that a species persists. Local environmental conditions are also very important. Local habitat conditions will influence a number of important processes, including colonisation, establishment, growth and reproduction. Although water quantity and quality are key habitat factors, the provision of suitable substrates, an abundant food supply and freedom from competition, predation and habitat disturbance, especially the impacts associated with invasive species (such as camels and carp), are also important. The recent invasion of cane toads and redclaw crayfish in the LEB are of great concern (Satish Choy, unpublished data). A warming climate will make conditions more favourable for some invasive species, particularly those invading from tropical regions.

Protecting, restoring and maintaining good quality aquatic habitats is integral to maintaining the key ecological processes that support both fully aquatic and water-dependent arid zone biota.

5.4.3 Evolutionary and genetic processes

The importance of genetic variation for maintaining biological diversity and evolutionary processes is well recognized and is an explicit goal of the Convention on Biological Diversity (CBD). Nevertheless, very limited action has been taken to protect genetic diversity on a global scale (Laikre, 2010).

The concept of the evolutionarily significant unit (ESU) was developed to provide an objective approach to prioritizing units for protection below the level of species. ESUs are recognised by the EPBC Act of 1999. Although there is debate as to how ESU's should be defined there is now a strong case to adopt adaptive evolutionary conservation to maximize preserving genetic diversity and evolutionary potential (Fraser & Bernatchez, 2001). Recognising ESU's is particularly important for the conservation of arid zone biodiversity.

The isolated nature of groundwater-dependent evolutionary refugia means that genetic diversity is often highly geographically structured and cryptic species (species that are genetically distinct but are indistinguishable morphologically) and ESU's are very common. Recent detailed studies of the population genetics of important species in subterranean aquifers in Western Australia and mound springs in South Australia have revealed the presence of species with very small ranges but relative demographic stability and high levels of genetic diversity (Guzik *et al.*, 2009, 2010, 2011; Murphy *et al.*, 2009, 2012; Perez *et al.*, 2005; Worthington Wilmer *et al.*, 2011). These species are highly 'resistant' because they have developed mechanisms to cope with the isolation and unique environmental attributes of their habitats. They are very vulnerable to factors that result in a loss of habitat, especially water extraction.

Genetic processes will vary according to the dispersal traits of individual species. For example, in insects that are strong fliers (dragonflies and some beetles) gene structure is likely to be homogenous over the entire arid zone. Preliminary results from molecular studies have indicated that this is the case for populations of the dragonflies, *Diplacodes haematodes* and *Orthetrum caledonicum*, and the whirlygig beetle, the gyrinid, *Macrogyrus gibbosus*, sampled in the central Australian ranges in January, 2012. This study needs to be extended to include populations of representative species across the entire arid zone.

In contrast, molecular analyses of populations of two species classified as weak aerial dispersers, the mayflies, *Tasmanoceon* and *Cloeon*, have detected significant genetic structure indicating the presence of sympatric cryptic species. Molecular analyses of populations of a passive disperser, a flatworm, have revealed the presence of allopatric cryptic species.

Significant genetic structure is likely to occur in populations of obligate aquatic organisms that are weak dispersers and occupy highly disconnected habitats (some species of fish and aquatic invertebrates). Genetic structure will depend on the amount of aquatic connectivity between sites and other factors, including strong or weak swimming ability and habitat suitability.

Preliminary results from molecular analyses of fish collected within the rivers of the eastern LEB have revealed genetic structure even with the most highly dispersive species, the spangled perch, *Leiopotherapon unicolor* (Figure 17).

Increasing the understanding of how arid zone waterbodies are connected, based on the genetic structure of representative species of fish and aquatic invertebrates, will provide important information for climate adaptation planning, particularly the prioritization of management and protection efforts.

5.5 Vulnerability assessments to determine the climate sensitivity and likely persistence of key habitats

The likely climate sensitivity and potential persistence of arid zone aquatic ecosystems can be assessed by understanding the environmental processes supporting the formation and maintenance of evolutionary refugia and ecological refuges and by determining where local climatic processes are decoupled from regional processes (Dobrowski, 2011). These are summarized in Table 2. The ability of evolutionary refugia to locally mitigate the effects of regional climate change is an important attribute for climate change adaptation planning (Ashcroft, 2010; Ashcroft *et al.*, 2012; Keppel *et al.*, 2012; Keppel & Wardell-Johnson, 2012). Including evolutionary refugia in protected area networks and in climate change management planning must be given high priority because they offer the only hope for *in-situ* persistence of poorly dispersed species (Game *et al.*, 2011).

All habitats supported by groundwater are at least partially decoupled from local rainfall. Subterranean aquatic habitats are the most highly decoupled from arid zone precipitation and temperature regimes. Most are supported by groundwater that has accumulated over much longer timescales than that of annual rainfall, and their underground location acts as a buffer from the extreme highs and lows of desert temperatures. The discharge springs, fed by the Great Artesian Basin (recharged from a much wetter climatic zone on the eastern margin of the continent) are most highly decoupled, spatially and temporally, from annual rainfall. However, because these springs lack shading by either topographic features or a well-developed canopy of fringing vegetation, they are fully exposed to contemporary thermal regimes.

The relict streams present within the Central Ranges, fed by local aquifers, are decoupled from annual rainfall but on shorter timescales (residence time ~100 years) than are the discharge springs supported by the GAB. Their location within shaded gorges also provides decoupling from ambient temperatures. In contrast, outcrop springs (by definition also supported by local aquifers) are similarly decoupled from annual rainfall, but are not topographically shaded, and so are fully exposed to ambient temperatures.

Most riverine waterholes and stream pools/rockholes are fully exposed to the arid regional climate. Sparse riparian vegetation provides little shelter from the extremes of inland continental temperature regimes. Large episodic rainfall events are the dominant source of water, resulting in extremely high hydrological variability. Permanent, deep riverine waterholes may also be partially sustained by groundwater held in local aquifers, providing some degree of hydrological buffering under low flow conditions and some thermal buffering, particularly where thermal stratification occurs.

Most isolated rockholes, and all temporary and ephemeral systems, including lakes, marshes, claypans and salt lakes are fully exposed to the regional climate. They are dependent upon surface water runoff generated by infrequent local precipitation and, unless very deep, are poorly buffered from local temperatures.

Table 2: Refugial importance of arid zone aquatic ecosystems (and associated traits of representative aquatic fauna) in relation to their sensitivity to regional climates (rainfall & temperature).

Ev = evolutionary refugium, Ec = ecological refuge. Variable indicates that the waterbody may provide an ecological refuge for some taxa, depending on the mobility of the taxa, the proximity of habitats in space and connectivity during flow events (which only applies to habitats within riverine networks). H = high, M = moderate, L = low.

* the hyporheic zone can be an important ecological refuge in perennial waterholes with sandy sediments

| Waterbody | Refugial Importance | Resistance Traits | Resilience Traits | Sensitivity ~Rainfall | Sensitivity ~Temp |
|---|----------------------------|--------------------------|--------------------------|------------------------------|--------------------------|
| Subterranean Aquifers | High (Ev) | H | L | L | L |
| Discharge Springs (GAB) | High (Ev&Ec) | H | L | L | M |
| Outcrop Springs | Variable | L | H | M | H |
| Relict Streams | High (Ev&Ec) | H/L | H/L | M | M |
| Perennial Riverine Waterholes* | High | H/L | H/L | M | M |
| Temporary Riverine Waterholes | Variable | L | H | H | H |
| Stream Pools | Variable | L | H | H | H |
| Isolated Rockholes | Variable | L | H | H | H |
| Temporary Lakes, Swamps, Marshes | Variable | L | H | H | H |
| Claypans | Variable | L | H | H | H |
| Salt Lakes | Variable | L | H | H | H |

Groundwater-dominated habitats have a higher likelihood of persistence under future climate change than surface water-dominated because they are largely independent of local precipitation. However, aridification over millennia means that groundwater systems in arid Australia are in a state of net discharge, not equilibrium (Hatton, 2001). Accordingly, the habitats and biota supported by groundwater are highly vulnerable to anthropogenic impacts, especially drawdown of groundwater for agriculture and mining.

Conceptualisation of different types of aquatic ecosystems based on their decoupling from the regional climate (temperature and rainfall) with the varying dispersal abilities of arid zone taxa (Figure 18) illustrates the major differences between evolutionary refugia (restricted gene flow but high climatic decoupling) and a range of ecological refuges (high gene flow but exposed to ambient climatic processes). Systems at one extreme (climatically decoupled, perennial hydroperiods) are either a refugium or refuge depending on the evolutionary history, gene flow and dispersal abilities of their taxa and their spatial context. Systems at the other extreme (climatically coupled, temporary and highly variable hydroperiods) are rarely likely to act as major refuges for all but a small number of highly mobile taxa.

Further investigations of gene flow in populations of arid zone aquatic species, particularly aquatic invertebrates with different dispersal modes (active, weak and passive), are needed to validate this conceptual model. We have only qualitatively identified refugia and refuges as generalized habitat types and further work is needed to produce a quantitative assessment. The variability in habitat characteristics, for example, the relative contributions of groundwater and surface water, and the degree of topographic shading, needs to be determined for some habitats (particularly riverine waterholes and outcrop springs). The very large areal extent of the Australian arid zone biome suggests that environmental factors will vary across the biome. For example, although aridity is the major environmental driver, other factors such as the timing of major rainfall events, from predominantly summer in the north to winter in the south, will also influence the capacity of aquatic habitats to act as ecological refuges.

Determining where local climatic processes are decoupled from regional processes provides important information for climate adaptation planning and management. Evolutionary refugia are the most highly decoupled habitats and so will potentially be the most persistent under a changing climate. Ecological refuges vary in their exposure to climatic influences. Prioritising the protection of aquatic evolutionary refugia and perennial aquatic ecological refuges is important because they offer the only chance for *in-situ* persistence of poorly dispersed species.

5.6 Reducing risk by reducing existing stressors (especially invasive species)

Reducing existing stressors on arid zone aquatic ecosystems and freshwater biota is likely to increase both their resistance and resilience to changing and increasingly variable climatic conditions. Additionally, implementing conservation programs that are good for biodiversity, regardless of future climates, represent valuable “no-regrets” actions (Groves *et al.*, 2012).

A recent risk assessment conducted for the Queensland portion of the LEB (Table 3, WPE, 2012) identified introduced species (feral species including camels, goats, pigs and donkeys) as the greatest threat to biodiversity. A major management program, funded by Caring for our Country 2, currently addresses the threat posed by camels (Figure 19).

Ongoing support for the Australian Feral Camel Management Program and additional programs to address the impacts of other feral species and livestock at arid zone waterholes are high priority climate adaption actions.

A risk assessment similar to that conducted for the Qld LEB is needed to identify the threats to aquatic ecosystems and freshwater biodiversity across the entire arid zone.

Table 3. Draft threat and risk assessment for aquatic ecosystems in the Qld Lake Eyre Basin based on a questionnaire and workshop.

The risk assessment results are ordered from the highest to lowest risk. The priority risks are highlighted: red- high risk; yellow-moderate risk. Source: WPE (2012).

| Threat | Risk | Confidence | Threat | Risk | Confidence |
|---|------|------------|---|------|------------|
| Introduced (non-native) riparian species (fauna) | 15 | 9 | Climate change | 2 | 1 |
| Instream pest species (fauna) | 12 | 5 | Instream pest species (flora) | 2 | 2 |
| Riparian weeds | 9 | 4 | Riparian habitat removal or disturbance – riparian connectivity | 2 | 6 |
| Riparian removal or disturbance | 8 | 6 | Acid soil runoff | 1 | 3 |
| Deposited sediments | 6 | 1 | Suspended Sediments | 1 | 4 |
| Flow management - waterhole pumping | 4 | 6 | Pathogens | 1 | 6 |
| Direct biota removal or disturbance | 4 | 6 | Salinity | 1 | 9 |
| Toxicants – mining | 4 | 9 | Organic matter | 1 | 9 |
| Nutrients | 3 | 3 | Instream habitat removal or disturbance | 1 | 9 |
| Instream removal or disturbance – instream connectivity | 3 | 9 | Thermal alteration | 1 | 9 |

5.7 Recognising adaptation opportunities – new water and novel ecosystems

Societal responses to climate change can provide novel opportunities to increase both the success and cost effectiveness of conservation. Initial efforts to incorporate ecosystem services into systematic conservation planning are considered to be promising but may also involve trade-offs with biodiversity conservation (Groves *et al.* 2012). An approach referred to as Ecosystem-Based Adaptation (EBA) has been proposed by the International Union for the Conservation of Nature (IUCN; www.iucn.org/) and the Climate Action Network (www.climatenetwork.org/). EBA is defined as: “a range of local and landscape scale strategies for managing ecosystems to increase resilience and maintain essential ecosystem services and reduce the vulnerability of people, their livelihoods and nature in the face of climate change” (CAN 2009). For the arid zone these could include strategies to improve the condition of waterbodies that represent important cultural and nature-based tourism sites. These are unlikely to be outright win-win situations for conservation because they include additional objectives to those that are specific to biodiversity conservation and they may be accompanied by emerging industries and sectors (such as biofuels) that pose new or additional impacts to biodiversity (Groves *et al.*, 2012). However, despite these concerns, emerging opportunities need to be considered as part of a broad strategic approach to arid zone climate adaptation planning.

Activities that create new waterbodies in the arid zone need be considered as part of a portfolio of climate adaptation options. The creation of perennial waterbodies through mine dewatering will provide novel ecological refuges for mobile arid zone aquatic biota. Opportunities for ‘new water’ or ‘biodiversity water’ need to be recognized and assessed. The trade-offs involved in activities such as dewatering, where groundwater is depleted but new surface waters are created, need to be clearly articulated and rigorously assessed. These opportunities should not be confused with the need to provide environmental flows.

New and novel waterbodies created by arid zone industries (e.g. mining) may represent valuable offsets for waterbodies lost through climatic drying. These opportunities need to be recognized but the possible trade-offs for biodiversity need to be clearly articulated and rigorously assessed.

5.8 Implementing climate adaptations within in a strategic adaptive management framework

The process of adaptive management, which recognises the inherent uncertainties of dynamic and unpredictable ecosystems and tests these uncertainties to progressively improve management (Walters, 1986) is well suited to addressing the uncertainties of a changing climate across the arid zone. Adaptive management, simply defined as ‘learning by doing’, incorporates both passive (trial and error) and active (experimentation) approaches. Strategic Adaptive Management (SAM) builds upon this to provide a framework for adaptive management for freshwater areas across socio-ecological systems and over large spatial scales (Kingsford *et al.*, 2011). The process is termed strategic because it is forward-looking, sets a desired future direction and focuses more on integration within social, economic and governance processes. It follows a generic process adopted by IUCN for protected area management based on: setting the ‘desired future condition’; management options; operationalization; and evaluation and learning. SAM encourages innovation, local adaptation, trust and overlapping governance structures. It appears well suited to the management of many arid zone aquatic ecosystems that are located outside protected areas within

landscapes managed for other human purposes. It acknowledges that complex behaviour arises from interacting drivers that change over time (rainfall, sedimentation, flow, human skills capacity and levels of trust) and embraces the inherent complexities and interdependent behaviour of socio-ecological interactions (Kingsford *et al.*, 2011).

Strategic adaptive management of arid zone aquatic ecosystems should include the following:

- A coordinated national approach to monitoring and evaluating changes in water quantity and quality in surface and groundwater-dependent ecosystems
- Inputs from mining and energy production arid zone monitoring and rehabilitation programs
- Training to support monitoring and management of arid zone aquatic assets and biodiversity by local communities, including indigenous ranger groups, pastoralists, tourism operators and school children.

A simple climate adaptation decision support framework (Figure 20) has been developed based on the identification of different types of aquatic ecosystems, differing water regimes (permanent or temporary) and the groundwater/surface water resources that support them.

A national system of storage and retrieval is needed to ensure that the environmental information collected by mining and energy companies working within the arid zone makes an enduring contribution to the management of Australia's unique biodiversity. The environmental data collected by mining and energy companies for impact assessment during exploration and site development provides important information on the ecology of arid zone aquatic assets and biota. Similarly, important environmental data is collected as part of the ongoing environmental management of mining or production sites and the rehabilitation of decommissioned sites. This information needs to be evaluated within a national context to support the development of national arid zone planning and management policies.

5.9 Supporting indigenous and local community engagement and education

Successful adaptation to climate change and increasing climatic variability requires good community engagement and education. An important part of this engagement is easy access to reliable information. Robust climatic scenarios and practical adaptation advice are needed. The latter must address the interactions between social, cultural, economic and environmental objectives for arid zone water resources and aquatic and terrestrial ecosystems.

Implementation of the recommended strategic adaptive management program will help address key aspects of community engagement and education. In particular, monitoring and management of key evolutionary refugia and ecological refuges by indigenous groups, local communities and school groups will strengthen community involvement in adaptation and increase local understanding of climatically - induced changes.

Measuring climatic, hydrological and ecological changes at aquatic assets across an area as large as the Australian arid zone can be achieved through the deployment of a range of remote sensing instruments managed and maintained by indigenous communities, pastoralists and school groups. Technological advances mean that the establishment of a network of robust and low cost sensors at strategic sites is now

feasible and affordable. These include mini-weather stations, depth and water quality loggers, surveillance cameras and bioacoustic sensors. A national network would record information from the representative freshwater assets across the continent. These would include the most important sites for biodiversity (especially evolutionary refugia and perennial ecological refuges) and sites with recognised historical and cultural significance. Advances in molecular techniques and greatly reduced costs of analysis have created very powerful tools for monitoring the expansion and contraction of biota from critical refugia. This includes not only the animals that live within springs and waterholes (fish and invertebrates) but also the terrestrial mammals and birds that rely on aquatic systems for survival within dryland and desert landscapes.

6. ADDRESSING KNOWLEDGE GAPS

The knowledge gaps identified by the Lake Eyre Basin Knowledge Strategy (<http://www.lebmf.gov.au/publications/pubs/leb-knowledge-strategy-summary.doc>) are pertinent to this plan. These are summarized as follows:

- waterholes
 - the issue of changes to low-flow hydrology from water abstraction and climate change
 - the importance of surface water/groundwater exchanges in ephemeral river systems
 - the effects of tourism and other local scale impacts on waterholes
- flow interception and infiltration
 - the need for models and predictions of how changing vegetation cover and condition will affect the quality and quantity of surface run-off and infiltration
 - better understanding of the effects of levees, roads and culvert crossings on downstream flow conveyance and floodplain vegetation
- futuring or foresighting activities
 - the need to better understand the aspirations and values of the broader community and how these may change in the face of a changing climate and economy

In addition the following topics and issues need consideration:

- How important are metapopulation dynamics in supporting the obligate (fish and aquatic invertebrates) and non-obligate (waterbirds and frog) communities of arid zone waterbodies? Molecular studies are needed to determine the present and past connectivity of key aquatic sites.
- The diversity and ecological roles of algae and aquatic plants. These are important in a climate adaptation context but were not addressed in this document because of time constraints.
- Stygofauna – relative to what is known about their diversity we know very little about their ecology and biology, especially in relation to habitat connectivity and environmental water requirements. This is recognised as a knowledge gap in the EIA process for mining in WA by the WA EPA. As a consequence a risk assessment approach is currently being used based on little data.
- Salt lakes - despite their ubiquity across the arid zone the flora and fauna of salt lakes is not well documented, especially the very complex playa systems of southern WA. These systems are increasingly affected by mining and water disposal. Molecular studies of key species are needed to determine current and past connectivity.
- Hyporheic zones – particularly their importance as dispersal corridors and ecological refuges and as habitat for future diversification under increasing aridity.
- The impacts of altered fire regimes on arid wetlands and the potential influence of climate change.
- More information is needed on the functional ecology of arid-zone wetlands to support the refinement of conceptual models of responses to disturbance.

- The effects of livestock on the condition of arid zone wetlands need to be determined and addressed.
- What mix of on-ground management tools is best for building climate resistance and resilience? When and where can reservation, fencing, landscape management, feral animal control and better water resource management be applied. This requires both research and the development of decision support tools.

7. SUMMARY OF ADAPTATION OPTIONS

Climate change adaptation is defined as the adjustment of natural or anthropogenic systems to a changing climate for the purpose of moderating impacts or capitalizing on novel opportunities (IPCC 2007). Groves *et al.* (2012) proposed five approaches to climate change adaptation that can be integrated into existing or new biodiversity conservation plans. These include: (1) conserving the geophysical stage, (2) protecting climatic refugia, (3) enhancing regional connectivity, (4) sustaining ecosystem process and function, and (5) capitalizing on opportunities emerging in response to climate change. A major strength of these approaches is that they are generally robust to the uncertainty in how climate impacts may manifest in any given location. The adaptation options we propose in this plan largely conform to these suggestions.

We have proposed a portfolio of adaptation approaches to maintaining aquatic habitats, the water resources that support them, and the species that depend upon them. In summary recommended climate adaptation actions include: implementing a national mapping program that identifies the major types of arid zone aquatic ecosystems and the surface water and groundwater resources that sustain them; recognising the importance of evolutionary refugia and ecological refuges as priority sites for arid zone climate adaptation planning and policy; protecting a dynamic (spatial and temporal) mosaic of perennial, temporary and ephemeral waterbodies to provide the range of conditions needed support aquatic and water-dependent species with varying life history traits and dispersal abilities; maintaining the integrity of the sediments of temporary and ephemeral waters to ensure the persistence of viable seed and egg banks; recognising the importance of key hydrological and ecological processes, particularly connectivity and dispersal; assessing the climate sensitivity and likely persistence of key habitats; reducing the existing stressors on aquatic ecosystems and aquatic biota; identifying new and novel waterbodies created by arid zone industries (e.g. mining, pastoralism) that could provide valuable offsets for aquatic systems lost through climatic drying; implementing climate adaptation actions within a strategic adaptive management framework accompanied by a dedicated program for community engagement and education.

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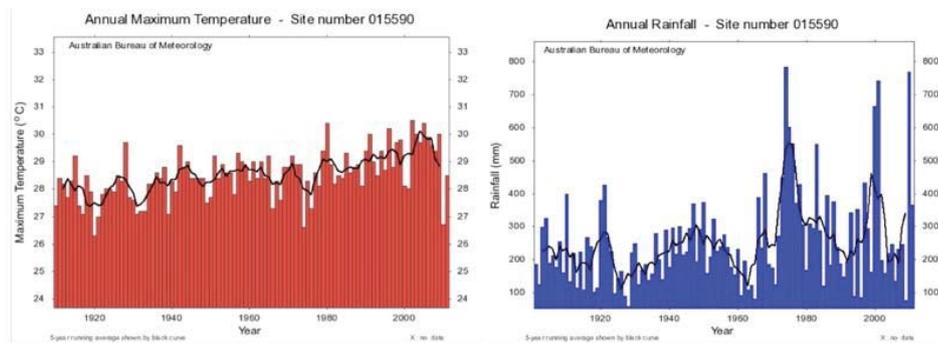


Figure 1. Time series with a five year moving average (continuous line) of: (a) annual maximum temperature; and (b) annual rainfall, Alice Springs, Northern Territory (23.8°S, 133.89°E).

Source: www.bom.gov.au

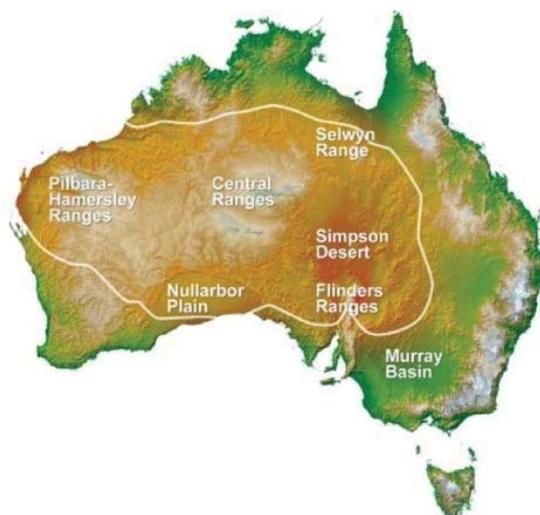


Figure 2. Extent of the arid and semi-arid regions comprising the Australian arid biome.

Source: Byrne *et al.* (2008)

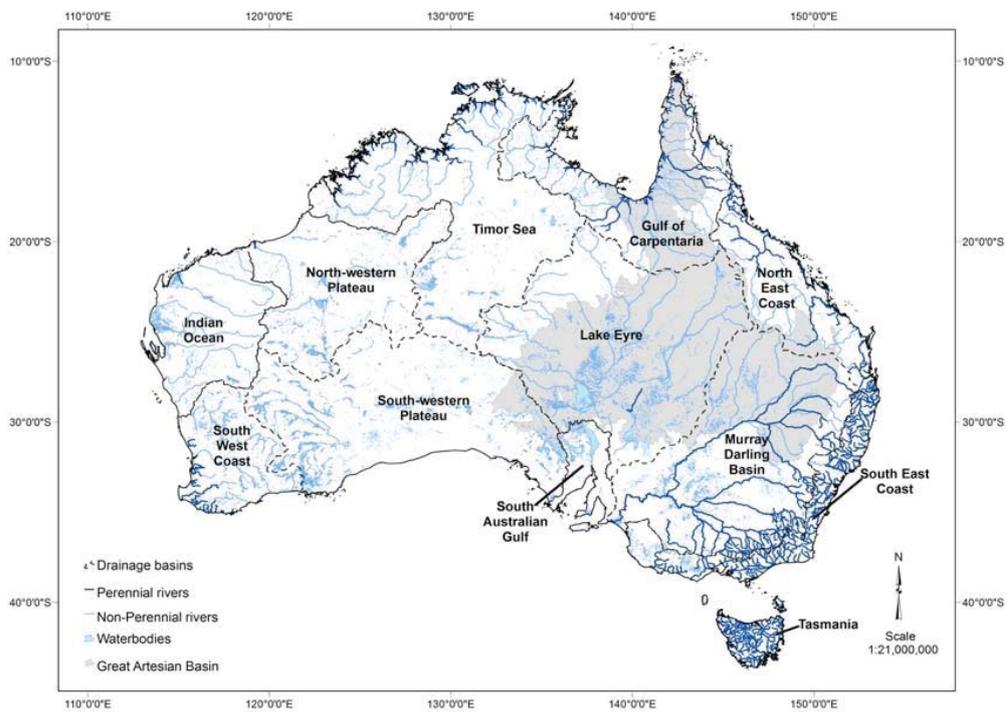


Figure 3. Map showing the location of drainage basins spanning arid and semi-arid zones, watercourses and the Great Artesian Basin. Source: GEOFABRIC v.2 surface drainage network layer <http://www.bom.gov.au/water/geofabric>.

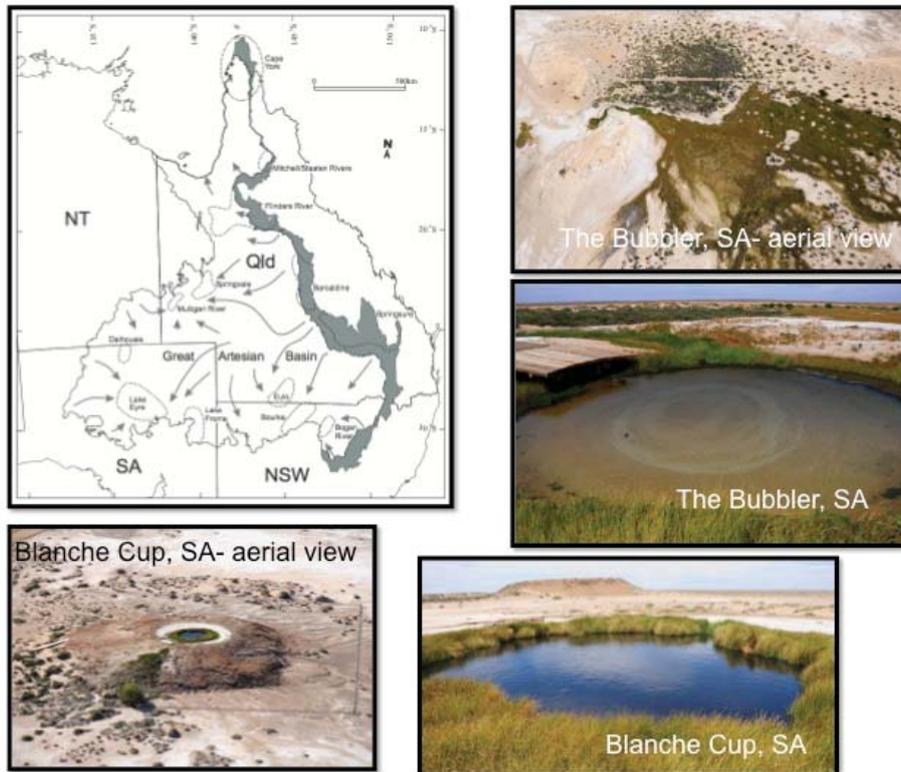


Figure 4. Map of the Great Artesian Basin showing recharge zones (shaded), spring supergroups (dotted lines), and flow direction (arrows). Source: <http://wetlandinfo.derm.qld.gov.au>; Aerial and ground views of discharge (mound) springs (The Bubbler and Blanche Cup) in the Lake Eyre South group, South Australia.



Figure 5. Relict streams in the Central Australian Ranges typically occur in deeply shaded, south-facing gorges, as illustrated by the aerial view of Serpentine Gorge, NT.

Groundwater seeping from rock faces supports relictual and other taxa dependent on permanent water, at sites such as upper Serpentine Gorge in the West MacDonnell Ranges and Stokes Creek in the George Gill Ranges, NT.



Figure 6. Riverine waterholes occur as perennial, temporary and ephemeral systems within dryland rivers.

The Finke River (aerial view) arises in the Central Australian Ranges, NT, and includes the perennial waterbodies of Two Mile (upper right), Running Waters (lower left) and Boggy Hole (lower right).



Figure 7. Many waterholes in the rivers of Lake Eyre Basin, SA, are characterized by high turbidities. Images: Dale McNeil

The waterholes illustrated here dry up after extended periods without flow, however, they are critical for fish to rebuilt resilient populations.

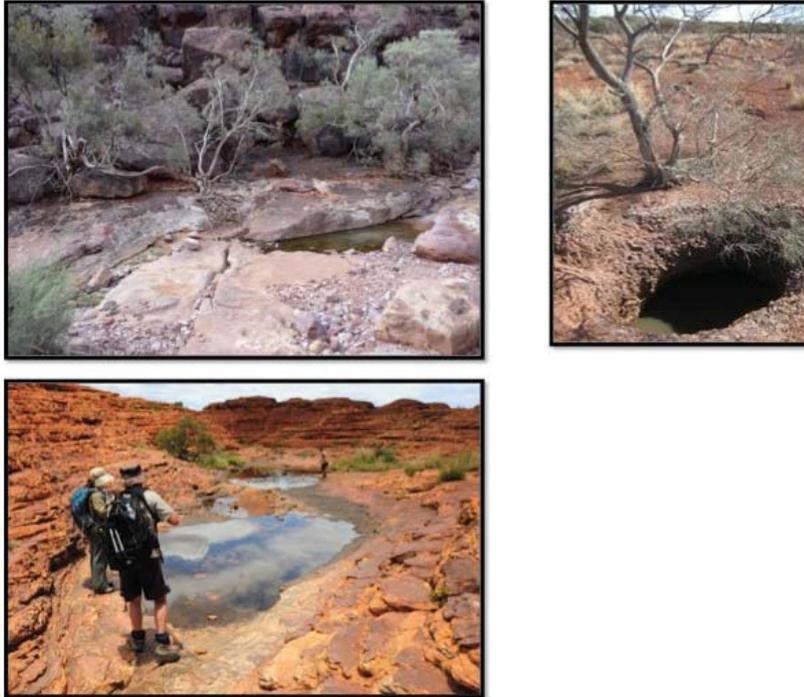


Figure 8. Outcrop springs (top left) occur near the base of ranges and rocky outcrops. Rockholes (top right) are very small and isolated habitats that are widespread, but not abundant, throughout the arid zone. Ephemeral rock pools (bottom left) appear after infrequent and unpredictable rain events.



Figure 9. Claypans (top) are distinctive shallow basins fed by local rainfall and often that occur throughout the arid zone. Similarly, salt lakes (bottom) are widespread and rarely contain water.



Figure 10. The Pilbara region, WA, contains a variety of waterbodies including: spring-fed stream pools (Skull Springs, top left); turbid river pools (Wackilina Creek Pool, top right); temporary wetlands (Fortescue Marsh, bottom left); and claypans (Croyden, bottom right).

Images: Adrian Pinder, Stuart Halse (Fortescue Marshes). Copyright: DECWA.



Figure 11. Stygofauna contain a range of adaptations to a subterranean existence including reduced size, lack of eyes and loss of pigmentation.

Images: Jane McRae. Copyright: DECWA

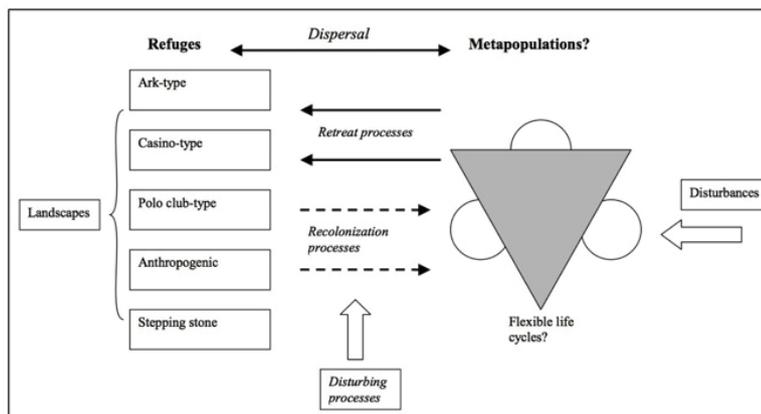
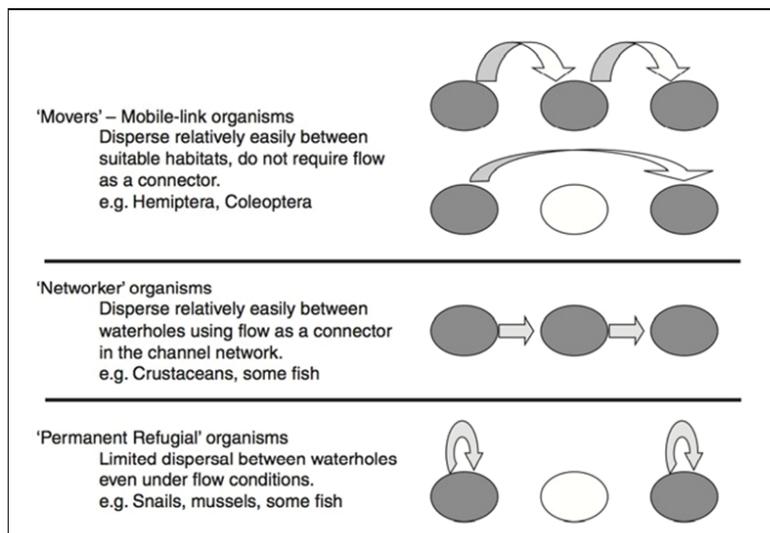


Figure 12. Upper box: The different dispersal strategies that are used by organisms in fragmented dryland rivers.

Waterholes denoted in grey contain water, whereas those in white are dry. Arrows depict movement of organisms within and among waterholes. Source: Sheldon et al. (2010).

Lower box: Conceptual summary of the relationships between refuge types, retreat and recolonisation processes, metapopulation processes and the effects of disturbance.

Source: Robson et al. (2008)

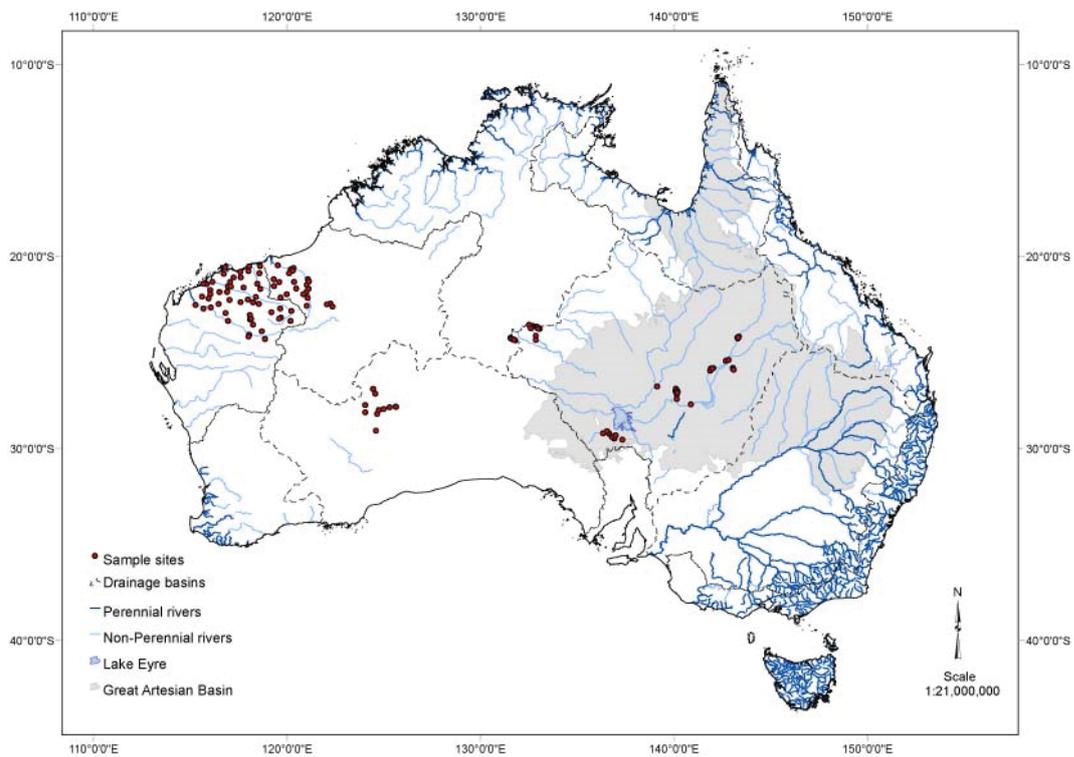


Figure 13. Location of sampling sites included in a comparison of aquatic invertebrate assemblages across the arid zone. Source: GEOFABRIC v.2 surface drainage network layer.

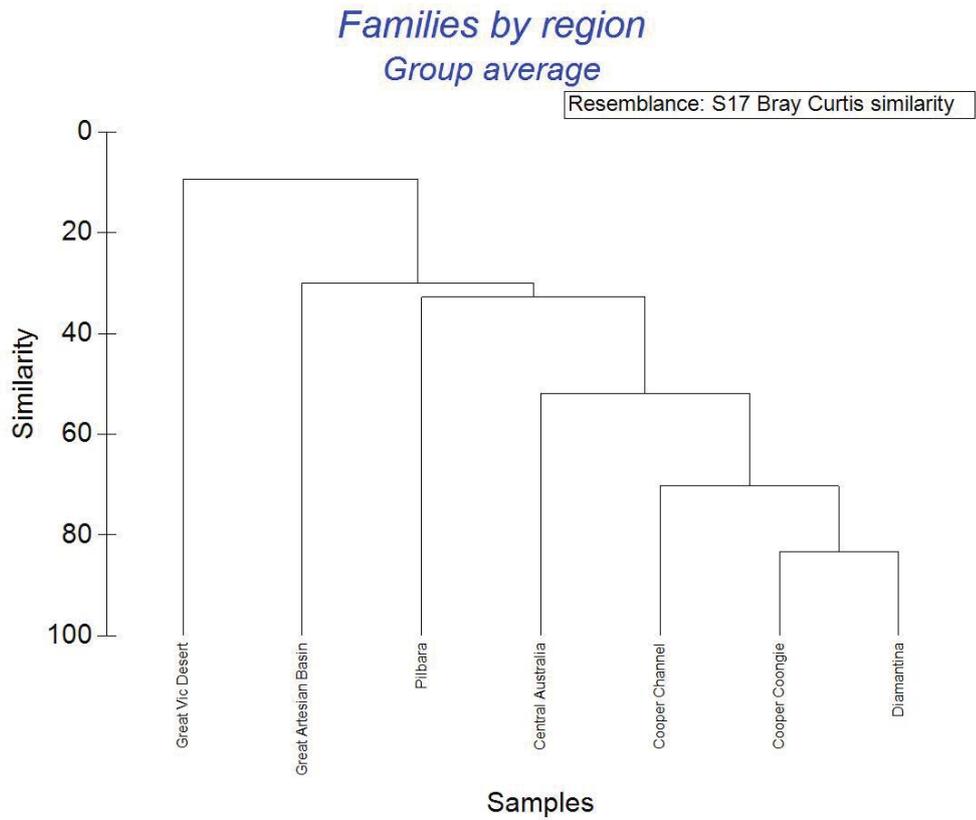


Figure 14. Bray-Curtis similarities of aquatic invertebrate assemblages across the Australian arid zone.

Waterbodies contain markedly different assemblages with isolated rockholes in the Great Victoria Desert and mound springs in the Lake Eyre South complex being the most dissimilar.

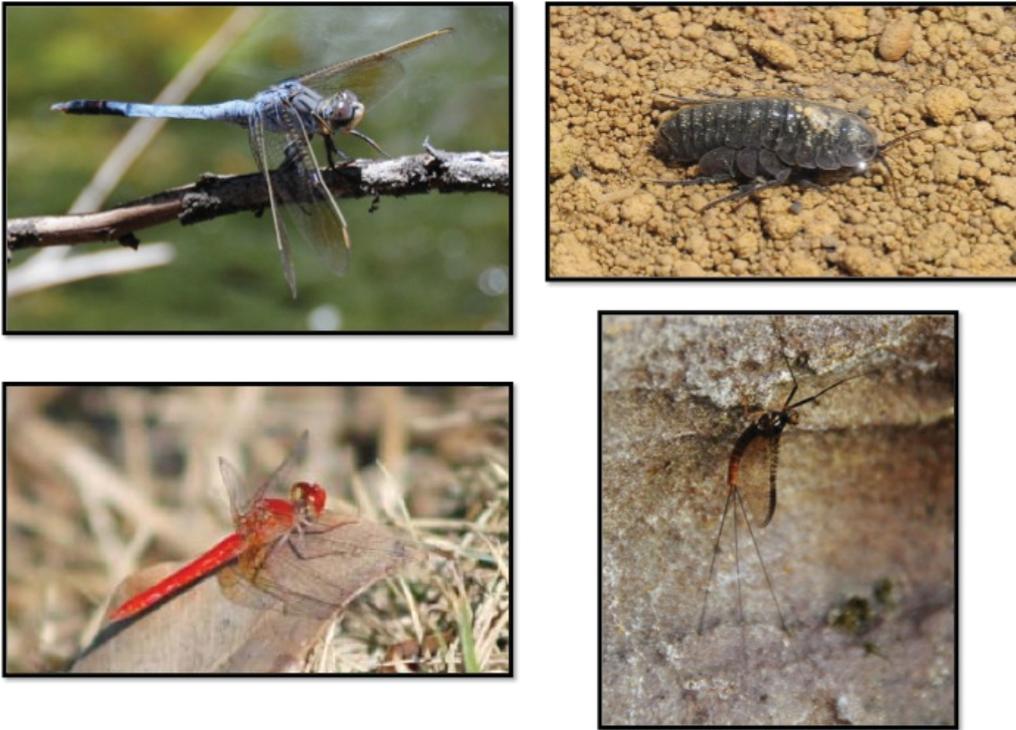


Figure 15. Adult dragonflies (top & bottom left, Cowards Springs, SA) are strong, active aerial dispersers, in contrast, adult mayflies (bottom right, Stokes Creek, NT), which are short-lived and small-bodied, are weak aerial dispersers. Isopods (top right, The Bubbler, SA), do not have an aerial dispersal phase, they are aquatic obligates and can only disperse when water is present water.

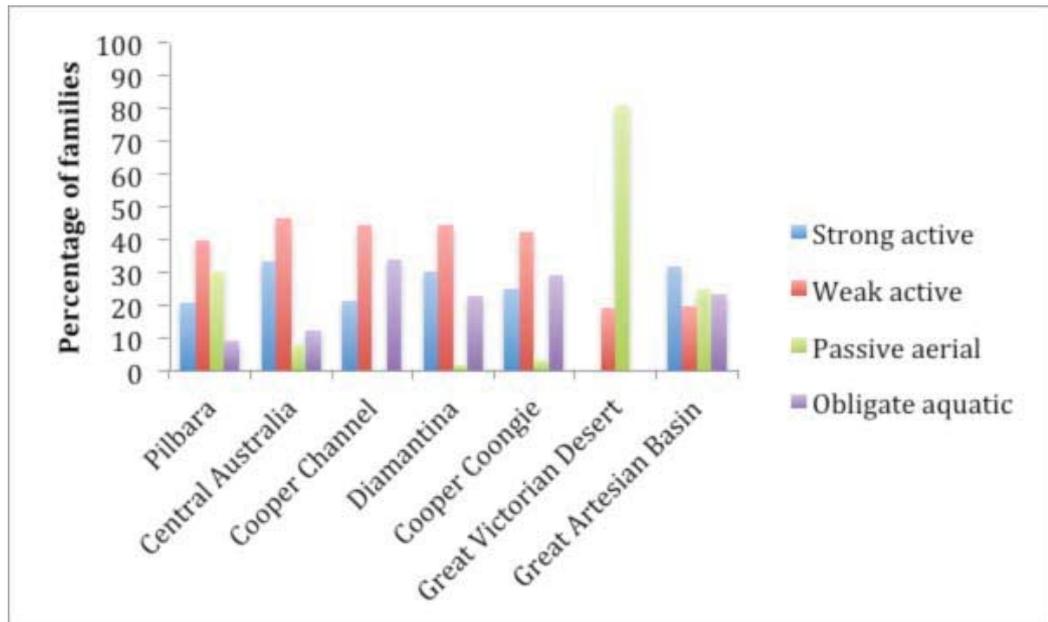
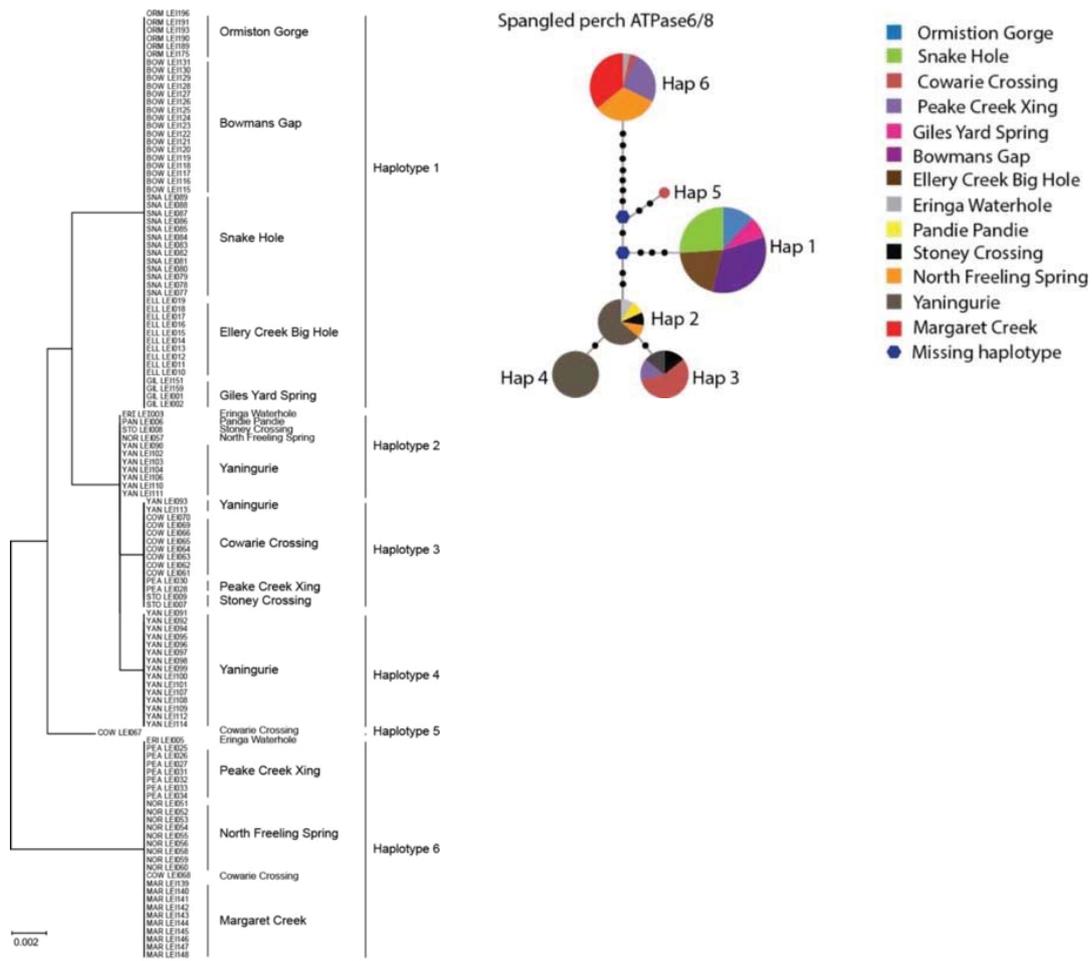


Figure 16. Differences in occurrence of dispersal traits (as percentages of families) of aquatic invertebrates in regions across the Australian arid zone.

Note: this analysis did not include rotifers.



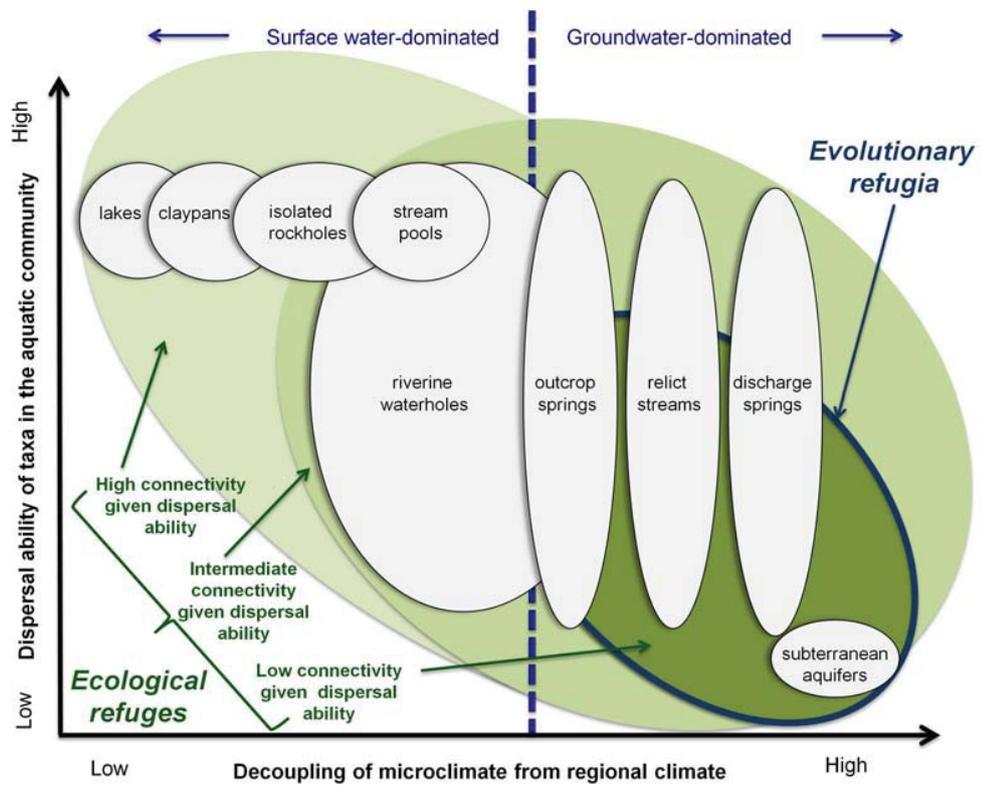


Figure 18. Conceptualisation of the major differences between evolutionary refugia (restricted gene flow but high climatic decoupling) and a range of ecological refuges (high gene flow but exposure to ambient climatic processes).

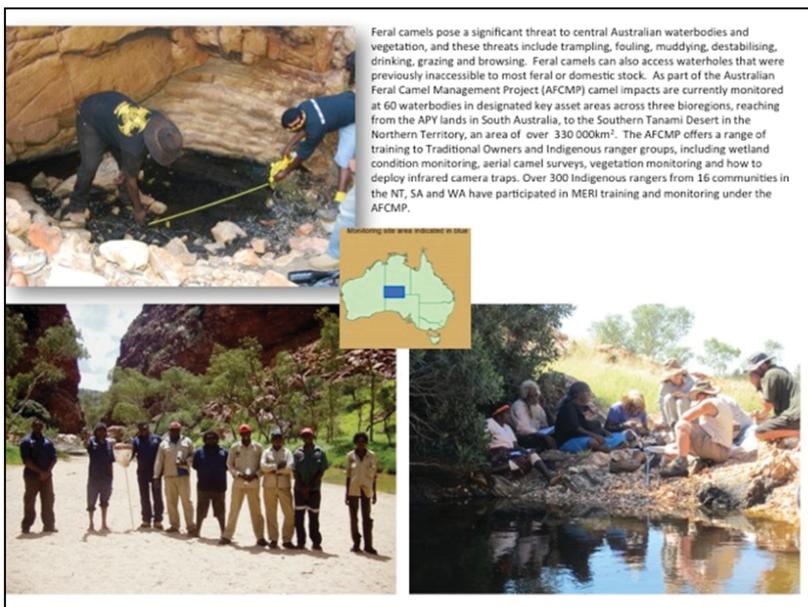
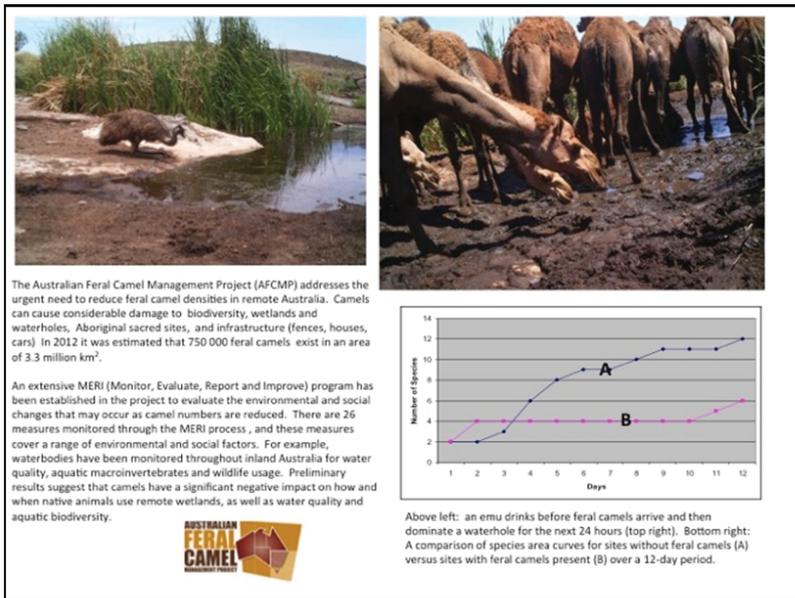


Figure 19. Upper box: The Australian Feral Camel Management Program is an important Commonwealth government initiative that addresses one of the greatest threats to arid zone aquatic ecosystems and freshwater biodiversity. Lower box: Traditional owners and indigenous ranger groups are actively involved in monitoring waterhole condition.

Source: Jayne Brim Box and Andrew Bubb

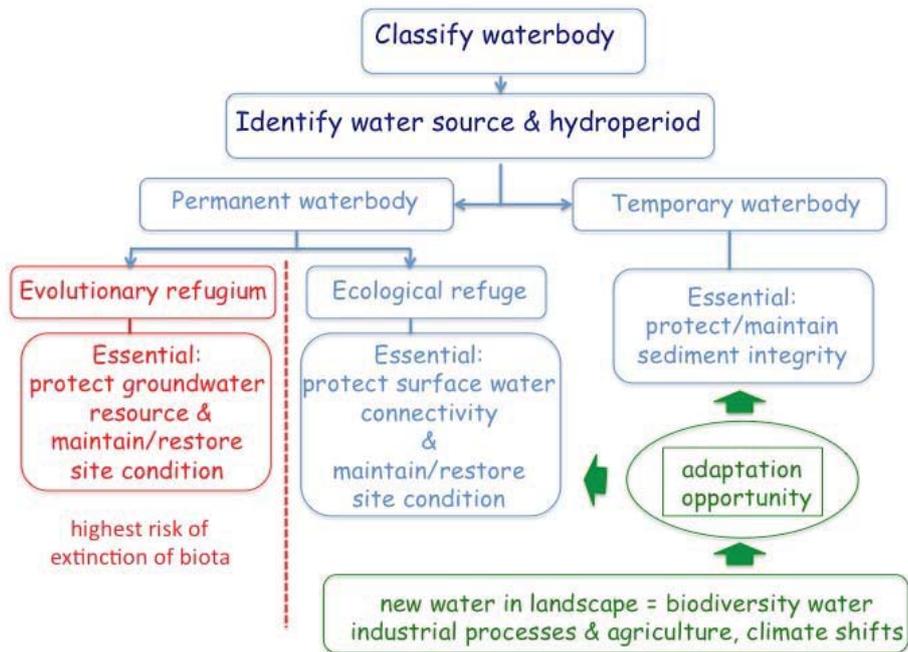
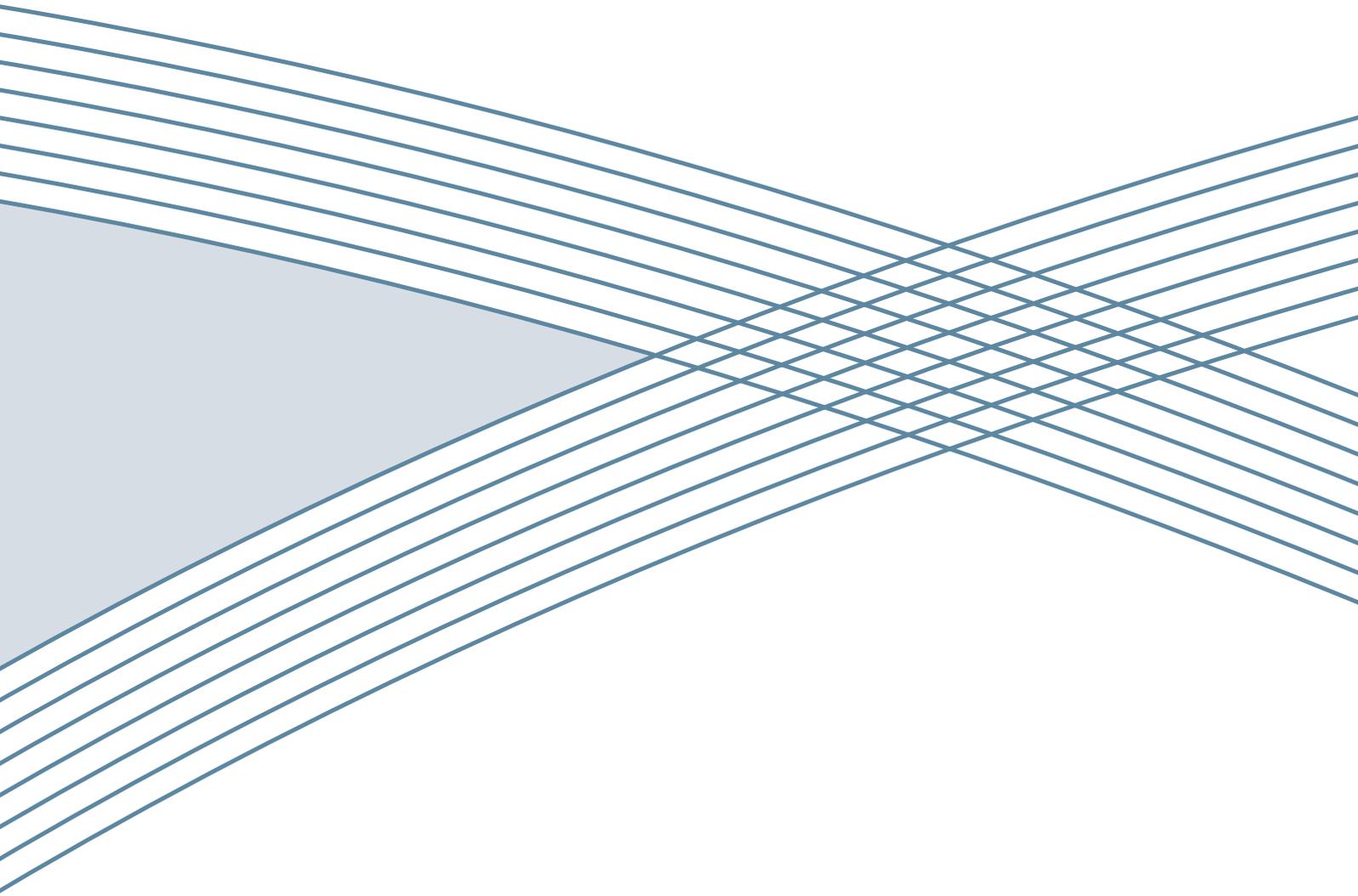


Figure 20. A simple decision framework for identifying essential climate adaptation actions for arid zone aquatic ecosystems



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