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Review & synthesis of drought refuge habitat knowledge and management

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Report citation

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Traditional Owner acknowledgement

The Centre for Freshwater Ecosystems, Albury–Wodonga is located on the land of the Latje Latje and Wiradjuri peoples. We undertake work throughout the Murray–Darling Basin and acknowledge the traditional owners of this land and water. We pay respect to Elders past, present and future.

Contents

Introduction

The aim of this document is to synthesise information on habitat refugia management, specifically focussing on drought refuges. The synthesis focuses on work done specifically in Australia, and primarily work commissioned by the Department of Sustainability and Environment (DSE) (former DELWP) and the Murray-Darling Basin Authority during the millennium drought (1997 – 2009). Relevant studies conducted after the millennium drought are also included.

The synthesis provides brief summaries of the main issues, primarily in dot point format, and how we currently track against managing for them. An overview of the literature types and scopes is first provided to set the scene. This is followed by a summary of the major findings and/or guidance that is relevant to water managers. In each section we include indications on how we are currently performing in a range of key areas. Of particular importance, and potential use to managers, are the sections on 1) effective refuge management (page 3); 2) threats and drivers impacting refuges (page 6); 3) the major flow and non-flow related actions available for refuge management (page 10); and existing knowledge gaps (page 15).

Scope and nature of key information

A total of 27 documents published from 2003 – 2019 were reviewed for this synthesis. These were mostly documents commissioned by Federal and State government agencies but also included some relevant scientific literature not explicitly funded by Government. A classification table was used to investigate the main themes emerging from the literature and to identify existing recommendations and information for managers, and where gaps exist that require further work. The variables under which the literature was categorised are described in Appendix 2, Table A3.

The documents could be grouped into five broad categories:

- Conceptual –conceptualisations of drought effects and biotic interactions. Conceptual literature did not contain any primary data.
- Empirical –primary data used to test hypotheses or characterise/locate landscape features
- Modelling – may have used primary data but primarily concerned with modelling effects rather than testing hypotheses.
- Reviews – overviews of information on biota and/or the effects of drought
- Strategy – documents focussing on management plans, frameworks or assessments.

Strategic documents were the most common, making up 37% of documents (Figure 1). Seven of these were Dry Inflow Contingency (DIC) Plans implemented by various, Victorian, Catchment

Management Authorities in 2007. Review, conceptual, empirical and modelling documents, together made up 63% of the literature.

Documents focussed on rivers and streams (13 documents) or were either applicable across, or focussed on, all waterbody types (14 documents). None of the documents focussed solely on non-riverine waterbodies such as wetlands. Empirical and modelling documents only focussed on rivers. All conceptual documents had a focus on the whole suite of waterbody types. Review and strategy documents were split between being focussed on all waterbodies (~66%) and focussing only on rivers (~33%).

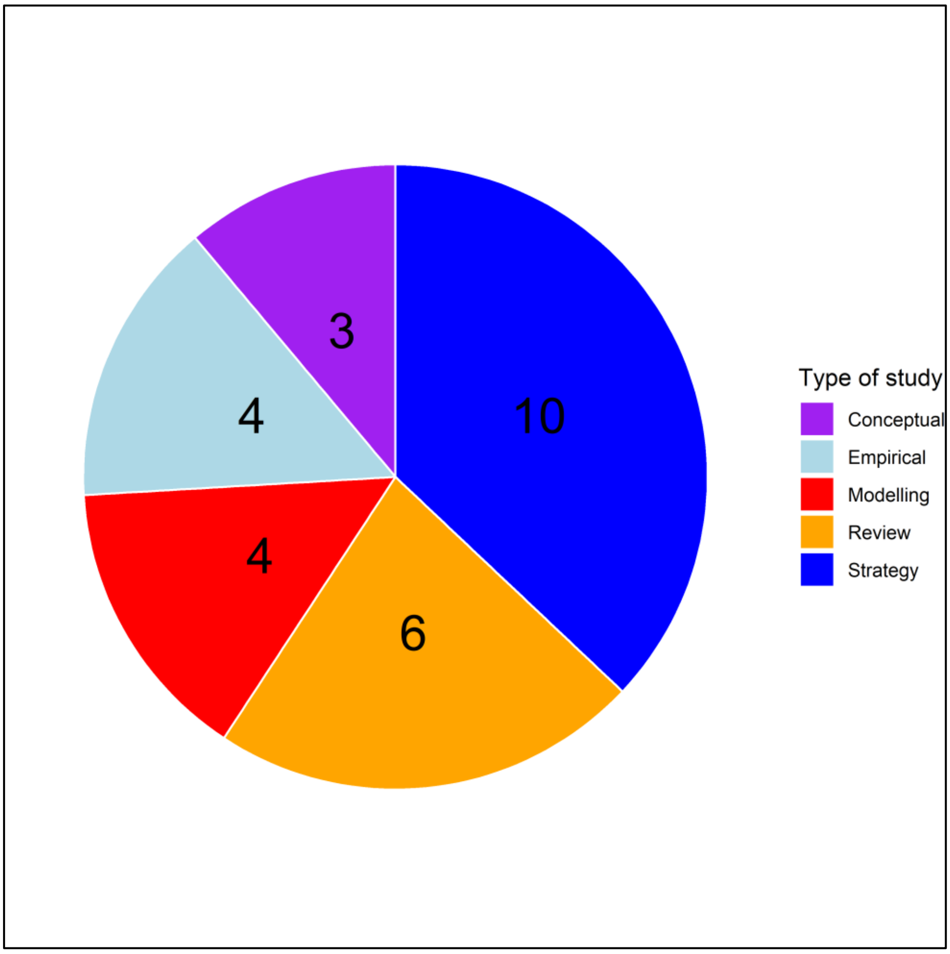

Figure 1 Distribution of literature types. Numbers indicate total number of documents of each type.

What were the major findings or guidance relevant to water managers?

Overview

From consideration of the conceptual and review documents, a road map for successful management of aquatic habitat emerges. Such management should be pro-active, consider refuges and other critical habitat patches in a broader landscape context, account for the impacts of drought over various time horizons, and cater for the diversity of habitat requirements of different biota. Below we summarise the main findings from the synthesis and how current management actions perform against them.

Protection of refuge habitats is critical for post-drought recovery of biota

- Refuge habitats provide physical places where organisms can persist during times of disturbance, such as drought or flooding (Hale 2018).
- Ultimately, the function of refuges is to maintain populations through drought periods such that they are capable of contributing to post-drought recovery and recolonization (Robson et al. 2008, McNeil et al. 2013a).
- While we have tools for identifying refuges, these tend to focus on habitat availability and species assemblages, rather than the long-term, post-drought contributions of refuge populations as centres of dispersal and recolonisation. Moreover, empirical studies are lacking in this area, resulting in a significant and important knowledge gap.

Effective management needs to be proactive, consider the broader landscape and manage for multiple species and habitat types

Proactively manage refuges by implementing actions that will increase drought resilience and resistance in organisms before drought occurs

- Management needs to be pro-active and to include preparation during all phases of climatic cycles, moving away from reactionary management implemented after the onset of drought (Crook et al. 2010). Proactive management, implemented well before the onset of drought, provides the best opportunities for populations to be resistant and resilient to drought (McNeil et al. 2013a).

- Examples of proactive management include actions such as prioritisation, mapping and modelling of likely refuge habitats across landscapes ready for when drought occurs, collecting baseline data to aid in assessing recovery post-drought, fencing and revegetating riparian zones, restoring habitat structure, implementing conservative water use strategies to preserve capacity, and removing barriers to dispersal.
- We currently perform poorly in this regard – for instance, reference to proactive management is lacking in strategy documents and many actions are implemented only when drought is well established.
- Many of the recommended actions included in the strategic documents lend themselves to proactive management, being either implementable at any period of the climatic cycle or having lasting effects; but they are not articulated as proactive strategies and are not implemented prior to drought with the specific aim of building ecosystems that are resilient and resistant to drought.
- Encouragingly, there is concordance between the management actions outlined in strategic documents and those suggested in the conceptual and review literature.

Consider the broader landscape – how refuges are spatially distributed and how they link in with the landscape

- Drought refuges and other key aquatic habitats need to be considered in relation to their surrounding landscapes and to their linkages with other refuge areas (i.e. within a meta-population context) (Morrongiello et al. 2006, Robson et al. 2008, Hale 2018).
- There is a need to understand where and how many refuges exist and for how long they persist (Bond 2007).
- A number of documents and tools are available for identifying, characterising and mapping refuge areas (e.g. Bond (2007), Raadik et al. (2017), Shipp et al. (2018).
- An increased ability to forecast the temporal persistence of refuges over varied time horizons is a critical knowledge gap.

Manage for multiple habitat types and multiple species

- Not all species have the same habitat requirements; however, guilds of species may be protected within the same habitat (Robson et al. 2008).
- Translocation of species of high importance from refugia does not protect the broader assemblage and is a last resort option that is only likely to be effective for highly threatened species. Protection/enhancement of habitat has benefits across the whole assemblage.

- Landscape-scale management should include multiple habitat types to maximise the diversity of species that refuge habitats support
- Strategy documents tend to include a variety of habitats but priority refuges are often chosen based on their social importance or the presence of threatened species, and selection lacks a nuanced approach where maximising diversity and resilience in ecosystems is achieved. However, protection of threatened species habitat will tend to have protective effects on other fauna and flora.
- Habitat distribution models and prioritisation tools, such as Zonation (Moilanen et al. 2005), could be more widely implemented to help prioritise and manage refuges in a way that optimises these factors.
- There is a good representation of regulated and unregulated systems in strategic and non-strategic documents. However, there are large knowledge gaps around the hydrology of unregulated systems that leave these systems vulnerable to ineffective management.
- The predominant research focus on drought in Australia to date is on fish, with some consideration given to invertebrates, very little to birds, amphibians and mammals and almost none to reptiles (Robson et al. 2008). Moreover, the importance of aquatic refuges for organisms not-traditionally considered aquatic, such as birds that utilise riparian zones, has been largely overlooked. The surveyed documents provided no indication on the merits of prioritizing some types of biota over others. However, Bond (2014) suggests that by prioritising threatened species for protection many other species will benefit. However, this applies where management involves habitat protection rather than actions such as translocation.
- While much research has been conducted, there are still large gaps in our knowledge of the ecology of water-dependent organisms and how they respond to droughts. In particular, little consideration is given to the specific habitat requirements of different life stages of organisms or which life stages are the most important to protect during drought and/or to enhance recovery post-drought (Robson et al. 2011).

Different taxa require different refuges but high quality refuges need to have sufficient area and suitable habitat.

- What characterises a refuge as high-quality will vary depending on the organisms that inhabit it, or are intended to inhabit it.
- The most important characteristics of drought refuges are sufficient area with suitable habitat that provide protection from insufficient water quality and excessive competitive

and predator-prey interactions (Robson et al. 2008, McNeil et al. 2013a, McNeil et al. 2013b).

- The presence of water does not guarantee an area will act as a refuge. Characteristics such as water quality, temperature, depth, source and persistence have a significant impact on refuge suitability.
- Habitat structures, such as large woody debris or fringing riparian vegetation, play an important role in refuges as species rely on such structures for shelter, breeding and substrate on which to attach and feed (Robson et al. 2008, Raadik 2018, Shipp et al. 2018).
- Connectivity among refuges may change as drought progresses leading to the loss and isolation of refuges. There may be tipping points at which extent of isolation results in areas changing from refuges to areas where species persist for some time but fail to contribute to future cohorts (i.e. species sinks).
- Persistence of species in refuges and ability to move into refuges depend on resilience and resistance traits. Information of these traits is greater for fish species than other species – for specific traits and habitat needs see Crook et al. (2010), McNeil et al. (2013a), (McNeil et al. 2013b) Robson et al. (2008) and Chessman (2013). Broad information is available in the DIC plans (e.g. CCMA (2007),NECMA (2007) and WGCMA (2007))
- General recognition that refuge requirements will vary depending on the life-stages of organisms (i.e. terrestrial adult vs aquatic larvae in invertebrates); however, empirical studies are lacking for many taxa.

Tools exist for identifying, classifying and mapping refuges at landscape scales, but we generally lack the ability to predict changes in refuge status

- A number of frameworks for identifying, classifying and mapping refuges already exist, with the following included among the reviewed literature:
    - Robson et al. (2008) – provides a framework for defining refuges, focussing on target species, with a case study example.
    - Bond (2007) – Provides and overview of the steps in identifying and mapping refuges.
    - Raadik (2018) – Includes methods for assessing refuge condition, primarily for fish.
    - Raadik et al. (2017) – Provides a method for locating groundwater dependant ecosystems.

    - McNeil et al. (2013b) – conceptual framework for assessing drought impacts on fish species
- Lacking ability to predict changes in refuge status over time – i.e. loss of refuges as drought progresses/intensifies (Lobegeiger 2010).

Maintaining or restoring hydrological and biological connectivity is important for long term management of species

- Hydrological and biological connectivity was recognised as important for maintaining long term populations and featured heavily among the lists of threats and drivers.
- Restoring connectivity among populations was a management recommendation in 8 documents, including conceptual, empirical, review and strategy type documents.
- Management focus tends to be on hydrological or structural connectivity with the assumption that organisms will move if these pathways are available. In some cases this assumption may be warranted, such as movements of fish following the removal of physical barriers. In other cases this assumption may be unjustified, for instance where other factors, such as lack of appropriate habitat, limit movement into otherwise accessible areas or for species that are sedentary.
- Very little knowledge on biological connectivity or dispersal of organisms out of and among refuges. Most knowledge is on fish species (e.g. Woods et al. (2010)), and even then, knowledge gaps exist with regards to the levels of connectivity that are required to maintain long-term population persistence.
- It should not be assumed that species for which we have good information provide a proxy for other species.
- It is only recently that genetics has been able to provide insights into connectivity at short time scales.

Key threats and drivers impacting biota

Threats and drivers could be summarised into 9 categories (Figure 2). Most were articulated across the majority of documents, for instance habitat loss/degradation was mentioned in 25 of the 27 documents (Figure 3). However, recreational fishing pressure was mentioned in only 5 documents and these were generally strategic type documents. Here we list these threats and drivers in order of their relevance, within the literature, and thus their assumed importance.

In-stream habitat loss/ degradation is the most significant driver impacting biota

Impacts leading to the loss and/or degradation of habitat were identified in nearly all documents (25/27) and were the most often cited threats. Impacts included factors such as erosion, damage caused by stock, and removal of physical structure. They were mentioned in 100% of the strategy, conceptual, review and modelling documents, suggesting that there is good synergy between science and management in this area. Habitat loss was considered in only one of the empirical documents, although this may reflect the specific nature of these types of documents rather than a disregard for this major driver.

Declining water quality can intensify as droughts persist and acutely impacts biota

Declining water quality was regularly cited as a threat and, in particular, rising salinity and low dissolved oxygen concentrations. Many of the management actions within the strategic documents were designed to mitigate poor water quality. For instance, flows were generally recommended for the purpose of maintaining water quality.

Groundwater inflows were mentioned as a source of water providing water permanence, but can become an issue where saline groundwater inputs increase the salinity of refuge water (Alluvium 2018, Shipp et al. 2018).

It was also recognised that increased input of sediment due to catchment erosion can lead to significant infilling, which can directly result in loss of habitat (Raadik 2018). Activities such as stock access and removal of riparian vegetation can exacerbate sedimentation (McNeil et al. 2013b).

Loss of riparian zones reduces habitat, shading, and capacity to buffer surrounding landscape impacts

Impacts to riparian zones were mentioned as important drivers of ecosystems within the strategy, review, and conceptual documents, and in one of the empirical documents. None of the modelling documents mentioned riparian zones. Riparian zones create buffers between terrestrial and aquatic systems, capturing runoff, reducing bank erosion and providing shade, as well as providing habitat structure for many water dependent organisms (Robson et al. 2008).

Hydrological impacts, such as reduction in wetted area and flow, have effects on development and dispersal of organisms as well as amount of habitat available to organisms

Hydrological impacts include reduction in wetted area and depth, loss of flow, loss of riffle habitats and shifts in flow regimes. The most noticeable effect of drought is decreases in water area and depth, which directly reduce refuge habitat availability. Declining water levels can have dramatic effects on refuge suitability for fauna and flora. Fish movement may change in response to water level (GBCMA 2007) and declines in water level were noted as the most likely cause of two major eel death events, presumably due to increases in salinity (GHCMA 2007). Cease to flow events directly impact on organisms that require flow, such as riffle inhabiting invertebrates, and can have detrimental effects on animals that require flow for cues such as spawning (McNeil et al. 2013a). Similarly, shifts in flow regime can impact on the timing of ecosystem processes, such as production and energy fluxes, and life-history events in many organisms (Robson et al. 2008, McNeil et al. 2013b).

Anthropogenic hydrological impacts, such as pumping, reduce water levels and habitat availability

Anthropogenic hydrological impacts are changes in hydrology directly relating to human activity, such as water abstraction. These impacts featured heavily across all document types, but were only considered in one of the four empirical documents. The abstraction of water was regularly cited as a threat in the DIC plans. and needs to be managed closely during drought periods.

Loss of hydrological and biological connectivity isolates populations, impacting post-drought recovery

Loss of connectivity was considered in both a hydrological and biotic sense. Hydrologically, loss of connectivity can be caused by the installation of barriers, occurrence of cease to flow events, and the disappearance of lateral connections between floodplains and river channels. Hydrological connectivity is important for transporting nutrients and organic matter through systems as well as providing passage for organisms, and thus biological connectivity. Reducing or severing the passage of individuals among populations leads to reduction in local gene pools and population sizes, which in turn increases the risks of local extinctions and decreases the sources for recolonization and population growth post-drought (Bond et al. 2008). Increases in distances between habitats exacerbate these effects and, at some point, what were once refuges may become species “sinks” as conditions within the refuges decline beyond species' tolerances. These sinks are areas that species move into but ultimately die off in without contributing to future cohorts. Species sinks reduce the available gene pool available for subsequent generations.

Invasive species compete with and/or prey on native species

Invasive species were mentioned as a threat in 14 documents. Nearly all of the strategy and all of the conceptual type documents mentioned invasive species as threats. Primarily invasive species were considered to compete with or predate on native wildlife. The effects of these interactions are exacerbated under drought conditions due to increased densities of fauna within smaller areas of available habitat (Robson et al. 2008, Raadik 2018).

Biological interactions, such as predation, competition and the spread of disease, increase as organisms move into smaller habitat areas

Biological interactions included interactions among species such as increased predation, competition and disease, and reduction in prey availability. These interactions were mentioned in 21 of the documents as drivers or threats. Predation was predominantly mentioned in relation to predatory native and non-native fishes as well as foxes, cats, birds and pigs (GHCMA 2007, Robson et al. 2008). Management actions tended to focus solely on reducing predation, probably because it is difficult to manage other biological interactions.

Recreational fishing pressure may have increased effects during drought

Fishing pressure was considered as an impact in only the review and strategy documents, where it was considered that fishing effects may intensify during drought because fish are vulnerable due to their high densities in limited refuges. The lack of mention of fishing pressure within the remaining document types indicates that this threat was either not considered important or that its potential effects are inadequately characterised.

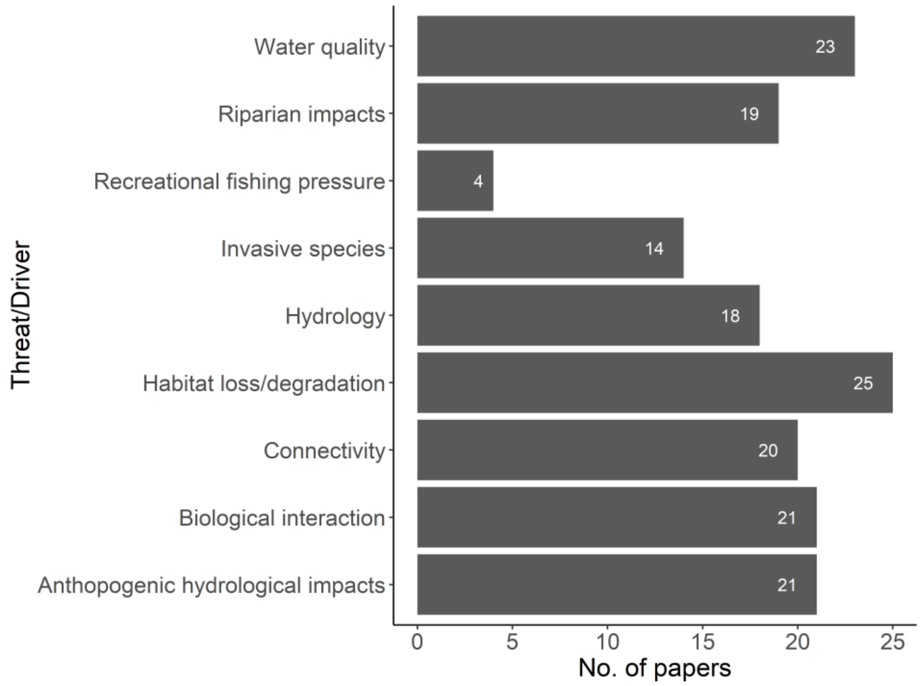

Figure 2 Key threats and drivers impacting biota, as articulated in the literature

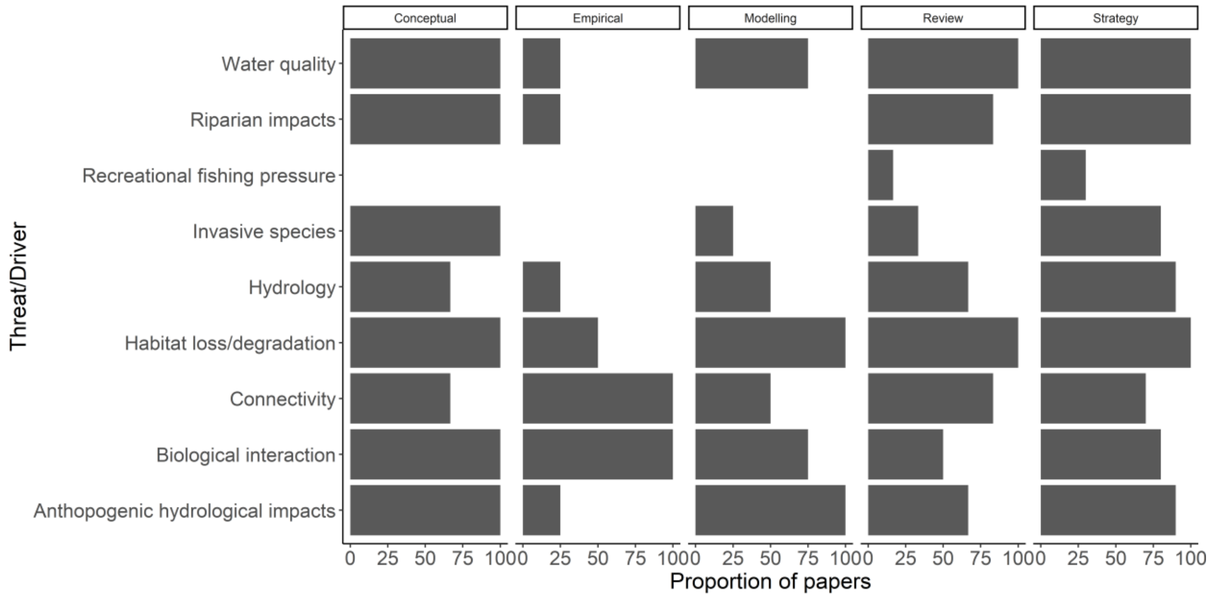

Figure 3 Key threats and drivers impacting biota, as articulated in the literature, grouped by document type

Strategies for protecting local refuges in different systems

There were many strategies for managing refuges mentioned in the literature. They could be categorised as either those that related directly to hydrological management and those that did not. The need for pro-active management, including preparing for drought during inter-drought periods, was emphasized among the review and conceptual documents, with the argument being that managing habitat for robust ecosystems during non-drought phases offers the best chance at resilience through the drought and recovery post drought (Bond et al. 2008, Crook et al. 2010, McNeil et al. 2013b).

Hydrological related recommendations

Flow management can be used to maintain flow dependant ecosystems

Managing flow was the action most often mentioned (Figure 4) and featured heavily across all literature types, being mentioned in all empirical and conceptual articles (Figure 5). The use of flow for maintaining hydrological and biotic connectivity was recommended by Bond et al. (2008) and Dexter et al. (2013). The use of environmental water made the bulk of strategies and was often accompanied by flow recommendations for specific reaches – primarily in the DIC plans. Developing site-specific flow recommendations, under different scenarios, is critical for effective management and delivering effective flows requires informed consideration of specific site characteristics. It was noted in some of the DIC plans that, as a consequence of the drought, environmental water was limited or unavailable (GHCMA 2007, WCMA 2007). In unregulated systems flow management actions are more limited. Regulating local pumping and ground water inputs may be used to manage unregulated systems, and non-direct actions such as reducing evaporative loss through shading may benefit.

Alternative water sources can be used to maintain refuge pools and wetlands

Off-stream sources of water were considered as possible actions in 11 papers. These included recommendations to use water from nearby lakes or urban stormwater sources (CCMA 2007); developing Infrastructure, such as pipes, to deliver water (Alluvium 2018, Shipp et al. 2018); and trucking in emergency water to maintain critical pools. It is important to ensure that areas identified as important refuges are not used as alternate water sources (McMaster et al. 2008).

Water extraction needs to be managed closely during drought and may include placing limits or bans on abstraction

The management of water extraction, including minimum passing flow requirements and placing or enforcing limits and bans on take, featured heavily in the literature. Of primary concern was the pumping of water from refuge pools and from ground water. The role of farm dams in their capacity to withhold water from river systems as well as provide possible anthropogenic refuges was also regularly mentioned. McMaster et al. (2008) mention the importance of ensuring that off-stream water is not pumped from refuge pools.

Monitoring flow/water level is critical for assessing refuge trajectories and can be implemented better with landholder engagement and support.

Monitoring flow was recommended in only 3 papers and primarily as a measurement taken along with other water quality parameters. However, Alluvium (2018), recommended monitoring of water level refuges as a specific tool for assessing the success of an engagement program involving landholder support for watering drought refuges. Infrastructure for monitoring water level is generally abundant in regulated systems but lacking in unregulated and off stream systems.

Water level may need to be managed to maintain water quality and the extent of available habitat

One research article, Dexter et al. (2013), recommended actively managing the persistence of water in refuge pools. Among the remaining literature, only GHCMA (2007) included water level control as an actionable item. Receding water levels are likely to directly impact water dependant biota such as fish through loss of water quality and extent, and indirectly effect biota such as birds by reducing available breeding habitat. However, receding water levels also provide temporary feeding opportunities for wading birds. Landholder engagement can be used to better manage refuge water permanence and level. See Lobegeiger (2010) for an approach to modelling refuge pool water level and persistence.

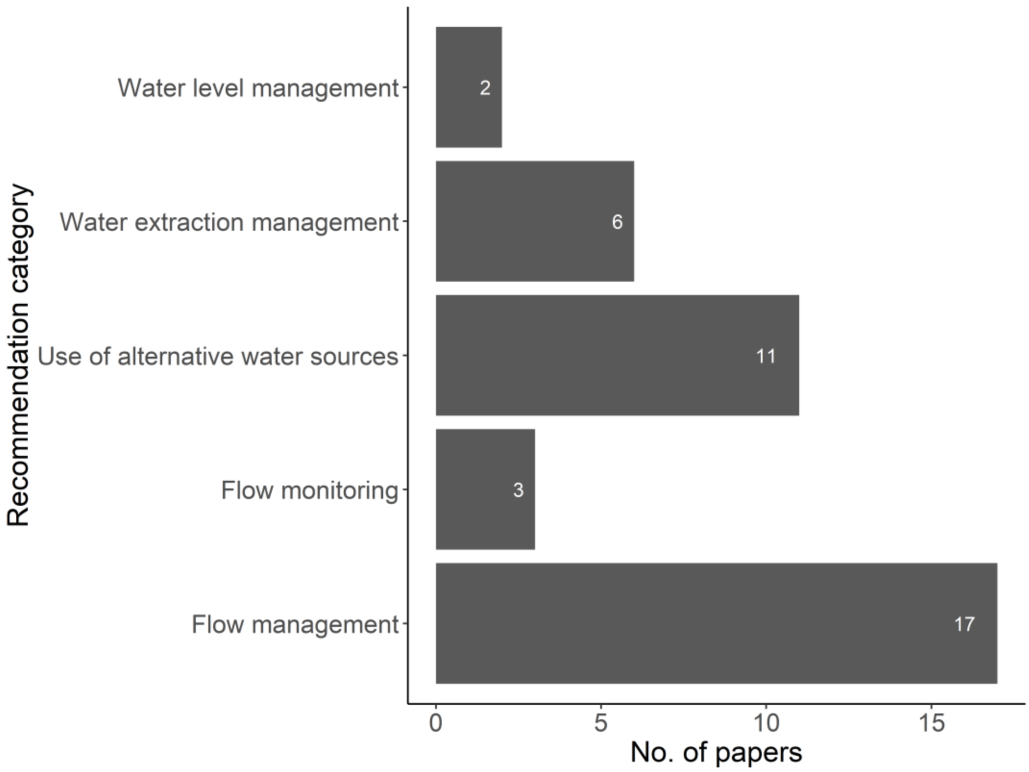

Figure 4 Hydrological related recommendations made in the literature

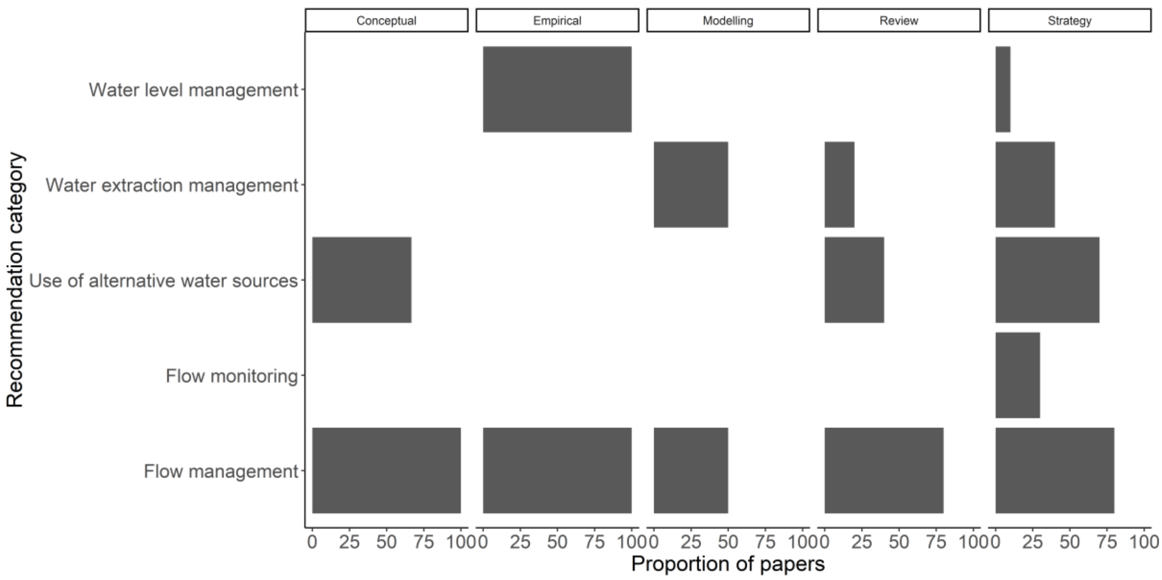

Figure 5 Hydrological related recommendations made in the literature grouped by literature type

Non-hydrological related management actions

Protect and enhance riparian and in-stream habitat to provide structure for biota

Protection and enhancement of in-stream and riparian habitat was the most cited management action, occurring in 21 documents. Included in this category were actions such as habitat restoration, stock management, fencing, re-snagging, willow management, and stream bank stabilisation, among others. Habitat protection was recommended across all document types, and in 100% of the strategy documents. The DIC plans regularly mention fencing of refuges and riparian zones, creating stock containment areas, erosion management, weed control and revegetation. A number suggest the creation of artificial habitat or returning natural structure back into refuges (CCMA 2007, EGCMA 2007, WGCMA 2007). Non-DICP strategy documents include site specific revegetation plans for the Wimmera River (Alluvium 2018, Shipp et al. 2018).

Identify, categorise and map refuges for management across landscapes

The identification, characterisation and mapping of refuges was mentioned across document types and a state-wide program for mapping refuges was among the key knowledge gaps. As mentioned above, there are several tools available for achieving this, but as yet tools that can project refuge persistence over various time horizons are lacking. Identifying refuges is a task that can be implemented proactively and, with current data sources, modelling refuge persistence should be possible. As a rule of thumb, loss rates of somewhere between around 10mm per day of depth can be expected to be lost from pools not maintained by groundwater inflows (Lobegeiger 2010).

Monitor biota and water quality to assess the effectiveness of refuge management, and have clear triggers for action

Monitoring tended to include surveying fauna and flora as well as water quality wherever it occurred in the documents. Strategic documents especially mentioned monitoring as a management action and the appropriateness was backed up by the review and conceptual literature. Without monitoring, negative trajectories of biota can go unnoticed until too late and the effectiveness of management actions cannot be measured. Monitoring needs to be undertaken before and after drought (e.g. Morrongiello et al. 2006), not just during drought, in order to assess the recovery of species. Of concern is that while it is recommended in the review and conceptual documents that triggers for intervention need to be designated, none of the documents provide specific triggers. Strategy documents either do not mention trigger levels or mention them in unspecified terms. For instance, an action in GHCMA (2007) is to monitor fish diversity, abundance and distribution and states that this information would be used as triggers for emergency response, without stating what such triggers are.

Have policies and guidelines in place that include clear directions for management

There are quite a few policies and guidelines in place or that were being developed for managing drought. However, this was an area that also featured heavily among the knowledge gaps within documents. In particular, standardised survey methods and specific, detailed drought management plans for fauna and flora are required. For some species, national recovery plans for threatened species may help inform more specific drought management plans, although the level of detail in recovery plans tends to be insufficient for the implementation of specific drought-related actions. Clear implementation dates and time frames over which actions are to be performed need to be established.

Some species will need specific management actions, such as translocating populations

Species management included actions that had specific effects on species, including translocation and reintroductions, restoring population processes, maintaining life cycle processes and the removal of pest species. Species management featured heavily in the strategy and conceptual documents but not at all in the empirical studies. Recommendations in this area were mostly broad, e.g. control fish biomass, rather than specific strategies for managing particular species. Robson et al. (2008) contains some information on optimal habitat for *Lectrides varians* (caddisfly), Sclerocyphon sp. (beetle), *Galaxias olidus* (fish), that includes consideration of the life cycles of the organisms (e.g. terrestrial adult and aquatic larval forms of insects). The DIC plans included some mention of management for particular species, predominantly fish such as Yarra Pygmy Perch (CCMA 2007), Australian Grayling (EGCMA 2007), and River Blackfish (EGCMA 2007), and the spiny crayfish (GHCMA 2007). Translocating and reintroducing species was mentioned as management action that may be required but generally no discussion was given as to whether these are effective measures. These are perhaps best used as a last resort and careful consideration needs to be given towards the effects on population genetics.

Undertake community and stakeholder engagement to increase awareness of impacts and management actions

Communication and engagement was an important aspect of the strategy documents and was mentioned as a management action in some of the review and conceptual documents. Engagement included increasing awareness of human impacts, such as fishing pressure, and providing appreciation of planned management activities. Effective engagement was considered critical for public acceptance of drought-related management interventions.

Restore connectivity among refuges to promote faster post-drought recovery

Restoring functional connectivity was considered a major aim of refuge management, given that refuges serve to provide population sources to the greater landscape post-drought. Restoring connectivity pathways is an action that should be considered before the impact of drought and is likely achieved through other management actions such as restoration of riparian zones, in-stream habitat and hydrological connectivity and the removal of barriers.

Filling in knowledge gaps by undertaking targeted research

There was a clear need for further research articulated in the conceptual, empirical and review documents but research was not present in the strategy documents. An assessment of the major research knowledge gaps related to drought effects and management are provided below.

Engage with landholders for better management of refuges on private property

Only one strategy document mentioned landholder engagement and this was in specific relation to engaging landholders in managing refuge water levels. This is an important yet overlooked management activity, as many refuges are likely to reside on private property and having landholders actively participating in the management of refuges on their land offers to increase engagement with and appreciation of natural resources by land owners, greater ability to monitor refuge status and to monitor more refuges, and in return savings on the costs associated with managing and monitoring refuges.

Links to other water management frameworks

- Frameworks for the delivery of environmental flows (e.g. Environmental Water Management Plans, FLOWS studies, VEWH's Seasonal Watering Plans) can feed directly into refuge management
- Data from biological assessments, such as the Southern Rivers Audit, can provide knowledge on species distributions and could be used for developing more sophisticated models for prioritising refuges (e.g. zonation).
- Some links already articulated in DIC plans, such as:
    - Stock containment areas program
    - Estuary mouth opening protocol
    - Emergency water supply points and water carting protocols
    - Water watch
    - Fish death response protocols
    - Fire recovery management plans
    - Water supply and demand strategies
    - Drought employment program
- Victorian Water Programs Investment Framework aimed at waterway restoration could explicitly consider extreme hydrological events (both drought and floods) and by necessity aquatic refugia, during the planning, implementation and evaluation phases.

What are the knowledge gaps?

Knowledge gaps articulated in the literature

Hydrological knowledge

- Require a better understanding of low flow hydrology, especially in smaller unregulated streams, and how climate and land use changes will affect hydrological regimes.
- Lack of knowledge on the spatial and temporal dynamics of refuges, including the location, number, quality and persistence of refuges.
- What are the hydrological effects of headwater dams, groundwater extraction, farm dams and localised pumping?
- Limited knowledge on the impacts of drought on water-dependant non-riverine wetlands, groundwater and terrestrial ecosystems.

Ecological knowledge

- Lacking knowledge on the resilience and resistance of biota (particularly non-fish) to drought and other disturbances.
- Very little knowledge of life history traits, habitat requirements and distributions for many non-fish biota. Information on life history traits and ecology is especially limited for aquatic invertebrates, frogs and reptiles (Robson et al. 2008, Robson et al. 2011)
- Little empirical knowledge on the recovery of species after drought and, thus, little knowledge on the effectiveness of areas recognised as refuges.
- Lack of understanding on the effect of drought on aquatic food webs.
- Paucity of knowledge of ecological cues for life history events, such as spawning and germination, for many taxa; although knowledge around fish is strong. Similar lack of knowledge on critical thresholds of species to hydrological, chemical, and water quality factors.
- The ecological value of anthropogenic habitats such as farm dams is relatively unknown.
- We lack an understanding of dispersal pathways and connectivity requirements for the long-term persistence of populations for many species.

Research, data, tools and databases

- Need for a coordinated and well-resourced research programme on droughts and their impacts. This includes the need for greater temporal replication of longitudinal studies and validation of models. Studies that can separate the effects of drought from other variables are required.

- More and better-quality stream flow data, especially for small unregulated steams.
- Sophisticated and more accurate tools for predicting impending future droughts that will aid in making pre-emptive decisions around on-ground management (Crook et al. 2010)
- Need for ground-truthed habitat suitability models to guide management responses
- Need for high resolution (colour and thermal infra-red), aerial photography across catchments that can be used to identify persisting pools across entire stream networks during drought periods
- Need for a publicly available central repository and database for Victorian groundwater dependant ecosystem investigations.

Management plans and frameworks

- Need for clear guidelines and policies for refuge management (Raadik et al. 2017).
- Need for a clear index of drought severity, such as the Palmer Drought Severity Index used in the USA, which would enable better comparisons of drought severity among different places and times (Bond et al. 2008).
- Need for management tools for restoring dispersal pathways of biota among habitats (Hale 2018).
- Standardised methods for faunal surveys (Elith et al. 2017).
- Drought management plans that are specific and detailed (Crook et al. 2010).
- Plans with implementation dates and time frames over which actions are to be performed (McMaster et al. 2008).
- Need for a state-wide program for identifying and characterising refuges (Raadik et al. 2017).

Overlooked knowledge gaps

- Lack the ability to forecast the presence of refuges over various time horizons.
- The extent to which landholders already manage refuge sites and what capacity exists to further engage landholders.
- Potential use of state-wide data on incidents on fish kills, algal blooms, black water events – these phenomena often coincide with drought (during or after) and may provide insights when interrogated collectively?
- Genetics -population structure of species
- Stress testing to identify what extent of impact we can manage

Conclusions

Refuges maintain populations through drought periods such that they can contribute to post-drought recovery and recolonization. The characteristics that make a refuge of high-quality vary depending on the organisms that inhabit it, or are intended to inhabit it. However, the most important aspects of refuges are sufficient area with suitable habitat that provides protection from insufficient water quality and excessive competitive and predator-prey interactions. Refuges do not exist in isolation and effective management of refuges requires consideration of their spatial distributions, persistence, and linkages with the surrounding landscape and other refuge areas. There are several tools already available for mapping and categorising refuge habitats and for predicting drought impacts on some taxa (predominantly fish). However, we currently lack the ability to forecast the presence of refuges across landscapes over various time horizons.

Drought management planning needs to be done throughout all phases of climatic cycle. Management should be proactive; for instance, identifying, categorising and prioritising refuge areas for intervention before the onset of drought. We currently perform poorly in this regard, with targeted drought management interventions occurring only well into drought cycles. Moreover, while populations are managed and monitored through drought periods, their recovery post-drought is often not assessed and thus we have little knowledge on the effectiveness of areas recognised as refuges.

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Appendix 1

Table A1 Bibliography of documents used for assessment

Reference	Title	Description and use to management
Alluvium (2018)	Wimmera River drought refuge management strategy	• Strategy document • Assessment of drought refuge areas in the Wimmera River • Provides strategies for drought management specific to refuges in the Wimmera River • **Example of how drought refuges may be assessed**
Bond (2007)	Identifying, mapping and managing drought refuges: a brief summary of issues and approaches. eWater Technical Report	• Review • **Brief overview of the steps involved in identifying, mapping and managing drought refuges** • Provides list of dis/advantages for different mapping approaches
Bond et al. (2008)	The impacts of drought on freshwater ecosystems: an Australian perspective	• Review • Overview of drought impacts on streams and rivers • **Provides management principles to be applied pre, during and post drought**
Bond et al. (2015)	Fish population persistence in hydrologically variable landscapes	• Modelling document • Provides spatially explicit population model for golden perch • Forecasts scenarios under increased aridity, drought frequency, and water extraction. • **Example of modelling approach**
Boulton (2003)	Parallels and contrasts in the effects of drought on stream macroinvertebrate assemblages	• Review • Provides conceptual overview of drought • Gives **examples of drought effects on macroinvertebrates in Australian** and English streams
Chessman (2013)	Identifying species at risk from climate change: traits predict the drought vulnerability of freshwater fishes	• Modelling document • Assesses how abundance and occurrence of MDB fish species correlates with dietary, life history and physiological traits • **Provides drought vulnerability ranking for MDB fishes**

		• **Example of methods for assessing drought tolerance**
CCMA (2007)	Corangamite CMA Dry inflow contingency plan for 2007-2008	• Strategy document • Example of planning drought management actions
Crook et al. (2010)	Using biological information to support proactive strategies for managing freshwater fish during drought	• Conceptual • **Provides conceptual framework to guide management of fish populations during drought** • Investigated resistance and resilience in MDB fish species • **Provides information on likely impact of drought on MDB fish species**
Dexter et al. (2013)	Dispersal and recruitment of fish in an intermittent stream network	
EGCMA (2007)	Dry Inflow Contingency Plan for the East Gippsland Region 2007-2008	• Strategy document • **Example of planning drought management actions**
Elith et al. (2017)	Understanding the impacts of drought on native fish populations in Victorian rivers: draft report	• Modelling • Examined a suite of drought-related environmental variables for modelling the distributions and abundances of fish species in Victoria • Used models for forecasting prolonged drought effects • **Example of approach for modelling impacts of drought**
GBCMA (2007)	Goulburn Broken Catchment Management Authority Dry Inflow Contingency Plan 2007-2008	• Strategy document • **Example of planning drought management actions**
GHCMA (2007)	Glenelg Hopkins Dry Inflow Contingency Plan 2007-2008	• Strategy document • **Example of planning drought management actions**
Hale (2018)	Drought refuges in Victorian aquatic ecosystems	• Review • Provides an overview of drought impacts and refuges in Victoria • **Gives key points for managing refuges** • **Some broad information on refuge types**
Lyon et al. (2019)	Increased population size of fish in a lowland river following restoration of structural habitat	• Empirical • Tests the effects of re-snagging on fish abundances • **Provides evidence for the use of returning large woody habitat to increase population sizes**
McMaster et al. (2008)	Review of the 2007/2008 CMA Dry Inflow Contingency Plans	• Review • Assesses the utility of the DIC plans

		• **Provides information on managing for droughts including further actions not mentioned in the DICPs**.
McNeil et al. (2013a)	Resistance and Resilience of Murray-Darling Basin Fishes to Drought Disturbance	• Review • Overview of the impacts of drought on MDB fish assemblages • **Synthesises current life-history and tolerance threshold data of MDB fish species** • **Provides conceptual frameworks for modelling drought impacts and responses of native fish**
McNeil et al. (2013b)	The protection of drought refuges for native fish in the Murray-Darling Basin. A report to the Murray-Darling Basin Authority.	• Conceptual • Overview of the current status of refuge management in the MDB • **Provides guidelines for identifying, prioritising and protecting drought refuges**
Morrongiello et al. (2006)	Impacts of drought on fish in Victorian rivers and streams	
NECMA (2007)	North East Catchment Management Authority Dry Inflow Contingency Plan 2007-2008	• Strategy document • **Example of planning drought management actions**
Raadik (2018)	Assessing condition and value of potential aquatic refuges in small, unregulated Victorian streams: a method.	• Modelling document • **Provides status of fish species in Victoria and the potential impact of drought on species and across geographical regions** • **Example of modelling approach for predicting the effects of drought and other environmental changes**
Raadik et al. (2017)	Locating potential aquatic refuges in small, unregulated Victorian streams: a pilot study.	• Empirical • **Provides methods for locating and mapping ground water dependent ecosystems**
Robson et al. (2008)	Identification and management of refuges for aquatic organisms, Waterlines report, National Water Commission	• Conceptual • Overview of drought impacts • **Provides conceptual framework for classifying refuges, with examples and application of a case study**
Shipp et al. (2018)	Maintaining drought refuge pools in the Wimmera River.	• Strategy document • **Example of planning drought management actions**
WCMA (2007)	Wimmera Catchment Management Authority Dry Inflow Contingency Plan 2007-2008	• Strategy document • **Example of planning drought management actions**

WGCMA (2007)	West Gippsland Catchment Management Authority Dry Inflow Contingency Plan 2007-2008	• Strategy document • **Example of planning drought management actions**
Woods et al. (2010)	Contemporary and historical patterns of connectivity among populations of an inland river fish species inferred from genetics and otolith chemistry	• Empirical • Assessed current and historical patterns in connectivity in Australian smelt, inferred from otoliths and genetics • **Example of method for measuring connectivity among species' populations.**

Table A2 Extended bibliography of documents not used for assessment

Reference	Title	Description
Bond et al. (2012)	The influence of antecedent flow conditions, long-term flow regime characteristics and landscape context on occurrence patterns of macroinvertebrate families in Victorian rivers. Report to the National Water Commission.	• Modelling study investigating the distribution patterns of macroinvertebrate assemblages in Victoria in relation to antecedent hydrological conditions • **Example of approach to modelling macroinvertebrate responses to drought impacts**
Bond et al. (2011)	Modelling the Impacts of Climate Variability and Change on Fish to Inform NRM Investment Strategies (DSE Refugia Project)	• Modelling document providing contextual information on where the persistence of freshwater biota is at least or most risk from extended drought • **Example of approach to modelling and forecasting drought impacts on fish assemblages**
Chester and Robson (2011)	Drought refuges, spatial scale and recolonisation by invertebrates in non-perennial streams	• Empirical study investigating where in the landscape recolonising organisms come from and what traits (resistance/resilience) drive effective recolonization • **Example of how post-drought recolonization may be assessed** • Focus on streams in the Grampians National Park, Victoria. • Post drought colonisation was driven by resilience traits • Colonisation across the landscape came from perennially flowing reaches and pools rather than from local refuges • Management should be at the whole draining network scale rather than single waterways • Management focus should be on perennial pools and reaches.

Chester and Robson (2013)	Anthropogenic refuges for freshwater biodiversity: their ecological characteristics and management	• Review • Explores the potential use of freshwater anthropogenic waterbodies as refuge habitats • **Provides information on the characteristics of anthropogenic waterbodies that are important for biodiversity resilience**
Hamilton et al. (2005)	Persistence of aquatic refugia between flow pulses in a dryland river system (Cooper Creek, Australia)	• Empirical study of the fractional water loss of refuge pools • **Example of method for predicting/forecasting permanence of refuge pools**
Lake et al. (2008)	An appraisal of studies on the impacts of drought on aquatic ecosystems: knowledge gaps and future directions	• Short review of literature on drought impacts • **Identifies key knowledge gaps and provides future direction for drought research**
Lennox et al. (2019)	Toward a better understanding of freshwater fish responses to an increasingly drought-stricken world	• Review and conceptualisation of how droughts effect fish species • **Describes major drivers of drought effects and what refuges for fish look like**
Magoulick and Kobza (2003)	The role of refugia for fishes during drought: a review and synthesis	• Review • **Provides information on what fish refuge are**
Rayner et al. (2009)	Small environmental flows, drought and the role of refugia for freshwater fish in the Macquarie Marshes, arid Australia	• Empirical study investigating fish communities in the Macquarie Marshes. • **Provides a conceptual model of fish use of refugia** • **Provides information on how small flows can be delivered to meet ecological needs**
Robson et al. (2011)	Why life history information matters: drought refuges and macroinvertebrate persistence in non-perennial streams subject to a drier climate	• Review • Evaluates utility of existing ecological concepts for predicting drought refuges role in sustaining biodiversity • Focus is on non-perennial streams • **Provides suggestions on traits that may determine invertebrate species' resistance or resilience.** • Limited knowledge of invertebrate life histories restricts the use of ecological concepts for predictive purposes

Appendix 2

Table A3 Descriptions of the variables considered for synthesis

Variable	Description	Classes	Description of class
Type of study	Categorises literature into 1 of five classes	Conceptual	provides conceptualisations on drought effects and biotic interactions. Conceptual literature do not contain any primary data
		Empirical	uses primary data to test hypotheses or characterise/locate landscape features
		Modelling	may use primary data but results are not tested, primarily concerned with
		Review	provides overview information on biota and/or the effects of drought
		Strategy	contains management plans, frameworks or assessments
Geographic area	Describes the region to which the literature relates		
Spatial scale habitat	Describes the spatial area over which the literature is focused	Reach	Focus is on a reach, or reaches, within a river
		River	Focus is on a river
		Not specified	No spatial scale is provided
		Catchment	Covers a catchment or catchments
		State	Relevant to whole of Victoria
		MDB	Relevant to whole of the Murray-Darling Basin
Temporal scale	Describes the temporal extent over which the literature can be applied	Snap shot	Provides information relating to a period in time
		One-year future	Concerned with the year following the paper
		Years projected future	Concerned with multiple years following the paper
		Decades projected future	Concerned with the decades following the paper

		A temporal	studies that utilise historic data to describe the present state without consideration of future states
Focus	The aspect of the ecology that the literature focusses on. Can include multiple classes	Habitat	Primarily concerned with habitat - includes descriptions of habitat for biota
		Species	Primarily concerned with taxa as individual management units (i.e. birds)
		Population	Considers populations of a taxon or taxa
		Community	Considers biotic communities/ species assemblages
		Traits	Concerned with traits of organisms rather than taxa
Single vs multiple species	Whether a single taxa or multiple taxa are considered	Single	
		Multiple	
Describes quality and types of refuge habitats	Does the articles describe some element of refuge quality and type, includes articles that describe/document actual refuge habitat or that describe refuge habitat types for biota	Yes	
		No	
Provides quantity of refuge habitats	Does the article provide a count of refuge habitat	Yes	
		No	
Biotic groups (fauna) considered	What animal taxa area considered		
Life history stage	What life stages are considered		
Biotic groups (flora) considered	What plant taxa are considered		
Threats and drivers articulated	Threats and drivers that were articulated grouped into 9 categories	Connectivity	Issues relating to connectivity among populations
		Water quality	Water quality threats such as salinisation, oxygen depletion and erosion - includes effects of stock access
		Invasive species	Impacts from introduced species
		Recreational fishing pressure	Impacts from recreational fishing pressure
		Hydrology	Non-anthropological hydrological impacts such as cease to flow events
		Riparian impacts	Impacts to riparian zones - includes effects of stock access

		Anthropogenic hydrological impacts	Hydrological impacts from anthropogenic sources such as water abstraction
		Biological interaction	Interactions among species such as predation, competition and disease
		Habitat loss/degradation	Impacts on in-stream habitat - includes effects of stock access
Existing management interventions	Interventions that are currently implemented grouped into 12 categories	environmental water	Use of environmental water
		efficiency improvements	Improvements to infrastructure such as pipes
		not applicable	No interventions mentioned or not applicable
		water restrictions	restrictions on domestic water use and pumping
		EEMSS for estuary mouth opening	Artificial estuary mouth opening
		restoration works	Habitat restoration, such as fencing, revegetating and re-snagging
		emergency water supply points	Use of off stream water supply points
		stock containment	Fencing of stock
		fire rehabilitation	Post-fire habitat rehabilitation programs
		irrigation restrictions	Restrictions on the use of irrigation water
		water quality monitoring	Monitoring water quality
		targeted species and population management	Management of species or populations
Recommends undertaking actions for different phases of the drought/inter-drought cycle	Does the article recommend that actions should be undertaken in various phases of the drought, including inter-drought cycles.	Yes	Includes actions that are not explicitly stated as inter-drought but could be implemented as such
		No	
Non-flow related actions provided	Actions that are recommended, which are not related to flow	Riparian/in-stream habitat protection/enhancement	Actions that protect (e.g. fencing) or enhance (e.g. re-snagging) riparian and instream habitat
		Development/review of policy/guidelines	Actions that result in the formation or update of management tools, including methods and guidelines
		stakeholder engagement	Actions that engage stakeholders such as landowners
		Connectivity restoration	Actions that result in restoring biotic and hydrological connectivity
		Education	Actions that involve education

		Hydrology restoration	Actions that involve manipulating hydrological regimes
		Monitoring	Monitoring fauna, flora and water quality
		Species management	Actions involving the management of specific species
		Identifying, categorising and mapping refuges	Actions that involve locating and describing refuge areas
		Research	Recommendations for further research
Provides management guidance material	What material does the article produce that can be useful to managers	Management/conceptual frameworks	Provides frameworks for undertaking activities or for conceptualising issues
		Models	Provides modelling approaches to issues
		Explicit site-based guidance	Provides guidance on specific sites
		Summaries inc. drought/biological/impacts	Reviews of the literature
		Biotic interactions	Provides insights into biotic interactions from empirical research
		Linkages between science and management	Discusses how management issues can be linked to scientific research
Flow related recommendations provided	Recommended actions that related to flow	Flow management	Manipulation of flows - includes the use of environmental water
		Use of alternative water sources	Use of off stream water supplies
		Water extraction management	Managing extraction of water, such as pumping
		Flow monitoring	Monitoring of flows
		Water level management	Managing water levels in refuge pools, without flows
		Research flow options	Research into flow regimes
Knowldege gaps articulated	What knowledge gaps are mentioned	Ecological knowledge	Knowledge involving taxa and their responses to environmental cues
		Management plans/frameworks	Need for the creation or review of management tools
		Research, data, tools, databases, etc	Need form more data and research tools, such as databases
		Hydrological knowledge	Knowledge of hydrological regimes