Prioritising fish research for flow management in the Murray-Darling Basin

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Authorship

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Photo credits

Wetland flooding in the Macquarie marshes (NSW) (Photo; J. Koehn), Murray hardyhead (Photo: G. Schmida)

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Summary

Effective natural resource management requires timely knowledge exchange between researchers and managers to support evidence-based decision making. To achieve this, it is essential that we align research outputs so that they support the current needs of management, policy and on-ground actions. The lifecycles of fishes are inextricably linked to flow, and in the Murray-Darling Basin (MDB), one of the most regulated river systems in the world, flow management is considered fundamental to river health and the restoration of fish populations. This project aimed to identify knowledge gaps regarding the flow-related ecology of freshwater fish to direct research to better inform environmental water management. Our major objective was to provide an up-to-date synthesis of knowledge pertaining to the flow-related ecology of fishes, from both scientific and management perspectives, and to use this to guide fish research for the MDB-Environmental Water Knowledge and Research (EWKR) project. We reviewed the contemporary scientific knowledge base and documented the knowledge needs of the managers providing water for fish outcomes.

Published literature was reviewed by interrogating previous comprehensive literature reviews for the Murray Darling Basin (MDB) and searching the Web of Science. We engaged managers, initially via a questionnaire, to understand their knowledge and research needs and their constraints to achieving outcomes. The results from the questionnaire were used to guide a workshop of fish and flow managers and ecologists to further identify and refine the key knowledge gaps and research needs appropriate to the management of fish and environmental flows in the MDB.

The knowledge review highlighted significant gaps for most native species, with the most research to date undertaken on the larger-bodied fishes, particularly Golden Perch, Murray Cod and Black Bream, although most research on Black Bream has been conducted outside the MDB. There is significantly less knowledge concerning small-bodied species, many of which are considered threatened. Even for the large-bodied species there are significant knowledge gaps in relation to understanding the spatial and temporal boundaries of populations, and key population characteristics, including survival rates between subsequent life-stages (e.g. larvae to juveniles to adults). Other key knowledge gaps include links between habitat and fish condition and ultimately how these factors interact with flow. To date, there are relatively few papers directly reporting the outcomes of environmental watering. Acquired results from both successful and unsuccessful watering outcomes remains vital to build our knowledge base.

Research has largely been focused on a few key geographic locations in the southern MDB, hence there remains a need to test the transferability of results across regions, especially to the northern MDB. This is crucial for management of fish populations in the Northern basin where there is a distinct lack of fish research and limited held water, complicating their management via flow manipulation. There is a need for further research in the northern MDB and also estuarine reaches.

Study of MDB fishes has generally moved from single locations and points in time, to larger-scales with multiple sites, rivers and catchments over longer time frames. There is also a trend from single life-stage studies to incorporating multiple life-stages ultimately leading to a greater focus on understanding of population processes. This includes factors such as understanding the relative rates of growth and survival between different life-stages and the key factors limiting population growth. Management of water must also consider other key stressors that may limit the effectiveness of flow management (e.g. connectivity). Indeed, a holistic approach to fish rehabilitation that includes flows and other complementary measures (such as connectivity and habitat restoration) has long been advocated.

In summary, four key ecological knowledge gaps were derived from ecological knowledge review: 1) rates of survival and growth; 2) recruitment; identifying the environmental covariates/drivers of dynamics in growth and survival; 3) spatial and temporal scales of population processes; and most importantly, 4) the understanding of population dynamics (incorporating all life stages). These ecological knowledge gaps represent the broad themes that can guide the evolution of specific research concerning fish and environmental flows in the MDB.

There were considerable synergies between ecological knowledge gaps and manager's priority needs. Both ecologists and managers highlighted the importance of understanding the key processes that influence the dynamics of populations and the spatio-temporal scales over which these processes occur. The drivers of fish condition and growth were factors considered important as they can affect rates of survival. Integrated studies that consider the influence of flow on these key processes were considered the highest priority for research in the MDB.

Managers clearly stated their desire for robust, evidence-based information (from research and monitoring) and timely, relevant advice to inform policy that can readily be applied to management decisions. Ideally such advice and information needs to be delivered in a way that is meaningful to waterway managers and their methods for water delivery. In particular, managers often now focus on designing hydrographs that are trying to mimic important ecological components of a natural flow regime. They require ecological inputs to this aspect of their watering plans. Managers want ecologists to be prepared to "give things a go". This may be translated as - don't be afraid to experiment and give advice, even if you are not completely sure that you are right. By getting things wrong we can also learn. They also stressed that a proactive, collaborative approach to determining research priorities and developing water plans was key to effectively generating and utilising the knowledge that managers require.

The key knowledge gap of survival rates between life stages and the influence these have on population growth or sustainability relates to the number one priority from both managers and our knowledge review – understanding population dynamics and recruitment to adults. This indicates that a focus on fish recruitment is an appropriate focus for research, as there are significant gaps for all species. Our review has demonstrated that we have reasonable general ecological knowledge with regards to the life-stages of some key MDB fishes, particularly large-bodied species, but there remain significant gaps. Given the difficulties of studying rare and threatened species, however, it is strongly recommended that EWKR fish recruitment research be targeted at the larger-bodied native fishes that have been identified by managers as target species and that have life cycles that are responsive to flow. In this respect, both Golden and Silver Perch (also threatened, but in larger numbers in the Murray River) provide ideal candidates for research projects. While some information is available on their early life history from hatchery studies, there is little known about these vulnerable egg and larval life stages in the wild. The high mobility of these species also necessitates the inclusion of movements of all life stages and the influence of these on population demographics. Both species provide primary objectives for fish-flow managers and the rehabilitation of Silver Perch populations in the MDB is a high priority.

1. Introduction

Effective natural resource management requires knowledge exchange between researchers and managers to support evidence-based decision-making (Koehn et al. 2014a; Cvitanovic et al. 2015). Limited resources, short time frames and a lack of easy access, however, mean that the ecological knowledge used in management may be less than ideal. Under these constraints, there is a need to improve mechanisms to ensure the timely provision of the best available science and knowledge that is aligned with current needs of policy, management and subsequent on-ground management actions.

Fishes of the Murray-Darling Basin (MDB) are important due to their ecological, biodiversity, scientific, cultural and recreational values. Recreational fishing is a significant pastime, with 19% of Australians participating annually, and it provides substantial social and economic benefits to rural communities ($1.3 billion per annum; Ernst and Young 2011; Henry and Lyle 2003). MDB fish populations, however, have suffered substantial declines and, overall, are now estimated to be at only about 10% of pre-European levels (MDBC 2004), with many species considered threatened (Lintermans 2007). The alarmingly poor state of native fish populations in the MDB provides an important context for water management, including the need to focus on the restoration of fish populations rather than just maintenance of the current state (Koehn and Lintermans 2012).

Provision of environmental water is now a well-recognized component for the rehabilitation of MDB rivers and their fishes (Arthington and Pusey 2003, Arthington et al. 2010, Arthington 2012). The Basin Plan (MDBA 2010, 2011) establishes the importance of environmental watering for the conservation of MDB fishes (Koehn et al. 2014b). As water is the primary component of fish habitats, they are the biota considered under the Basin Plan that are most critically dependent on flow regimes to sustain their populations. The Basin Watering Strategy (BWS) (http://www.mdba.gov.au/sites/default/files/pubs/Final-BWS-Nov14_0816.pdf) that supports the Basin Plan identifies broad themes and objectives to be achieved through complementary strategies and plans developed at state and regional levels. The development of this wide-ranging flow restoration program, together with the annual watering plans and objectives, has been a major step forward in the management of flows in the MDB for ecological outcomes.

The lifecycles of riverine fishes are inextricably linked to flows, and the alteration to flows in the MDB, one of the most flow regulated riverine systems in the world (Nilsson et al. 2005), poses a key threat to fish populations (Koehn and Lintermans 2012). This emphasises the importance of appropriate flow management as a component of the restoration of fish populations (Koehn et al. 2014a). Our understanding of fish-flow interactions and the management and delivery of environmental water is developing at a rapid rate with many examples of new fish-flow research results (e.g. Beesley et al. 2011; King et al. 2016; Tonkin et al. 2017a, 2017b), knowledge syntheses (e.g. Bice et al. 2014; Koehn et al. 2014b, NSW DPI 2014, 2015a, 2015b; Ellis et al. 2015) and management directions (e.g. King et al. 2010; Mallen-Cooper and Zampatti 2015). While these can all be used to guide and further develop the management of flows for fishes, there remains an urgent need for new knowledge that can be quickly incorporated into management objectives and decision making (Koehn et al. 2014a, 2014c).

Given the commitment to the Basin Plan and increasing volumes of environmental water available, there will be increased public scrutiny of the use of water allocations and an expectation to demonstrate the environmental benefits. While there have been major advances in our scientific knowledge of fishes in Australia, our understanding of how to allocate water to best achieve native fish outcomes is in its infancy. We need to better understand flow regimes, their various components and how these relate to the life-history and fish population dynamics overall. Limited research budgets, however, mean that it is even more essential that programs and projects are carefully targeted toward the key ecological questions that meet the needs of managers (Koehn et al. 2014b). For successful environmental flow management in the MDB it is imperative that these priorities are developed in collaboration between the relevant researchers and water managers.

The MDB Environmental Water Knowledge and Research (EWKR) project is a 5-year, $10 million project, initiated in March 2014, that aims to improve the science available to support environmental water management, and thereby contribute to achieving Basin Plan objectives (http://www.senatorbirmingham.com.au/Latest-News/ID/2460/10-million-for-research-to-support-the-Basin). This includes better understanding the links between flow and ecology, and the impacts of multiple threats and pressures on the achievement of environmental outcomes (Burns and Gawne 2014). The EWKR project aims to use a collaborative approach between water managers, asset managers, water planners, relevant community groups and scientists to identify research priorities, and undertake research targeted at addressing these priorities to guide targeted research. MDB EWKR research priorities were identified by integrating responses from two consultation processes: 1) with environmental water managers to identify their knowledge needs and research priorities associated with the achievement of Basin Plan objectives and 2) with researchers to identify their suggested priority research questions associated with the achievement of Basin Plan objectives (Burns and Gawne 2014).

The prioritisation process identified four research themes for MDB EWKR: water dependant vegetation, native fish, water birds and food-web processes. The overarching question of the MDB EWKR Fish Theme is “What are the key drivers of sustainable populations and diverse communities of native fish” – with three priority research areas:

1. Recruitment of native fish populations
2. Survival of native fish populations
3. Reproduction of native fish

After the initial fish leadership team meetings were held to derive potential projects within the scope of available budgets and likely success within time constraints, the theme of fish *recruitment* was given the priority for research focus. From this point project proposals were submitted for consideration and feedback from the Scientific Advisory Group (SAG). After consultation between the SAG and EWKR Management team three synthesis projects were given priority with the aim to subsequently guide final project proposals:

1. Theoretical synthesis and conceptualization of flow related ecology on fish recruitment

2. Knowledge and management of flows and fish recruitment in the MDB

3. Review and synthesis of the factors limiting spawning and recruitment and how these are influenced by flow and other stressors

Here we report on the second conceptualisation project centred around our current knowledge of fish and flows and priority knowledge needs for their management in the MDB.

1.1. Goals and objectives

This project aimed to identify knowledge gaps regarding the flow-related ecology of freshwater fish to direct future research to assist environmental water management. We reviewed the contemporary scientific knowledge base and needs of water managers for fish outcomes. Hence, our major objective was to provide an up-to-date synthesis of fish and flows knowledge from both scientific and management perspectives to assist the delivery of water under the Basin Plan.

Specific aims of this project were to:
1. To review contemporary knowledge regarding the flow-related ecology of MDB fishes
2. To gain an understanding of the knowledge needs of managers to implement contemporary flow management for fish across the MDB.
3. To identify knowledge gaps (in relation to providing outcomes for fish) relevant to flow management and fish objectives under the Basin Plan
4. To provide directions for research to support water management to meet the needs of the Basin Plan for fish.

2. Methods

2.1 Review of knowledge

To review contemporary ecological knowledge regarding the flow-related ecology of native fishes we integrated: 1) information from recent reviews of the literature undertaken by MDBA and state agencies; and 2) interrogated published literature using the ISI –Web of Science. Several comprehensive fish-flow ecology reviews have already been undertaken by MDBA and state agencies (e.g. King et al. 2009; Bice et al. 2014; Koehn et al. 2014a; NSW DPI 2014, 2015a, 2015b; Ellis et al. 2015) and these were reviewed for information relevant to this EWKR project and used to target the literature searches. We approached the contemporary knowledge review to examine the scientific trends over time and potential knowledge gaps both in relation to individual species and aspects of their life-cycles.

For our peer-reviewed literature search, we searched the ISI –Web of Science (13/04/2016) using the following terms: Australia, fish and flow – then each in combination with population, spawning, growth, movement, recruitment, condition and habitat. Due to the limited scope of this project we were only able to review titles, abstracts and keywords. Data papers were considered relevant providing they were using real data (not modelled) and literature reviews were not included. Search terms had to be the focus of a given study such as relating directly to the study aims. Only studies of native species were included (these could be diadromous). Papers were largely restricted to MDB, but were included if they were relevant to MDB species and in close vicinity to the MDB (e.g. Lake Eyre Basin). We also tried to capture other relevant information including the scale of study, macro-habitat type (e.g. river, wetland, estuary, etc.), location, species and life-stages investigated.

The following caveats apply to restricting our search to the one database. The search will only include ISI registered journals that have been fully published (not early on-line). We realise that by only utilising the abstract, titles and keywords and it is likely that we may miss some information for multi-species papers and potentially some drivers. There is also potential to miss information if publication terminology was not consistent (e.g. if abundance is used in place of recruitment) or across time or scientific disciplines.

The knowledge gained from both the ISI database search combined with recent literature reviews on fish-flow ecology that had been undertaken by MDBA and State agencies enabled us to report on available knowledge and trends in relation to species, life history stages and recruitment drivers. A set of flow drivers suggested to impact fish recruitment was developed early in the EWKR fish theme (see Section 3.2). Our knowledge review enabled us to provide a summary of knowledge for individual species in relation to these drivers, and also to review the drivers themselves.

2.2 Engagement with fish-flow managers

In establishing the EWKR project, MDFRC consulted with the States, MDBA and the Commonwealth Environmental Water Office through a series of targeted questionnaires and workshops. In 2014, managers involved in general water policy, planning, delivery, monitoring and science support were canvassed to identify their priority environmental outcomes and key stressors that inform environmental watering. They were also requested to rate their level of confidence in existing knowledge regarding outcomes and stressors (Burns and Gawne 2014). The outcomes to these consultations were reviewed as part of this project to guide both our initial questions to water managers and then to present to a workshop with managers (see below) as additional information for them to consider.

For this fish and flow knowledge needs synthesis we considered it imperative that those managers dealing directly with environmental water for fish outcomes be closely engaged to ensure that their perspectives, needs and priorities were comprehensively included.

The engagement with fish-flow managers had three components:

1. A pre- workshop questionnaire
2. A workshop with invites to fish ecologists, fish managers and flow managers relating to fish 1)
3. A post workshop review of outcomes and priorities

To structure the workshop and to allow for opinions unbiased by workshop discussions to be collected, we provided a questionnaire to all fish-flow manager invitees (not to fish ecologists) one month prior to the workshop. This included the option to complete the questionnaire even if workshop attendance was not possible. The questionnaire related to: how water was managed for fish outcomes, including relevant spatial and temporal scales; the knowledge/information needed; how management and needs have/will change; priority fish species; risks and constraints to management; and what managers want from fish ecologists (Appendix 2a). A slightly modified set of questions was also put to a small group of anglers (*n* = 4) and fisheries managers (*n* = 4) that were representatives of the Australian Fisheries Management Forum to seek their views relating to environmental water and the recreational angling species of their interest (for full responses see Appendix 2b).

The workshop was conducted on 5 May 2016 at the Arthur Rylah Institute for Environmental Research in Heidelberg, Melbourne with representative fish ecologists, fish and flow managers invited from across the MDB (Table 3). The objective of this workshop was to engage with those practitioners that manage flows in the MDB for fish outcomes to determine the most relevant research questions for future flow management (Appendix 1). The workshop provided background to the EWKR project, an update on current fish-flow ecology and management concepts, a report from the ecological knowledge synthesis including new concepts and ecological knowledge gaps, and case study presentations made by fish-flow managers from each State rep (plus MDBA and CEWO). The outcomes of the workshop were agreed to by consensus.

Responses to the questionnaire were discussed and the final summary of research priorities workshopped to develop a consensus of priority of knowledge gaps from an ecological (a science only perspective) and those prioritized by managers. These agreed knowledge gaps were collated and sent to all participants after the workshop. This enabled further consideration, amendment and agreement by participants to ensure that this was an accurate reflection of the workshop outcomes. The outcomes of both the scientific review and management questions workshop were compared to examine whether the scientific gaps and directions identified in our literature review were aligned with those needed for effective management of MDB fish species. Whilst the objective of the workshop was to elucidate management priorities and knowledge gaps to provide guidance for EWKR fish research, final decisions on research projects would ultimately be made by the EWKR fish team and the EWKR project managers (Figure 1).

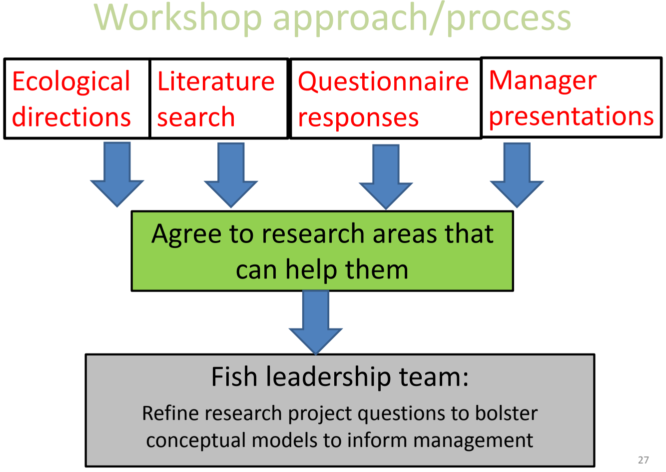

Figure 1. The components for the fish-flows manager's workshop

3. Results

3.1 Ecological Knowledge Review

The review of scientific studies pertaining to the flow-related ecology of freshwater fishes in the MDB started with the smallest combination of search terms to provide the broadest possible list (using Australia & fish & flow); identifying 745 papers. Based on the time available for the review it was not possible to examine such an extensive list and thus all subsequent searches included this first basic search combination followed by the addition of one further term. The following list shows each of the ISI search terms used with the number of papers listed and the final number retained (in brackets) based on relevance to this project.

1. Australia & fish & flow – 745 papers
2. Australia & fish & flow & population – 312 papers (31)
3. Australia & fish & flow & spawning – 87 papers (11)
4. Australia & fish & flow & growth – 99 papers (5)
5. Australia & fish & flow & movement – 98 papers (37)
6. Australia & fish & flow & recruitment – 79 papers (9)
7. Australia & fish & flow & condition – 186 papers (8)
8. Australia & fish & flow & habitat – 288 papers (1)

Overall, these searches revealed 60 relevant papers (Appendix 3) (note some were represented by more than one combination of search terms). The papers covered a range of species but the majority were focussed on large-bodied species, principally Murray Cod, Golden Perch and Black Bream (although the majority of studies for the latter species were outside the MDB). There was a concentration of papers in a few regions, particularly the lowland River Murray downstream of Yarrawonga, indicating a limited spatial coverage across the whole basin, with few papers representing the northern MDB. The majority of studies into the flow-related ecology of fishes in the MDB have occurred recently, with a continuous increase since 2008. To summarise the general trends through time, Figures 3-5 break the 60 papers into life stages (Figure 3), factors impacted by flow that will likely influence population demographics of native fish (Figure 4) and population demographics investigated within each paper (Figure 5). In relation to life stages, there were more studies on juveniles and adults compared to eggs and/or larvae, with a consistent output of papers on juvenile and adult studies from 2006 onwards.

Prior to 2008, there were few studies dealing with flow-related factors that influence breeding, but since then there has been a general increase in papers examining flow-related habitat, growth and/or condition and movement (Figure 4). Several of these papers were estuarine studies, with a general paucity of studies in riverine environments. Interactions between flow and fish growth or condition was not a major focus of studies prior to 2010, however, this has increased since that time. Similarly movement studies have become more prevalent since 2008. For those papers dealing with spawning, recruitment and population demographics, the earliest papers only examined spawning and early life-stage recruitment with population level studies increasing in frequency since 2009 (Figure 5). It is noted that that there was a lack of papers dealing explicitly with flow-fish ecology questions that relate directly to envrionmental flows and the management of native fishes in the MDB. The spatial scales of studies was usually limited to single sites/river reaches. The temporal scales were similarly limited to short time scales (e.g. one or two sampling occasions or single year studies) with few having longer time series. There was also a focus largely on lowland assemblages or species, with few upland studies.

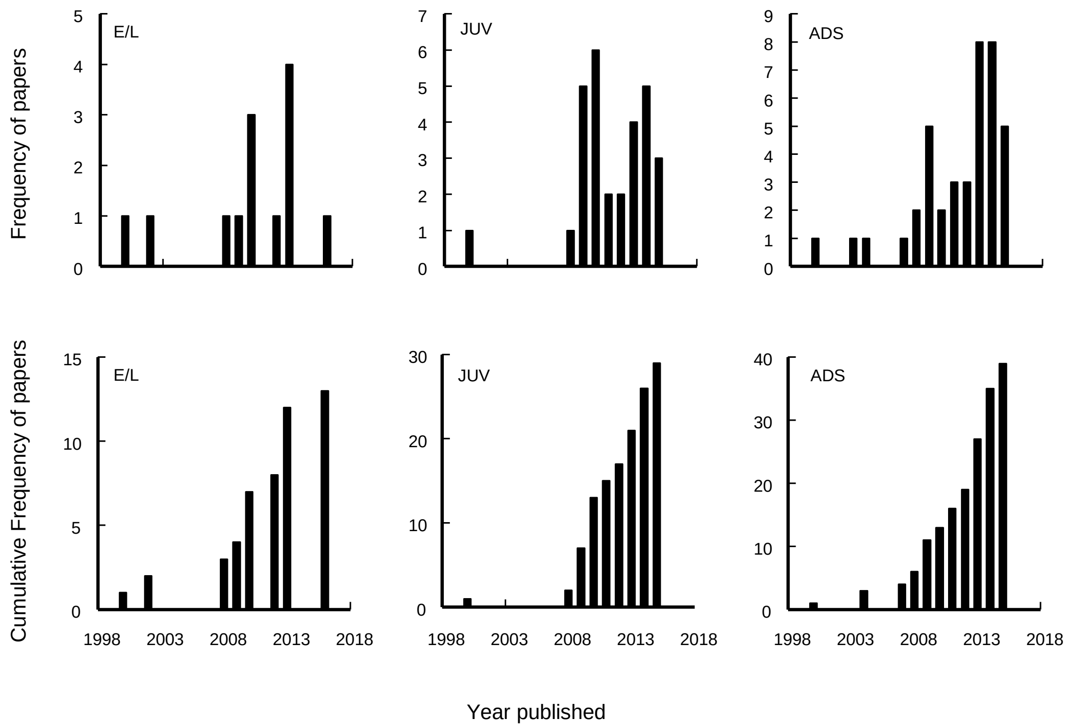

Figure 3. Number of published published peer reviewed papers from the Web of Science (frequency and cumulative frequency) reporting on flow ecology of fish relevant to the Murray Darling Basin. Plots arranged for papers investigating three life-stages: Eggs or Larvae (E/L), Juveniles (JUV) and Adults (ADS).

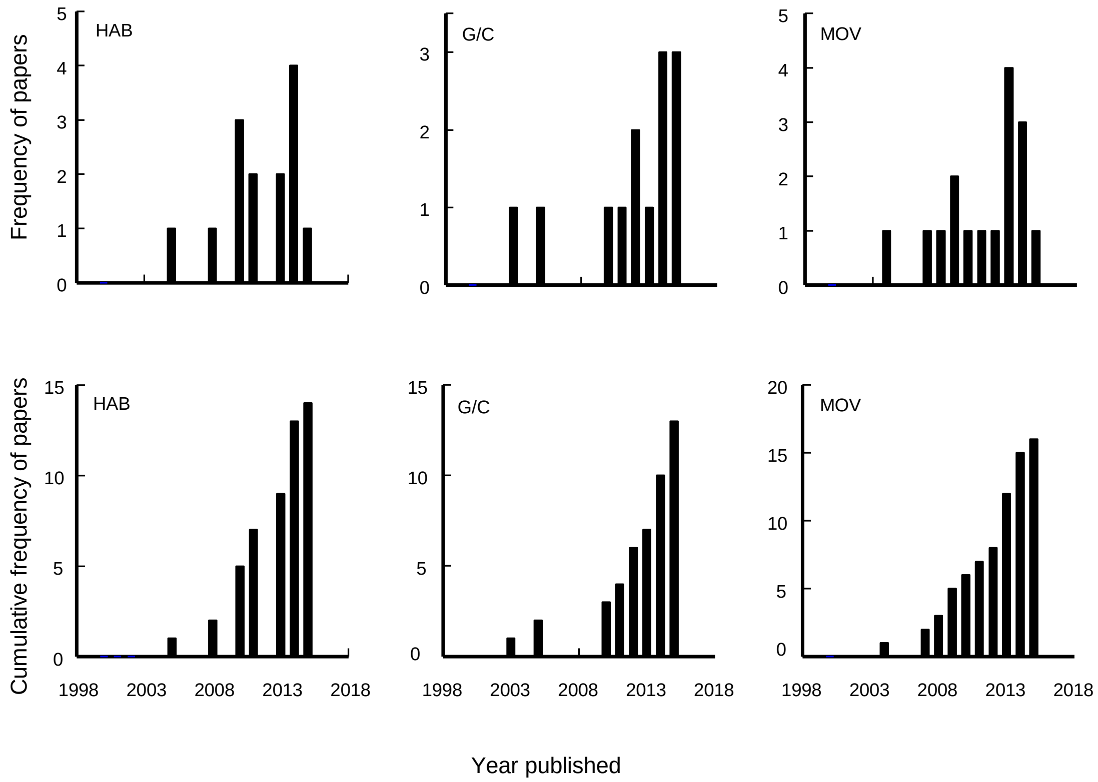

Figure 4. Number of published published peer reviewed papers from the Web of Science (frequency and cumulative frequency) reporting on flow ecology of fish relevant to the Murray Darling Basin. Plots arranged for papers investigating three aspects important for recruitment outcomes: Habitat (HAB), growth or condition (G/C), Movement (MOV).

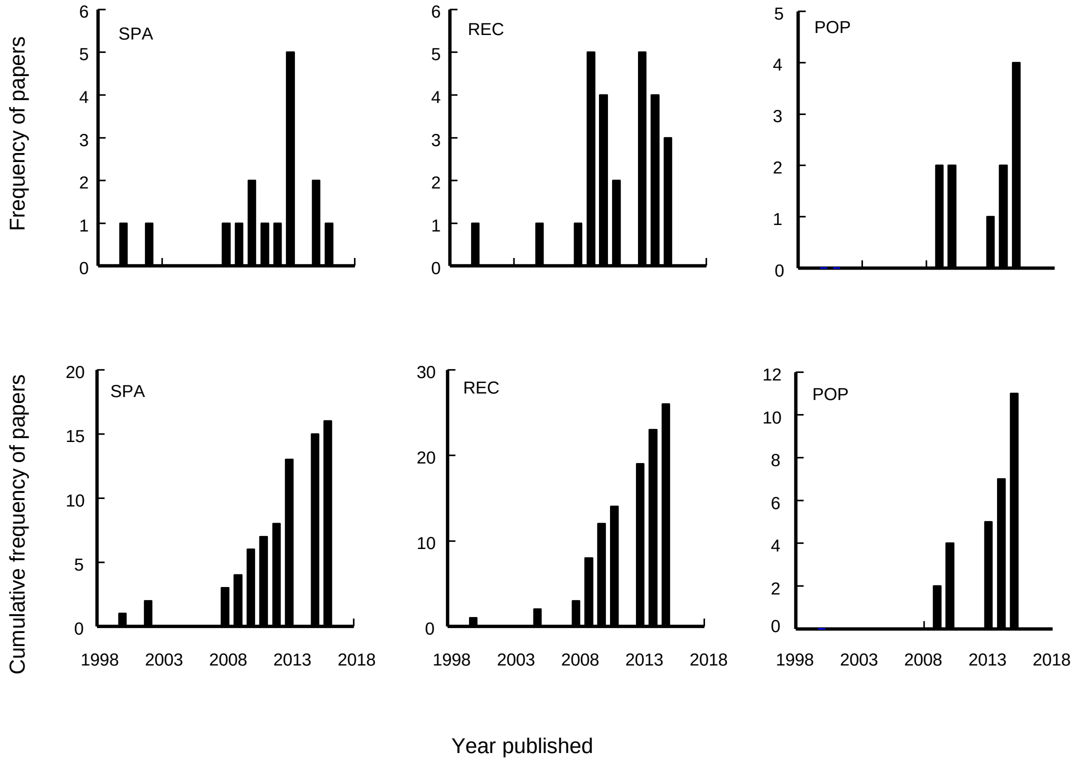

Figure 5. Number of published published peer reviewed papers from the Web of Science (frequency and cumulative frequency) reporting on flow ecology of fish relevant to the Murray Darling Basin. . Plots arranged for papers reporting on three key aspects of fish reproduction outcomes: Spawning (SPA), Recruitment (REC), Population (POP).

3.1.1 Emerging Trends and current gaps

Research on fish ecological responses to flow is moving in a positive direction to help manage and measure the potential success of using environmental water to improve fish populations. For example, early studies were often at single locations, with recent studies looking at multiple sites and whole rivers or catchments. Similarly, there is a trend from single life stage studies to incorporating multiple life-stages. New technology is allowing for a greater understanding of population processes and spatial extent of populations, with emerging methods such as isotopes and other chemical tracers used in otolith chemistry studies.

Knowledge gaps required to be filled improve management of fish populations using flows in the MDB under the Basin Plan included determining the spatial and temporal boundaries of populations, understanding the relative rates of growth and survival between different life-stages, and the consequent factors that limit population growth. Other important knowledge needs include links between flow, habitat and fish condition and ultimately how these factors interact and influence recruitment to adults.

There were few papers directly related to the outcomes of environmental watering. Such knowledge remains vital (including both successful and unsuccessful outcomes). Also, given the major focus on a few key geographic locations in the MDB, there remains a key concern regarding the transferability of results- e.g. north to south, east to west, perennial to intermittent rivers. In general, there are key knowledge gaps concerning the flow-related ecology of fish in the northern MDB. For example, for a widespread species such as Golden Perch-is their ecology similar across their whole range? Surprisingly there was a lack of peer-reviewed studies on threatened species and those that do exist were often last gasp efforts to rescue populations, rather than providing greater knowledge for population growth.

3.2 Review of current knowledge for key MDB fish species

Briefly, utilising the literature review, we summarised the status of knowledge of the biology and ecology of key fish species in the MDB (Table 1) and provide further assessments of our knowledge for the life stages of those species in relation to recruitment drivers (Table 2, Figure 5). The species considered were chosen due to their presence in catchments that could be targeted for flow management outcomes and their status as target species for managers (see section 3.5.2) (e.g. recreational fishing or threatened/endangered). Each stage was ranked by the authors in relation to the knowledge obtained from literature reviews and our ISI search.

The most ecological knowledge relating to flows, across all life stages, is available for large-bodied species, particularly Murray Cod, Trout Cod and Golden Perch (Table 1). Knowledge for the smaller bodied, threatened species is limited. Overall, for all species we have the least knowledge for juvenile life-stages. Knowledge for eggs and larvae in the wild is greatest for Murray Cod and Trout Cod and although there is some knowledge for these life stages of Golden and Silver perch (included in this assessment score), much of this is from hatchery data.

Table 1. Ecological knowledge for key-species life stages (from peer review and grey literature). Scores range from 1 to 10, with1 indicating limited knowledge and 10 considerable knowledge.

Species	Spawning	Eggs	Larvae	Juveniles	Adults
Murray Cod (MC)	9	9	8	6	9
Trout Cod (TC)	9	9	8	6	9
Freshwater Catfish (FWC)	6	4	4	3	6
Golden Perch (GP)	6	7	5	4	8
Macquarie Perch (MP)	6	7	5	4	9
Silver Perch (SP)	6	7	5	4	7
Olive Perchlet (OP)	3	4	3	3	5
Purple Spotted Gudgeon (PSG)	4	4	3	3	5
Southern Pygmy Perch (SPP)	4	4	3	3	5
Yarra Pygmy Perch (YPP)	3	4	3	3	5
Murray Hardyhead (MHH)	4	4	3	3	6

Our review of key recruitment drivers expanded the flow drivers from four (timing, magnitude, duration, rate of change) to seven, and recruitment drivers from nine (food quality and quantity, temperature, hydraulics, predation, competition, disease, wash-out, desiccation of eggs, dispersal) to sixteen (Figure 6). This review served two purposes. Firstly, it enabled consideration of terms and processes that could be used in our ISI search and secondly, it provided a mechanism to summarize the knowledge from the full review (ISI and previously mentioned literature review reports) and place this knowledge in context for key species and life-stages (Table 2, Appendix 4).

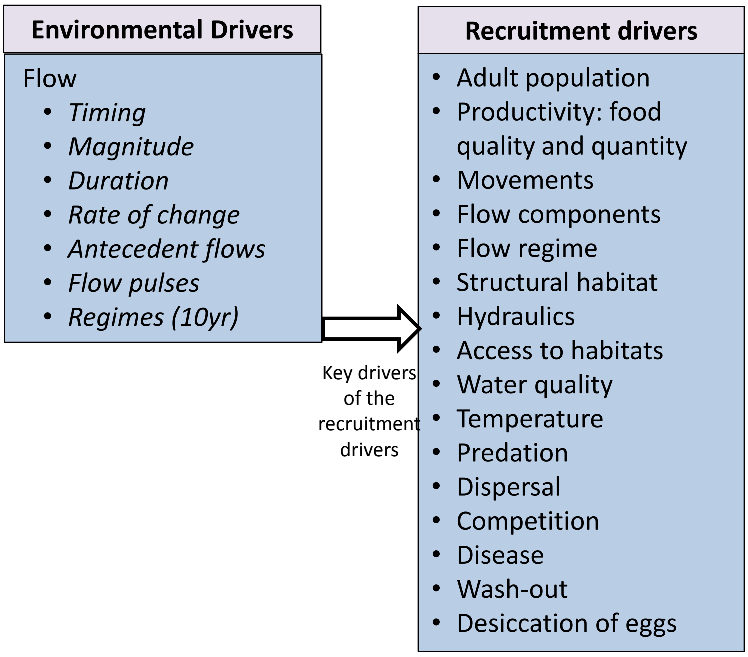

Figure 6. Revised environmental and recruitment assessed to impact fish populations and recruitment.

An expert assessment of the knowledge (from peer reviewed and grey literature) for key drivers of recruitment for priority species is provided in Table 2. In relation to these key drivers, there are many knowledge gaps across all species, particularly for ecosystem productivity, predation, competition, disease, wash-out and desiccation of eggs (Table 2). Like our reviewed knowledge for life-stages of key species, the greatest knowledge of key recruitment drivers exists for larger-bodied species, with less knowledge for smaller-bodied fishes. Many threatened species occurred in both categories, emphasising the general need for knowledge in this area.

Whilst the focus of the EWKR project will be on the influence of flow on recruitment, it is recognised that many other stressors also influence recruitment and fish populations including geomorphology, cover, substrate, specific attributes of flow (hydraulics depth, velocity, water abstraction, flow changes), physical habitat, habitat degradation, alien species, barriers to connectivity, exploitation, water quality, land-use impacts, climate and landscape context. All of these stressors will be further explored in a parallel knowledge synthesis project. It is imperative that managers also consider these stressors in addition to flows.

Table 2. Relative knowledge for key drivers of recruitment for key species (from peer review and grey literature). Scores range from 1 to 10, with 1 indicating limited knowledge available and 10 high available knowledge. See Table 2 for species abbreviations.

Species	Adult popns	Ecosyst product	Move	Flow components	Flow regime	Structural habitat	Hydraulics	Habitat access	Water quality	Temp	Predn	Dispersal	Compn	Disease	Egg washout	Desicc of eggs
MC	5	3	6	6	6	8	6	6	5	5	1	5	2	1	2	2
TC	5	2	5	5	5	7	5	5	5	6	1	4	2	1	1	2
FWC	2	2	3	3	3	2	2	4	2	2	1	3	2	1	1	1
GP	5	6	8	6	6	7	6	7	5	5	1	6	2	1	1	1
MP	6	2	6	6	6	8	6	8	6	7	3	6	1	1	1	1
SP	4	2	6	5	5	3	5	6	5	7	1	6	1	1	1	1
OP	3	5	2	3	3	6	1	6	4	6	2	3	2	1	1	1
PSG	3	2	3	2	1	4	2	5	4	3	2	2	1	1	1	1
SPP	3	2	2	3	3	5	2	7	5	3	2	3	2	1	1	1
YPP	3	2	2	3	3	5	2	7	5	3	2	3	2	1	1	1
MHH	3	3	2	6	6	7	3	7	5	3	2	3	3	1	1	1

3.4 Initial jurisdictional input to the EWKR project

The review of States and Commonwealth inputs into the original EWKR research identification process (Burns and Gawne 2014) highlighted the following research/knowledge needs relating specifically to the management of flows and fish.

Victoria
No fish specifics, but relevant high level questions

- Relationship between site outcomes and landscape/regional outcomes (scale)
- What role food webs play (primary productivity)
- Flow related thresholds, recovery, resistance

Queensland
Fish specifics

- At what scale do populations operate (population dynamics and scale)
- What are the drivers of food webs (primary productivity)?
- Regulated flows and drought refugia (resilience?)

South Australia
Relevant high level questions

- Understanding relationships between flow and processes that lead to critical demographic processes of key biota

Fish specific

- Understand water regime required to provide resources to support recruitment of flow-cued spawning fish, including mechanistic links (productivity, food webs, recruitment, population dynamics)
- Responses to attenuated events or small in-channel flows

New South Wales
Fish specific

- Are we achieving the targeted recovery trajectory?
- What are the key drought refuge pools for targeting flows?
- What are the key life history stages that guide watering decisions?

Murray-Darling Basin Authority
Fish specific

- Key drivers of fish recruitment
- Sensitivity of outcomes to 'partial' events
- Legacy impact of blackwater and drought

Department of the Environment and Energy
Relevant high level questions

- Connectivity, in particular, longitudinal connectivity

Fish specific

- Refuge habitats in northern Basin (habitat)
- Drivers for fish pops. In episodic northern basin systems.

Common themes across all States and the Commonwealth were:

- At what scales do populations operate, population dynamics, demographic processes, connectivity, etc?
- Recruitment; particularly relationships between recruitment and flow, habitat, food resources, etc
- Food webs, primary productivity, food resources
- Flow related thresholds, less than optimum duration, partial events, etc

- Refugia, intermittent rivers, northern MDB
- Scales of life histories and management: sites, regional, landscape

3.5 Engagement with fish-flow managers

The fish-flow manager's workshop was attended by 19 participants; with overall input from 28 managers. An additional 18 managers were invited but were unable to attend, and 13 managers (in bold) provided responses to the questionnaire (Table 4).

Table 3: Invitees and attendees for the fish-flow manager's workshop. Bold = provided a questionnaire response (13).

Fish Ecologists	Fish-flow managers	Water managers	Project Managers
Accepted			
John Koehn*	**Anthony Townsend (NSW)**	**Damian McCrae (CEWO)**	
Brenton Zampatti*	**Katherine Cheshire (NSW)**	Louise Chapman (Mallee CMA)	Nadia Kingham (ED)
Stephen Balcombe*		Emma Wilson (OEH)	Anthony Moore (ED)
Lee Baumgartner (CSU)		**Alana Wilkes (CEWO)**	Jessica Davidson (EWKR)
Wayne Koster		**James Dyer (OEH)**	
Amina Price (MDFRC)		**Jan Whittle (SA)**	
		Fiona Spruzen (Vic. W & C)	
		Rebecca Turner (SA)	
Apologies			
Ivor Stuart	**Heleena Bamford (MDBA)**	**Tim Hosking (NSW)**	
Zeb Tonkin	Adam Sluggett (MDBA)	Beth Ashworth (VEWH)	
Jason Thiem	Sam Davis (NSW)	Ryan Breen (SA)	
	Marty Asmus (NSW)	Peter Brownhalls (Qld) del	
		Andrew Warden (CEWO)	
		Debbie Love (Nth) staff	
		Tracey Steggles (SA)	
		Anna Lucas (Vic. W & C)	
		Courtney Johnson (VEWH)	
		Paul Reich (Vic. W & C)	
		Paula D'Santos (OEH)	

*Project team

3.5.1 Fish and flows manager's questionnaire responses

The following section summarises the manager's responses to the pre-workshop questionnaire (Appendix 2a):

How do you manage water for fish outcomes?

- Long-term environmental watering plans
- Priority watering actions
- Water delivery for particular outcomes
- Protecting unregulated water

What spatial scale do you manage for?

- All scales: site–Basin

What temporal scale do you manage for?

- Long-term water plans are out to 20 years
- Annual Watering Priorities
- Seasonal; 1-3 year basis; antecedent 10 years

What fish knowledge/information do you use?

- Monitoring
- Direct expert advice (fisheries managers, researchers, local knowledge)
- How fish respond to flows various species, life stages
- Fish population dynamics- population or conceptual models

What are your typical hydrological scenarios for fish outcomes?

- Pulses (small, large): late Spring, 'return movement' in summer, inundate benches
- Maintain higher than minimum baseflows
- Spawning and recruitment of large bodied natives
- Movement cues, dispersal, facilitate fish passage- weir drown outs

How has this evolved in the last 5-10 years?

- Population outcomes/whole lifecycle/recruitment rather than spawning
- New information on fish needs
- Monitoring
- Flows and connectivity

How will this change in the future?

- More monitoring and knowledge and refinements
- Landscape/system-scale (not based on jurisdictions)
- Better understanding of trade-offs
- Adaptive Management

What are your actual or perceived risks when delivering water for fish outcomes?

- Carp
- Water quality/fish kills
- Pest species
- Not achieving outcomes
- Uncertainty in knowledge

What are your actual or perceived constraints when delivering water for fish outcomes?

- Insufficient water available, timing, and competing demands for water
- Operational constraints
- Barriers to movement (adequate flows for fishways)
- Public anxiety of risks/3rd party impacts

What do you and don't you want from fish ecologists?
Do:

- Provide robust, evidence-based information (research and monitoring) and timely, relevant advice to inform policy and be applied management in simple terms
- Be prepared to 'give things a go'
- A proactive, collaborative approach to determining research priorities and water proposals
- Hydrographs
- Carp (Koi herpes)

There were limited responses relating to what managers did not want from researchers (academic research, non-verified translation of results from the southern to the northern MDB and sporadic monitoring). Full responses from Managers are included in Appendix 5.

3.5.2 Angler's questionnaire responses

No response was received from fisheries managers from any state. Recreational fisheries managers had largely not previously been engaged in the EWKR consultation process and consideration of early engagement of this group in future flow-fish science programs may result in better support for environmental flows and cooperation with research projects. Four responses were received from recreational anglers representatives (Rob Loats, VIC; Joe Legrady, QLD, Peter Teakle, SA; and Steve Samuels, ACT) and are summarized as follows:

The following section summarises angler's responses to the questionnaire:
How do you think water should be managed for fish outcomes?

- Target spawning cues and recruitment, fish movements and ecosystem outcomes, must reflect the river system's needs first
- Native fish migration and the food chain
- Need 'real time' management to mimic natural flow attributes
- Fish outcomes should have the same priority as irrigation releases

What fish knowledge/information do you think should be use?

- Current scientific knowledge that is recognised as best practice
- Whole of system knowledge
- Links to historical flows and rainfall
- Timing, volumes suitable for native fishes

What hydrological/flow scenarios should be used for fish outcomes?

- Must reflect best ecosystem deliverables
- Flow rates matched to breeding cycles, pulsing of flows, provision for migration and not for pest fishes
- All releases (including irrigation) must have favourable fish outcomes

How has this evolved in the last 5-10 years?

- Better use of current knowledge
- Hasn't changed-most flows still managed for irrigation supply

How will this change in the future?

- A key factor is water availability and need to question whether icon site water has precedence over river flows
- Koi herpes virus, further impacts from irrigation demands
- Change will only occur when managers acknowledge the importance of native fish

What fish knowledge do you think is really needed?

- Have lots of knowledge but it is not being used. Icon site watering not being delivered for fish outcomes. This is assisting pest species.
- Understanding barriers to breeding and river health for better fishery outcomes
- Breeding cycles and survival rates, food for fry

Do you have priority fish species? What are they?
- Murray Cod, Golden Perch, Silver Perch, Freshwater Catfish, Estuarine species, smaller often forgotten species
- Murray Cod, Golden Perch, Silver Perch, Freshwater Catfish,
- All of equal importance

What spatial scale should be managed for?
- Larger- rivers and streams
- The length of the MDB river systems

What temporal scale should be managed for?
- Drought refuges for fish
- The age of Murray cod, the longest-lived fish

What are the actual or perceived risks when delivering water for fish outcomes?
- Timing, icon site watering
- Mismatch of water delivery and breeding needs; non-native species
- Carp
- Backlash from irrigators, blackwater events

What are the actual or perceived constraints when delivering water for fish outcomes?
- Water availability, irrigation water deliverables
- Reduced flow integrity, reduced flows, economics of irrigation
- Irrigator demands

What do you think should and shouldn't be provided by fish ecologists?
- Knowledge on spawning cues and recruitment, fish movements and ecosystem outcomes
- What to do about pest fishes
- There must be an active and continual role in planning and monitoring water releases. Water managers must not be allowed to do this in isolation

Any further comments?
- Need to reconsider the value of icon site watering
- Weir pools a real issue in SA

There were numerous synergies between the responses of water managers and anglers. These included:
- A need to manage spawning, recruitment and movement for population level outcomes for the fisheries (e.g. to legal size), and that this may need to occur over a range of scales (site–river system). Crucial to this is an ecological understanding of how populations function and how flow and other factors influence key life-history processes
- Many of the species of concern were large bodied fishes (e.g. Murray Cod, Golden Perch, Freshwater Catfish), but there was also a recognition of small-bodied threatened fishes, and the need to manage fish assemblages in a holistic manner
- Need for monitoring and adaptive management, using the *best available* science
- Risks include Carp and blackwater

Anglers did have concerns that the management of water for multiple uses may not always result in in positive outcomes for native fish and there was sentiment that most flows were still managed to meet irrigation demands. For example, environmental water delivery targeted at Icon sites, may achieve poor outcomes for native fish whilst at the same time promoting invasive species (especially Carp), with many of the native species that do end up in these sites becoming stranded on drawdown. Similarly, anglers would like to see a balance between flows for fish and irrigation requirements. While the views of these fishers may be counter to water managers, they form a legitimate consideration in water management and research projects and possibly reflect the need for greater engagement with the environmental flow process to improve understanding.

3.5.2 Fish-flow manager's workshop

Workshop discussions

The workshop provided an engaging environment with lots of discussion and generous conversations between participants, especially researchers and managers. The workshop was collegiate and managers were forthcoming about priority knowledge needs. There was a definite desire for new knowledge that can be applied to flow-management to assist fish outcomes. Managers have clear objectives for fish in their watering plans, which can briefly be described as: more fish!! (i.e. overall increased population abundances; achieved by improving survivorship from recruitment through to adults, or through increased distributions). Managers are happy to use interim measures such as the presence of early life stages to indicate progress toward longer-term goals but need to be able to illustrate the benefits of their actions to their stakeholders (regional public, irrigators, anglers).

Current management occurs at a range of spatial (from site to whole of Basin) and temporal (from annual watering priorities to long term water plans that extend over 20 years) scales. Management has changed rapidly over the past 5 years being influenced by a range of factors, including:

- Multi life-cycle and population outcomes rather than single processes (e.g. spawning)
- Increased monitoring to determine causal relationships
- Flows, connectivity, movements and spatial scales now being included as important ecological components for populations
- Continuing requirement for new knowledge and mechanisms to effectively transfer this to managers

Discussions at the workshop also recognised the importance of the following themes:

- The need for strong links to build on other research and applied management projects
- Predictive capacity and strong causal relationships needed to strengthen fish-flows science increase confidence in water delivery
- Numerical, process-based computer modelling being an important tool, but is in need of supportive science
- Pathways to adoption should be included with all research projects
- Understanding the scale at which populations operate; population dynamics, demographic processes, connectivity, etc. These must be included.
- Recruitment to adults is the key measure of success
- Food webs, primary productivity, food resources should be incorporated into management decisions
- The effect of flow-related thresholds, less than optimum duration, partial events, flow sequences, etc, need to be explored
- Refugia, intermittent rivers and the northern basin require further work
- Appropriate, cost-effective, science needs to be undertaken by scientists with the appropriate skills (e.g. fish experts for fish questions), sufficient experience, capability and capacity, preferably in conjunction with managers

Changes that are expected to occur in the future include:

- More monitoring and knowledge, and refinements
- Landscape/system-scale approaches (coordination between jurisdictions)
- Better understanding of trade-offs
- Better application and completion of the Adaptive Management cycle

Providing causal relationships for fish and flow relationships (correlations) is a key request from fish-flow managers. Workshop discussions emphasized that current management now widely designs and uses hydrographs as a tool for flow managers to help water delivery planning achieve environmental objectives. These hydrographs are generally constructed on an annual basis to reproduce some of the vital flow cues or components that may influence the lifecycles of selected fish species. They will be most successful when developed in consultation with fish ecologists to provide a robust conceptual basis. Figure 7 provides a theoretical example of how environmental water can alter the shape of a relatively benign hydrograph resulting from a flow release to potentially target spawning outcomes of Golden and Silver Perch. Such hydrographs can be refined through time depending on the resultant outcomes of the environmental watering. Note that this Figure is indicative only and has been used for planning water delivery under a range of constraints at one particular site.

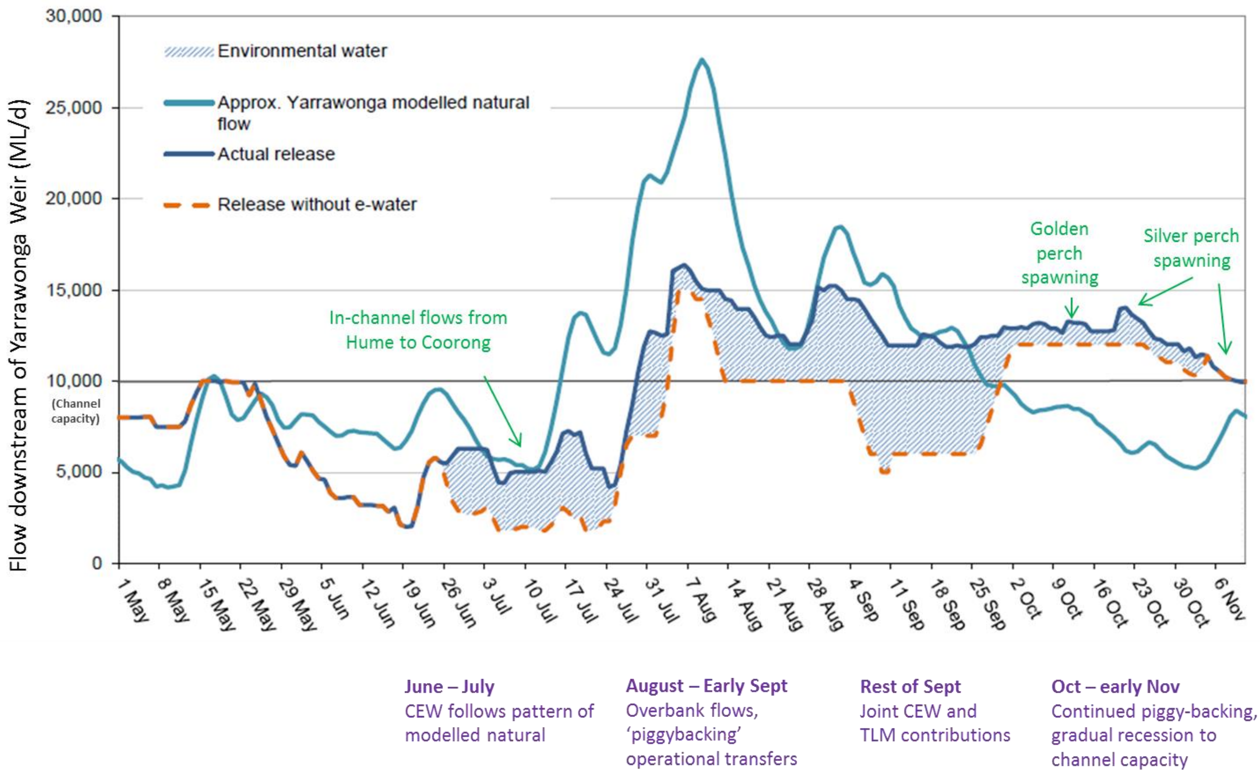

Figure 7. An example of a hydrograph designed to utilise environmental water allocations for specific fish purposes in the mid-Murray river (provided by Alana Wilkes, CEWO).

3.5.2 Priority knowledge gaps

The following is a summary of priority knowledge gaps identified in the fish-flows manager's workshop and agreed upon by participants:

Ecological knowledge gaps (provided by ecologists)
Highest priorities
1. Population dynamics (incorporating all life stages)
2. Spatial and temporal scales and population processes
3. Survival, growth rates:
4. Recruitment drivers (food, etc.)

Secondary priorities
1. Fish condition (and effects on survival and recruitment)
2. Fecundity

Management knowledge gaps (provided by managers)
Highest priorities
1. Population dynamics
2. Recruitment to adults
3. Movement, dispersal and connectivity

4. Mechanisms/causal links and thresholds (scale of variability; what are the drivers)

Secondary priorities

- Trade-off processes
- Species-specific responses to flows
- Life stage-specific responses to flows
- Scale - Landscape/system – site
- Refugia Flow thresholds, maintain or not, top up or not
- Recovery time (drought/blackwater) – recolonization, barriers

There were considerable similarities between ecological knowledge gaps and manager's priority needs. Both ecologists and managers highlighted the importance of understanding the key processes that influence the dynamics of populations (i.e. recruitment and movement) and the spatio-temporal scales that these processes occur. Integrated studies that consider the influence of flow on these key population processes were considered the highest priority for research concerning the flow-related ecology of fish and management of environmental water in the MDB. The secondary priorities raised by managers often related to the type of relationships, discussions, ecological knowledge and assistance that they are seeking from researchers. A summary of the key knowledge gaps is provided in Appendix 6.

3.5.2 Manager's priority species

Manager's species priorities often focus on large-bodied native fishes of community relevance. Nevertheless, there is also consideration of the whole of fish community, which may be addressed through consideration of umbrella or keystone species, and the needs of threatened species. Estuarine and diadromous species are also priorities for managers in South Australia but need to be included in the planning and were supported by all MDB jurisdictions. There was a general recognition of the need for a wider, more holistic approach to flow management to meet local species and water planning requirements.

Priority species for managers:

- Large-bodied natives (priority order): Murray Cod, Golden Perch, Trout Cod, Silver Perch, Macquarie Perch, Freshwater Catfish
- Small bodied natives (priority order): Southern Pygmy Perch, Southern Purple Spotted Gudgeon, Olive Perchlet, Murray Hardyhead, Yarra Pygmy Perch
- Carp (especially in relation to the likely impacts of the Koi herpes virus)

4. Discussion

This project has provided a synthesis of the contemporary state of knowledge regarding the flow-related ecology of native fishes in the MDB. It has also provided an appreciation of the knowledge requirements for fish-flow management across the MDB. The knowledge review demonstrated how research has progressed in this field, particularly given there were few peer-reviewed journal articles relating flow to fish population outcomes prior to 2008. This fundamental research is critical to answering ecological questions; nevertheless, given the significant investment in environmental water and scrutiny on outcomes it is key that such research aligns with the needs of water managers. Managers have provided clear indications of their knowledge needs, their objectives and priorities and also the collaborative relationships they would like to have with fish ecologists.

4.1 The state of knowledge

Study of MDB fishes has moved from single locations and points in time, to larger scales with multiple sites, rivers and catchments over the longer term. There is also a trend from single life stage studies to incorporating multiple life-stages ultimately leading to a greater focus on understanding of population processes. This includes factors such as understanding the relative rates of growth and survival of and between different life-stages and factors limiting population growth. Most research has been conducted in lowland southern rivers, with a need for further research in the northern MDB and estuarine reaches. Management of water must consider other key stressors that may limit the effectiveness of flow management (e.g. connectivity). Indeed, an holistic approach to fish rehabilitation that includes flows and other complementary measures (such as habitat restoration) has long been advocated (Koehn and Lintermans 2012). Limitations on the successful management of flows for native fish by other stressors is being undertaken in a separate EWKR project

Four key ecological knowledge gaps were derived from recent reviews/compilations of knowledge and a review of the published-peer review literature:

1. population dynamics (including all life stages)
2. spatial and temporal scales of population processes
3. rates of survival and growth
4. recruitment (drivers, food production, etc)

These ecological knowledge gaps represent the broad themes that can guide the evolution of specific research concerning fish and environmental flows in the MDB. For example, within questions around population dynamics, there has been a trend to multi-stage life-cycle studies. Recruitment to adults is a key requirement for managers. In relation to the dynamics of populations there has been a trend of research increasing in both spatial and temporal scales. This will result in a greater understanding of the scale of species population processes and the intrinsic role of flow management in facilitating these processes. Our review has demonstrated that we have reasonable knowledge for some life-stages of some key MDB fishes, particularly large-bodied species, our knowledge for many other species is limited. There is less knowledge concerning small-bodied species, many which are considered threatened.

4.2 Population dynamics

One of the key knowledge gaps for many species is survival rates between life stages and this influence on population growth or sustainability. This relates to the number one priority from both managers and our knowledge review – recruitment to adults and understanding population dynamics. These results demonstrate that a focus on fish recruitment is an appropriate focus for research and there are significant gaps for all species in relation to the drivers of successful adult recruitment.

Whilst single life-history stages may be a useful interim response measure for environmental water actions, individually they are not the only aspects that influence population dynamics. As the objectives for managers is to have greater numbers of fish, this means recruitment and survival to the adult stage. Often other definitions of recruitment are also used (such as to post larval fish, into the fishery, or to age 0+) and this can cause confusion. To avoid this confusion, the stage to which recruitment is being referred should be clearly stated in flow-recruitment studies. Other components of populations that need to be considered are: the number of adults (particularly female fish as they provide egg numbers) that provide the actual reproductive stock; the survival rates between each life stage of the species, and movements (into or out of the population) (see Figure 8). The spatial scale of ecological processes such as movement, barriers to connectivity and their impacts on fish population recovery rates, vary between species and life stages (see Appendix 4) but need to be considered. Movement requirements depend on the species, life-stage and ecological purpose (see Koehn and Crook 2013) and these include: longitudinal movement (along rivers and tributaries) lateral movement (to and from floodplains and wetlands), diadromous fish movement (between the Coorong estuary and freshwater), movement to maintain genetic mixing and dispersal to reduce density dependant mortalities. Some of these aspects are being explored through EWKR investigations of the natal origins of some species (MDFRC 2016). There are many factors that influence population processes across all life stages (Figure 8) and include a wide range of other stressors.

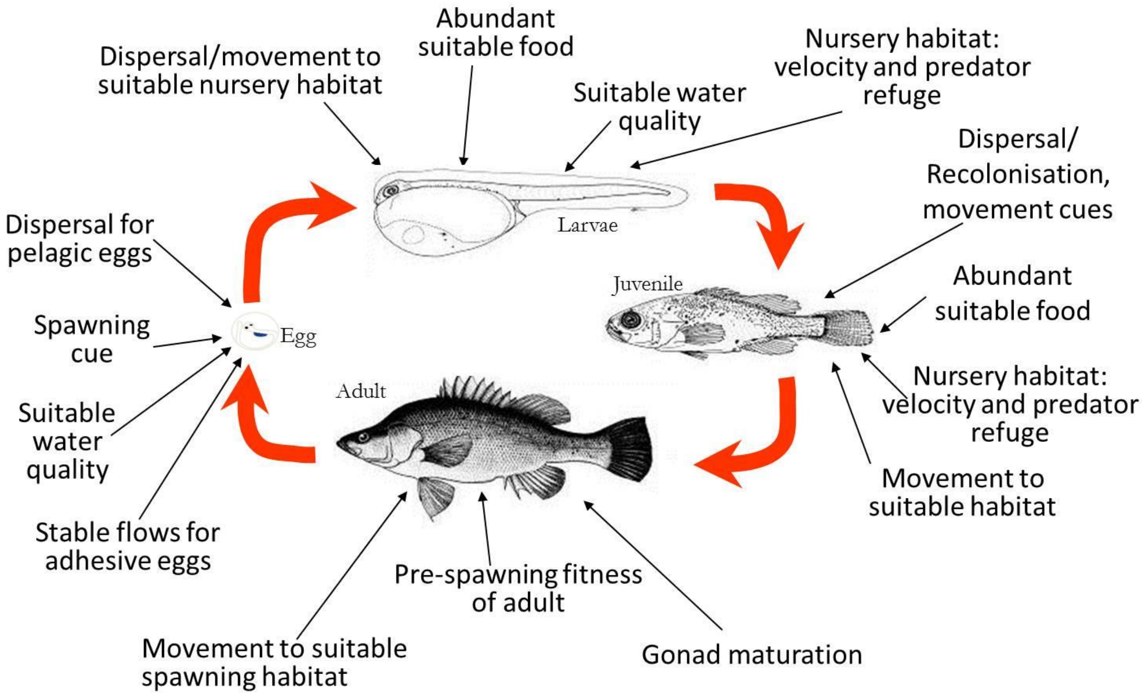

Figure 8. Some of the effects of river flows on various stages of a fish's life cycle (from Koehn et al. 2014b).

4.3 Management needs and priorities

Managers provided clear messages on the knowledge they require and the help they expect from research scientists. Managers' knowledge gaps, in order of priority, were: population dynamics; recruitment; movement, dispersal and connectivity; and mechanisms/causal links and thresholds. This demonstrated a convergence of ideas between our scientific knowledge (and gaps) with water manager's knowledge needs where both sets of priorities nominated a greater understanding of population dynamics for native species as the number one issue. For the science knowledge gaps priorities 2 and 3 (scales of population processes and rates) are a sub-set of understanding population dynamics, while recruitment was considered an important gap for both science and management.

By necessity, managers target particular species with environmental water. Manager's species priorities are often public driven, thus tend to focus on large-bodied native fishes of community relevance. In addition, however, there is also consideration of the whole of fish community, umbrella or keystone species and the need to address the requirements of threatened species. Despite being a significant knowledge gap, there are considerable difficulties studying small, rare and threatened species (low numbers, small, fragmented populations). Hence, in order to assist the priorities of managers, it is suggested that EWKR recruitment studies be targeted at the larger, important angling species that have life cycles that are highly responsive to changes to flows. In this respect, both Golden and Silver Perch provide ideal candidates, and while some information is available on their early life history stages for hatchery studies, there is little known about these vulnerable life stage in the wild. The high mobility of these species necessitates the inclusion of movements of other life stage into and out of populations. Both species are targeted by fish-flow managers and the rehabilitation of Silver Perch populations in the MDB is a high priority (Koehn et al. 20014a). Estuarine and diadromous species are important priorities in South Australia. The large bodied species listed by managers in order of priority were: Murray Cod, Golden Perch, Trout Cod, Silver Perch, Macquarie Perch, Freshwater Catfish, while small-bodied species in priority order were Southern Pygmy Perch, Southern Purple Spotted Gudgeon, Olive Perchlet, Murray Hardyhead, Yarra Pygmy Perch. Managers also stressed the importance of a better understanding around how water management influences Carp populations and any likely outcomes from the potential release of the Koi herpes virus on Carp populations.

4.4 The future

Managers gave clear directions as to what they expect from ecologists to assist decision their making. This was highlighted in a secondary list of priorities that related to other assistance that managers would like to have from research scientists: trade-off processes; species-specific responses to flows; life stage-specific responses to flows; scale - landscape/system – site; refugia flow thresholds, barriers, recovery times (e.g. from drought/blackwater) and recolonization rates. This set of second tier priorities revealed a desire by managers for much more knowledge than one project such as the EWKR fish theme can deliver. However, being aware of such needs will assist targeted, applied research into the future. Managers want robust, evidence-based information (research and monitoring) and timely, relevant advice to inform policy. Ideally such advice needs to be assist managers in their design and use of hydrographs to provide the appropriate flow cues for fish. Managers want ecologists to be prepared to "give things a go" – translated to don't be afraid to experiment and give advice even if not sure – by getting things wrong we often learn more. This approach, however, must be based on the best available science, together with a design that may provide answers to some key ecological questions. They also stressed that a proactive, collaborative approach to determining research priorities and collegiate inputs to watering plans was key to moving this applied field of applied environmental water management forward.

The trend toward large scale, multi-stage, life-cycle population dynamics through experimental field approaches is not the only way to explore relationships between fish population dynamics and flow. Statistical-based exploration of existing datasets (especially long-term ones) in conjunction with key environmental variables can provide valuable alternative approaches. The use of such existing resources should be given full consideration in both theoretical and applied science in this field. The collation of contemporary knowledge (including some unpublished data) allows for the development of conceptual models for each species to aid ecological understanding. This combined with other tools such as population models can allow managers to explicitly explore the likely outcomes and risks of their actions within an adaptive management framework. If the expected outcomes do not occur, managers can return to the conceptual models and reset their hypotheses and objectives. Such models rely on results from fundamental research. This study assists fish-flow management by outlining some clear research gaps and priorities that are aligned with management needs. To further assist managers, transfer of results must occur through the presentation of clear, understandable messages and that is undertaken with a collaborative approach.

5 Conclusion

Through consensus between ecologists and managers, this project has provided a focus on priority research to explore relationships between fish population dynamics and flow. The synthesis has highlighted trends in research and management which will be useful when planning future research programs. Initially, environmental water management and science were largely site focussed with short-term goals, however, this has rapidly progressed to larger spatial scales (e.g. river catchments) and incorporated an appreciation of the dynamics and spatio-temporal bounds of populations, including, where appropriate, connectivity across multiple catchments. While we have the most knowledge of larger-bodied fishes, in relation to some life-stages and recruitment drivers; there is considerable knowledge still to be gained. There remains much to be learnt about small-bodied species that are of conservation concern. Most of these are now restricted to isolated off-channel waterbodies, limiting their ability to colonise alternative habitats in association with high flows. Research and management interventions for these species to-date, have essentially been a last gasp effort to save species from extirpation (e.g. Murray Hardyhead). There remains limited knowledge of relative rates of survival and growth for all life stages of most species and this is essential to understand how to improve adult populations- the objective of managers. Golden and Silver Perch provide ideal candidates for future research. Both are important species for fish-flow managers and the rehabilitation of Silver Perch populations is a high priority (Koehn et al. 20014a). They are species that respond to flows, have some information is available on their early life history stages (eggs and larvae) from hatchery studies but little known about these vulnerable life stage in the wild. The high mobility of these species necessitates the inclusion of movements of all life stages, and the influence of movement on population demographics. Other gaps include the transferability of knowledge from the southern to northern MDB, where there is a dearth of research. This synthesis study assists fish-flow management by defining knowledge gaps and research priorities that are aligned with the needs of water managers.

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6 Appendices

Appendix 1 – Agenda for the fish-flow manager’s workshop.

Fish-flow manager’s workshop.
5 May 2016, Arthur Rylah Institute for Environmental Research

Objective: to determine the most relevant research questions for future flow management

Agenda:

9.00am Introductions (JK) <10 min>

9.10am Outline for the day (JK) <10 min>

9.20am EWKR Project background (AP) <10 min>

9.30am Current fish-flow ecology-management concepts (JK) <20 min>

9.50am Knowledge synthesis: Fish and flow ecology, trends, gaps, concepts, directions, ecological knowledge gaps (SB) <40 min>

10.30am Morning tea <30 min>

11.00am Current guidance for EWKR fish research (BZ) <15 min>

11.15am Flow manager’s feedback by each State rep (plus MDBA and CEWO) (10 min + 5 questions each) <75 min>

12.30pm Lunch <45 min>

1.15pm Questionnaire responses summary and discussion (JK) <75min>
What have we missed?
What else can help?

2.30pm Knowledge gaps and priorities for flow management for fish (BZ) <90 min>
Where do we all want flow management to be in 10 years’ time

4.00pm Wrap Up

Appendix 2 – a. Fish-flow manager's questionnaire

Name:____________________________Organisation______________________________

How do you manage water for fish outcomes?

What fish knowledge/information do you use?

What are your typical hydrological scenarios for fish outcomes?

How has this evolved in the last 5-10 years?

How will this change in the future?

What fish knowledge do/will you need?

Do you have priority fish species? What are they?

What spatial scale do you manage for?

What temporal scale do you manage for?

What are your actual or perceived risks when delivering water for fish outcomes?

What are your actual or perceived constraints when delivering water for fish outcomes?

What do you and don't you want from fish ecologists?

Any further comments?

Thanks greatly, we really do appreciate your time and effort to provide direction to research that may fill knowledge gaps that help you. **Responses by 27 April please.**
Thanks
John Koehn john.koehn@delwp.vic.gov.au

b. Fishery Manager's and angler recreational questionnaire

Name:____________________________Organisation______________________________

How do you think water should be managed for fish outcomes?

What fish knowledge/information do you think should be use?

What hydrological/flow scenarios should be used for fish outcomes?

How has this evolved in the last 5-10 years?

How will this change in the future?

What fish knowledge do you think is really needed?

Do you have priority fish species? What are they?

What spatial scale should be managed for?

What temporal should be managed for?

What are the actual or perceived risks when delivering water for fish outcomes?

What are the actual or perceived constraints when delivering water for fish outcomes?

What do you think should and shouldn't be provided by fish ecologists?

Any further comments?

Thanks greatly, we really do appreciate your time and effort to provide direction to research that may fill knowledge gaps that help fishes. **Responses by 27 April please.**
Thanks
John Koehn	john.koehn@delwp.vic.gov.au

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Appendix 4 – Summary of the ecological attributes of fish species in the Murray-Darling Basin.

LB= Large-bodied, M= medium, S=small (<200 mm).

Species	Size	River type	Preferred habitat features	Longevity (years)	Scale of adult/juvenile movements	Spawning season and temperature (estimated)	Spawning method	Fecundity (eggs, per female, per annum)	Larval drift
Murray Cod	LB	Slopes, lowland	Hydraulically complex streams containing submerged structure (e.g. rocks and snags).	Long-lived (< 60 yr.)	Meso	Sept-Dec (>18 °C)	Nesting, parental care	10,000 - 90,000	Yes
Trout Cod	LB	Montane, slopes	Deep flowing pools containing submerged structure (e.g. rocks and snags)	Long-lived (< 60 yr.)	Meso	Sept-Nov (>20 °C)	Nesting, parental care	1,000 - 10,000	Yes
Bony Herring	M	Slopes, lowland	Warm lotic and lentic waterbodies (streams and wetlands).	Medium-lived (< 5 yr.)	Meso	Oct-Feb (>18 °C)	Serial (multiple events per year)	33,000-800,000	Yes
Freshwater Catfish (Eel-tailed)	M	Montane, slopes, lowland	Slow-flowing streams and wetlands; well vegetated habitats containing snags, with fringing and riparian vegetation.	Medium-lived (< 8 yr.)	Meso	Sept-March (>20 °C)	Nesting, parental care	10,000-50,000	Yes
Golden Perch	M	Slopes, lowland	Lowland rivers; submerged structure (e.g. rocks and snags).	Long-lived (< 26 yr.)	Macro	Oct-April (>17 °C)	Serial (multiple events per year)	100,000-500,000	Yes
Macquarie Perch	M	Montane, slopes	Connected pools riffles and lakes, mainly in upper reaches with fringing and	Long-lived (< 25 yr.)	Meso	Oct-Dec (>17 °C)	Batch/Serial	10,000-100,000	No

			riparian vegetation.						
River Blackfish	M	Montane, slopes	Clear flowing water, gravel substrate with dense submerged and riparian structure. Occurs in some lakes.	Medium-lived (3-9 yr.)	Meso	Oct-Jan (>16 °C)	Nesting, parental care	200-500	No
Two-spined Blackfish	M	Montane, slopes	Clear flowing water in upland or montane streams. Dense submerged and riparian structure.	Medium-lived (3-9 yr.)	Meso	Oct-Dec (>17 °C)	Nesting, parental care	80-420	No
Silver Perch	M	Slopes, lowland	Lowland rivers; submerged structure (e.g. rocks and snags).	Long-lived (< 26 yr.)	Meso	Oct-Apr(>20 °C)	Serial (multiple events per year)	200,000-300,000	Yes
Spangled perch	M	Slopes, lowland	Warm lotic and lentic waterbodies including rivers, wetlands, drains and isolated water holes.	Medium-lived (< 5 yr.)	Meso	Nov-Feb (>20 °C)	Serial (multiple events per year)	20,000 - 115,000	Yes
Short-finned Eel (1)	LB	Slopes, lowland	Low flowing rivers and waterbodies in coastal catchments, occasionally in the Murray River. Spawning and early life stages at sea.	Long-lived (< 26 yr.)	Macro	Dec-Feb	Spawn at sea	500,000 - 3,000,000	Yes
Short-headed Lamprey (1)	M	Slopes, lowland	Marine/estuarine except for upstream spawning runs to flowing lowland rivers.	Medium-lived (5-6 yr.)	Macro	Aug-Nov	Serial (multiple events per year)	3,800 - 13,400	No
Congolli (1)	M	Slopes, lowland.	Estuarine areas and wetlands of coastal rivers. Prefers submerged structure.	Medium-lived (< 5 yr.)	Macro	May-Sept	Spawn at sea		Unknown

Australian Smelt	S	Montane, slopes	Low flowing pelagic habitat.	Short-lived (< 3 yr.)	Micro-meso	Sept-Feb (> 11°C)	Batch	100-1,000 eggs/batch	Yes
Carp Gudgeon (species)	S	Montane, slopes, lowland	Slow flowing well vegetated streams and wetlands.	Medium-lived (< 5 yr.)	Micro	Sept-April (>20 °C)	Batch, parental care	100-2,000	Sometimes
Dwarf Flat-headed Gudgeon	S	Slopes, lowland	Slow flowing well vegetated streams and wetlands.	Medium-lived (< 5 yr.)	Micro	Sept-April (>20 °C)	Batch, parental care	500-900	Sometimes
Flat-headed Gudgeon	S	Montane, slopes	Slow flowing well vegetated streams and wetlands.	Medium-lived (< 5 yr.)	Micro-meso	Sept-Feb (>20 °C)	Batch, parental care	500-900	Sometimes
Mountain Galaxias (3)	S	Montane, slopes	Pools and riffles in small and large streams (lowland and montane).	Medium-lived (3-9 yr.)	Meso	Sept-Dec (7-11 °C)	Batch	50-400	No
Murray–Darling Rainbowfish	S	Slopes, lowland	Slow flowing well vegetated streams and wetlands.	Medium-lived (< 5 yr.)	Micro-meso	Sept-Feb (>20 °C)	Batch	35-350	Sometimes
Flat-headed Galaxias	S	Montane, lowland	Slow flowing well vegetated streams and wetlands.	Short-lived (< 2 yr.)	Meso	Aug-Sept (>10.5 °C)	Serial (multiple events per year)	2,000-7,000	No
Olive Perchlet	S	Slopes, lowland	Slow-flowing streams and wetlands; well vegetated habitats containing snags.	Medium-lived (< 4 yr.)	Micro	Oct-Dec (>22 °C)	Serial (multiple events per year)	200-700	No
Purple Spotted Gudgeon	S	Montane, slopes, lowland	Slow-flowing streams and wetlands; well vegetated habitats containing snags.	Medium-lived (< 10 yr.)	Micro	Sept-Feb (>20 °C)	Batch, parental care	200-1300	No
Southern Pygmy Perch	S	Montane, slopes, lowland	Still or slow-flowing well vegetated streams and wetlands.	Medium-lived (3-7 yr.)	Micro	Sept-Jan (>16 °C)	Batch	100-4,000	No
Unspecked Hardyhead	S	Slopes, lowland	Slow flowing well vegetated streams and wetlands.	Short-lived (< 2 yr.)	Micro	Sept-April (>18 °C)	Batch	50-500	Sometimes
Murray Hardyhead	S	Slopes, lowlands	Saline habitats; often vegetated wetlands.	Short-lived (< 2 yr.)	Micro	Sept-April (>18 °C)	Batch	80-500	No
Climbing Galaxias (2)	S	Montane, slopes	Normally coastal streams; translocated and	Medium-lived (3-7 yr.)	Meso	April-May	Batch	7,000-23,000	Yes

			persists in upland Murray River tributaries.						
Spotted Galaxias (2)	S	Slopes, lowlands	Snags, rocks and overhanging banks of lowland coastal habitats. Translocated population in upper Campaspe and Loddon rivers.	Medium-lived (3-7 yr.)	Meso	Sept-Dec	Batch	1,000-16,000	Yes

Appendix 5 - Fish-Flow Manager's Questionnaire: Full responses.

Number of identical responses given in parentheses. Black text= summary of priority answers; blue text= other answers.

How do you manage water for fish outcomes?
Long-term environmental watering plans
Associated environmental water requirements
Annual environmental watering priorities, priority watering actions
Water delivery for particular outcomes
Protecting unregulated water

Fish outcomes are explicitly considered in ALL systems
Ecological targets: fish; systems; 'whole of system'
Design hydrographs- to mimic natural hydrographs (4)
Reinstate a portion of the natural flow regime, natural cues / modelled natural flows,
Lateral and longitudinal movement of fish (3) throughout the Basin
Floodplain for productivity/ fish (3)
Completion of native fish life cycles
Water quality
Access to a diversity of habitats
Managed floodplain inundations
Development of watering proposals and management/ monitoring
Provide information to delivery partners
Not just for fish

What fish knowledge/information do you use?
Monitoring4
Direct expert advice (Fisheries managers, researchers, local knowledge (4)
How fish respond to flows (3) various species, lifestages
Fish population dynamics (3)
Best available science (local and relevant international)
Recruitment, movement/habitat/food/ productivity requirements.
Survival rates
Designing hydrographs,
Real time advice as operational decisions are made (operational advisory groups).
Reports, journals, etc.
Mostly anecdotal
Information against Carp
WQ
Information consolidated into simple and straightforward messages for managers

What are your typical hydrological scenarios for fish outcomes?
Pulses (small, large): late Spring, 'return movement' in summer, inundate benches (3)
Maintain higher than minimum baseflows (2)
Spawning and recruitment (2)of large bodied natives
Movement cues (2), dispersal, facilitate fish passage- weir drownouts
Refuge pools: maintain/reconnect
Hydrograph components
Overbank events
All include fish
Inundation of habitat for small bodied threatened fish species
Outflows for migration and recruitment of diadromous fish, estuarine conditions
WQ

Depends on situation

How has this evolved in the last 5-10 years?
Population outcomes/whole lifecycle5 Recruitment rather than spawning3
New information on fish needs4
Monitoring4
Flows and connectivity 2
Greater complexity
The 'whole of system' approach v specific 'events'
Whole fish community. diadromous species
Fish specific objectives are now included
Design hydrographs (specific events)
AM
Increased scale
Refugia/preventing loss in drought
Larger volumes of water
Increased understanding of risks of loss
Improved understanding of Carp

How will this change in the future?
More monitoring and knowledge and refinements (7)
Landscape/System scale (not based on jurisdictions (6)
Better understanding of trade-offs (4)
Adaptive Management (2)
Coordination with off-channel watering events, river operations
Predicting and testing responses
Cues
Improved understanding by waterway managers
Wider range of species and life stages
Better understanding of food chain

What fish knowledge do/will you need?
Native fish responses to flow components (9)
Drivers of recruitment to increase native fish populations/population ecology/ dynamics (8)
Demonstration of fish outcomes (movement, general) (6)
Fish requirements understanding what is needed to achieve (2)
Ongoing monitoring (4) (incl thr spp)
Other pest species (3)
All life stages and species (2)
Koi virus be released, and water management strategies to maximise the effectiveness of it (2)
Ways to not benefit carp Carp (2)
Scale of effects (2)
Winter requirements (2)
Productivity from floodplain (2)
Current, previous and future fish distributions/status (2)
Water delivery across wider scale/connected systems (2)

Fish condition
Natal origin
Effect of antecedent flow conditions
Conceptual models for different fish flow ecology + the data that sits behind these.
Cues
Impact of environmental regulators
Trade-offs
Understanding habitat needs, predation risks

WQ tolerances
Declines due to other pressures
The value of unregulated water v regulated

Do you have priority fish species? What are they?
Large bodied native species (3): Murray Cod (6), Golden Perch (5), Trout Cod (3), Silver perch (4), Catfish (2) 'Macquarie perch
Threatened/listed species (5), Small bodied natives', 'others':- SPP (2), SPSG, OP MHH(2), YPP
All species- whole of fish community (5)
Diadromous species2- congollis, galaxiids, lampreys
Estuarine- black bream, greenback flounder, Mulloway, small mouthed hardyheads
Carp
Habitats/ecosystem needs/ productivity

What spatial scale do you manage for?
River reach (4)
Valleys/Catchments (3)
Basin scale/ Whole of Murray SA); southern connected
Wetlands
Connected- estuary fresh marine

What temporal scale do you manage for?
Long-term water plans are out to 20 years (6)
Annual Watering Priorities (6)
1-3 year basis. 1-5 years (2)
Seasonal
Use antecedent 10 years (2)

What are your actual or perceived risks when delivering water for fish outcomes?
Carp (6)
Water quality/Fish kills (4)
Pest species (2)
Not achieving outcomes (2)
Uncertainty in knowledge (2)
Water level management- operational issues/cannot achieve flows needed (2)
Get adverse outcomes
Opportunity cost to other values
Confounding factors
Flooding private land

What are your actual or perceived constraints when delivering water for fish outcomes?
Insufficient water available, timing, and competing demands for water (8)
Operational constraints (6)
Barriers to movement (3) (adequate flows for fishways)
Public anxiety of risks/3rd party impacts (3)
Lack of knowledge
Influence of carp
Policy constraints
The need to operate regulators- negating instream processes

What do you and don't you want from fish ecologists?
Do:
Provide robust, evidence-based information (research and monitoring) and timely, relevant advice to inform policy and be applied management in simple terms (11)

Be prepared to ‘give things a go’ (3)
A proactive, collaborative approach to determining research priorities and water proposals (3)
Hydrographs (2)
Carp (2) (Koi herpes)

Provide advice on potential trade-offs
Provide evidence to demonstrate outcomes
Monitor fish targets to determine outcomes of watering – positive and negative
How much is enough water
Gambusia
Help with changes to river operations/water delivery

Don’t:
Unfunded or dis-continuous fish MER programs
Southern basin fish outcomes that are untested in the northern basin
Academic research

Appendix 6 - Summary of knowledge gaps identified in the fish-flows manager's workshop

In order to get a range of views regarding knowledge gaps for potential EWKR projects, a workshop held at ARI on the 5 May that included fish ecologists and fish-flows managers representing regions across the MDB. In conjunction with the results from a previously distributed questionnaire, workshop presentations (ecological literature, management directions and regional managers), and considerable discussion, the following summary represents the outcomes derived in the final whiteboard discussion: broken into knowledge gaps from an ecological (a science only perspective) and those prioritized by managers.

Ecological knowledge gaps

1. **Population dynamics**
2. **Spatial and temporal scales and population processes**
3. **Rates: survival; growth**
4. **Recruitment (drivers, food, etc)**

Secondary priorities

- Fish condition (and effects on survival and recruitment)
- Fecundity

Management knowledge gaps

Highest priorities

1. **Population dynamics**
2. **Recruitment**
3. **Movement, dispersal and connectivity**
4. **Mechanisms/Causal links and thresholds (scale of variability; what are the drivers)**

Secondary priorities

- Trade-off processes
- Species-specific responses to flows
- Lifestage-specific responses to flows
- Scale - Landscape/system – site
- Refugia Flow thresholds, maintain or not, top up or not
- Recovery time (drought/blackwater) – recolonization, barriers.

Other

- Scales: of variability; temporal scales and water management
- Mechanism – what is the driver
- Community relevance
- Baseline habitat mapping to support monitoring and evaluation
- Flow components (whole hydrograph)
- Winter shut down
- Productivity (food web/floodplain)
- Carp/pest species
- Fish condition
- Flow integrity and source water, nutrient dilution, blue sky floods
- Water quality, DO – sub-lethal impacts

Comments
<u>Scientists need to be brave and adventurous</u>.
We all need to practice adaptive management

Manager's priority species
Manager's species priorities are often public driven, often focusing on large-bodied natives of community relevance. In adition, however, there is also consideration of the whole of fish community, umbrella or keystone species and particularly the need to address the needs of threatened species.
Large-bodied (priority order): Murray cod, Golden Perch, Trout Cod, Silver Perch, Macquarie Perch, Freshwater Catfish.
Small bodied fishes (priority order): Southern Pygmy Perch, Southern Purple Spotted Gudgeon, Olive Perchlet, Murray Hardyhead, Yarra Pygmy Perch.
Estuarine and diadromous species are also priorities in South Australia.
Carp.

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