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Background Paper: Use of life history conceptual models of fish in flow management in the Murray-Darling Basin

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Executive Summary

Conceptual life history models can form the basis of natural resource management but often the practical link between models and on-ground actions is unclear. For fish, conceptual models that link spawning and recruitment (survival of young), to broad hydrological categories such as floods, in-channel flows, or low-flows, provide little quantitative guidance for management. Significantly, fish do not respond to flow (i.e. discharge) *per se* but to the hydraulic characteristics of flow at a range of spatial scales and these features are the basis for the *ecohydraulic recruitment guilds* developed in this paper. The guilds distinguish between fish that spawn and recruit in lotic (flowing water) and lentic (still-water) habitats, over micro (< 100 m), meso (100s m to 10s km) and macro (100s km) spatial scales.

The guilds readily identify groups of threatened fish species that share ecohydraulic characteristics. All species that require lotic habitats (e.g. Murray cod) and all species that are lentic (wetland) specialists (e.g. southern pygmy perch) have declined and these two groups contain almost all threatened species in the MDB. Conversely, almost all species that are habitat generalists and spawn and recruit in lentic and lotic habitats over a micro or meso-scale (e.g. carp gudgeons) remain relatively abundant. This group also includes most of the non-native fish species.

The immediate implication for flow management is that the high priority rehabilitation actions in the MDB are: i) creating or maintaining lotic habitats at the meso- and macro-scale, and ii) providing flows to create or maintain specialised lentic habitats for wetland specialists. Examples are provided in Mallen-Cooper and Zampatti (2015)[1] .

Ecohydraulic recruitment guilds enable qualitative and quantitative environmental outcomes to be developed directly for flow recommendations, and the use of spatial scale and hydraulics readily lends itself to SMART (Specific, Measurable, Attainable, Realistic, Tim-Related) flow targets. For example, fish in the *macro-lotic guild* with a Qualitative Environmental Outcome of ‘enhance spawning and recruitment’ would have a Quantitative Environmental Outcome of ‘provide lotic conditions for sufficient uninterrupted longitudinal distance’, and SMART flow targets of: distance >500 km; mean channel velocity >0.2 m/s and Reynolds number > 2500.

Using hydraulics and spatial scale in *ecohydraulic recruitment guilds* helps identify where flow can be used for the most effective ecological outcome and areas that have high potential for rehabilitation.

[1] Background Paper: The Natural Flow Paradigm and managing flows in the Murray-Darling Basin.

Contents

TERMINOLOGY

Lotic

Refers to flowing water (also called running water). In riverine ecology, this is a current that is readily detected by eye (Padmore 1997). It is more specifically defined as a mean current velocity between 0.1 and 1.0 m/s (Wetzel 2001) but the ecological threshold for flowing water and lotic biota is generally greater than 0.2-0.3 m/s (e.g. (Ramírez and Pringle 1998; Passy 2001)).

Lentic

Refers to still-water habitats (also called standing water) such as lakes, wetlands and weir pools.

Hydraulic complexity

Variation in water depth, width, velocity and vector (direction). Includes turbulence which is a function of velocity and varying vectors.

Hydrodynamics

Distribution and variation in hydraulic complexity over a range of spatial (e.g., cm, m, km, 100s km) and temporal scales.

Flow

Discharge or the rate that a volume of water passes a specific point over a unit of time (e.g. m^3/s, ML/d, GL/month). *Streamflow* is used to describe flow in rivers and streams.

Hydrology

Study of streamflow and the various characteristics associated with discharge (e.g. magnitude, duration, rate of rise and fall, seasonality, etc.).

1 INTRODUCTION

Conceptual models are representations of complex systems that use available data and contemporary understanding of causal factors to describe ecological processes and patterns and interactions between these. They can be simple or complex and are usually pictorial or diagrammatic, but can also be a concise description in text. The strength of conceptual models is that, in addition to being predictive, they link components of a system together to present a holistic view. The model, and the process of constructing the model, can highlight knowledge gaps, identify research and monitoring priorities, and clarify and synthesise thinking.

Conceptual models of life history and ecology are fundamental to natural resource management. They represent contemporary understanding of available data and are used to inform management decisions. For example, investment in fishways is based on data of fish migration that forms a conceptual model about the whole life history of fish (e.g. adults migrate upstream; spawning occurs; larvae drift downstream) and the role that migration plays in sustaining populations. Various elements of the model (e.g. distance of downstream larval drift) remain as knowledge gaps but this does not restrain using the model to inform management and investment.

In this paper we briefly examine a broad conceptual model of fish and flows to highlight the differences in the management of fish and aquatic biota compared to terrestrial floodplain flora and fauna. We then propose a series of *recruitment guilds* that can be used to develop flow management objectives for fish and could further lead to qualitative and quantifiable environmental outcomes. Using these guilds we show how hydrologic change in the Murray River has led to declines of fish populations and where to target rehabilitation.

2 CONCEPTUAL MODELS

2.1. Flow-habitat-connectivity; a universal model for freshwater fish

At a high level, a fundamental ecological model for riverine fish is that “*flow*, *habitat* and *connectivity* are all required for sustainable fish populations”. Any one aspect can affect fish populations but the extent varies between species depending on life history flexibility. *Flow* here incorporates hydrology, hydraulics (hydrodynamics) and water physico-chemistry, which are all particularly relevant to the management of floodplain rivers. These characteristics, plus *habitat* and *connectivity*, differentiate fish and aquatic biota from floodplain flora and fauna, where water depth, inundation area and duration are more important. *Connectivity* is often considered in terms of the movement of biota but it also includes hydrological connectivity, where the river and floodplain hydrographs are in phase and transport of carbon and propagules occurs freely, and hydrodynamics, where a mosaic of interconnected lotic and lentic habitats are maintained.

Implications for flow management

Delivery of flow for aquatic ecosystems needs to consider *connectivity* and *habitat* to optimise benefits. For example, flows that are delivered to river reaches that are less fragmented by weirs and have more diverse habitat, including hydrodynamic diversity, are likely to result in greater ecological outcomes.

2.2. General Models of Recruitment

There are seven general models of recruitment that apply to fish in the Murray-Darling Basin. Recruitment is defined here as the survival of young (eggs and larvae) in the first year of life, which overcomes the period of highest mortality.

Flood recruitment (Lake 1967)

Recruitment occurs when floodplains are inundated, increasing productivity and larval survival. Likely applies to all lowland and arid species to some degree.

Implications for flow management

Hydrological and hydrodynamic connections between the river and floodplain are important in managing flows for the environment, to enable carbon transport between the river and floodplain and to enable fish to use multiple habitats.

In-channel flow recruitment (Mallen-Cooper and Stuart 2003)

Recruitment occurs when there is variation in within-channel flows in spring and summer. Applies to golden perch, silver perch, and possibly Murray cod and trout cod. Potentially applies to the Southern and Northern Basin, including arid rivers.

Implications for flow management

In-channel flow pulses are a part of the hydrograph that has been severely impacted by river regulation in the Murray-Darling Basin, particularly in the Murray and Darling rivers (Maheshwari *et al.* 1995; Thoms 2003; Zampatti and Leigh 2013).

Low-flow channel recruitment (Humphries *et al.* 1999)

Recruitment occurs within channel habitats of lowland slow-flowing rivers at low stable flows. Applies to generalist species which, apart from freshwater catfish and dwarf flat-headed gudgeon, remain common in regulated rivers in the Murray-Darling Basin.

Implications for flow management

Downstream of irrigation areas low flows are common throughout the Basin and in many cases accentuated. Between storage dams and irrigation areas, however, low flows are often impacted by the spring/summer delivery of water for consumptive use, hence flows are unseasonally high. The impact of artificially high flows in these reaches is difficult to mitigate as they are primary conduits to deliver irrigation flows. Nevertheless, increasing the structural complexity of these reaches (e.g. reinstatement of snags) may provide greater hydrodynamic diversity.

Off-channel (lentic) recruitment

Survival of young to maturity occurs entirely within off-channel habitats, such as wetlands, billabongs, lakes, and isolated anabranches. Includes wetland specialists such as southern pygmy perch and flat-headed galaxias, and generalists such as carp gudgeons and freshwater catfish. Applies to rivers with well-developed floodplains, usually with permanent off-channel habitats, although suitable lentic habitats can occur in the river channels with zero or very low flows.

Implications for flow management

Flows are required to maintain off-channel refugia as the full life cycle is completed in habitats that can be disconnected from the river and are susceptible to dessication.

Arid refugia recruitment

Spawning and recruitment occurs in zero flows in channel refugia in arid rivers (Balcombe *et al.* 2006; Kerezsy *et al.* 2011). (For some species recruitment is enhanced by pulses of flow, conforming more to in-channel flow recruitment).

Implications for flow management

Abstraction of low flow needs to consider the maintenance of channel refugia, especially since their volume and permanency may have been reduced by sedimentation.

Estuarine recruitment

Spawning and recruitment occurs in the estuary, either by estuarine residents (e.g. black bream) or freshwater species after migration from upstream (e.g. *Galaxias maculatus*).

Implications for flow management

Flow is required to connect freshwater habitats with the estuary and create a gradient of salinities. Estuarine recruitment is dependent on productivity created by influxes of freshwater.

Marine recruitment

Spawning occurs in the sea after migration from freshwater (e.g. shortfinned eels and congolli).

Implications for flow management

Flow is required to connect freshwater habitats with the estuary, stimulate downstream migration of adults and upstream migration of juveniles. Recruitment of these species is probably not dependent on productivity in the estuary.

For the fish that recruit in freshwater (the first five groups above) these models provide broad principles for flow management, particularly with regards to hydrology. Nevertheless, they generally lack reference to scale and a hydraulic perspective. These two factors, which incorporate principles of connectivity, habitat and hydrodynamics, are integral to understanding the life history processes (and hence population dynamics) of freshwater fishes and provide new opportunities for flow management.

2.3. Fish Guilds

2.3.1. Background

Guilds have been used for Murray-Darling fishes to understand the broad relationships between recruitment (survival of young) and floods (Lloyd *et al.* 1991), and to group fishes based on reproductive characteristics such as fecundity (number of eggs), size of embryo and parental care (Humphries *et al.* 1999; Growns 2004). “The implicit assumption for the use of guilds for management . . . is that species with the same traits . . . respond in the same manner to the same ecological conditions” (Growns 2004). In the regulated rivers of the Murray Darling Basin, however, there are species within the same reproductive guild that have severely declined while others thrive. Examples are carp gudgeons (thriving) and southern pygmy perch (declined) in Humphries *et al.*’s (1999) Mode 3b (long spawning period, low fecundity, small eggs, short period to first feed), or flat-headed gudgeon (thriving) and trout cod (declined) in Grown’s (2004) Guild C2 (parental care, no spawning migration, adhesive demersal eggs). Hence, under the same environmental conditions, fish within the same guild are responding very differently.

More recently Murray–Darling fishes have been grouped using reproductive characteristics, longevity, and partly habitat, trophic level, and response to flow; to develop four flow guilds (long-lived apex predators, flow-dependent specialists, foraging generalists, and floodplain specialists) (Baumgartner *et al.* 2013). These guilds enabled the development of hydrographs and frequency of application.

Rather than reproductive characteristics, we propose a model of *recruitment guilds* based on the primary characteristics of the river to which fish respond i.e. hydrodynamics, spatial scale and habitat. These *ecohydraulic* characteristics correspond to the major changes in river systems in the MDB – flow, fragmentation by dams and weirs, and habitat - and to the key management tools available for rehabilitation. We use hydrodynamics rather than flow (i.e. discharge) because this not only incorporates volumes of water and rates of movement but includes hydraulic complexity (depth, width, velocity, vector [direction] and turbulence) over time and space; it thus makes the important ecological distinction between *lentic* and *lotic* habitats, and it is these features which have a fundamental influence on life history processes such as migration, dispersal, feeding, spawning and recruitment. Changes to these hydraulic parameters are not described by discharge metrics.

2.3.2. Ecohydraulic Recruitment Guilds

To develop ecohydraulic recruitment guilds of freshwater fish species in the MDB we examined two key characteristics (Table 1):

i) *Hydrodynamics of habitats where recruitment occurs*: *lotic* or *lentic*, applying to spawning and recruitment (i.e. nursery areas). Lotic habitats include flowing streams with a pool-riffle structure and large flowing rivers. Lotic recruitment was differentiated if it: i) occurred wholly in lotic habitats, ii) occurred in large lentic habitats downstream of lotic habitats, or iii) was enhanced by increasing discharge within–channel, or overbank flooding.

ii) *Minimum spatial scale of spawning and recruitment*: the minimum scale over which spawning movements occur and over which recruitment occurs. Scales comprise micro (< 100 m), meso (100s m to 10s km) and macro (100s km). Fish that recruit at small-scales can recruit at larger scales, given the appropriate environmental conditions, but larger-scale species cannot recruit at smaller scales.

The broad habitat type (channel, off-channel or intermittent arid river) in which the life cycle is completed (i.e. not only recruitment) - determined by the presence of larvae and adults in a habitat - was then examined to review correlation of ecohydraulic recruitment guilds with habitat guilds and align these with flow management. Short-lived species that were present only in isolated off-channel habitats, preferably including adult and early life stages, were considered lentic.

We included species found presently or historically in the lowlands (<400m[1]) of the Murray-Darling Basin but excluded diadromous species in the lower lakes because they are not riverine. Short-headed lamprey is the only diadromous species included because it utilises and spawns in riverine habitats.

For context, Table 1 includes characteristics that were not used in the classification, including population trend (based on threatened species status and SRA data), body size, longevity, and conservation status. The biological information is from books on Australian fish biology (Merrick and Schmida 1984; McDowall 1996; Pusey *et al.* 2004; Lintermans 2007) or peer reviewed literature as referenced in Table 1.

Based on hydrodynamics and spatial scale there are three specific recruitment guilds of *macro lotic*, *meso lotic,* and *micro lentic;* and two combined guilds *of meso lotic-lentic, micro-lotic-lentic* which have species with flexible recruitment strategies (Figure 1).

A few species do not clearly fit the guilds. The spatial scale of the lotic-lentic guilds is uncertain for four species and is shown as overlapping in Figure 1. The non-native species, carp, is considered a lotic-lentic generalist and completes its life cycle in a range of habitats, but it requires specific spawning habitats that most frequently occur in wetlands. The spatial scale of small-bodied fish movements is also poorly known, but it is assumed that if they

[1] Only one species is found exclusively above 400 m elevation: barred galaxias.

Table 1. Freshwater fish in the lowlands (< 400m elev.) in the Murray-Darling Basin, with habitat and hydrodynamic recruitment characteristics. Diadromous species in the lower lakes are excluded. Threatened species (state or federal) are shaded in grey.

	CRITERIA USED IN CLASSIFICATION											
	HABITATS (completes life cycle)			SCALE	LOTIC			LENTIC				
	Channel habitats	Off-channel habitats (wetlands)	Intermittent arid rivers	Minimum spatial scale of spawning and recruitment • micro (< 100 m) ● meso (100s m–10s km) ⬤ macro (100s km)	Spawning and recruitment in lotic habitats	Recruitment in large lentic habitats downstream of lotic habitats	Recruitment enhanced by increasing discharge within-channel and/or floodplain inundation	Spawning and recruitment in lentic habitats	Specific substrate required for spawning	Pop^{n}. trend ↓↓ severe decline ↓ decline — stable ↑ increasing	Bodysize • Small ● Medium ⬤ Large	Longevity • Short ● Moderate ⬤ Long
Golden perch	✓[xx]		✓	⬤	✓[xx, i]	✓[ii]	✓[iii]	?[iv]		↓	●	⬤
Silver perch	✓[xx]		✓	⬤	✓[xx]		✓[v]			↓	●	⬤
Shortheaded lamprey	✓			⬤ [vi]	✓[vii]					↓	●	●
Murray cod	✓[xx]			●[viii, ix, x]	✓[xx, xi]		✓[xii]			↓	⬤	⬤
Trout cod	✓[xx]			●[xiii]	✓[xx]		?		?	↓↓	⬤	⬤
Macquarie perch	✓			●	✓[xiv]				✓	↓↓	●	⬤
River blackfish	✓			●	✓[i, xv]				✓	↓	●	●
Two-spined blackfish	✓			●	✓				✓	↓	●	●
Broad-finned galaxias (T[xvi])	✓[xx, i]			●	✓[xx, i]	✓				↑	•	?
Spotted galaxias (T?)	✓			●	✓	✓				↑	•	?
Mountain galaxias	✓[xx]			●[xvii]	✓[xx]					↓	•	?
Darling River hardyhead	✓			?	?		?	?		?	•	•
Dwarf flat-headed gudgeon	✓	✓		?	?			?		↓	•	•
Freshwater catfish	✓	✓	✓[iv]	●[xviii, xix]	✓		?	✓		↓	●	●
Bony herring	✓	✓	✓	●	✓		✓	✓		—	●	●
Spangled perch	✓	✓	✓	●	✓		✓	✓		—	●	●
Flat-headed gudgeon	✓[i, xx, xi]	✓[xx]		•	✓[i, xx]		✓[xi]	✓[xx]		—	•	•
Un-specked hardyhead	✓[xi]	✓[xx]		•	✓[xi]		✓[xi]	✓[xx]		—	•	•
Murray–Darling rainbowfish	✓[i, xi]	✓	✓	•	✓[i]			✓?		—	•	•
Carp gudgeons	✓[xx, i, xi]	✓[xx, xxvi]	✓	•	✓[i, xx]		✓[xi, xxi]	✓[xx, xxvi]		—	•	•
Australian smelt	✓[i, xx, xi]	✓[xx, xxvi]	✓	•	✓[i, xx]		✓[xxii]	✓[xx, xxvi]		—	•	•
Southern pygmy perch		✓		•	?[xx]		✓[xxiii]	✓[xxiii]	?	↓↓	•	•
Yarra pygmy perch		✓		•				✓	?	↓↓	•	•
Southern purple-spotted gudgeon		✓		•				✓	?	↓↓	•	•
Flat-headed galaxias		✓		•				✓		↓	•	•
Murray hardyhead		✓		•				✓		↓↓	•	•
Olive perchlet		✓	✓	•	?			✓	?	↓↓	•	•
Desert rainbowfish			✓	?				✓		?	•	•
Rendahl's tandan			✓	?				✓		?	●	?
Hyrtl's tandan			✓	?			✓	✓		?	●	?

	CRITERIA USED IN CLASSIFICATION											
	HABITATS (completes life cycle)			SCALE	LOTIC			LENTIC				
	Channel habitats	Off-channel habitats (wetlands)	Intermittent arid rivers	Minimum spatial scale of spawning and recruitment • micro (< 100 m) ● meso (100s m–10s km) ⬤ macro (100s km)	Spawning and recruitment in lotic habitats	Recruitment in large lentic habitats downstream of lotic habitats	Recruitment enhanced by increasing discharge within-channel and/or floodplain inundation	Spawning and recruitment in lentic habitats	Specific substrate required for spawning	Pop[n]. trend ↓↓ severe decline ↓ decline — stable ↑ increasing	Bodysize • Small ● Medium ⬤ Large	Longevity • Short ● Moderate ⬤ Long
Non-Native Species												
Carp	✓[i,xx]	(✓)[xxiv,xx]	✓	●	?[i]	✓	✓[xxv]	✓[xxv]		—	●	⬤
Goldfish	✓[xx]	✓[xx]	✓	•				✓		—	•	?
Eastern gambusia	✓[xx]	✓[xx, xxvi]	✓	•		✓	✓	✓[xxvi]		—	•	•
Redfin perch	✓[xx]	✓[xx]		•	?[i]	?[i]		✓		—	●	●
Tench	✓	✓		●?				✓		—	●	⬤
Oriental weatherloach		✓[xx]		•?			✓	✓		↑	•	•

[i] Humphries, P., and Lake, P. (2000) Fish larvae and the management of regulated rivers. *Regulated Rivers: Research & Management* **16**(5), 421-432.
[ii] Recruitment occurs in terminal systems or large floodplain lakes that fill from lotic riverine habitats (e.g. Menindee Lakes, Lake Cowal)
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[xv] Very low level of current required (McDowall, R. (1996) 'Freshwater fishes of south-eastern Australia.' (Reed))
[xvi] T = translocated
[xvii] Recolonisation by juveniles at meso-scale:
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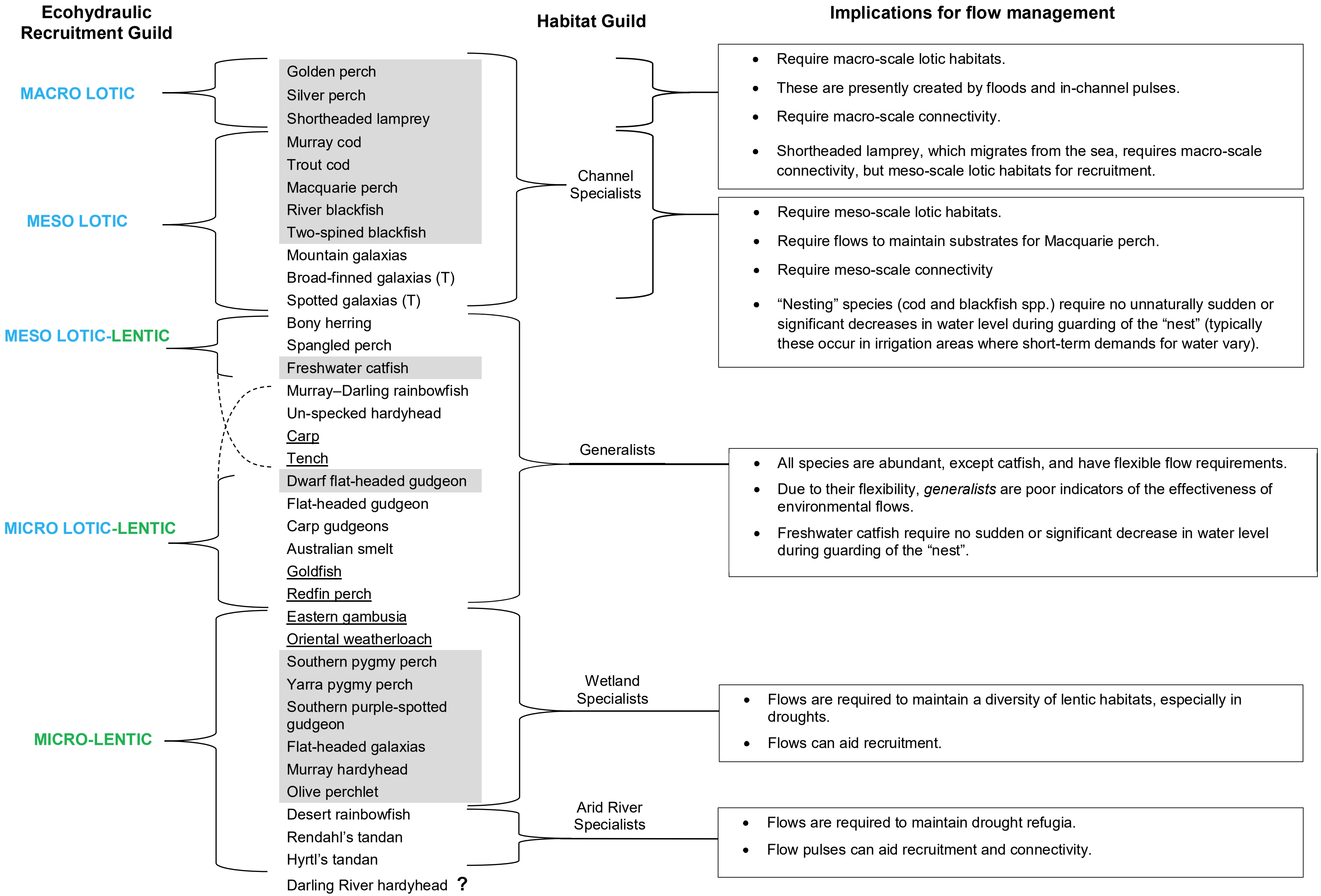


Figure 1. Ecohydraulic Recruitment Guilds and Habitat Guilds for native fish in the Murray-Darling Basin, shown with flow recommendations. Shaded species are threatened or have declined significantly.

complete their life cycle in small lentic habitats that a larger spatial scale is not specifically required in rivers. The life history of the Darling River hardyhead is poorly known in general.

As noted earlier, fish that recruit at small-scales can recruit at larger scales. Murray cod is classified as *meso-lotic*, however, for this species it may be that macro-scale recruitment is more significant for population dynamics and sustaining populations over the long term.

The recruitment guilds are presented in Figure 1 alongside habitat guilds and implications for flow management. All these guilds do not include the parameters of water temperature or water quality. Spawning of all fish is seasonal and related to water temperature and often day length. Water temperature is impacted by low–level offtakes of dams releasing cold water. The recruitment guilds apply to rivers that are not impacted by reduced water temperature or poor water quality, as these factors would override the life history characteristics considered here.

The habitat guilds align well with ecohydraulic recruitment guilds (Figure 1). The *macro-* and *meso-lotic* species are channel specialists while the *micro-lentic* guild has two identifiable habitat guilds of: wetland specialists and arid river specialists.

All species that can spawn and recruit in both lentic and lotic habitats, over a meso- or micro-scale, are generalist species that remain relatively abundant. Four of the six non-native species (carp, goldfish, redfin and tench) are also generalist species, while two (gambusia and oriental weatherloach) are wetland specialists.

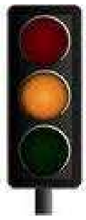
The recruitment guilds are independent of reproductive characteristics such as fecundity or size of larvae, but importantly they identify: i) the type and scales of flows that are required for fish recruitment and, ii) the guilds that have declined in regulated rivers of the MDB. Declining species, with the exception of freshwater catfish and dwarf flat-headed gudgeon, either require *lotic* habitats over macro or meso scales, or specific *micro-lentic* (wetland) habitats.

The immediate implication for flow management is that the high priorities are: i) creating or maintaining lotic habitats at the meso- and macro-scale, and ii) providing flows to create or maintain specific lentic habitats for *wetland specialists*. The first can be achieved through: management of weir-pools; water delivery to meet a minimum velocity and hence create lotic conditions; use of irrigation systems based on natural anabranches; and reconnecting anabranches that have been cut off from the river (Mallen-Cooper and Zampatti 2015[1]). The second priority can be achieved through identifying suitable wetlands and maintaining them as a network of permanent drought refugia, which would require small amounts of water but could be achieved independently of large-scale floodplain watering (Mallen-Cooper and Zampatti 2015[1]).

The following discussion of guilds expands on the management implications and uses traffic light symbols that indicate priorities of very high (red), high (orange), and low (green). There is no group that is a moderate or intermediate priority. *Arid river specialists* have been tentatively included as a group that has not declined as they are still regularly collected, but little is known of their natural abundance.

[1] Background Paper: The Natural Flow Paradigm and managing flows in the Murray-Darling Basin.

2.3.2.1. Macro-lotic Guild



Three species are represented in this guild: golden perch, silver perch and short-headed lamprey (Figure 1). These fish spawn and recruit in lotic habitats but golden perch is more flexible, as it recruits in lentic habitats, such as semi-terminal lakes, that are downstream of macro-scale lotic spawning areas in rivers (Rolls and Wilson 2010; Sharpe 2011). Examples of these sites include Menindee Lakes and Lake Cowal (Lachlan River catchment).

Golden perch and silver perch have drifting larvae and are considered to conform to the flood-recruitment model. These two species also have strong year classes associated with in-channel pulses (Mallen-Cooper and Stuart 2003; Zampatti and Leigh 2013). In both these hydrological scenarios, continuous lotic habitats occur over 100's of kilometres of river, presumably with larval drift over this scale.

The life cycle of short-headed lamprey is macro-scale; adults migrate from the estuary up to 2000 km upstream, passing through lentic (weir-pools) and lotic conditions. Recruitment, however, appears to be meso-scale with spawning in lotic habitats with substrates of sand, pebbles or gravels, and juveniles (ammocetes) found in slow-flowing, but not lentic, habitats of sand, silt or mud (Koehn and O'Connor 1990; Lintermans 2007). A diversity of lotic conditions and substrates at the meso-scale is important for this species.

Management Implications

The *macro-lotic guild* is highly susceptible to river regulation due to the fragmentation and loss of connectivity, and loss of lotic habitats. Physical connectivity for species that are moving over large distances is being addressed through fishways across the Basin, most notably the Hume-to-Sea fish passage program, although passage of lampreys through fishways remains unknown.

Flow management needs to consider protection of macro-scale flow events that create suitable hydrodynamic conditions. In the Murray River in particular, large floods (e.g. >100,000 ML/d) remain little impacted by river regulation but the smaller flood events and in-channel pulses, such as flows with a 1 year Annual Recurrence Interval[1] (ARI), have been severely impacted by flow regulation (Maheshwari *et al.* 1995; Thoms 2003; Zampatti and Leigh 2013).

Restoration of the 1 year ARI would be a desirable ecological goal but is unlikely to be practical on a macro-scale. Considering that the species in this guild are long-lived, a productive discussion would be on the merits and practicality of reinstating the 1 year ARI volume and spatial scale, but at a lower frequency, such as 1-in-3 years. Using this temporal scale suggests that management of environmental flows needs to consider decadal hydrological cycles.

[1] A peak flow with a probability of occurring once a year.

2.3.2.2. Meso-lotic Guild

The meso-lotic guild has eight species, five of which are threatened or have declined including Murray cod, two blackfish species, trout cod and Macquarie perch. *Meso-lotic* species move over 100s metres to 10s kilometres and spawn in lotic habitats that are slow-moving (e.g. blackfish) to faster flowing (e.g. Macquarie perch). As noted earlier, the minimum scale of recruitment for Murray cod is meso but the population dynamics may be dependent on macro-scale recruitment events.

These species could also be tentatively grouped into two sub-guilds based on specificity of spawning substrates. Murray cod are known to spawn on rocks, large woody debris and even in earthen ponds. Trout cod are presumed to be similar in reproductive biology to Murray cod, but unlike Murray cod do not spawn in earthen ponds suggesting they have more specific spawning substrate requirements. Trout cod have demersal, adhesive eggs and rocks and logs have been suggested as spawning substrates; both of these habitat features have declined due to desnagging and sedimentation. Compared to Murray cod, trout cod also prefer slightly faster-flowing habitats (Koehn and Nicol 2014), which have been more impacted by weirs. Interestingly, when trout cod were present in the lower Murray (i.e. downstream of the Darling River junction) they were referred to as “rock cod” (Stead 1929), often being collected at sites with rocky substrates and fast flow.

Macquarie perch also appear to require specific substrates for spawning; in this case cobbles or gravel riffles (Lintermans 2007). These habitats have been severely impacted by the creation of weir pools and sedimentation in the lowlands of the MDB. Within the *meso-lotic guild* Macquarie perch and trout cod have had a major reduction in distribution while Murray cod, which use a wider range of spawning substrates, have declined in abundance but retain much more of their original range. The two blackfish species have declined in range and abundance but not to the same extent as Macquarie perch and trout cod.

An interesting unifying feature of the threatened species in this group is that they all have eggs that are either attached to a substrate and guarded by a parent (cod and blackfish species), or spawned in a substrate (Macquarie perch); both strategies have direct implications for flow management that are discussed below.

Management Implications

Fish in the *meso-lotic guild* are less susceptible to the fragmentation of habitats in regulated rivers than the *macro-lotic* guild, if three conditions are met:

i) the spatial scale of the life cycle is not fragmented (i.e. the life cycle can be completed between barriers);

ii) there are sufficient lotic habitats available; and

iii) spawning substrates are available.

The meso-lotic guild is more susceptible to changes in spawning substrates than other guilds, which is likely to be a major contributing factor in the decline of these species.

The spawning strategy of these species, to have attached or placed eggs, also makes them particularly susceptible to rapid and unseasonal changes in water levels, which can occur when water is delivered for consumptive use and is exaggerated near irrigation areas which have short-term demands. Rapid decreases in water level (e.g. 0.5 m over a few days) in the spawning season may cause adult fish to abandon the nest, or eggs to be directly exposed, in both cases causing the eggs to die.

Meso-scale is a highly manageable scale as it frequently fits within present flow management units. Flow recommendations for this guild need to incorporate two key hydrodynamic objectives: 1) maintaining lotic conditions and 2) restricting sudden water level changes in the spawning season.

Lotic conditions appear critical for the survival of larvae of the two cod species and critical for spawning of Macquarie perch and the two blackfish species. To quantify lotic conditions for management, the simplest and most readily applicable measure is mean channel velocity (e.g. 0.4 to 0.9 m/s). Further investigation could also use measures of hydraulic roughness or turbulence, using the extent of rocky substrates, snags and the sinuosity of the stream channel, to reflect hydrodynamic complexity.

Sudden level changes, mainly decreases, are easily measured and need to be avoided during the spawning season. Managing levels can be done through flow management or by topping up irrigation flows with environmental flows to suppress variation. This approach has recently been demonstrated in Gunbower Creek (Sharpe *et al.* 2014).

Meso-lotic conditions need to be protected where they presently occur. Site examples include Mullaroo Creek, near Lock 7, the Chowilla anabranch creeks in the vicinity of Lock 6, and the Murray River downstream of Yarrawonga and Torrumbarry weirs.

Identifying meso-lotic conditions as a feature for spawning and recruitment of a group of fish provides opportunities for investigating habitats where these conditions could be created or enhanced. Examples include optimising flow in anabranch creeks that are presently used for irrigation, lowering weir-pools, and managing flows in the lower Darling River (downstream of Menindee). Most of these can be achieved without additional flow (Mallen-Cooper and Zampatti 2015).

The effects of floods, which are macro-scale, are variable in this guild. Murray cod recruitment is enhanced by floods (Rowland 1998; Ye and Zampatti 2007) and it is possible that trout cod follow the same pattern. Macquarie perch and blackfish are now restricted to upland streams that have little floodplain development and high flows in these streams post-spawning may cause displacement and mortalities of eggs and larvae (Mark Lintermans, pers. comm.).

Using the term *meso-scale* in these guilds refers to the minimum spatial scale of recruitment within one season or year, and to the spatial scale of the flow regime. *Macro-scale* movements are still required to maintain genetic heterogeneity of metapopulations[1] and to repopulate areas following large-scale perturbations such as drought and blackwater events.

2.3.2.3. Lotic-lentic guilds

There are two combined lotic–lentic guilds, at the micro and meso scale. Although the minimum scale of recruitment of some species is uncertain, all species in these guilds are *habitat generalists*, spawning and recruiting in a wide range of lentic and lotic habitats including river channels, weir-pools, and wetlands of varying sizes (Koehn and Harrington 2005; Smith *et al.* 2009). With the exception of dwarf flat-headed gudgeon and freshwater catfish, these fish appear not to have declined in the Murray-Darling Basin, and in the artificial lentic habitats of weir-pools, are arguably more abundant.

Management Implications

Since the *habitat generalists* have declined little and, in a regulated, modified river system, they have extensive habitat for spawning and recruitment, specific environmental flows are not required for this group. These species are also inappropriate indicators of the effectiveness of environmental flows as they are likely to recruit under most conditions. Large natural floods appear to be the only conditions where recruitment of this group is reduced in the main channel (Bice *et al.* 2013), but they remain abundant in wetlands.

2.3.2.4. Micro-lentic Guild

Native fish in the *micro-lentic guild* can be divided into two sub-guilds based on habitat use. The first are the *wetland specialists*, which spawn and recruit in lentic habitats and have specific requirements for wetland size, aquatic vegetation, turbidity and connectivity. These are generally off-channel habitats but rivers and streams that cease to flow can develop suitable lentic characteristics. The species in this group are all threatened and have suffered major reductions in range and abundance.

The second sub-guild is the *arid river specialists*. These spawn and recruit in arid rivers with intermittent flow and frequent periods of zero flow with lentic conditions, but also in flow pulses or floods (Balcombe *et al.* 2006; Kerezsy *et al.* 2011).

Management Implications

The *wetland specialists* are a management priority and consideration of habitat quality as well as flow is integral. At the most basic level flow is required to maintain these habitats, which are susceptible to desiccation in droughts due to storage and diversion of flow (Hammer *et al.* 2013). Two modes of flow management are applicable to this group: 1) localised application of flow to maintain specific refugia and 2) managing large events to establish a mosaic of habitats.

For the second sub-guild of *arid river specialists* two major processes structure the fish assemblage: 1) refugia shape and size (Balcombe et al. 2006) and 2) flow pulses

[1] A population with physically separated, but genetically linked groups, where gene flow between the groups maintains heterogeneity.

or floods (Balcombe and Arthington 2009; Puckridge et al. 2010). Under natural conditions, permanent refugia are prevented from desiccation by small flow pulses which compensate for evaporation (Hamilton et al. 2005). An essential flow management objective for this sub-guild and for these ecosystems is to prevent desiccation and protect small flow pulses from abstraction. It is worth noting that historical flows may not provide accurate indicators of the required flow, or an acceptable level of abstraction, as land use and sedimentation may have affected the depth of these refugia, as it has elsewhere in the MDB (Bond and Lake 2005), making them more prone to evaporation. The connectivity of arid rivers in the Basin has also been affected by weirs, reducing the opportunities for recolonisation from 100% during periods of flow to less than 5% of the time (Nichols *et al.* 2012).

2.4. Floods, in-channel pulses and ecohydraulic recruitment guilds

Floods and in-channel pulses have specific ecological roles in river-floodplain ecosystems and these directly relate to the proposed ecohydraulic recruitment guilds (Figure 2). Large floods are major ecological events that inundate the floodplain and release carbon leading to large increases in productivity. This is a fundamental part of the Flood Pulse concept (Junk *et al.* 1989) and leads to the Flood Recruitment Model for fish (Lake 1967) where high productivity produces high densities of plankton and high survival of fish larvae. All species in the *macro-lotic guild*, except short-headed lamprey, appear to conform to the Flood Recruitment Model and, since they are also long-lived, it may be the fundamental process of recruitment that structures these populations and provides resilience in the long-term.

In-channel pulses are known to increase recruitment of two *macro-lotic* species, golden perch (Zampatti and Leigh 2013) and silver perch (Mallen-Cooper and Stuart 2003), and arid river species that also recruit in zero flows and meso-lentic habitats (Balcombe *et al.* 2006; Kerezsy *et al.* 2011). Although the productivity of in-channel pulses is not documented, benches within the river channel and dry anabranches are terrestrial sources of carbon that would provide a productivity pulse from these flows (Francis and Sheldon 2002; Sheldon and Thoms 2006; McGinness and Arthur 2011). Equally, a pulse of flow between arid river refugia would likely pick up carbon and transport it with associated productivity to waterholes.

In addition to increasing recruitment of *macro-lotic* species and arid river species; floods and in-channel pulses directly affect the *meso-lotic guild* by maintaining substrates for species such as Macquarie perch. The *wetland specialists* in the *meso-lentic guild* are also dependent on floods for maintaining a diversity of off-channel lentic habitats and to pulses of flow that prevent desiccation of low-lying refugia in droughts.

3 USING RECRUITMENT GUILDS FOR FLOW MANAGEMENT

3.1. Guilds, Flow Targets and Quantitative Environmental Outcomes

Ecohydraulic recruitment guilds can be directly used for flow management. Knowing the spatial scale over which fish are likely to respond, and the hydrodynamics in which spawning and recruitment occurs, enables flow to be targeted to meet these criteria.

Table 2 provides examples of two guilds and their application to flow management. The guilds enable qualitative and quantitative environmental outcomes to be developed and the use of spatial scale and hydraulics readily lends itself to SMART (Specific, Measurable, Attainable, Realistic, Time-Related) flow targets. The suggestions for SMART targets in Table 2 are not comprehensive for the guilds shown and are examples only. If this approach was considered appropriate, further work and peer review would be needed to provide sufficient detail for application. Two temporal hydrological parameters of timing and duration are included for context. Some key structural habitat features are also included as these determine hydraulic complexity.

SMART flow targets based on ecohydraulic recruitment guilds would help identify where flow can be used for the most effective ecological outcomes and help identify areas that have high potential for rehabilitation. In one scenario for example, existing rating curves could be used to determine whether a particular discharge or volume is sufficient to develop threshold channel velocities and create lotic habitats in the spawning season. If the volume was insufficient it could be saved until additional water became available.

For rehabilitation, hydrodynamic modelling can be used to assess areas with potential for different guilds. In some cases the spatial scale may be fragmented and flow may already be present; hence, providing connectivity would expand the spatial scale and more guilds would benefit. SMART flow targets can also be used to identify areas to protect (e.g. *meso-lotic* examples discussed in section 2.3.2.2).

Table 2. Example of using two *ecohydraulic recruitment guilds* to develop measurable flow targets. Items shaded in blue are key hydrological attributes, while areas in green are habitat attributes that are independent of flow but enhance the ecological value of flow.

Guild	Qualitative Environmental Outcomes	Quantitative Environmental Outcomes	Examples of SMART Targets for flow management
Macro-lotic	• Enhance spawning and recruitment with in-channel flow pulses	• Provide lotic conditions for sufficient uninterrupted longitudinal distance	• Longitudinal distance >500 km
		• Provide continuous hydrodynamic complexity in–channel	• Mean channel velocity >0.3 m/s (as a surrogate for cross-sectional channel complexity, with slow littoral zones)
			• Reynolds number[1] >2500 (non-laminar flow; also a surrogate for cross-sectional complexity)
			• >50 LWDs[2] per km in channel
		• Inundate instream benches to incorporate terrestrial carbon to initiate a productivity pulse	• 90% of instream benches inundated.
		• Timing	• Southern Basin: spring, early summer. • Northern Basin: spring, summer, autumn.
		• Duration	• 1-3 weeks
	• Enhance spawning and recruitment in floods	• Synchronised river and floodplain hydrographs over large spatial scale	• > 500 km of river, combined with inundation of 50% of floodplain.
		• Provide continuous hydrodynamic complexity in–channel	Achieved in floods and not manageable
		• Provide continuous hydrodynamic complexity in anabranches and flood	• Uninterrupted movement of flow through lateral floodplains (not applicable

[1] Reynolds number is the ratio of inertial forces over viscous forces; in stream ecology it provides a measure of stream turbulence and the change from lentic to lotic conditions.
[2] Large woody debris ("snags")

Guild	Qualitative Environmental Outcomes	Quantitative Environmental Outcomes	Examples of SMART Targets for flow management
		runners	to semi-terminal lakes).
		• Floodplain productivity is transported to and synchronised with the river, especially for *channel specialist* species	• Connectivity, transparency and integrity of flow between river and floodplain
		• Timing	• Southern Basin: spring, early summer. • Northern Basin: spring, summer, autumn.
		• Duration	• >2 weeks
Meso-lotic	• Enhance spawning and recruitment	• Provide lotic conditions for sufficient uninterrupted longitudinal distance	• Longitudinal distance >5 km
		• Provide sufficient continuous hydrodynamic complexity in-channel	• Mean channel velocity >0.3 m/s
			• Reynolds number >2500 (non-laminar flow; also a surrogate for cross-sectional complexity)
		• Ensure parental care of 'nesting' species (e.g. Murray cod)	• From October to early December (Southern Basin), reduction of water level within main channels (not on floodplain) < 0.1 m per day and < 0.5 m over 6 weeks.
		• Provide spawning habitats	Depending on biogeographic zone and species: • LWD: >50 per km in channel • Rocks: D_{50} 300-2000mm; >100m^2 continuous area • Cobbles, gravels: D_{50} 20-300mm; >100m^2 continuous area
		• Timing	• Permanent
		• Duration	• Permanent[1]

[1] Existing populations have permanent habitats, which may be necessary to ensure homing.

3.2. Flows for the whole fish community and complementary benefits

Management of aquatic ecosystems in the MDB needs to provide conditions that promote improvement of the whole fish community and all aquatic biota. The ecohydraulic recruitment guilds are a useful tool to do this as they not only potentially encompass all aquatic species - invertebrates, macroinvertebrates (including mussels and crayfish), and even biofilms differ in lentic and lotic habitats - but also they specifically identify priorities for management. The present background paper, for example, has identified generalist species that, with the exception of two species, are abundant in regulated reaches of rivers. Generalist species use lotic or lentic conditions for recruitment over meso- or micro-scales and require little, if any, specific flow recommendations. This group would be accommodated by any flow recommendations for the other guilds. Importantly, targeting the needs of generalist species would dilute the needs of those species with specific flow requirements.

In many cases flow recommendations for a specific guild will have overlapping and complementary benefits. Flows for the macro-lotic guild are likely to directly overlap with the meso-lotic guild, although the reverse does not apply. Flows for either of these guilds could also be used to provide refugia flows for the meso-lentic specialists, while all flows will aid generalist species.

3.3. Complementary actions

Identifying guilds provides opportunities for complementary actions to support flow management. Those species using lotic habitats for recruitment require hydrodynamic complexity (variation in water velocity and turbulence), which can be enhanced through the additional actions of re-snagging or adding rocky habitats. Lowering weirpools is a complementary action that increases the extent of lotic habitats.

Species in the macro-lotic guild are dependent on connectivity on a broad scale and fish passage becomes an important complementary action. Wetland specialists were severely impacted in the Millennium Drought; to avoid a repeat of those impacts flow management needs to include complementary actions such as nominating a network of refugia where water can be delivered.

3.4. Potential sites

The ecohydraulic recruitment guilds readily group fish species into those that have declined and those that are common. This provides flow priorities that can be addressed using hydrodynamic characteristics and identifies potential sites. For example:

Macro-lotic guild

Hydrodynamic flow target:

> Manage flows that generate mean channel velocities > 0.3 m/s over a longitudinal distance > 500 km.

Potential sites:

- Mid-Murray (Yarrawonga–Darling or Torrumbarry–Darling.
- Lower Murray (downstream of Darling River Junction).
- Middle Darling (Brewarrina to Menindee).
- Lower Darling (downstream of Menindee).
- Murrumbidgee.

Meso-lotic guild

The scale of the meso-lotic guild enables flow to be managed over smaller scales of 10s of kilometres to provide environmental benefits for fish. It also provides a suite of new possibilities where streams and anabranches can be used for regional rehabilitation of fish populations, creating new lotic habitats to compensate for lost lotic habitats in the weirpools of the main channels of rivers.

Hydrodynamic flow target:

> Manage flows that generate mean channel velocities > 0.3 m/s over a longitudinal distance > 5 km.

Potential sites:

i) Managing/protecting flows in existing lotic habitats:

- All macro-lotic sites above.
- Upland streams with Macquarie perch and blackfish species (e.g. Cotter River).
- Anabranches that presently have permanent flow (e.g. Mullaroo Creek and Chowilla).

ii) Creating new lotic habitats

- Lower weirpool elevations of the Murray River. Lotic habitats can be created by lowering weirpools without the addition of flow.
- Irrigation areas based on anabranch systems (e.g. Gunbower Creek, Pyramid Creek, Edwards-Wakool system). These require: i) permanent flow [presently little flow in the irrigation off-season of winter], ii) connectivity [fishways required in some cases], and in a few cases, iii) habitat rehabilitation such as re-snagging. Flow is returned to the Murray, less channel losses.
- Carrs Capitts Bunberoo system (anabranch near Lock 9); requires a higher, permanent baseflow [new inlet regulator] and connectivity [fishway]. Flow is returned to the Murray, less minor channel losses.
- Bookmark Creek (anabranch near Lock 5); requires a higher, permanent baseflow [new inlet regulator] and connectivity [fishway]. Flow is returned to the Murray, less minor channel losses.
- Several creeks in the Katarapko and Pike anabranch systems of the lower Murray.

Micro-lentic guild (wetland specialists)

Hydrodynamic flow target:

Create a network of permanent wetland refugia.

Potential sites:

- Barmah Forest.
- Gunbower Forest.
- Koondrook-Pericoota Forest.
- New floodplain SDL regulators.
- Jury Swamp (downstream of Lock 1).
- Hunters Creek, Hindmarsh Island.

4 CONCLUSION

Key Messages

1. Reproductive guilds or broad models of fish recruitment and flow provide little quantitative guidance for flow management.

2. *Ecohydraulic recruitment guilds* are based on the primary characteristics of the river to which fish respond - hydrodynamics, habitat and spatial scale – and these also correspond to the key tools available for management and rehabilitation.

3. All the fish species in the two guilds that require flowing water (lotic) rather than still-water (lentic) have had major population declines and almost all are threatened.

    - Protecting, rehabilitating and creating flowing water habitats for these lotic species can be achieved, in many cases, through changed management and additional infrastructure with zero or minimal additional water (Mallen-Cooper and Zampatti 2015). In other cases restoration of macro-scale (100s kms) annual in-channel pulses may be needed.

4. The species in the guild that uses specialized still-water (lentic) habitats (e.g. small permanent wetlands with aquatic vegetation) have all had major population declines and are all threatened.

    - Protecting, rehabilitating and creating habitats for these species would use minimal additional water (Mallen-Cooper and Zampatti 2015).

5. The guild that contains habitat generalists that use still-water habitats (e.g. weir-pools, wetlands etc.) includes all the abundant native fish species and these thrive independently of flow. This group seldom requires specific flow recommendations and are also poor indicators of the effectiveness of environmental flows.

6. The proposed guilds can be used to develop SMART flow targets which would help identify where flow can be used for the most effective ecological outcomes and areas that have high potential for rehabilitation.

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