2014–15 Basin-scale evaluation of Commonwealth environmental water — Fish

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Final Report

2014–15 Basin-scale evaluation of Commonwealth environmental water — Fish

Report prepared for the Commonwealth Environmental Water Office by The Murray–Darling Freshwater Research Centre

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1.1   Context and objectives

The Long Term Intervention Monitoring (LTIM) project aims to monitor the response of several ecological indicators to managed flows within Australia's Murray–Darling Basin (MDB). LTIM is specifically concerned with evaluating the impacts of flows managed by the Commonwealth Environmental Water Office (CEWO). In addition to monitoring and evaluation of flow impacts, LTIM also aims to improve capacity to support flow allocation decisions, as part of the adaptive management of environmental water within the MDB, both over the first 5 years of LTIM (2014–15 to 2018–19) and beyond (Gawne *et al.* 2013, 2014).

Fish are one of six indicators (Basin Matters) of response to flows being monitored within the LTIM Project. The remaining five Basin Matters are: Hydrology, Vegetation Diversity, Stream Metabolism and Water Quality, Ecosystem Diversity and Generic Diversity. These Basin Matters are being monitored across seven LTIM 'Selected Areas' throughout the MDB (Figure 1). Fish are a prominent indicator in all but one of these Selected Areas (Junction of the Warrego and Darling rivers), and so throughout this document we commonly refer to fish data collected across six selected areas, not seven.

Fish are an important indicator of flow response within the MDB. Native fish diversity, condition, reproduction and recruitment contribute to the biodiversity objectives stated in the Murray–Darling Basin Plan (Commonwealth of Australia, Basin Plan 2012[1]). Fish have substantial socioeconomic value, and so evaluating and reporting fish response to flows is critical from the perspective of stakeholders.

Here we present the 2014–15 Basin Matter report for fish monitoring within the LTIM Project. This is the first of five Fish Basin Matter reports to be delivered within the project. The annual Fish Basin Matter reports differ from those of Selected Areas in two ways: first is the focus on qualitative and quantitative analysis of outcomes across all six Selected Areas where fish are a focal indicator. That is, the analysis is concerned with trends and outcomes at the Basin scale. Within LTIM, analysis of ecological pattern and process at the Basin scale does not mean analysis of pattern and process in all catchments throughout the MDB. LTIM Basin-scale analyses are analyses of outcomes across multiple catchments or, in particular, multiple Selected Areas. Thus, LTIM Basin Matter reporting concerns patterns and processes at spatial extents (*sensu* Wiens 1989; Kotliar & Wiens 1990; Levin 1992) that exceed those of individual Selected Areas. With respect to the spatial scaling literature concerning rivers, LTIM's Selected Area scale and Basin scale are the same as, respectively, Fausch *et al.*'s (2002) segment scale and drainage-basin scale.

Second, the Fish Basin Matter is concerned with long-term outcomes, particularly those pertaining to the impacts of flow events (hydrographs spanning 1 year or less) and regimes (hydrographs spanning multiple years) on population dynamics, not just short-term responses of individual population processes (e.g. spawning, movement).

Details concerning the approach to fish monitoring and evaluation, as well as a work plan for LTIM fish monitoring during 2014–15 to 2018–19 can be found in the LTIM Fish Foundation Report (Stoffels *et al.* 2016a). The capacity to evaluate fish response to flows will increase with time, as more LTIM data become available, and as the models that are dependent on those data develop. Figure 2 and Figure 3 help place the content of this year's report in the context of the broader Fish

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[1] https://www.legislation.gov.au/Details/F2012L02240

Basin Matter work plan (Stoffels *et al.* 2016a). Note that Fish Basin Matter outputs are planned to increase each year (Figure 3).
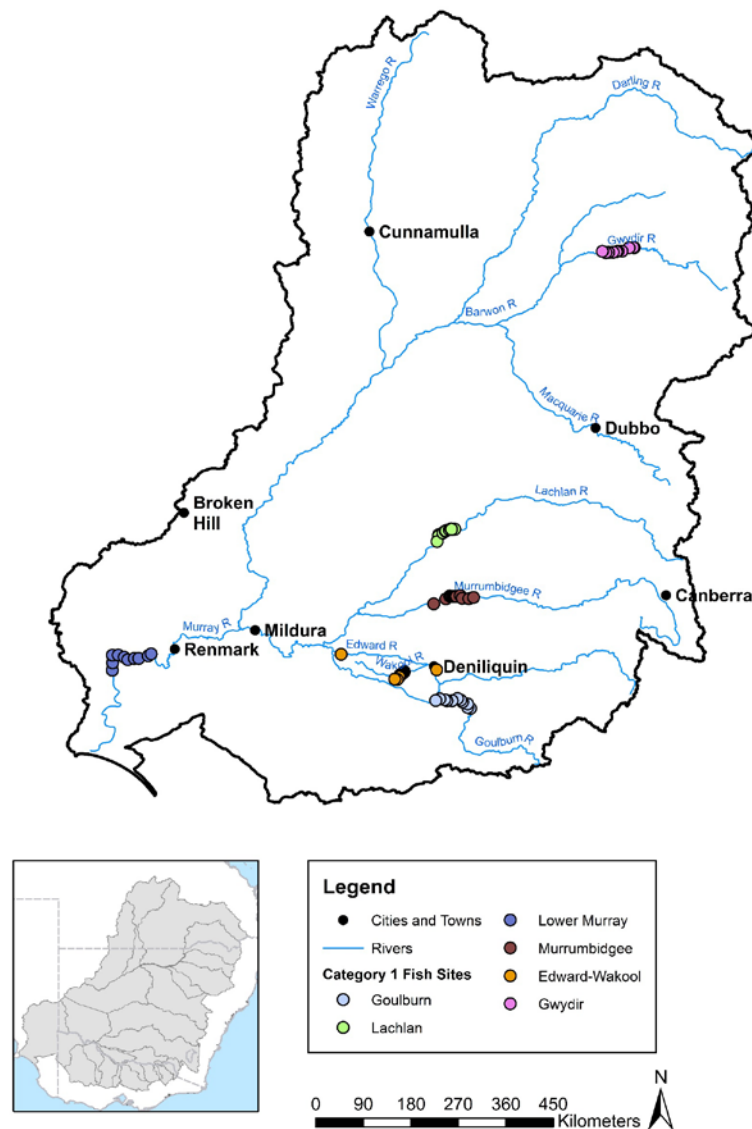
Figure 1. Map of the Murray–Darling Basin showing the location of the six Selected Areas of LTIM focusing on fish response to flows. The six Selected Areas are the Lower Murray River, Edward–Wakool river system, Murrumbidgee river system, Goulburn River, Lachlan river system and Gwydir river system.

The objectives for the 2014–15 LTIM Fish Basin Matter report were as follows (Stoffels *et al.* 2016a):

1. Review technical reports for outcomes from Commonwealth environmental watering actions during 2014–15 and present a synthesis of those outcomes. This synthesis focuses mostly on the six Selected Areas where LTIM fish monitoring is taking place, but also

includes the Macquarie Marshes and other areas where ad hoc monitoring of fish outcomes took place (e.g. Cardross and Hattah Lakes).

2. Undertake baseline analyses of fish populations and community structure across the six Selected Areas. Specifically, determine how the following vary across Selected Areas
   a. abundance of all target species
   b. length structure of large-bodied target species
   c. age structure of large-bodied target species
   d. population condition of large-bodied target species
   e. composition of the fish community (hence diversity).

Within LTIM, fish monitoring targets certain species ('target species') for population analyses. The list of target species is presented and justified in Section 1.3. From the above two objectives of this year's report, this year's Basin Matter evaluation consists of a qualitative analysis. The second objective essentially involves reporting on the condition of the Basin's fish community (*sensu* Stoffels *et al.* 2016a) at the beginning of LTIM.

Before we present the methods and analyses of this year's report, we include two subsections providing further background to the LTIM Fish Basin Matter. In Section 1.2, we present the overarching objectives of the Fish Basin Matter. In Section 1.3, we present a literature review and simple conceptualisation of the responses fish may exhibit to flows.
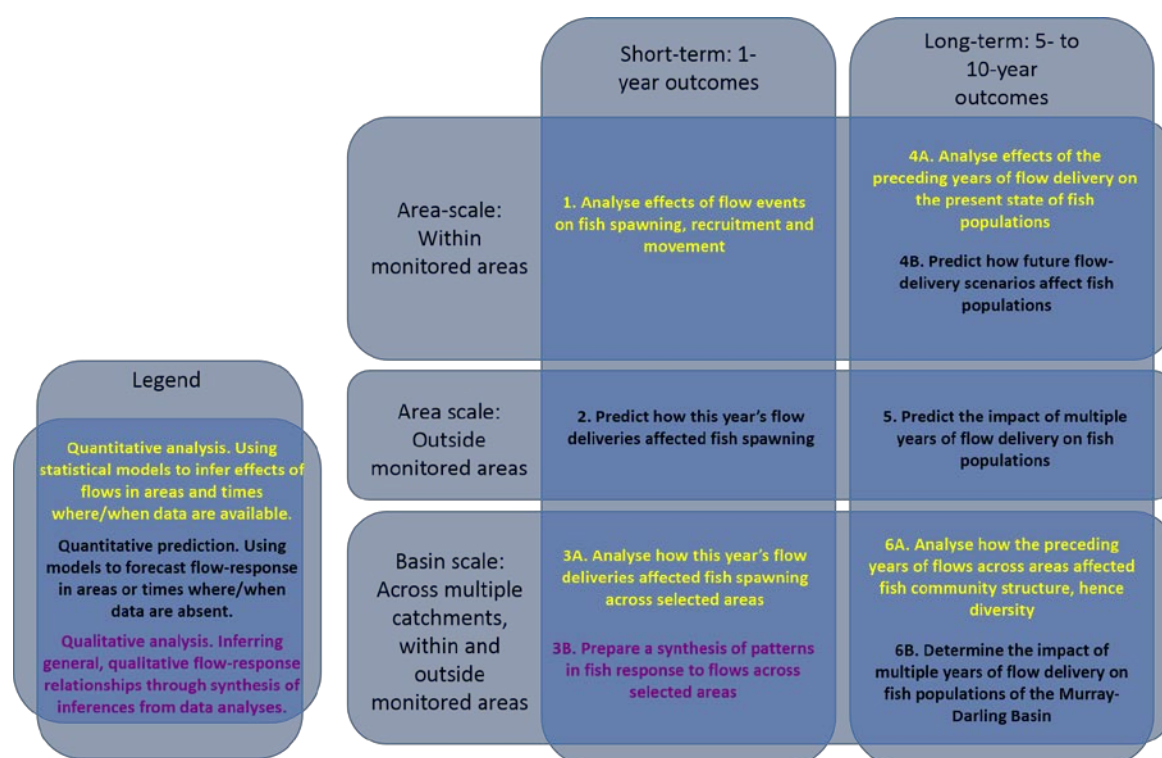
Figure 2. Fish analysis and prediction activities within LTIM fit into one of six groups, which are defined by the spatial and temporal scales of analysis/prediction. Activities are colour-coded by whether they involve analysis of data or prediction, and by whether the analysis or prediction is qualitative or quantitative. Note that as of July 2016, the Fish Basin Matter team — which includes fish experts within all Selected Areas — is still refining scope of the Fish Basin Matter activities.
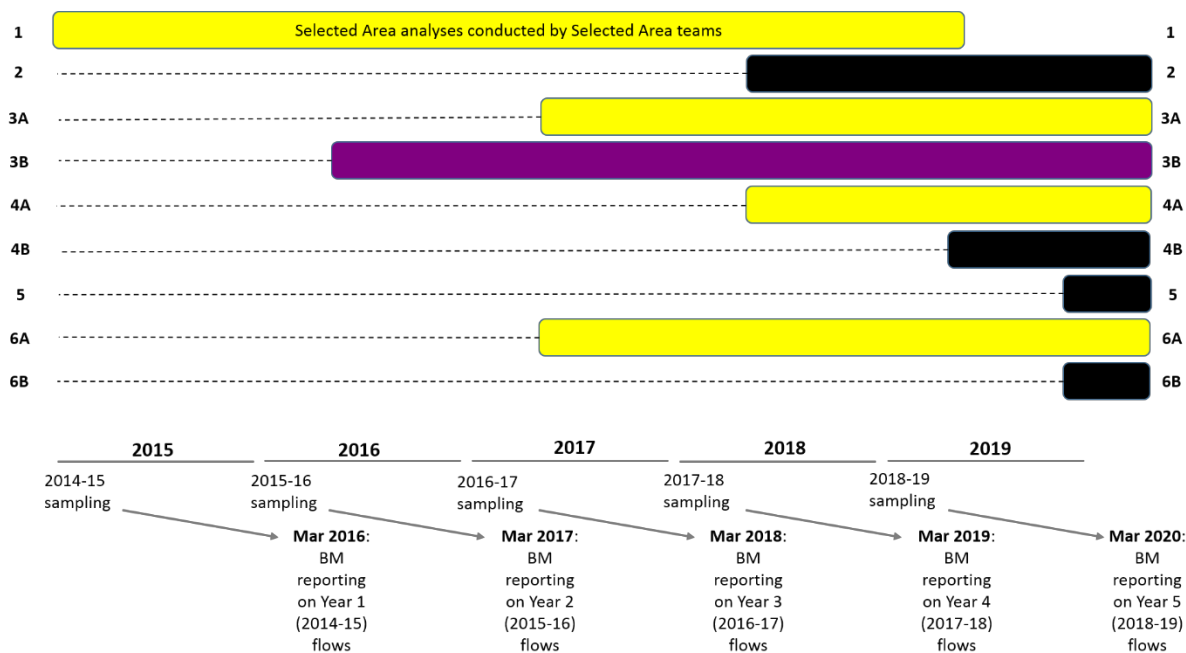
Figure 3. Gantt chart of analysis and prediction activities of Figure 2.

1.2 Overarching objectives of the Fish Basin Matter

LTIM evaluation questions can be divided into those that concern short- and long-term outcomes to flows. These short- and long-term evaluation questions reflect the fact that certain ecological variables can respond rapidly to environmental change, while others are slower to respond (Levin 2000). The LTIM evaluation questions for fish are:

- long-term

    - What did Commonwealth environmental water contribute to sustaining native fish populations?

- short-term

    - What did Commonwealth environmental water contribute to sustaining native fish reproduction?
    - What did Commonwealth environmental water contribute to sustaining native fish survival?

Thus, the first overarching objective of the Fish Basin Matter is to answer these questions. These questions, however, belie the broader aims of LTIM. Indeed, a key objective of LTIM is to improve our capacity to predict ecological response to flow events and regimes (Gawne *et al.* 2013, 2014). Prediction within LTIM will facilitate the following three activities:

1. Improve capacity to evaluate decisions in monitored areas. Analysis of outcomes from adaptive management is rarely conducted within the statistical frameworks developed for classical experimental designs (Walters 1997; Westgate *et al.* 2013). Adaptive management of flows is no exception, with flow perturbations to channels being unreplicated, and rivers elsewhere in a drainage basin often serving as poor references for the perturbation of interest (Konrad *et al.* 2011; Olden *et al.* 2014).

Time-series analysis provides a way for determining the impact of perturbation in unreplicated ecosystem experiments (Box & Tiao 1975; Carpenter 1990). In turn, simulation models play a pivotal role in time-series analysis, enabling us to contrast observed time series with what we predict would have happened in the absence of the flow event(s) (Stewart-Oaten & Bence 2001). Further, simulation models enable us to screen hypotheses of flow response that are most unlikely to result in observed time series (Walters 1997; Shea 1998).

2. Evaluating flow impacts in unmonitored areas. A common challenge of adaptive management programs worldwide is the need to scale management outcomes detected in monitored areas, to those in areas without monitoring (Gregory *et al.* 2006). Within LTIM, we aim to develop models that facilitate predicting responses of population processes (e.g. spawning) and population dynamics to flow events and regimes in areas of the MDB where fish monitoring is not taking place (Gawne *et al.* 2013, 2014). Simulation models are an essential tool for spatial scaling (Levin 1992; Urban *et al.* 1999; Rastetter *et al.* 2003; Urban 2005). Such predictive capacity would greatly facilitate CEWO's capacity for making flow decisions at the scale of the MDB.

3. Decision-making. Good decision-making (e.g. When should we deliver water? How much water should be delivered?) involves predicting the likely outcomes from a set of different management options (decisions), given certain antecedent conditions, and a set of future environmental states (Walters & Holling 1990; Clark *et al.* 2001; Conroy & Petersen 2013). In the context of fish monitoring within LTIM, antecedent conditions would include, for example, current population structure, while future environmental states would include forecast climatic conditions and, hence, demand for water by end users that may compete with the environment. Decisions in need of evaluation may involve flow events or regimes; hence, concern predictions over 1- or multi-year time frames. Simulation models — be they statistical or 'process-based' — are a very useful tool for making these predictions (Shea 1998). Simulation models incorporate antecedent conditions, are accompanied by explicit sets of assumptions, and project outcomes bound by confidence intervals, thus improving our ability to characterise uncertainty and compare decisions (Walters 1997; Clark *et al.* 2001; Polasky *et al.* 2011).

It follows, therefore, that the second overarching objective of the Fish Basin Matter is to develop predictive models that fulfil the above three functions. Based on our descriptions of the uses of prediction above, it should be clear that meeting Objective 2 improves our ability to meet Objective 1. Our approach to monitoring within LTIM has been shaped by the requirement to meet both objectives (Stoffels *et al.* 2016a).

1.3   Concepts: how fish respond to flows

The conceptualisation presented here extends that presented by MDFRC (2013), in that (a) we aim to link flows to the population processes LTIM is targeting with data collection; and (b) the models are divided by life-history strategy. An overarching conceptual model demonstrating how flows affect fish population processes is presented in Figure 4.
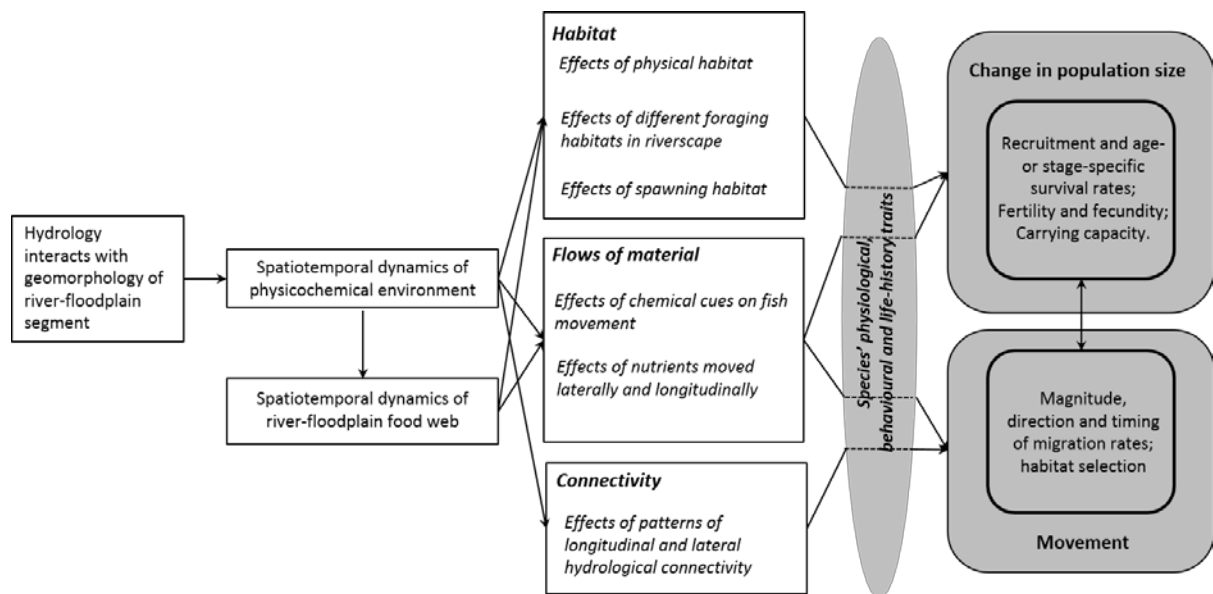
Figure 4. Conceptual diagram capturing the key mechanistic pathways by which flows change fish population size and drive dispersal. A flow will interact with the geomorphology of the river–floodplain landscape to affect the spatiotemporal dynamics of waterbodies. By 'spatiotemporal dynamics' we mean the physical and chemical character of the various habitats of the river–floodplain landscape, as well as the patterns of connectivity between habitats at various spatial scales. Once flow sets the spatiotemporal structure of the river–floodplain landscape, this then impacts fishes through three classes of effects (habitat; flows of material; connectivity), which can in turn be further subdivided into individual effects (e.g. effects of physical habitat within the class of habitat effects). Effects of flow interact with the 'lens' of species traits before impacting population processes, including movement. Population processes are divided into two categories: those that directly affect changes in population size, and those that affect the distribution of individuals in the river–floodplain landscape, which may in turn affect those processes that change population size. Changes in population size are affected by flow impacts on habitat and material flows, while flow affects movement through impacts on material flows and connectivity.

1. Flows may affect fish population processes through the impact flow has on **habitat** (Figure 4):
   a. Flows may affect the **physical nature of habitat**, including both water chemistry (e.g. temperature, dissolved oxygen) and habitat hydraulics (e.g. depth, velocity). Physical habitat is known to affect fish condition, survival and reproduction (Fry 1971; Pichavant *et al.* 2000, 2001; Wu 2009; Gorski *et al.* 2010; Stoffels 2015) and movement (Sykes *et al.* 2009; Tiffan *et al.* 2009).
   b. Flows change the habitat composition of the riverscape (e.g. slackwaters, floodplain wetlands), which in turn changes the **types of foraging habitats available** to fishes. Food quantity and quality are known to strongly affect fish fitness generally (Jobling 1993; Clements *et al.* 2009) and, although poorly studied, there is growing evidence that spatiotemporal variation in river–floodplain food-web structure affects fish population processes (Feyrer *et al.* 2006; Limm & Marchetti 2009). Unfortunately, we have a very poor understanding of the nutritional value of different habitat units (even as coarsely as floodplain versus channel) to river–floodplain fishes.
   c. As flows change the habitat composition and connectivity in river–floodplain landscapes, they change the accessibility and quantity of **spawning habitat** (Poizat and Crivelli 1997; Zeug & Winemiller 2007; Gorski *et al.* 2010; Burgess *et al.* 2013).

2. Flows may affect fish population processes through the impacts they have on the **flows of particulate and dissolved materials** both longitudinally and laterally in the river–floodplain landscape (Figure 4):
   a. Floods can mobilise dissolved materials that serve as important cues to changes in fish behaviour (Lewis 2002). In turn, recent work has highlighted the possibility for flows to affect fish movement — hence, access to habitats that may affect population size — through the impact they have on **chemical cues** for fish dispersal (Stoffels *et al.* 2014).
   b. Flows may affect fish population productivity without necessarily changing the habitat structure of the river–floodplain landscape. Flows may **mobilise and transport dissolved nutrients**, which may interact with existing habitat to boost productivity of food chains (Hunt *et al.* 2012; Jardine *et al.* 2012; Baldwin *et al.* 2013, 2014.
3. Flows may also affect population size through another indirect pathway, by affecting the hydrological **connectivity** (Figure 4); hence, affecting movement of individuals throughout the river–floodplain landscape (David & Closs 2002; Koster & Crook 2008; Jones & Stuart 2009; Lyon *et al.* 2010; Crook *et al.* 2013; Koster *et al.* 2014; Stoffels *et al.* 2016b).

One of the challenges for environmental monitoring is that it is unrealistic to collect data on all species simultaneously. However, despite their diversity, different species will often share traits, such as fecundity, growth rates, and sensitivities to pollution and so on. Because traits are often correlated among species and one another, species can be classified into a relatively smaller number of groups based on their traits (referred to as 'guilds'). For marine and freshwater fishes, it has been shown that individual species can be classified into a number of distinct guilds based on their life-history characteristics (Winemiller & Rose 1992).

Three guilds are commonly recognised: equilibrium, periodic and opportunistic (Winemiller & Rose 1992). Each of these life-history guilds might respond to a particular flow regime in unique ways, and so focusing monitoring on species from only one guild is likely to result in misleading inferences concerning the effects of flow on fish diversity (Humphries *et al.* 1999; Shenton *et al.* 2012; Yen *et al.* 2013). This is why a trait-based approach to riverine fish monitoring programs is considered part of best practice (Rose *et al.* 2015), and why we are taking a guild-based approach in LTIM. By targeting species representing different guilds, we hope to gain a fuller appreciation of how flow regimes affect multispecies communities — hence, diversity —rather than just a single iconic species.

Within LTIM Selected Areas, four species are being targeted:

1. equilibrium — Murray cod (large adult size; long-lived; non-flow spawner; greater investment in offspring)
2. periodic — golden perch (large adult size; long-lived; flow-spawner; little investment per offspring) and bony herring (medium adult size; medium longevity; spawning not tightly linked to flows)
3. *opportunistic* — carp gudgeon (small adult size; short lifespan; spawning not tightly linked to flows, but data inconclusive at this stage).

Below we present diagrammatic conceptual models for these four target species. The primary purpose of each model is to serve as a visual representation of our expectations based on the accompanying literature review. For each species, we have aimed to capture only the most prominent links between three types of flow (base, fresh and overbank) and the processes for which data are being collected.

1.3.1 Periodic species — golden perch

Base flows

Generally, we expect the impact of base flows on golden perch to be low (Figure 5), unless the base flow is delivered during particularly dry periods, whereupon such flows may maintain suitable water quality during periods of otherwise poor water quality (high temperatures and/or low dissolved oxygen; not shown in Figure 5). If base flows have an impact, then we propose that impact is on survival rates of juvenile and adult golden perch (Figure 5) through provision of desirable physical and foraging (e.g. backwaters) habitats (Balcombe *et al.* 2006).

Fresh flows

We propose that freshes may have high impacts on golden perch population processes, particularly spawning, recruitment and movement (Figure 5). Increases in discharge have been correlated with golden perch spawning and recruitment previously (Humphries *et al.* 2002, 2008; Roberts *et al.* 2008; King *et al.* 2009, 2016; Zampatti and Leigh 2013), although certain studies have documented spawning and recruitment in the absence of notable peaks in the hydrograph (Mallen-Cooper & Stuart 2003: Ebner et al. 2009). Hydrology is not the sole driver of golden perch spawning, and the combination of appropriate thermal (18–22 °C) and hydrological conditions are likely required for golden perch spawning (King *et al.* 2016). Changes in discharge rates are also known to be a key driver of longitudinal movements in golden perch, which may be attributed to spawning behaviour (O'Connor *et al.* 2005; Koster *et al.* 2014).

Impacts of freshes on golden perch survival rates may also be expected, given the role of freshes in increasing food availability (Balcombe *et al.* 2012: Sternberg *et al.* 2012).

Overbank flows

Juvenile golden perch have been documented undertaking lateral movements of large magnitude during natural overbank flows (Balcombe *et al.* 2007: Stoffels *et al.* 2014, 2015). These movements are likely associated with foraging behaviour, whereby juveniles gain access to the productive foraging habitats of the floodplain (Balcombe *et al.* 2007; Rolls & Wilson 2010; Stoffels *et al.* 2014). Although untested, it is possible that episodic access to the rich foraging habitats of the floodplain increases survival rates of juveniles for some time horizon following an overbank flow. Although large overbank flows are currently out of scope for managed flows, if they occur in particularly wet years, then we expect overbank flows to have a high impact on survival rates of juvenile golden perch (Figure 5).
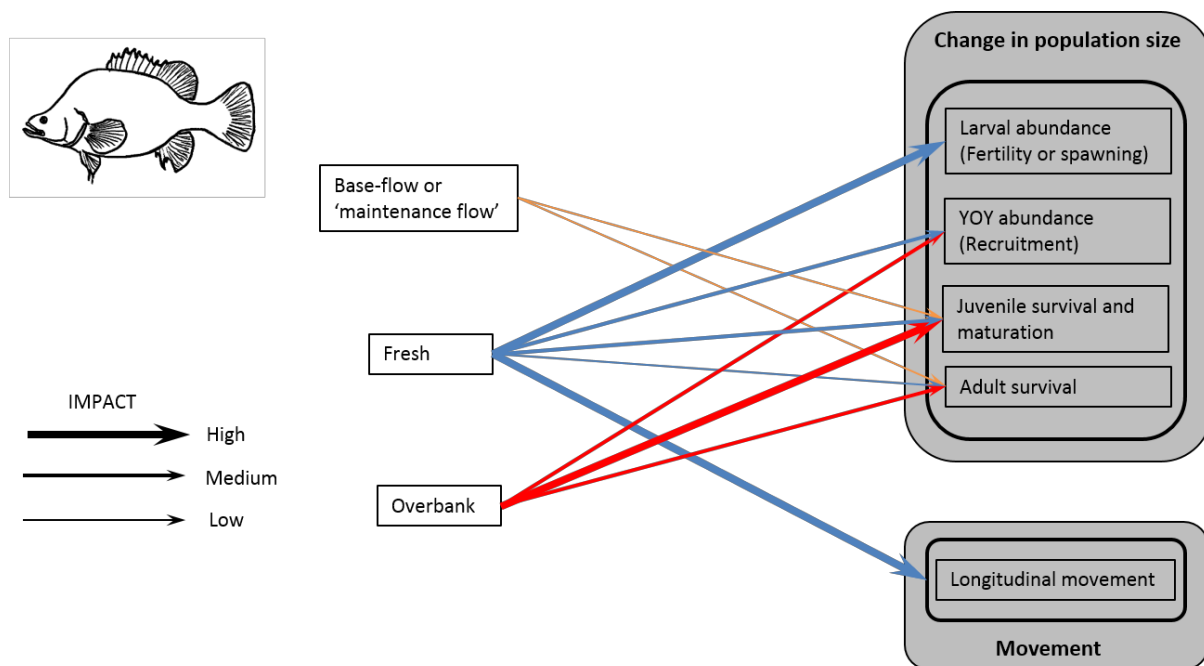
Figure 5. Conceptual model of how flows affect the population processes of golden perch, *Macquaria ambigua*, assuming the three flow types on the left are delivered under 'average' discharge conditions (i.e. not particularly dry or wet years). Only those processes that LTIM data-collection activities target are presented. The model is an adaptation of Figure 4, and so an explanation of broad mechanistic pathways can be found in the body of the document. Three types of flow are considered: base (or maintenance); fresh; and overbank. These sources of hydrological variability are linked to fish population processes using lines of different colour.

1.3.2   Periodic species — bony herring

Base flows

As is the case for golden perch, we expect base flows will have generally low impacts on bony herring. The exception would be during particularly dry years, when base flows may play an important role in improving survival, which would have otherwise significantly declined due to low water quality. If base flows have an impact during 'average' rainfall years, it would be through the provision of foraging habitats, such as backwaters (Balcombe & Arthington 2009).

Fresh flows

Unlike golden perch, there is very little evidence to suggest that bony herring spawning is affected by freshes, with spawning more tightly linked to temperature (Puckridge & Walker 1990; Pusey *et al.* 2004) (Figure 6). However, there is growing evidence for a significant impact of freshes on bony herring recruitment and condition; hence, possibly survival of juveniles and adults (Balcombe *et al.* 2006, 2012; Sternberg *et al.* 2008; Balcombe & Arthington 2009). Although there has been very little investigation as to how freshes affect juvenile and adult survival of bony herring, we expect medium impacts of freshes on bony herring survival rates (Figure 6).

Overbank flows

We expect the greatest impacts of flows on bony herring when they are large flows that inundate floodplains. Bony herring are known to exhibit lateral movements of great magnitude in response to overbank flows (Puckridge *et al.* 2000; Balcombe *et al.* 2007; Kerezsy *et al.* 2013; Stoffels *et al.* 2014, 2016b). Floodplain habitats may be used for spawning and, in particular, foraging (Balcombe *et al.*

2005, 2007; Rolls & Wilson 2010). If we experience large flows that increase lateral connectivity, then we expect to see high impacts on juvenile and adult survival rates (Figure 6).
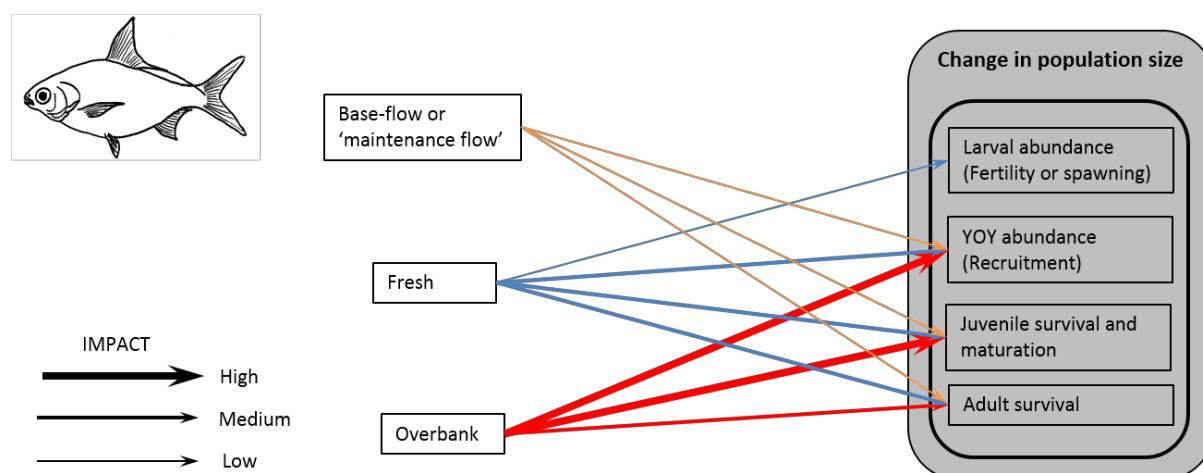
Figure 6. Conceptual model of how flows affect the population processes of bony herring, *Nematalosa erebi*, assuming the three flow types on the left are delivered under 'average' discharge conditions (i.e. not particularly dry or wet years). Only those processes that LTIM data-collection activities target are presented. Note that flow effects are not linked to movement as there is no monitoring of bony herring movement within LTIM. The model is an adaptation of Figure 4, and so an explanation of broad mechanistic pathways can be found in the body of the document. Three types of flow are considered: base (or maintenance); fresh; and overbank. These sources of hydrological variability are linked to fish population processes using lines of different colour.

1.3.3   Equilibrium species — Murray cod

Base flows

As is the case for all target species, while we expect base flows to have low impacts on Murray cod during wet and average flow years, they may have a high impact during very dry years, by reducing habitat availability and, under cease-to-flow conditions, exposing fish to poor water quality (high temperatures and low dissolved oxygen).

Fresh flows

The evidence for flow-induced spawning in Murray cod is equivocal. Humphries (2005) and Koehn and Harrington (2006) found little evidence for flow impacts on spawning (see also King *et al.* 2009). More recently, King *et al.* (2016) presented evidence for increased cod spawning during high discharge events within the Murray River. There appears to be unequivocal evidence for the role that increasing temperature plays in initiating Murray cod spawning, with spawning occurring once temperature exceeds 15 °C (Humphries 2005; Koehn & Harrington 2006; King *et al.* 2009, 2016). Given our current understanding, we expect low impacts of freshes on Murray cod spawning (Figure 7).

We expect to observe medium impacts of flows on Murray cod recruitment and survival rates (Figure 7). Although the evidence was weak, King *et al.* (2010) observed increased recruitment of cod following a large fresh within the Murray River (see also King *et al.* 2009). The effects of freshes on juvenile and adult survival are unknown, but if such flows inundate foraging habitats for small juvenile cod and/or increase instream productivity, then we may observe medium impacts on survival rates.

Murray cod, like many ambush predators, generally exhibit site fidelity (Jones & Stuart 2007), but they may exhibit quite large movements, which may be related to spawning behaviour (Koehn *et al.* 2009; Leigh & Zampatti 2013). Based on peer-reviewed literature, one would expect freshes to have only low impacts on longitudinal movements in Murray cod. However, unpublished acoustic array studies from the Edward–Wakool river system have demonstrated Murray cod movement may coincide with freshes, so we suggest here that freshes may have a medium impact on Murray cod movement (Figure 7).

Overbank flows

There is little evidence for Murray cod utilising floodplain habitat (Jones & Stuart 2007; Leigh & Zampatti 2013). We speculate, however, that being an apex carnivore (Ebner 2006; Stoffels 2013), Murray cod is a species that is particularly likely to benefit from the boost in food-web productivity that comes with large, overbank flows (Bayley 1991; Hunt *et al.* 2012; Baldwin *et al.* 2013, 2014). Thus, we propose overbank flows will have a high impact on recruitment and survival (Figure 7).
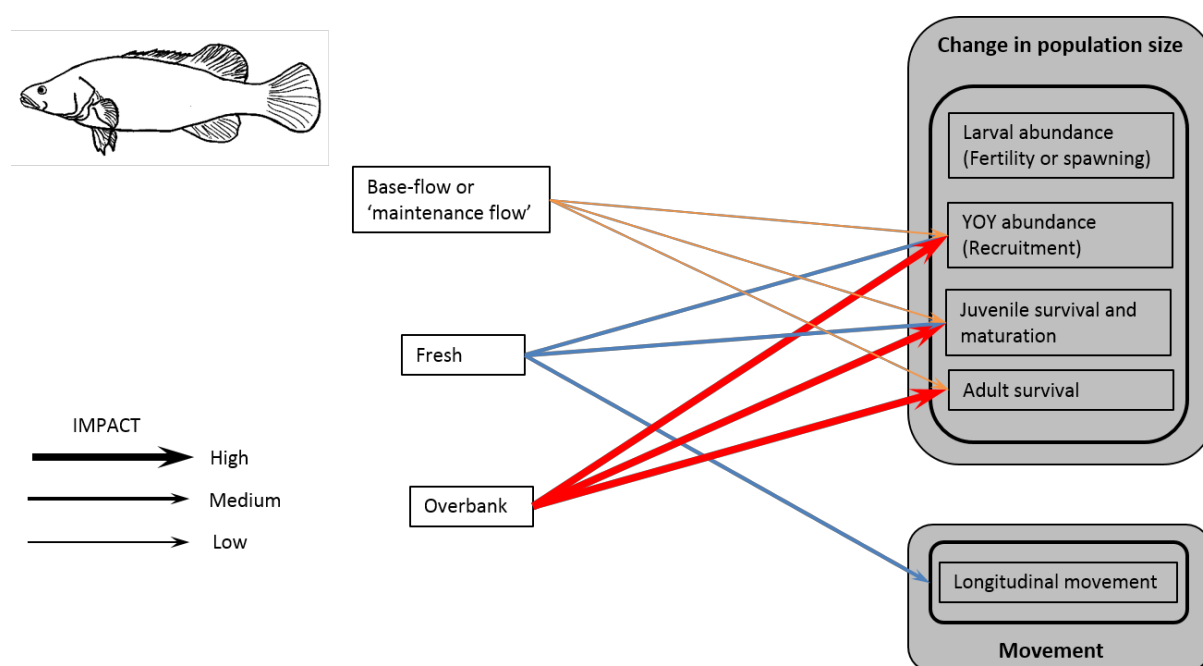
Figure 7. Conceptual model of how flows affect the population processes of Murray cod, *Maccullochella peelii*, assuming the three flow types on the left are delivered under 'average' discharge conditions (i.e. not particularly dry or wet years). Only those processes that LTIM data-collection activities target are presented. The model is an adaptation of Figure 4, and so an explanation of broad mechanistic pathways can be found in the body of the document. Three types of flow are considered: base (or maintenance); fresh; and overbank. These sources of hydrological variability are linked to fish population processes using lines of different colour.

1.3.4   Opportunistic species — carp gudgeon

Carp gudgeon is broadly considered a 'flow generalist' (Humphries *et al.* 1999; King *et al.* 2003; Reich *et al.* 2010). We are not sure how population dynamics of this species will respond to flow regimes within the channels of the Basin's rivers. The scant literature presents discordant views on whether carp gudgeon population dynamics are linked to flow, from studies suggesting key processes are

promoted by increased discharge (Vilizzi 2012), through to those suggesting abundance is impaired by high flows (Bice *et al.* 2014). In any case, population density of this species within streams can vary by several orders of magnitude among years, and these fluctuations may be related to hydrological dynamics (Perry & Bond 2009). Sampling of this species within LTIM is aimed at determining whether any such temporal fluctuations in population size are linked to flow events and regimes within Selected Areas.

We do not present a conceptual model for this species because there is a particularly high level of uncertainty concerning the impacts of flow events and regimes on population dynamics due to the scant and contradictory literature. Instead, we present a brief review of the literature against each of the three flow types.

Base flows

As is the case for all other species, we anticipate that base flows will be most important to opportunistic species in situations when, due to low-flow conditions, water quality needs to be maintained. However, Bond *et al.* (2010) found that carp gudgeon were more abundant at sites with sustained higher flows (higher mean monthly flows), so we may find that carp gudgeon abundance fluctuates less, and is higher on average, in areas that receive less variable flow conditions.

Fresh flows

There is discordance in the literature concerning the impact of freshes on carp gudgeon abundance. Vilizzi (2012) presents evidence that, although carp gudgeon spawn each year irrespective of discharge, freshes are associated with spawning of greater magnitude. In contrast, other studies suggest discharge has no observable impact on carp gudgeon spawning (Humphries *et al.* 2002; King *et al.* 2003). The population-level impact of freshes is unknown for this species.

Overbank flows

Bice *et al.* (2014) has suggested that overbank flows that have a negative impact on aquatic vegetation may, in turn, reduce carp gudgeon abundance. In contrast, if overbank flows are viewed as providing access to floodplain habitats, then overbank flows may increase the size of carp gudgeon populations (Puckridge *et al.* 2000; Beesley *et al.* 2012, 2014; Ho *et al.* 2012). As is the case for freshes, the impact of overbank flows on the dynamics of carp gudgeon populations in the channel is unknown.

2 Methods

2.1 Sampling

All sampling methods, including the logic and rationale underlying their design, are given in Hale *et al.* (2013), Dyer *et al.* (2014), Frazier et al. (2014a), Frazier et al. (2014b), SARDI *et al.* (2014), Wassens *et al.* (2014), Watts *et al.* (2014), Webb *et al.* (2014) and Stoffels *et al.* (2016a). Here we briefly explain the approach to this year's qualitative and quantitative analyses. The technical detail is kept to a minimum, but provides key references that readers can refer to for further technical details.

Throughout this document — and LTIM documentation in general — Category 1, 2 and 3 methods are mentioned. Hale *et al.* (2013) explains the reasoning underlying the implementation of categorised methods, and explains in detail all Category 1 and 2 methods. Here we very briefly define Category 1–3 methods:

- Category 1 methods are standardised methods implemented across all six Selected Areas with a fish-monitoring focus. Data generated from Category 1 methods are used for Basin-scale analyses of fish response to flow and environmental change.
- Category 2 methods are standardised methods implemented across a subset of the six Selected Areas with a fish-monitoring focus. They may also be used for Basin-scale analyses, but are primarily used to inform area-scale evaluation of flow impacts.
- Category 3 methods are not standardised, but are area-specific methods aimed at informing area-specific evaluation questions.

This report analyses data arising from Category 1 annual censuses, which take place once each year during autumn. Within the six Selected Areas, annual censuses consisted of intensive electrofishing for large-bodied species and fyke netting for small-bodied species. Each Selected Area comprised of 10 sites, each consisting of an 800 m reach of the main channel. A total of 2880 seconds (s) of electrofishing 'on-time' was randomly taken from within each site. Ten fyke net (fish trap) samples were also taken from within each site. Fyke nets were randomly positioned and set overnight. Abundances from electrofishing and fyke nets were calculated as numbers of individuals per 90 s 'on-time', and per net, per hour, respectively.

2.2 State of fish populations

To determine the state of target fish populations at the beginning of LTIM, we compared and contrasted the length structure, age structure and condition among Selected Areas. LTIM's three large-bodied target fishes were the focus of our population analysis: bony herring, golden perch (both in the periodic guild) and Murray cod (equilibrium guild). We did not include the fourth target species, carp gudgeon (opportunistic guild), in this analysis because feedback from Selected Area scientists suggests carp gudgeon populations have a homogeneous structure across Selected Areas, with the overwhelming majority of individuals being young-of-year (0+).

All analyses of population structure were carried out using R (R Core Team, 2015, http://www.R-project.org/).

2.2.1 Length and age structure

Comparisons of length structure among areas were carried out through visual examination of length-frequency histograms overlayed with kernel-smoothed density functions. The kernel-

smoothed density functions can serve as a useful visual aid, as they capture the dominant shape characteristics (modes, skewness, etc.) of the frequency distribution.

Comparisons of age and length structure among Selected Areas then involved two steps:

1. Develop age–length keys (ALKs) for the three target species, using LTIM age–length data — sourced from the LTIM otolith collections — from each Selected Area.
2. Use fish length data obtained from Category 1 censuses (Hale *et al.* 2013) which serve as input to an algorithm that estimates the proportionate age composition of the length sample.

Step 1: Development of ALKs

Development of the ALK for each species follows standard techniques in fisheries stock assessment (Quinn & Deriso 1999, Ch. 8). An ALK is a matrix whose i,jth entry is the probability that a fish of length-class i is of age j [$P(j|i)$] (Fridriksson 1934). When constructing ALKs, the width of length classes (in cm) varied among species, and reflected the range in length for each species. That is, the larger the species gets, the wider the length class used for ALK construction. For bony herring, golden perch and Murray cod, the length class widths were 1, 2 and 3 cm, respectively.

A single ALK was developed for each of the three target species using age–length pairs, obtained from otoliths collected across the Selected Areas. Within species, age–length data from Selected Areas were pooled, such that we may obtain large samples for estimates of the $P(j|i)$ values. In pooling data, we made the assumption that age–length functions of fish populations do not vary across Selected Areas. If this assumption is false, our current ALKs will inflate errors around our estimates of the proportionate age composition of each population. In the long term, we aim to relax this assumption, by collecting more otoliths from target species, towards development of Selected Area–specific ALKs (Stoffels *et al.* 2016a). The total number of age–length pairs that were used to estimate ALKs for each species, as well as a breakdown by Selected Area, are provided in Table 1.

Table 1. Number of otoliths, hence number of age–length pairs, obtained from each of the Selected Areas for each large-bodied target species.

Selected Area	Number of otoliths		
	Bony herring	**Golden perch**	**Murray cod**
Gwydir river system	59	58	54
Lachlan river system	53	61	103
Murrumbidgee river system	38	52	63
Edward–Wakool river system	55	77	52
Goulburn River	0	49	50
Lower Murray River	0	77	10
Total	**205**	**374**	**332**

Each ALK went through three stages of development. First, the raw age–length pairs of a species were used to populate the matrix, such that the i,jth entry represents the number of individuals within length class i of age j. Second, we made the assumption that lengths within an age cohort were normally distributed. A normal curve was fitted to the data within each column of the ALK using maximum likelihood estimation. Thus, we now have an ALK whose i,jth entry is the expected frequency of individuals in length class i of age j, assuming a normal length distribution within each

age cohort. At this stage, column totals — but not row totals — sum to one. The final stage of ALK development was to transform the matrix such that row totals sum to one, as is required when row entries represent the probabilities $P(j|i)$.

Step 2: Inferring age structure from ALKs

ALKs were used in a Monte Carlo (MC) algorithm to determine the mean proportionate age composition for each species within each Selected Area. This algorithm also estimates 95% confidence intervals (CIs) about the proportionate age composition, where the CIs represent uncertainty due to variation in length at age.

Once a vector of fish lengths is passed to this algorithm, an individual run consists of assigning an age to each individual fish length with probability $P(j|i)$. Because ages are assigned to lengths probabilistically, an individual length will not necessarily be assigned to the same age between runs. By running this MC algorithm many times, we estimate mean proportionate age composition of a length sample and 95% CIs around each mean. The width of CIs is, therefore, determined by the distribution of $P(j|i)$ values within each row of the ALK and the size of the length sample passed to the MC algorithm. Mean proportionate age compositions, and their corresponding CIs, were multiplied by catches per unit effort (CPUEs) to yield the CPUE of each cohort, within each Selected Area, and the corresponding uncertainty.

R scripts for the above analyses are available from the lead author of this document.

2.2.2 Condition

Variation in mean condition of individuals among Selected Areas was determined using linear mixed-effects models. In this analysis, *ln*-transformed mass (g) was modelled as a linear function of *ln*-transformed length (mm), and differences in intercepts or slopes among Selected Areas indicated differences in mean condition of individuals. Exploratory analysis of the length–mass relationships showed that slopes, as well as intercepts, may vary among populations, so we utilised linear mixed-effects models allowing random intercepts and slopes. Details of such analyses can be found in Zuur *et al.* (2009: pp 105–111).

2.3 State of fish assemblages

Non-parametric multivariate analyses were used to determine how fish community structure varies among Selected Areas. Variation in fish community structure (species composition and relative abundances) among the six Selected Areas was visualised using both parametric and non-parametric multidimensional scaling (MDS). MDS was carried out on both log-transformed and untransformed CPUEs. MDS on log-transformed CPUE downplays the role of particularly dominant species in driving inter-area patterns in fish community structure. As such, rarer species may influence inferences concerning spatial variation in community structure when using log-transformed data. In contrast, inferences about spatial variation in fish community structure using untransformed CPUEs are often shaped by how the abundances of the most numerous species change among areas. Permutational multivariate analysis of variance (PERMANOVA) was used to determine whether community structure varied significantly across Selected Areas.

In addition to the multivariate analysis, we also provide the summary statistics of species richness and 'nativeness' of the fish community by Selected Area. Species richness is the number of species recorded within a Selected Area, while nativeness is the proportion of total CPUE comprising native species.

2.4   Synthesis of Selected Area outcomes

The qualitative synthesis is presented largely in tabular form. We reviewed short-term outcomes (spawning and, to a lesser degree, recruitment outcomes) presented in technical reports (Dyer *et al.* 2015: Southwell *et al.* 2015: Stocks *et al.* 2015' Wassens *et al.* 2015, 2016; Watts *et al.* 2015a, b; Webb *et al.* 2015; Ye *et al.* 2015). The review focused mostly on the six Selected Areas where LTIM monitoring is taking place, but also includes the Macquarie Marshes and other areas where ad hoc monitoring of fish outcomes took place (e.g. Cardross and Hattah Lakes).

2.5   Expected 1–5-year outcomes at the Selected Area scale

The capacity to identify expected outcomes over 1–5 years at the Selected Area scale will be underpinned by the LTIM Project's development of quantitative models. In the absence of these models and a limited pool of data, consideration of expected outcomes over 1–5 years was conceptually based on the Outcomes Framework (Gawne *et al.* 2013) that links short-term flow outcomes to longer term and broader scale outcomes for fish populations.

3   Basin-scale patterns and outcomes

3.1   Highlights

These highlights are reported in more detail through Sections 3.2 onwards.

3.1.1   *The quality of LTIM fish data is high*

Baseline analyses of fish population and assemblage structure demonstrate that LTIM Category 1 census methods put us in a very strong position to determine the long-term impacts of flows on fish population and assemblage dynamics. Furthermore, the analyses presented here — in addition to precision analyses currently taking place — demonstrate that the Category 1 methods yield sufficient precision for parameterising models that enable ecological forecasting.

3.1.2   *Basin-scale recruitment of target species Murray cod and bony herring*

The population analysis clearly demonstrates widespread recruitment of bony herring and Murray cod throughout the MDB. Although we are not yet in a position to link such recruitment to flows (but see the above highlight), the reporting of recruitment at the Basin scale is a good sign, with respect to population persistence.

3.1.3   *Demonstrable benefits of the LTIM fish multispecies approach*

Population analyses based on Category 1 data demonstrated some contrasts in fish recruitment dynamics at the Basin scale. The strong differences appear linked to contrasting responses of native fishes to flow regimes in the long term, and it is clear that we cannot achieve an understanding of how flow regimes maintain fish diversity by focusing exclusively on individual iconic species. Indeed, different fishes recruit under different flow scenarios. These differences validate the LTIM approach of targeting species with different life-history characteristics.

3.1.4   *Strong representation of the Basin's fishes across Selected Areas, with generally high 'nativeness'*

The Category 1 annual census, implemented across the six LTIM Selected Areas, is sampling most of the fishes we would expect to find in lowland rivers of the MDB. Lintermans (2007) stated that alien species make up approximately 70% of the numbers in fish assemblages of the MDB. The first year of LTIM data shows that alien species generally made up less than 50% of the numbers in 2014-15.

Therefore, compared with the figures presented by Lintermans in 2007, alien fishes are less dominant. Indeed, native species comprised well over 70% of the numbers in four of six Selected Areas (see 'nativeness' in Table 2).

3.2   State of fish populations

3.2.1   *Length and age structure*

Bony herring

High-quality length- and age-structure data for bony herring was obtained across all four areas where they are a target species (Gwydir, Lachlan, Murrumbidgee and Edward–Wakool; Figures 8 and 9). Indeed, our capacity to infer age structure of bony herring populations across Selected Areas is particularly strong. This is due to three factors. First, we have obtained a satisfactory number of otoliths relative to the longevity of the species (~5 years; Pusey *et al.* 2004). This has led to good sample sizes of age–length pairs within each length class of the ALKs (Section 2.2.1), thus improving our ability to infer age from length.

Second, large length sample sizes were obtained by Selected Area teams. The effect of length sample size on uncertainty around age composition can be seen in Figure 9, in which a negative relationship between length sample size and the width of the 95% CIs around age-specific CPUEs is clear.

Third, there appears to be little spatial variation in age–length relationships of bony herring across Selected Areas. This resulted in relatively little variation in lengths within age cohorts of the ALK, reducing uncertainty when assigning ages to lengths.

Length-frequency histograms demonstrate a general pattern of left-skew, hence a preponderance of smaller individuals (Figure 8). This skew to the left is explained by the age-structure analysis, which shows strong recruitment of bony herring across all four Selected Areas (Figure 9). We can be confident that this is natural recruitment, given bony herring is not a sportfish; hence, not a species stocked by state fisheries agencies. Although bony herring is not a sportfish, its ecological value is likely very great. The bony herring is a detritivorous fish (Stoffels 2013) capable of reaching great densities within the MDB (Puckridge & Walker 1990; Puckridge *et al.* 2000). Similar fishes have been shown to play a key role in regulating ecosystem nutrient cycles elsewhere (Vanni 2002; Glaholt & Vanni 2005; Higgins *et al.* 2006). Nutrient cycling aside, strong recruitment pulses of bony herring, such as those reported here, may contribute significantly to productivity of larger fishes, such as Murray cod (Ebner 2006).
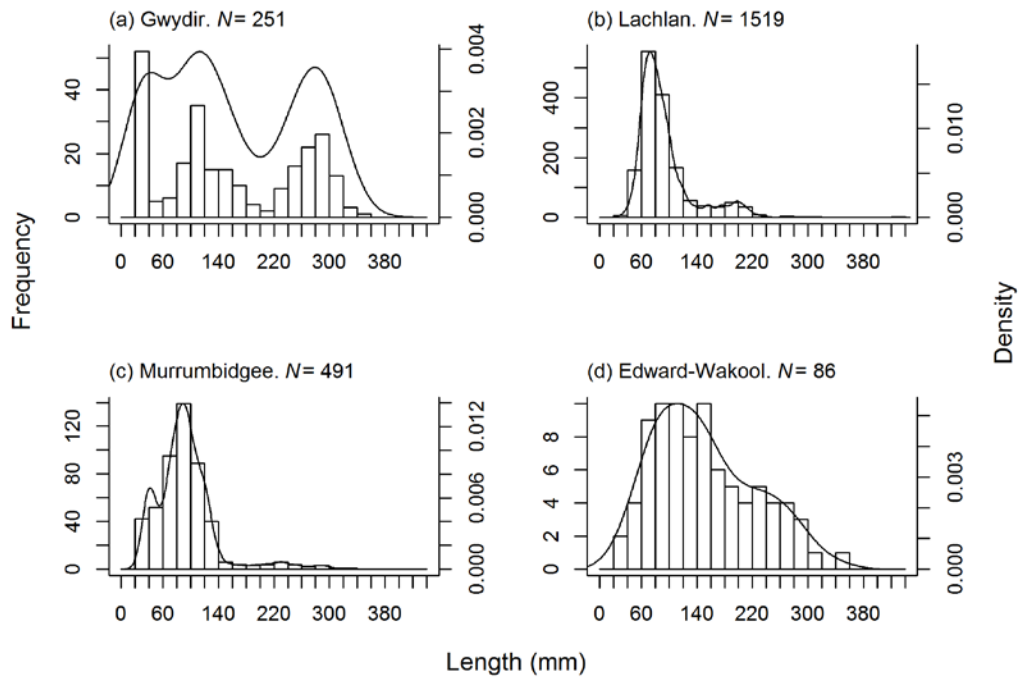
Figure 8. Length-frequency histograms, with overlayed kernel-smoothed density functions, for bony herring, *Nematalosa erebi*, collected from four LTIM Selected Areas of the Murray–Darling Basin during autumn 2015. Sample sizes are provided. Units on the right-hand y-axis for the density functions are point-probabilities; the area under the density functions sums to unity.

Figure 9. Age composition of bony herring, *Nematalosa erebi*, populations in four LTIM Selected Areas of the Murray–Darling Basin, autumn 2015. Mean catche per unit effort (CPUE) is presented, with units of number of individuals per electrofishing (EF) unit (Hale *et al.* 2013). Error bars are 95% confidence intervals and represent uncertainty in age-specific CPUE due to: variation in age within length classes; and size of sample from which lengths were obtained. Bony herring is a target species at four of six Selected Areas.

It is possible that managed flows contributed to the strong bony herring recruitment during 2014–15, especially in the Gwydir river system Selected Area which would have experienced significant low flows if not for watering actions. At this very early stage of LTIM, however, our confidence concerning flow impacts on recruitment and survival of target species is low; the analytical approach we are taking involves determining how flows affect population structure across years (Stoffels *et al.* 2016a).

Golden perch

The LTIM Category 1 census data for our second target species, golden perch, were of high quality. Good sample sizes were obtained, particularly in the Lachlan river system, Edward–Wakool river system and Lower Murray River Selected Areas. Our estimations of golden perch age structure within Selected Areas was characterised by more uncertainty than those for bony herring (see Figure 11). This increased uncertainty in age at length is due to two factors. First, there was likely more spatial variation in golden perch growth among Selected Areas, resulting in wider age probability distributions within our 'pooled-area' ALKs (see Section 2.2.1).

Second, due to the greater longevity and size of golden perch, more age–length data (more otolith data) are required to reduce uncertainty of the ALK. Further otolith collection scheduled within LTIM, as well as increased sharing of otolith data across projects, will greatly reduce uncertainty of the golden perch ALK; hence, improving our ability to determine — and predict — flow impacts on golden perch populations.

In complete contrast to the bony herring length histograms, the golden perch histograms are right-skewed, showing a preponderance of larger individuals (Figure 10). Age-structure analysis shows that golden perch populations across all six Selected Areas are dominated by adults; individuals in their sixth year of life (5+) or older (Figure 11). The consistency in golden perch age structure across Selected Areas of the MDB is particularly striking (Figure 11). Below, we offer two explanations for this pattern.
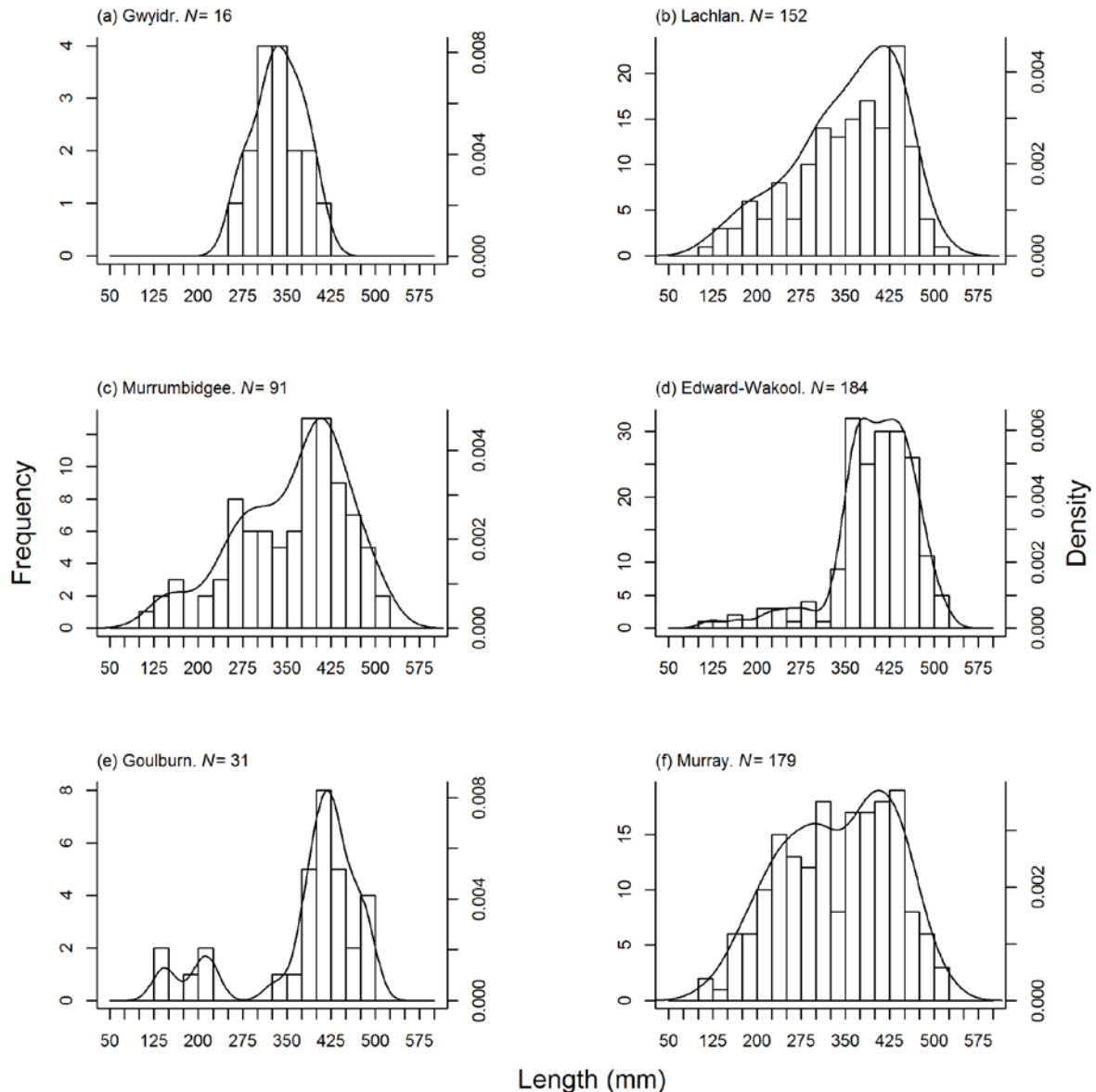
Figure 10. Length-frequency histograms, with overlayed kernel-smoothed density functions, for golden perch, *Macquaria ambigua*, collected from six LTIM Selected Areas of the Murray–Darling Basin during autumn 2015. Sample sizes are provided. Units on the right-hand y-axis for the density functions are point-probabilities; the area under the density functions sums to unity.

First, it is possible that boat electrofishing is particularly biased when sampling golden perch, with catch probability increasing with body length; hence, age. It is generally appreciated that electrofishing catch is biased towards larger fish (e.g. Peterson *et al.* 2004). With respect to Australian native fishes, there has been very little research on the sampling bias and precision associated with different methodologies. A study by Lyon *et al.* (2014) showed that electrofishing catch probability of golden perch is generally low, with catch probability increasing marginally with length.

Notwithstanding the results of Lyon *et al.* (2014), Selected Area experts have suggested that, in their experience, pulses of recruitment and juvenile survivorship have been observed using boat

electrofishing, within their respective Selected Areas (BP Zampatti, pers. comm.). These observations suggest that electrofishing should detect recruitment pulses when they occur.[2]
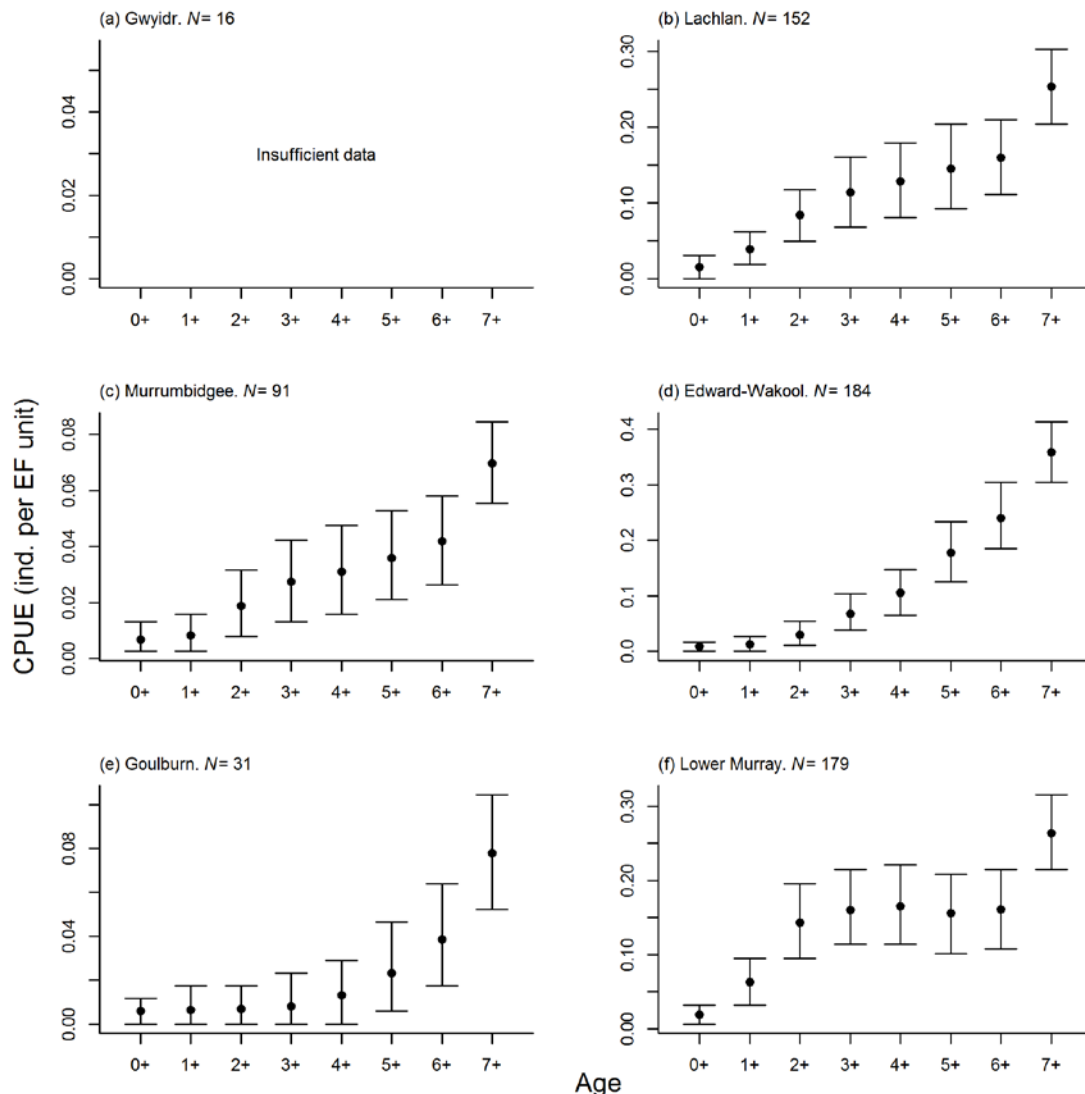
Figure 11. Age composition of golden perch, *Macquaria ambigua*, populations in five LTIM Selected Areas of the Murray–Darling Basin, autumn 2015. Mean catche per unit effort (CPUE) is presented, with units of number of individuals per electrofishing (EF) unit (Hale *et al.* 2013). Errors bars are 95% confidence intervals and represent uncertainty in age-specific CPUE due to: variation in age within length classes; and size of sample from which lengths were obtained.

The second explanation for the consistency in golden perch age structure across Selected Areas is that the dynamics of golden perch recruitment are driven by Basin-scale events, and that a particularly strong recruitment pulse occurred 6–8 years ago, with little recruitment in recent years.

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[2] It is worth noting here that LTIM fish flow-response modelling does not require estimates of absolute numbers or density, only that methods remain standardised so that relative differences in CPUE across years can be detected with minimal bias.

Apparently, this explanation accords with the observations of golden perch experts (pers. comm. with Selected Area scientists). Population dynamics such as these, in which strong episodic recruitment is observed under favourable environmental conditions, are not uncommon. Indeed, the pattern exhibited by long-lived species where population size is driven to a large degree by episodic breeding and recruitment events is known as the 'storage effect' (Chesson 1998), named to indicate that long-lived populations store the benefits of episodic opportunities.

Irrespective of which explanation is closest to the truth, the above discussion highlights the importance of high-quality population data collected as part of long-term monitoring programs like the LTIM Project. If recruitment events of our long-lived fishes are responses to infrequent, large-scale flow events, then programs like LTIM are essential to detect and understand such dynamics.

Murray cod

As was the case for golden perch and bony herring, the quality of the data returned by the Category 1 LTIM method were excellent. Large sample sizes were obtained in the Lachlan river system, Edward–Wakool river system and Murrumbidgee river system Selected Areas in particular. Where the size of length samples was large, our capacity to infer age structure of the populations was high (see Figure 13). Again, our capacity to infer age structure — and hence determine the impact of flows on survival — will increase as further age–length data come to hand, and are incorporated in models being developed as part of the LTIM Fish Basin Matter.

Unlike golden perch, the Murray cod length histograms indicated a left skew, suggesting recruitment and juvenile survival in recent years (Figure 12). Analysis of age-structure showed good recruitment of Murray cod in most Selected Areas of the MDB (Figure 13). Individuals in their second and third years of life (1+ and 2+ individuals) were also well represented in most Selected Areas, particularly the Edward–Wakool (Figure 13).

While it is possible flow management contributed to the observed Murray cod recruitment, uncertainty concerning flow impacts on recruitment and survival of cod is too great at this early stage to be certain. Given the quality of the data arising from LTIM methods, we have strong prospects during the first 5 years of LTIM of linking flows with cod recruitment and survival.
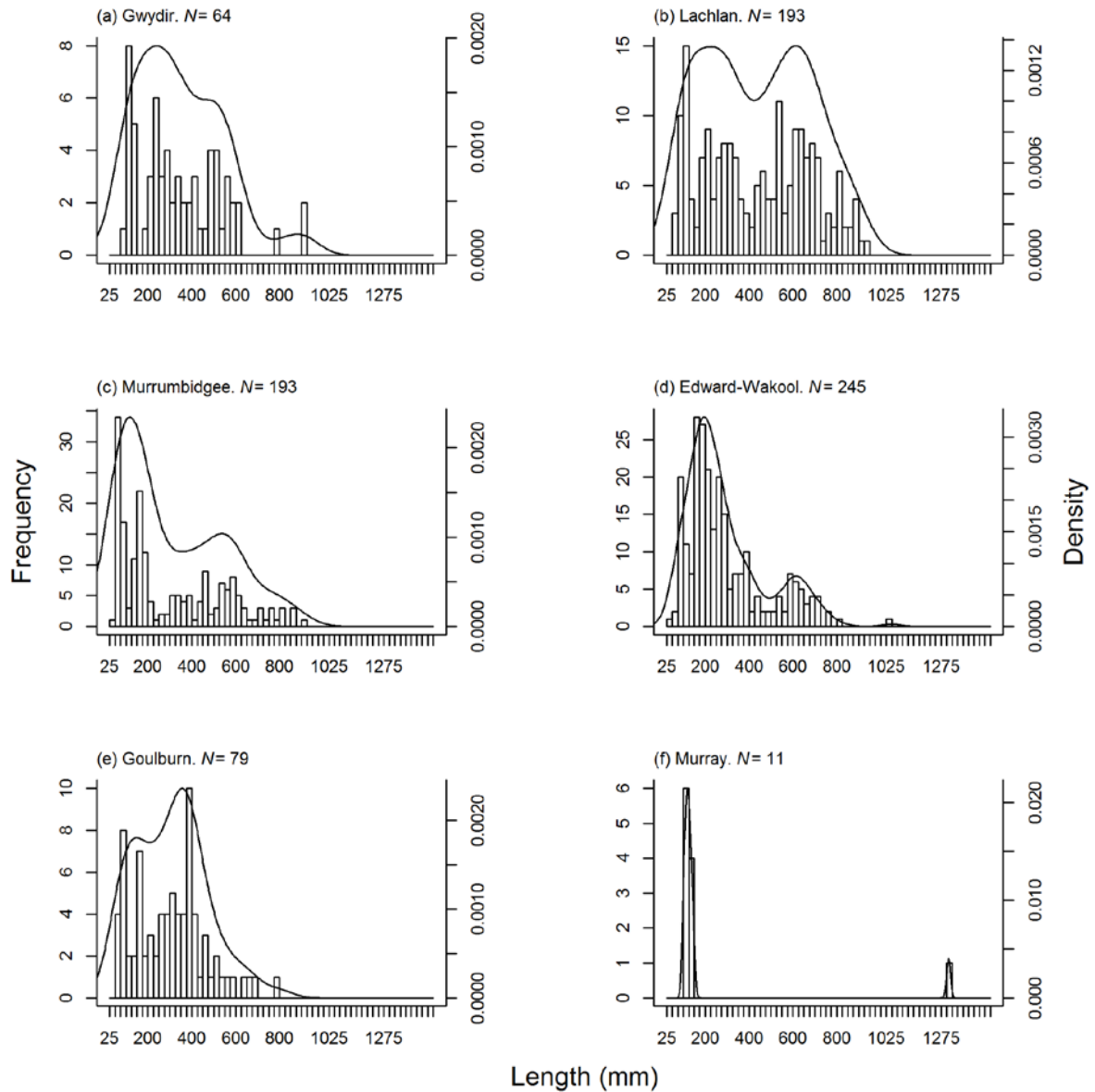
Figure 12. Length-frequency histograms, with overlayed kernel-smoothed density functions, for Murray cod, *Macullochella peelii*, collected from six LTIM Selected Areas of the Murray–Darling Basin during autumn 2015. Sample sizes are provided. Units on the right-hand y-axis for the density functions are point-probabilities; the area under the density functions sums to unity.
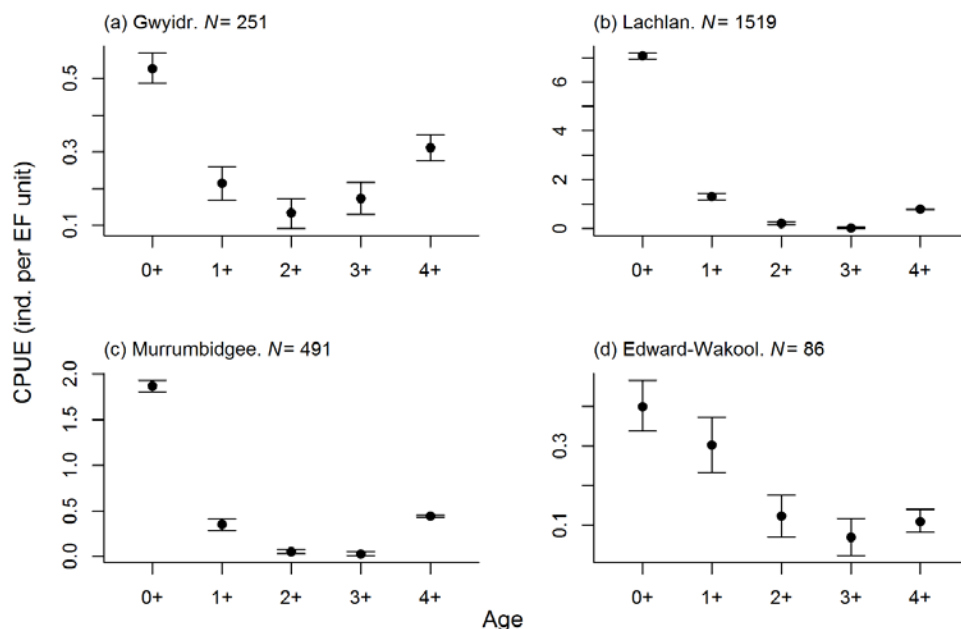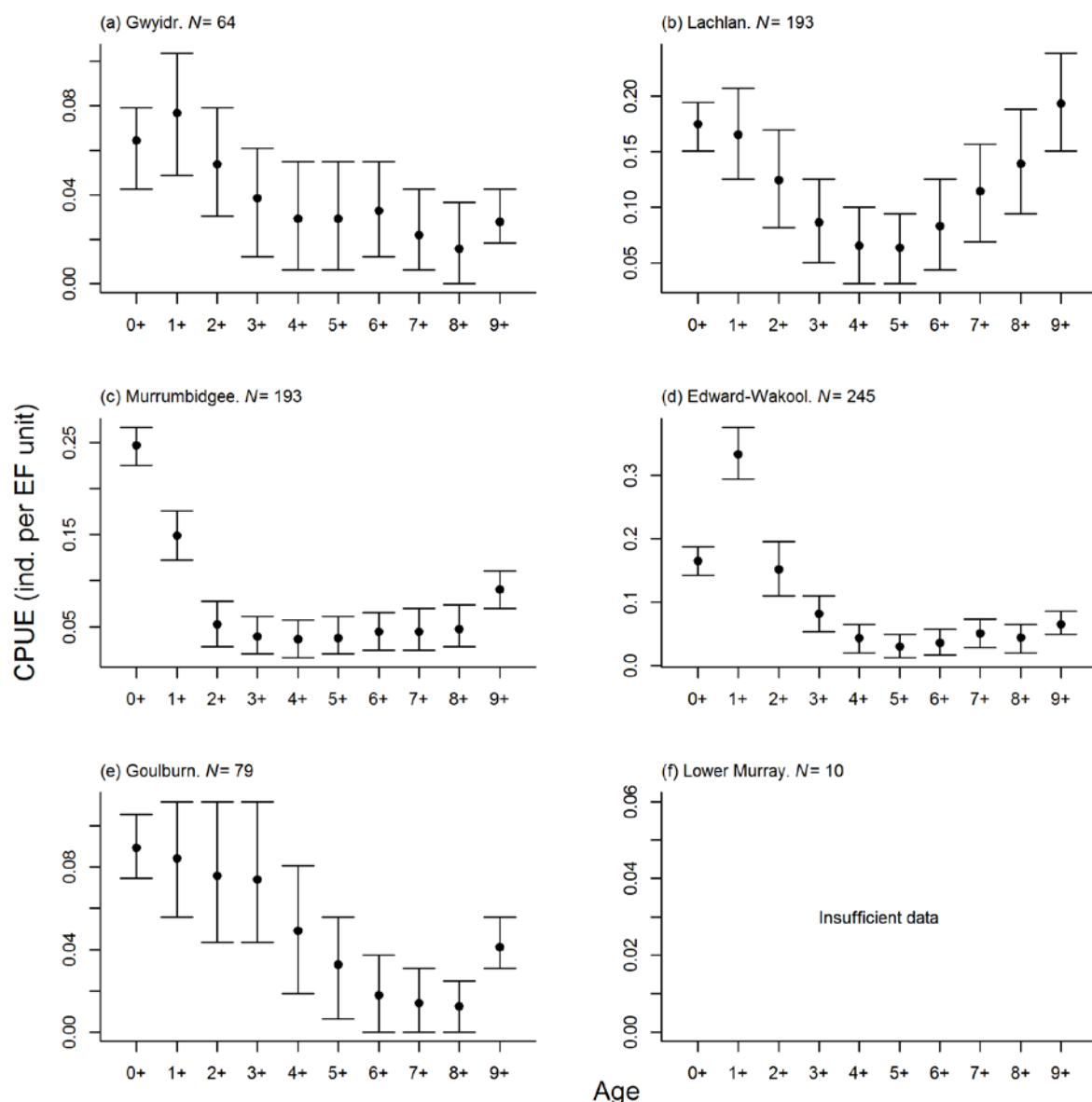
Figure 13. Age composition of Murray cod, *Macullochella peelii*, populations in five LTIM Selected Areas of the Murray–Darling Basin, autumn 2015. Mean catche per unit effort (CPUE) is presented, with units of number of individuals per electrofishing (EF) unit (Hale *et al.* 2013). Errors bars are 95% confidence intervals and represent uncertainty in age-specific CPUE due to: variation in age within length-classes; and size of sample from which lengths were obtained.

3.2.2   Condition

The condition of target species golden perch and Murray cod varied very little across Selected Areas. This is demonstrated in Figure 14, where little evidence can be found for points of different colour and shape falling along lines of different intercept (or elevation) and slope (steepness) in the plots. The only target species that did exhibit significant variation in condition among Selected Areas was bony herring. This can be seen in Figure 15a, where Selected Area–specific regression lines between length and mass show a strong departure from the Basin-wide average. In particular, there was strong variation in the condition of juvenile bony herring among Selected Areas (Figure 15a).
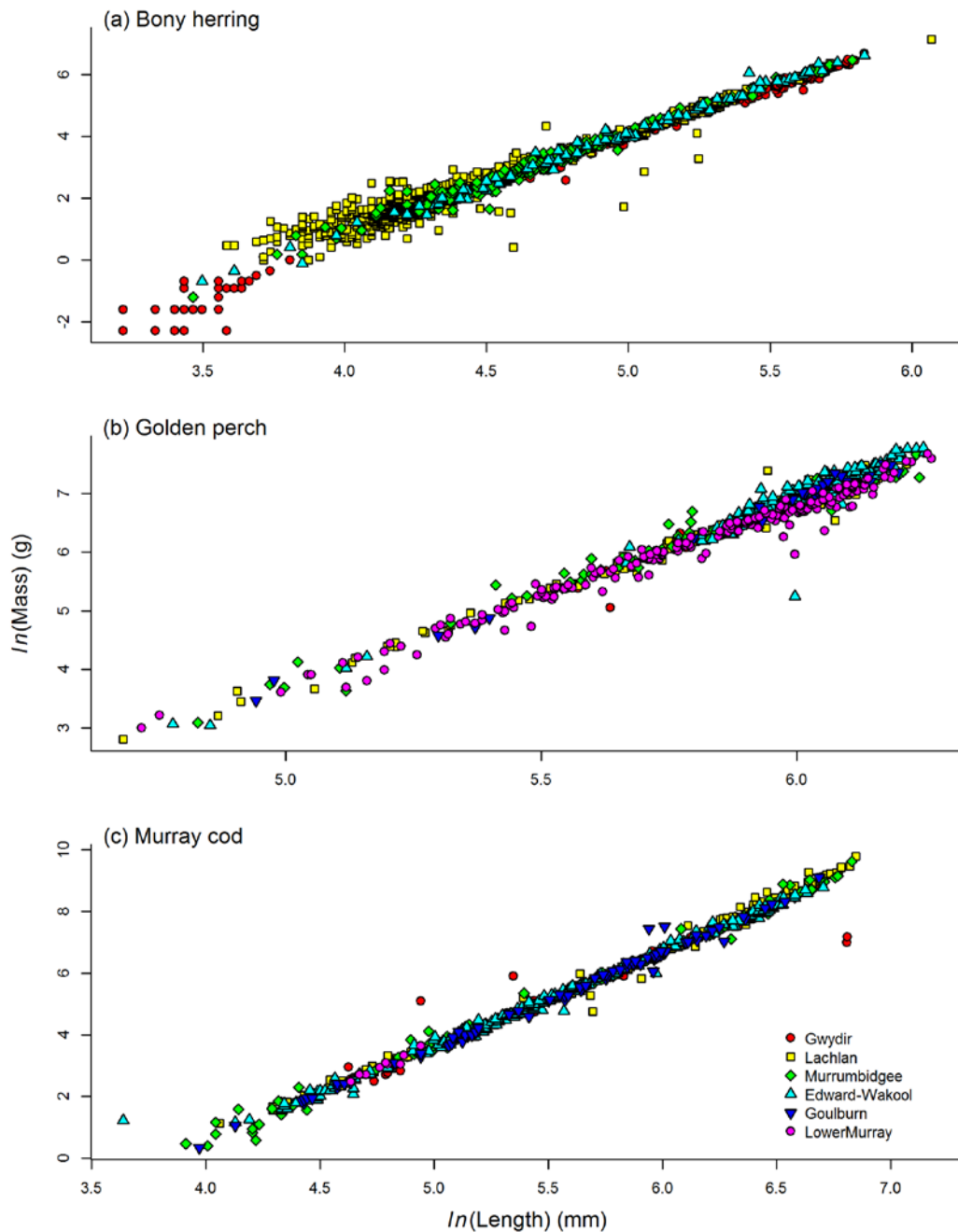
Figure 14. Relationship between *In*-transformed body mass and *In*-transformed length in the three large-bodied target species of LTIM: (a) bony herring, (b) golden perch and (c) Murray cod. Spatial variation in condition would show as points of different colour/shape falling along lines of different intercept (or elevation) and slope (steepness).

The gradient in juvenile bony herring condition across Selected Areas could be described by the inequality Lachlan > Murrumbidgee > Edward–Wakool > Gwydir. This gradient in juvenile condition is interesting, as it accords with our observations concerning recruitment across Selected Areas. The Lachlan and Murrumbidgee experienced the greatest and second greatest recruitment pulses for bony herring, respectively. These areas contained juvenile bony herring of the best and second best condition, respectively. Further observations through time will shed light on the relationship between flows, condition and recruitment. Recent studies have drawn strong links between flows and fish condition within the MDB (Balcombe *et al.* 2012, Stoffels *et al.* 2015), but these studies have

relied on time series to demonstrate this. Thus, further samples through time are required to link flows to condition.

The Gwydir juvenile bony herring were of very poor condition, despite strong recruitment. This poor condition may be related to the drying of the Gwydir during autumn 2015; hence, increased concentrations of fishes in pools.
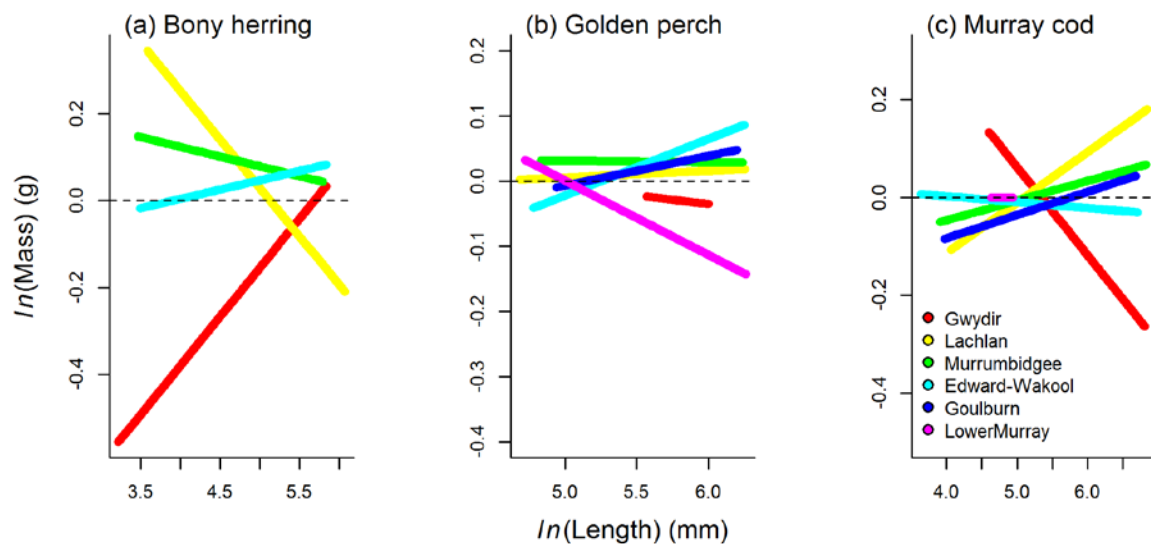
Figure 15. Variation in condition as a function of length across Selected Areas in (a) bony herring, (b) golden perch and (c) Murray cod. Lines present the predicted difference between the 'population' (Basin wide; fixed effects) and Selected Area–specific models (random effects). Predicted values derived from random intercepts and slopes mixed effects models of *In*(mass) as a function of *In*(length). Dashed line indicates zero difference between Selected Area–specific and Basin-wide models. Positive values indicate mean condition of individuals is greater than we would expect on average, based on the Basin-wide model. Negative values indicate poorer condition, relative to the Basin-wide case.

3.3   State of fish assemblages

A total of 17 fish species were sampled across Selected Areas during the first year of LTIM, 13 of which were native. Lintermans (2007) lists 22 native species of fish associated with lowland rivers of the MDB. It follows the the Category 1 annual census, implemented across the six LTIM Selected Areas, is sampling most of the fishes we would expect to find in lowland rivers of the MDB. The species listed in Lintermans (2007) that were not detected using LTIM sampling were very rare species, such as purple-spotted gudgeon, *Mogurnda adspersa*, and Murray hardyhead, *Creterocephalus fluviatilis*.

Lintermans (2007) stated that alien species make up approximately 70% of the numbers in fish assemblages of the MDB. The first year of LTIM data show that alien species generally made up less than 50% of the numbers in 2014-15 (see 'nativeness' in Table 2). Therefore, compared with the figures presented by Lintermans in 2007, alien fishes are less dominant. Indeed, native species comprised well over 70% of the numbers in four of six Selected Areas (Table 2).

Table 2. Total number of individual fish caught within each LTIM Selected Area using Category 1 standard annual census methods (Hale *et al.* 2013) during autumn 2015. This table does not include abundances of larval fishes sampled. Species richness and nativeness (mean and standard deviation) are provided at the bottom of the table. 'Nativeness' is calculated as the proportion of total CPUE comprised of native species.

	Lower Murray	Goulburn	Edward–Wakool	Murrum-bidgee	Lachlan	Gwydir
Large-bodied natives						
Murray cod (*Maccullochella peelii*)	11	79	210	126	193	63
Golden perch (*Macquaria ambigua*)	181	29	107	39	150	16
Bony herring (*Nematalosa erebi*)	9471	0	31	438	1555	218
Silver perch (*Bidyanus bidyanus*)	4	2	5	1	0	0
Eel-tailed catfish (*Tandanus tandanus*)	6	0	0	0	0	0
Spangled perch (*Leiopotherapon unicolor*)	0	0	0	0	0	73
Trout cod (*Maccullochella macquariensis*)	0	1	0	1	0	0
Small-bodied natives						
Carp gudgeon (*Hypseleotris* spp.)	18 826	170	4302	205	60	1988
Flathead gudgeon (*Philypnodon grandiceps*)	20	0	0	0	0	0
Dwarf flathead gudgeon (*Philypnodon macrostomus*)	86	0	0	0	0	0
Australian smelt (*Retropinna semoni*)	76	9	2	26	1	9
Murray–Darling rainbowfish (*Melanotaenia fluviatilis*)	350	58	168	401	0	249
Unspecked hardyhead (*Craterocephalus stercusmuscarum fulvus*)	425	0	64	2	0	149
Large-bodied alien species						
Common carp (*Cyprinus carpio*)	105	107	167	112	223	221
Goldfish (*Carassius auratus*)	18	8	21	11	11	48
Redfin (*Perca fluviatilis*)	1	0	0	0	0	0
Small-bodied alien species						
Mosquitofish (*Gambusia holbrooki*)	1253	0	175	735	271	60
Summary statistics						
Species richness	*15*	*9*	*11*	*12*	*8*	*11*
Nativeness	*0.98 (0.01)*	*0.48 (0.22)*	*0.76 (0.09)*	*0.79 (0.10)*	*0.88 (0.05)*	*0.48 (0.31)*

Spatial heterogeneity in fish assemblage structure (composition and relative abundances of species) was low within the Lower Murray River , Edward–Wakool river system, Murrumbidgee river system and Lachlan river system Selected Areas, moderate in the Goulburn River Selected Area, and very high in the Gwydir river system Selected Area (Figure 16). The spatial heterogeneity in the Gwydir likely reflects the high hydrological and environmental heterogeneity of that Selected Area. Two things are of note in Figure 16. First, as touched on above, the MDS plots show significant and strong variation in fish assemblage structure across Selected Areas (PERMANOVA; $P < 0.001$; Figure 16), demonstrating that LTIM Selected Areas cover a good diversity of assemblage types within the MDB. It follows that, in the long term, LTIM will be monitoring the effects of flow regimes on a diverse suite of fish assemblages within the MDB.

Second, despite the high spatial heterogeneity within the Gwydir, area centroids — which describe the mean assemblage structure — were surrounded by small confidence regions (Figure 16). As was the case for population data (Section 3.2), the very small confidence regions presented in Figure 16 are a testament to the quality of Category 1 LTIM data. These small confidence regions demonstrate our estimates of Selected Area assemblage structures are precise. In turn, this gives us confidence that, given flow variation across Selected Areas, we will improve our understanding of how flows impact on whole fish assemblages using a multiple before–after control–impact (MBACI) design type and multivariate statistics.
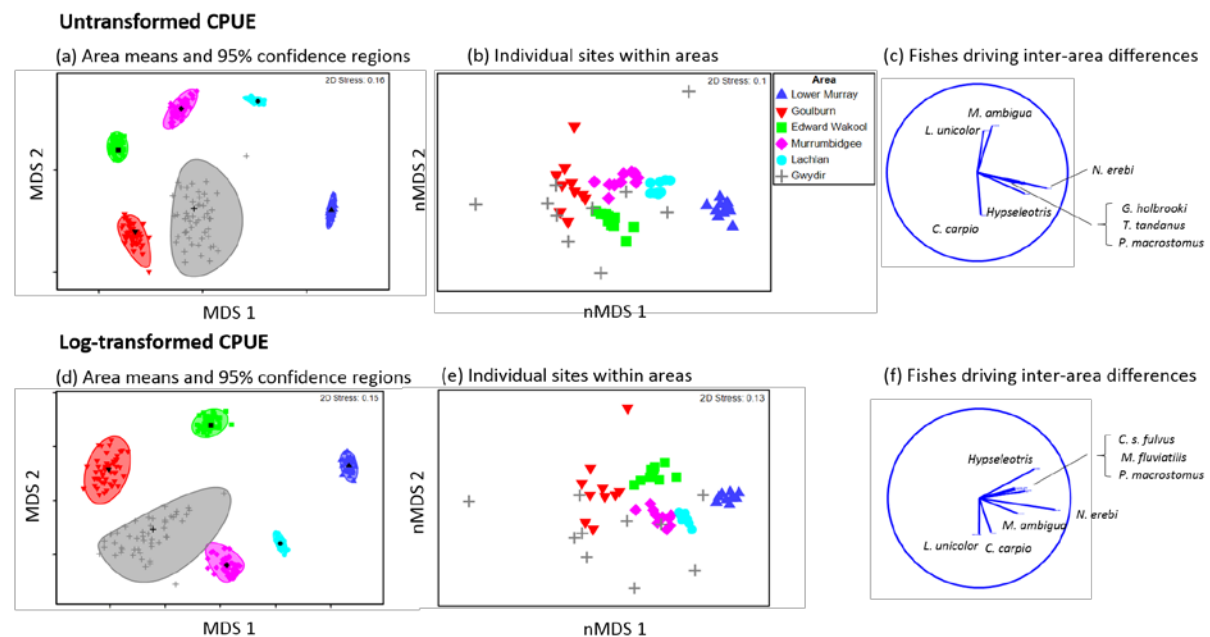
Figure 16. Variation in fish community structure (species composition and relative abundances) among the six LTIM Selected Areas that are including fish in their flow-response monitoring. Ordinations for untransformed catch per unit effort (CPUE) and log-transformed CPUE are presented — log-transformed CPUE allows rarer species to have a greater influence on distances between samples (sites or areas). Area centroids and 95% confidence regions are presented on the left (a, d); individual sites (10 per area) are presented in the middle (b, e); and vector plots on the right (c, f) show the direction and magnitude of correlations between species abundances and multidimensional scaling (MDS) axes for certain species. One may interpret the vectors of each species as 'pointing' to the region of the ordination characterised by increased abundances of those species (e.g. sites on the right of (b) are characterised by high abundances of *N. erebi*). Species common names: *L. unicolor* = spangled perch; *M. ambigua* = golden perch; *N. erebi* = bony herring; *G. holbrooki* = mosquitofish; *T. tandanus* = eel-tailed catfish; *P. macrostomus* = dwarf flathead gudgeon; *Hypseleotris* spp. = carp gudgeon; *C. carpio* = common carp; *C. s. fulvus* = unspecked hardyhead; *M. fluviatilis* = Murray–Darling rainbowfish.

3.4 Synthesis of reported outcomes 2014–15

Table 3 presents a summary of fish monitoring outcomes within LTIM Selected Areas of the MDB during 2014–15.

3.4.1 Overview of watering actions with expected outcomes for fish

With respect to Commonwealth environmental watering actions with expected outcomes for fishes, a total of 62 watering actions, culminating in a volume of around 1080 gigalitres (GL), were delivered throughout the Basin during 2014–15. Of these, 20 watering actions (32%) were specifically monitored for fish outcomes, as part of LTIM. A detailed table of 2014–15 Commonwealth environmental watering actions with expected outcomes for fish is in Appendix A.

3.4.2 Base flows

Of the watering actions for which short-term monitoring data are available, three watering actions (two in the Lower Murray River and one in the Edward–Wakool river system) were base flows for which there were expected outcomes around spawning and recruitment. Both these Selected Areas have several years of monitoring data available to provide a reference, so we can have some confidence in the inferences made within these areas, which is that base flows did not trigger spawning of flow-cued spawners (golden perch and silver perch) in these areas.

Within the Edward–Wakool river system, the base flow was expected to promote spawning of opportunistic, small-bodied species through the provision of possible spawning habitat (inundation of slackwaters and flooded vegetation around channel margins) (Watts *et al.* 2015b). During 2014–15, there was no evidence that the base flow within the Yallakool Creek system improved spawning or recruitment of these species (Watts *et al.* 2015a). However, the watering action did increase wetted area within the Yallakool Creek system and a positive response of aquatic vegetation was observed (Watts *et al.* 2015a). Given aquatic vegetation may be used by certain opportunistic species as spawning habitat, it is anticipated that the improvement in aquatic vegetation communities resulting from flows during the 2014–15 season may result in increased fish spawning in subsequent years.

The Edward–Wakool watering action was also expected to improve recruitment of Murray cod (Watts *et al.* 2015b). This expected outcome was not observed (Watts et al. *2015a*). A base flow — or, as referred to in this instance, a maintenance flow — might be expected to improve recruitment if it either increased or prevented a decrease in the amount of a limiting habitat. As discussed above, the watering action did increase wetted area, but why this did not translate into improved cod recruitment is currently unclear. As years of data accumulate for the Yallakool Creek system, and models develop accordingly, our ability to ascertain how base flows affect fish recruitment will improve.

In the Lower Murray, very low numbers of golden perch larvae were recorded, and it was clear the base flows did not trigger spawning of golden perch (Ye *et al.* 2015). This was concordant with our conceptual understanding of golden perch response to flows.

3.4.3 Fresh flows

Three of the monitored water actions were freshes (two in the Goulburn, one in the Lachlan). The monitoring of the first fresh in the Goulburn River (Watering Action Reference (WAR) 10002-01: 14/10/14 – 11/11/14) detected only a relatively weak spawning response and only a few individuals moved short distances (Webb *et al.* 2015). It appears unlikely that the limited spawning and movement was due to the characteristics of the hydrograph as the subsequent fresh that started a month later after the first fresh started was shorter and smaller and yet there was greater golden

perch spawning activity observed. This leaves the possibility that lower water temperatures may have played a role in limiting the response to the first event.

The second fresh monitored in the Goulburn River (WAR 10020-01: 20/11/14 – 30/11/14) was also expected to lead to spawning and movement (Webb *et al.* 2015). Monitoring revealed a larger spawning by golden perch, and silver perch also spawned (Webb *et al.* 2015). A larger number of fish also undertook movements over longer distances and these coincided with the watering action (Webb *et al.* 2015). The main reason proposed for the larger response is the alignment of appropriate flows and water temperatures (Webb *et al.* 2015).

An important aspect to the spawning response to the second fresh was the potential influence of antecedent conditions. Previous freshes delivered in the Goulburn River have not elicited as large a response from flow-cued species. It has been suggested that the sequence of flows delivered in the Goulburn may have contributed to achieving the outcome (Webb *et al.* 2015). This will be an area worthy of further investigation in the evaluation of future watering actions.

There was one fresh monitored in the Lachlan river system for which the expected uutcome was spawning and recruitment of fishes. The fresh resulted in a 1 m increase in depth (peak) at a time when the daily average water temperature was 19 °C (Dyer *et al.* 2015). The pulse was associated with an initial decrease in both primary production and community respiration, suggesting dilution of existing algae and organic matter rather than entrainment of additional organic matter from river banks of benches (Dyer *et al.* 2015). The monitoring did not record any larvae from flow-cued spawners (golden perch and silver perch), but did record larvae of equilibrium species (Murray cod) and small numbers of opportunistic species (flathead gudgeon, Australian smelt and carp gudgeon). It is likely these species would have spawned in the absence of the watering action and therefore it is uncertain what, if any, influence the watering action had on spawning in these species.

3.4.4   Wetland inundation

During 2014–15, there were three areas that undertook wetland inundation (Murrumbidgee (WAR 10023-01, 10023-02, 10023-03, 10023-06), Gwydir (WAR 00016-02) and Macquarie (WAR 10015-01) river systems). The Murrumbidgee suite of watering actions inundated a number of different wetlands that started in August 2014 and continued until June 2015 (Wassens *et al.* 2016). During this period, flows in the channel were elevated due to the delivery of environmental flows and there were two deliberate return flows (flow returning from an inundated wetland) in October 2014 and February 2015 in the downstream reach. There were no expected outcomes for fish for these watering actions; however, fish larval monitoring was undertaken in the two upstream reaches of the Murrumbidgee Selected Area (Wassens *et al.* 2016). The monitoring identified spawning by equilibrium species (Murray cod and trout cod), flow-cued species (golden perch and silver perch) and opportunistic species (carp gudgeon, unspecked hardyhead, Murray–Darling rainbowfish and Australian smelt). The complexity of the hydrograph and larval fish responses means that there was difficulty in inferring the influence of flow on larval fish abundance. It is anticipated that our capacity to identify the influence of flow will improve with the development of the quantitative models described earlier.

Between 13 October 2014 and 12 December 2014 (WAR 10015-01 in Appendix A), Commonwealth environmental water was delivered to support native fish in the Macquarie River with the expected outcome being increased reproduction and subsequent recruitment of native fish species and an increase in native fish condition. Fish community sampling found juveniles from equilibrium species (Murray cod, eel-tailed catfish and bony bream), and opportunistic species (Australian smelt and carp gudgeon) but no golden perch or silver perch (periodic life-history) were caught (Stocks *et al.* 2015). Ageing of these juveniles revealed that opportunistic species spawned during sustained periods of elevated flow or the receding limb of a flow pulse (Stocks *et al.* 2015). The bony bream sampled appear to have been spawned in July, before the Commonwealth environmental flow,

during freshes in the Macquarie Marshes and the Barwon River. At the time, water temperature was approximately 13 °C (Stocks *et al.* 2015). The lack of spawning by golden perch and silver perch was attributed to the magnitude of the flow being too small (Stocks *et al.* 2015).

The Gwydir river system was dominated by two environmental flows of relatively long duration (39 and 129 days) during September to March (Stocks *et al.* 2015). These flows represented the majority of the flow in the river system over this period. There was no monitoring of spawning or recruitment; however, the annual census undertaken in autumn 2015 identified a number of species with young-of-year, suggesting spawning in the previous 12 months (Southwell *et al.* 2015). The species included opportunistic species (carp gudgeon, Murray–Darling rainbowfish and Australian smelt), equilibrium species (Murray cod) and periodic species (bony herring) (Southwell *et al.* 2015). More than a single year of censuses are required to link a watering action with recruitment; however, given there would have been no flow in the system without the Commonwealth environmental water, it appears likely that this water had an influence on these species spawning and subsequently recruiting to young-of-year.

Table 3. Synthesis of watering actions, expected and observed outcomes (from monitoring reports), as well as influences on inferences and outcomes, for fish monitoring across seven Selected Areas within the Murray–Darling Basin during 2014–15. Expected and observed ecological outcomes and influences were taken from the 2014–15 Selected Area annual reports (Dyer *et al.* 2015; Southwell *et al.* 2015; Stocks *et al.* 2015; Wassens *et al.* 2015, 2016; Watts *et al.* 2015a, b; Webb *et al.* 2015; Ye *et al.* 2015).;

Selected Area	Water delivery dates (start–end)	Flow component type	Commonwealth environmental water volume delivered (GL)	Monitored site(s)	Expected ecological outcome	Observed ecological outcomes	Influences
Lower Murray River	Sep 2014 – Jan 2015	In-channel base flow	389.205	The Floodplain (Border to Lock 3); the Gorge (Lock 3 to Mannum)	Increases in flow above regulated entitlement flow (in-channel or overbank) in spring–summer will promote the spawning and recruitment (to young-of-year) of golden perch and silver perch	No significant flow-induced spawning and recruitment of either golden or silver perch.	**Flow variability.** Insufficient variability in spring–summer hydrograph for Lower Murray possibly resulted in absence of cues (e.g. rate of depth increase) for spawning. There is possibly a trade-off between water delivery to achieve in-channel flow variability within the Lower Murray, and water allocation to upstream icon sites like Chowilla.
Lower Murray River	Jan–Mar 2015	In-channel base flow	191.833	The Floodplain (Border to Lock 3); the Gorge (Lock 3 to Mannum)	As above	As above	As above
Goulburn River	Oct–Nov 2014	In-channel fresh flow	67.46	Zones 1 & 2	Golden perch and silver perch spawning, coincident with Commonwealth environmental water flow peaks	Golden perch spawning showed a very weak increase in response to the Oct fresh (cf. next action).	**Temperature**. Cooler temperatures at this time of year (cf. Nov) may have depressed spawning response of golden perch and silver perch. Modelling by Webb *et al.* (2015) indicates temperature is an important co-variable.

Selected Area	Water delivery dates (start–end)	Flow component type	Commonwealth environmental water volume delivered (GL)	Monitored site(s)	Expected ecological outcome	Observed ecological outcomes	Influences
					Increased golden perch movement, coincident with flow peaks	Only weak/infrequent movement, cf. flows later in year.	**Temperature**. Movements appear to be associated with spawning downstream, and so flow-cued movement at this time of year may be rare due to the absence of appropriate flow–temperature interactions.
Goulburn River	Nov–Dec 2014	In-channel fresh flow	14.472	Zones 1 & 2	Golden perch and silver perch spawning, coincident with Commonwealth environmental water flow peaks	Golden perch exhibited a strong spawning response to the environmental flow. Silver perch also spawned in association with increased flows at this time of year.	**Temperature**. Higher temperatures (cf. Oct) may have interacted with the flow pulse to promote stronger spawning of these flow-cued spawners (also see previous action).
					Increased golden perch movement, coincident with flow peaks	Long-distance movements coincided with increases in flow associated with environmental flow releases. Long-distance movements occurred primarily downstream into the lower reaches.	**Temperature**. Movements appear to be associated with spawning downstream. Flow-cued movement at this time of year may have been stronger than in Oct due to the coincidence of appropriate flow and temperature conditions for spawning-related movement.
Goulburn River	Spring–summer 2014–15	Multiple in-channel freshes	Total fresh and base flows delivered from Aug 2014 through to June 2015: ~136	Zones 1 & 2	Increased recruitment of golden perch within the lower Goulburn	Population surveys revealed no strong relationships between golden perch spawning and recruitment, suggesting that spawning may not necessarily translate	**Life-history of species**. It is possible that larvae of focal species (golden perch) drift out of the Goulburn catchment and recruit to the regional (not local) population. This results in area-scale sampling yielding only part of the story concerning flow impacts on golden

Selected Area	Water delivery dates (start–end)	Flow component type	Commonwealth environmental water volume delivered (GL)	Monitored site(s)	Expected ecological outcome	Observed ecological outcomes	Influences
						into recruitment of juveniles into the local population.	perch recruitment. Future analysis of golden perch and Murray cod movement histories conducted by the Goulburn and Lower Murray teams will shed some light on regional recruitment–flow relationships in these species.
					Increased survival of larval golden perch through to 0+ (young-of-year) age	Although golden perch spawned in 2014, no young-of-year fish were collected. Thus, while increased flows can promote golden perch spawning, this may not necessarily lead to immediate in situ recruitment of juvenile fish.	**Life-history of species.** As above.
Edward–Wakool river system	Aug 2014 – Jan 2015	In-channel base flow; 'cod maintenance flow'	34.563	Yallakool Creek	Improved recruitment of Murray cod in Yallakool Creek compared with other zones not receiving maintenance flows	There was no evidence that recruitment of Murray cod was enhanced by the delivery of the 'maintenance flow' in Yallakool Creek.	**Small variance in flow characteristics between reference sites and sites receiving watering actions**. During 2014–15, sites serving as references and receiving Commonwealth environmental water experienced conditions conducive to recruitment of Murray cod. Our ability to detect impacts of flows on cod recruitment will improve as more data become available, and as analytical models improve.

Selected Area	Water delivery dates (start–end)	Flow component type	Commonwealth environmental water volume delivered (GL)	Monitored site(s)	Expected ecological outcome	Observed ecological outcomes	Influences
Edward–Wakool river system	Aug 2014 – Jan 2015	In-channel base flow	34.563	Yallakool Creek	Increased spawning of opportunistic (small-bodied) species in Yallakool Creek compared with other zones of Edward–Wakool	No evidence for greater abundance of larvae of opportunistic species in Yallakool Creek.	**Unknown.**
Murrum-bidgee river system	Oct 2014 – Jan 2015	In-channel return flow	40	Murrumbidgee River; Balranald reach	Note: These were return flows, not delivered with explicit expected outcomes for fish in channel. However, larval fish were monitored to determine whether spawning showed any association to flow variability in the Murrumbidgee channel.	Murray cod, golden perch, silver perch, carp gudgeon and Australian smelt all spawned within the Murrumbidgee during spring–summer 2014–15, but spawning timing and intensity showed no obvious links to the hydrograph.	**Unknown**. Our capacity to link flows to fish spawning in the Murrumbidgee will improve as more data become available, and as analytical models improve.
Lachlan river system	Sep 2014	Fresh flow	5	Zone 1; Lachlan River channel between Brewster Weir and Booligal	Increased spawning of fish in general, through the provision of cues and appropriate habitat for spawning	Larvae of Murray cod, flathead gudgeon and Australian smelt were observed 1–2 months after the environmental flow. These species are not considered flow-cued spawners, and likely would have spawned irrespective of Commonwealth environmental water fresh. No larvae of flow-cued spawners were	**Unknown**. Our capacity to link flows to fish spawning in the Lachlan will improve as more data become available, and as analytical models improve.

Selected Area	Water delivery dates (start–end)	Flow component type	Commonwealth environmental water volume delivered (GL)	Monitored site(s)	Expected ecological outcome	Observed ecological outcomes	Influences
						observed (golden perch and silver perch).	
					Increased recruitment of larval fish into the 0+ (young-of-year) juvenile cohort, following provision of cues and appropriate habitat for spawning	Young-of-year Murray cod, flathead gudgeon, bony herring and Australian smelt were observed in autumn 2015, but there were insufficient data to infer recruitment of these species was impacted by the Sep 2014 Commonwealth environmental water fresh.	**Insufficient data.** Multiple years of data are required to infer impact of flows on recruitment within the Lachlan.
Gwydir river system	No monitoring of short-term responses of fish processes to flows in 2014–15.						
Junction of the Warrego and Darling rivers	Monitoring of flow response in the Warrego–Darling focuses on hydrology, water quality, vegetation, microinvertebrates, frogs and waterbirds. No fish response monitoring was carried out.						

4   Expected 1–5-year outcomes

Our capacity to predict the long-term outcomes of the use of Commonwealth environmental water is currently constrained by the limited capacity to predict the outcomes of flow regimes over multiple years. It is anticipated that the LTIM Project's development of quantitative models will improve the capacity to predict responses and develop long-term expected outcomes that will comprise an important component of the Basin evaluation.

The Outcomes Framework does, however, provide a conceptual framework for making qualitative predictions about expected outcomes over 1–5 years. Many of the watering actions undertaken in 2014–15 had spawning and recruitment as expected outcomes. Qualitatively, the long-term expected outcome is that the abundance of the target species will increase and there will be associated changes in the population structure. The extent to which this long-term outcome will be achieved depends on how future flow regimes interact with species traits.

For guilds of fish that are expected to breed every year (periodic and opportunistic species), the short-term data are not sufficient to determine whether Commonwealth environmental water influenced either the amount of spawning or subsequent survival of larval fish. Multiple years of data and quantitative models will be required to undertake this analysis. For small opportunistic species (carp gudgeon, Australian smelt and Murray–Darling rainbowfish), the annual census data showed recruitment at all areas sampled, which is perhaps not surprising given their short life-history, and presence in the system means that they have been able to spawn and recruit within highly modified flow regimes. The issue is once again the extent to which Commonwealth environmental flows either increased spawning or the proportion of larvae that subsequently recruited. The number of carp gudgeon recruits and their body condition have been observed to respond to wetland inundation (Beesley *et al.* 2014) while growth rates of Australian smelt have been observed to increase in response to both floods and in channel pulses (Tonkin *et al.* 2011). This information means that it is possible for Commonwealth environmental water to contribute to improved recruitment of opportunistic species.

For Murray cod, most areas reported the presence of recruits. The question is whether Commonwealth environmental water influenced recruitment or survival of Murray cod through provision of food or habitat. Currently, there are not enough data to evaluate this. Tracking the fate of key Murray cod stages will be an important area through which the LTIM program will be able to inform future environmental flow management.

For flow-cued spawners (golden perch and silver perch), Commonwealth environmental water appears to have influenced spawning within the Goulburn River during 2014–15. Despite this, the Goulburn River census found no recruits. There are two potential explanations for this observation: (1) larvae may be transported long distances downstream, in which case golden perch and silver perch larvae may have recruited to the juvenile stage, but not in the area within which they were spawned; or (2) recruitment is failing because the habitat or food required to support recruitment of these species is not available.

If the lack of recruits is due to their having dispersed, then long-term population outcomes will depend on survival in the areas to which they have dispersed and subsequent dispersal back to the Selected Area. Without additional information, it is not clear what the implications for the future management of Commonwealth environmental water might be for this scenario.

If the lack of recruits is due to habitat or food shortages, further insight may emerge from the monitoring data. Little is known of larval golden perch and silver perch habitat requirements, but there is some information on food requirements. The Goulburn River sampling revealed an increase in macroinvertebrate abundance in response to the flow, while the Lower Murray River recorded an increase in microinvertebrates in response to return flows, but numbers declined once these returns

ceased. In the Murrumbidgee river system, there was no clear microinvertebrate response to the environmental flows. From a productivity perspective, none of the in-channel pulses was associated with an increase in either primary production or community respiration. There appears, therefore, to be a response of food availability to environmental flows, but the links between invertebrate and fish responses to flow are not yet clear.

5 Expected Basin-scale outcomes

In addition to the above sections, which present patterns in fish population and community structure across multiple Selected Areas, we discuss here two particular cases of Basin-scale outcomes:

- localised effects of watering actions that are of significance to the Basin
- movement outcomes — impacts of flows on fish dispersal.

5.1 Localised impacts of significance to the Basin

Five rare, listed species are noteworthy, and may benefit from Commonwealth environmental water. Trout cod were only recorded at two Selected Areas (Goulburn River and Murrumbidgee river system) and no larvae or recruits were observed (Table 4). Currently we have insufficient data to infer the impacts of watering actions on a species as rare as trout cod.

Adult eel-tailed catfish were found in one Selected Area (Lower Murray River) and larval catfish were detected at two (Macquarie river system and Lachlan river system). Once again, eel-tailed catfish is an equilibrium species, spawning each year with apparently little dependence on flow, and it is not clear whether watering actions provided any benefit to spawning. Future improvements to larval sampling methodology will improve our ability to infer flow impacts on catfish spawning and recruitment.

Monitoring of the Murray hardyhead (*Craterocephalus fluviatilis*) — which listed as endangered under the *Environment Protection and Biodiversity Conservation Act 1999* (Cwlth) (EPBC Act) — indicates a strong positive response to Commonwealth environmental water in South Australia. In contrast, after Commonwealth environmental water was delivered to Cardross Lakes, only very low numbers of Murray hardyhead were recorded (S Huntley, in prep.).

High abundances of the species were recorded at the Berri Saline Water Disposal Basin in February 2015 after the Commonwealth watering action. Murray hardyhead are largely an annual species (populations dominated by individuals aged less than 1 year) and therefore heavily reliant on yearly recruitment (Ellis & Kavanagh 2014). It appears likely that the South Australian watering action provided ideal spawning and recruitment conditions, whereas the Cardross Lakes action may have reduced salinity and exposed the Murray hardyhead to competition from other small native fish (S Huntley, in prep.).

A number of significant wetlands also received Commonwealth environmental water and fish may have benefited. The important wetlands include:

- Cardross Lake
- Hattah Lakes
- Lowbidgee Floodplain
- Gwydir–Gingham system
- Riverland (South Australia)
- Macquarie Marshes.

Table 4. Summary of monitoring findings for the four listed species sampled in 2014–15.

Species	Category	Area
Eel-tailed catfish	Present	Macquarie, Lachlan, Lower Murray
	spawning	Macquarie, Lachlan
	recruitment	Not observed
Murray hardyhead	Present	Cardross Lakes, Berri Saline Water Disposal Basin
	Spawning	Not sampled
Silver perch	Present	Edward–Wakool, Goulburn, Lower Murray, Murrumbidgee
	Spawning	Goulburn, Murrumbidgee
	Recruitment	Edward–Wakool
Trout cod	Present	Goulburn, Murrumbidgee
	Spawning	Not observed
	Recruitment	Not observed
Murray cod	Present	All Selected Areas
	Spawning	All Selected Areas where larval sampling is taking place
	Recruitment	All Selected Areas

In most of these cases, we have no data on fish response to wetland inundation. A key source of uncertainty concerning the long-term benefit of wetland inundation to species' persistence is whether or not fish are able to return from wetlands when they begin drying, so that individuals that may have benefited from wetland access can pass those benefits on to subsequent generations. In certain wetlands, the risk of entrapment is noteworthy (e.g. Hattah Lakes, Lowbidgee Floodplain). In the case of Hattah Lakes, monitoring revealed that small numbers of fish did return from the lakes to the river (Brown *et al.* 2015). In cases where fish do not return, predation by waterbirds may contribute to maintenance of waterbird populations.

It is also not clear the extent to which the Macquarie Marshes fish community benefited as the community within the Marshes appears degraded and the strongest fish responses occurred in the river upstream of the Marshes. It does appear that the flow encouraged the movement of bony bream into the Marshes.

5.2   Movement outcomes — impacts of flows on fish dispersal

At this stage, two out of three Selected Areas aiming to determine impacts of flows on fish movement do not yet have their acoustic array system online; movement data will be collected from these areas in either Year 2 (Edward–Wakool) or Year 3 (Gwydir) onwards. However, data collected this year on golden perch movement from the Goulburn River demonstrates the capacity of flows to affect fish movement within the MDB. Most of these movements appeared to be associated with spawning and most individuals returned to their pre-flow location following downstream movements. It is hoped that more data obtained both within LTIM and from other programs (e.g. the MDB Environmental Water Knowledge and Research (EWKR) Project) will contribute to our understanding of how flow regimes shape metapopulation processes in MDB fishes.

6 Adaptive management

6.1 Timing of flows affect fish outcomes

Data from the Goulburn River collected during 2014–15 indicate that the concurrence of appropriate flows and temperatures are required to initiate spawning and associated movements of golden perch and silver perch. That is, flows delivered in November–December that coincided with warmer water had a greater impact on spawning than flows delivered during the cooler period of October–November. This finding is concordant with previous work on spawning and movement of these two species (O'Connor *et al.* 2005; Roberts *et al.* 2008; King *et al.* 2009, 2010; Zampatti & Leigh 2013). It is worth noting, however, that these species may exhibit considerable flexibility of life-history (Mallen-Cooper & Stuart 2003), and future LTIM monitoring comparing and contrasting golden perch and silver perch responses to flows across numerous catchments will strengthen our general understanding of how flows may be managed to promote the persistence of these species.

6.2 Potential importance of antecedent conditions

The outcome in the Goulburn River of a large spawning response to a fresh suggests that antecedent flows may influence the outcome. In this case, it has been proposed that earlier freshes helped prepare the fish for spawning. For managers, this will mean considering the impact that antecedent conditions may have on the probability of achieving expected outcomes. Further monitoring and modelling will improve our understanding of the role that flow sequences play in driving fish responses to environmental water.

6.3 Long-term monitoring is essential

The striking results pertaining to population structure of golden perch at the Basin scale demonstrate the fundamental importance of (a) long-term monitoring; and (b) detailed population censuses that facilitate inferences concerning age structure of the population. Golden perch is a species that exhibits what population ecologists call the 'storage effect', whereby they experience episodic recruitment events, then store those benefits for several years in between favourable conditions. These data demonstrate the need to collect quality time series — and LTIM methods are fit for that purpose — for periods that span decades, in order to fully understand how long-term flow regimes affect the population dynamics of long-lived animals.

6.4 Larval fish monitoring

The solid link between flows and fish spawning in the Goulburn demonstrates the importance of taking the right approach to monitoring spawning. At the 2016 LTIM forum, the fish experts will be learning from the Goulburn experience to redesign and implement improved larval monitoring methods. We anticipate improved capacity to link fish spawning to flows from 2016 onwards.

7 Contribution to achievement of Basin Plan objectives

We are not yet in a strong position to comment on the contribution of Commonwealth environmental water to long-term Basin Plan objectives (increased diversity and recruitment within populations). We can, however, report that Commonwealth environmental water contributed to the Basin Plan objectives of increased spawning and associated movements in the short term, within the Goulburn River. In addition, inasmuch as LTIM Selected Areas represent the broader MDB, 2014–15 was characterised by native species numerically dominating the assemblages, which is an improvement from the situation reported 10 years earlier in Lintermans (2007).

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Appendix A. Table of watering actions with fish expected outcomes

Information sourced from Commonwealth Environmental Water Office (CEWO) acquittal reports, with the exception of the last three columns, which contain information gleaned from Selected Area reports (Dyer *et al.* 2015; Wassens *et al.* 2015, 2016; Watts *et al.* 2015a, b; Webb *et al.* 2015, Ye *et al.* 2015).

Surface water region/asset	Watering Action Reference (WAR). Grey shading indicates LTIM Selected Area	Commonwealth environmental water volume (GL)	Dates	Flow component	Primary (P), secondary (S) or unclassified expected outcome (X)	Expected outcomes at catchment/parent asset scale (from CEWO water acquittal report)	Expected outcome in Selected Area report (AL = as left; NP = not provided; or cited verbatim from report if neither AL nor NP). Expected outcomes not monitored as part of LTIM = Unmonitored.	Quantitative evaluation in Selected Area reports (data-based evaluation, e.g. statistical analysis)?	Qualitative evaluation in Selected Area reports (not based on data, e.g. prediction based on expert understanding of system)?
NSW / Vic Murray – River Murray Hume Dam to Coroong	10031-01	23.5	22/06/15 – 30/06/15	Fresh flow	P	* Maintain diversity, extend distributions, improve breeding success & numbers of short, moderate & long-lived native fish species — River Murray	Unmonitored	–	–
NSW / Vic Murray – River Murray Hume Dam to Coroong	10031-01	23.5	22/06/15 – 30/06/15	Fresh flow	S	* Maintain diversity, extend distributions, improve breeding success & numbers of short, moderate & long-lived native fish species — Lower Lakes & Coorong	Unmonitored	–	–
NSW Murray – Edward–Wakool: Colligen–Niemur System	10008-04	2.949	12/01/15 – 28/01/15	Base	P	* To prevent a sharp drop in the Colligen Creek hydrograph, create a gradual recession flow from 12–28 January 2015 to benefit the native fish	NP	No	No
NSW Murray – Edward–Wakool: Tuppal Creek	10008-05	0.05	15/09/14 – 23/11/14	Base flow; fresh flow	P	* Improve water quality, replenish refuge pools, & provide connectivity between Tuppal Creek & the Edward River for native fish passage	NP	No	No
NSW Murray – Edward–Wakool: Tuppal Creek	10008-03	2	15/09/15 – 23/11/14	Base flow; fresh flow	P	* Improve water quality, replenish refuge pools & provide connectivity between Tuppal Creek & the Edward River for native fish passage * Replenish refuge pools * Provide connectivity between Tuppal Creek & the Edward River for native fish passage	NP	No	No

Surface water region/asset	Watering Action Reference (WAR). Grey shading indicates LTIM Selected Area	Commonwealth environmental water volume (GL)	Dates	Flow component	Primary (P), secondary (S) or unclassified expected outcome (X)	Expected outcomes at catchment/parent asset scale (from CEWO water acquittal report)	Expected outcome in Selected Area report (AL = as left; NP = not provided; or cited verbatim from report if neither AL nor NP). Expected outcomes not monitored as part of LTIM = Unmonitored.	Quantitative evaluation in Selected Area reports (data-based evaluation, e.g. statistical analysis)?	Qualitative evaluation in Selected Area reports (not based on data, e.g. prediction based on expert understanding of system)?
NSW Murray – Edward–Wakool: Yallakool Creek and Wakool River	10008-01	34.563	12/08/14 – 09/01/15	Base flow	P	* Maintain spawning habitat for Murray cod	*Primary objective:* Commonwealth environmental water will contribute to maximising Murray cod recruitment by providing a Murray cod maintenance flow — about 500 ML/day — in Yallakool Creek through to end of the Murray cod spawning season.	Yes	NA
NSW Murray – Edward–Wakool: Yallakool Creek and Wakool River	10008-01	34.563	12/08/14 – 09/01/15	Base flow	S	* Fish movement, spawning, recruitment & condition	*Secondary objectives:* It is expected this action will also contribute to increased hydrological connectivity, improved opportunities for movement, condition, reproduction and recruitment of other native animals (e.g. small-bodied native fish, frogs, shrimp, etc.), maintain/improve vegetation condition and water quality.	Yes	NA
Goulburn – Reaches 4 and 5	10002-01	14.472	20/11/14 – 30/11/14	Fresh flow	P	* Breeding & movement of native fish	Spawning and movement of golden perch	Yes	NA
Goulburn – Reaches 4 and 5	10002-01	18.291	01/12/14 – 28/02/15	Base flow	P	* Support native fish condition & macroinvertebrates * Longitudinal connectivity, fish passage	NP	No	No
Goulburn – Reaches 4 and 5	10002-01	21.103	01/03/15 – 15/03/15 13/04/15 – 12/06/15	Base flow	P	* Support native fish condition & macroinvertebrates * Longitudinal connectivity, fish passage	NP	No	No
Goulburn – Reaches 4 and 5	10002-01	12.986	25/08/14 – 25/09/14	Base flow	P	* Support native fish condition & macroinvertebrates abundance/diversity * Longitudinal connectivity, fish passage	NP	No	No

Surface water region/asset	Watering Action Reference (WAR). Grey shading indicates LTIM Selected Area	Commonwealth environmental water volume (GL)	Dates	Flow component	Primary (P), secondary (S) or unclassified expected outcome (X)	Expected outcomes at catchment/parent asset scale (from CEWO water acquittal report)	Expected outcome in Selected Area report (AL = as left; NP = not provided; or cited verbatim from report if neither AL nor NP). Expected outcomes not monitored as part of LTIM = Unmonitored.	Quantitative evaluation in Selected Area reports (data-based evaluation, e.g. statistical analysis)?	Qualitative evaluation in Selected Area reports (not based on data, e.g. prediction based on expert understanding of system)?
Goulburn – Reaches 4 and 5	10002-01	1.315	10/11/14 – 17/11/14	Base flow	P	* Support native fish condition	NP	No	No
Goulburn – Reaches 4 and 5	10002-01	67.46	14/10/14 – 11/11/14	Fresh flow	S	* Breeding & movement of native fish	AL	Yes	NA
Gwydir – Gwydir wetlands	00016-01	30	17/09/14 – 07/03/15	Wetland inundation	S	* Provide refuge habitat for waterbirds, fish & other aquatic species * Maintain ecosystem resilience by supporting individual survival & condition	*Maintain habitat such as waterholes for fish condition and survival*	Yes	NA
Gwydir – Mallowa wetlands	00016-02	9.667	17/09/14 – 07/03/15	Wetland inundation	S	* Provide habitat for waterbirds & native aquatic species * Improve habitat quality & increased within ecosystem diversity to support survival of native fish & other fauna	*Maintain habitat such as waterholes for fish condition and survival*	Yes	NA
Lachlan – Lower Lachlan	10013-01	5	03/10/14 – 29/10/14	Fresh flow	X	* Support native fish condition & reproduction by providing cues & appropriate habitats	*The objectives of the watering action were to:* *• preserve the integrity of small to medium unregulated flows through the Lachlan river system through spring–summer to provide natural cues for native fish to migrate and spawn.* *• contribute to habitat access, fish condition, spawning and larval survival.*	No	Yes
SA Murray – Berri Creek	10009-03	1.241	01/09/14 – 30/06/15	Wetland inundation	P	* Murray hardyhead	NP	No	No
SA Murray – Murray River from Wentworth to Lower Lakes	10026-01	389.205	01/01/15 – 30/06/15	Base flow	X	* Protect aquatic vegetation & native fish habitat condition from increasing salinity * Maintain hydrological connectivity between River Murray, Lakes Alexandrina & Albert, Coorong & Murray Mouth,	NP	Yes	NA

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						support fish movement & increase export of salt & nutrients			
SA Murray – Murray River from Wentworth to Lower Lakes	10009-01	191.833	04/09/14 – 31/12/14	Base flow	X	* Improve diversity & condition of native fish, habitat, breeding & recruitment	NP	No	No
Murrumbidgee – Mid North Redbank	10023-01	40	12/08/14 – 20/01/15	Wetland inundation	P	* Maintain & improve diversity & condition of native aquatic fauna through maintaining suitable habitat & supporting opportunities to move, breed & recruit	AL	Yes	NA
Murrumbidgee – Mid North Redbank	10023-01	40	12/08/14 – 20/01/15	Wetland inundation	S	* Support habitat requirements for waterbird, frog & native fish	AL	Yes	NA
Murrumbidgee – Paika Lake	10023-06	8.498	25/05/15 – 27/06/15	Wetland inundation	S	* Support habitat requirements for waterbird, frog & native fish	AL, but not monitored	No	No
Murrumbidgee – Upper North Redbank	10023-03	20	01/10/14 – 25/03/15	Wetland inundation	P	* Maintain & improve diversity & condition of native aquatic fauna through maintaining suitable habitat & supporting opportunities to move, breed & recruit	AL, but not monitored	No	No
Murrumbidgee – Upper North Redbank	10023-03	20	01/10/14 – 25/03/15	Wetland inundation	S	* Support habitat requirements for native fish, frogs & waterbirds	AL, but not monitored	No	No
Murrumbidgee – Yanco Creek	10005-02	2.462	23/06/15 – 30/06/15	Wetland inundation	P	* Maintain & improve diversity & condition of native aquatic fauna through maintaining suitable habitat & supporting opportunities to move, breed & recruit	AL, but not monitored	No	No
Murrumbidgee – Yanco Creek	10005-02	2.462	23/06/15 – 30/06/15	Wetland inundation	S	* Support habitat requirements for waterbird, frog & native fish	AL, but not monitored	No	No

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Murrumbidgee – Yanga National Park	10023-02	74.512	23/10/15 – 10/04/15	Wetland inundation	P	* Maintain & improve diversity & condition of native aquatic fauna through maintaining suitable habitat & supporting opportunities to move, breed & recruit	AL, but not monitored	.	.
Murrumbidgee – Yanga National Park	10023-02	74.512	23/10/15 – 10/04/15	Wetland inundation	S	* Provide & support habitat for native fish, frogs & other vertebrates	• *provide habitat for native fish, frogs and other vertebrates* • *support habitat requirements for waterbird, frog and native fish*	Yes	No
Wimmera–Mallee – Brickworks Billabong	10011-02	0.0999	x – x	Wetland inundation	P	* Maintain & improve health of aquatic vegetation & suitable water quality to support Murray hardyhead	Unmonitored	–	–
Campaspe – Reaches 2 and 4	10003-01	5.7914	09/10/14 – 22/10/14	Fresh flow	X	* Stimulate fish movement * Protect, maintain, improve diversity & condition of water-dependent native flora & fauna, water quality, ecosystem function	Unmonitored	–	–
Wimmera–Mallee – Cardross Lakes	10011-02	0.2883	x – x	Wetland inundation	P	* Existing Murray hardyhead sites	Unmonitored	–	–
Vic Murray – Hattah Lakes	x	share 34.2389	26/05/14 – 17/01/15	Wetland inundation	X	* Restore & maintain wetlands & floodplain habitat to support fish communities & waterbird breeding	Unmonitored	–	–
Loddon – Reaches 3 and 4 and fringing wetlands	10001-01	2.8695	21/09/14 – 07/10/15	Fresh flow	P	* Contribute to native fish reproduction & condition	Unmonitored	–	–
Goulburn – Lower Broken Creek	10020-01	13.592	03/10/14 – 30/12/14	Base flow	P	* Increase habitat for large bodied fish during migration & breeding seasons	Unmonitored	–	–
Goulburn – Lower Broken Creek	10020-01	2.644	21/04/15 – 15/05/15	Base flow	P	* Maintain fish passage through fishways	Unmonitored	–	–

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Goulburn – Lower Broken Creek	10020-01	13.592	03/10/14 – 30/12/14	Base flow	S	* Support aquatic & fringing vegetation, fish condition & Murray outcomes (maintain & improve diversity & condition of water-dependent native flora & fauna, water quality & ecosystem function)	Unmonitored	–	–
Goulburn – Lower Broken Creek	10020-01	13.13	01/01/15 – 20/04/15	Base flow	S	* Support aquatic & fringing vegetation, fish condition & Murray outcomes (maintain & improve diversity & condition of water-dependent native flora & fauna, water quality & ecosystem function)	Unmonitored	–	–
Goulburn – Lower Broken Creek	10020-01	2.644	21/04/15 – 15/05/15	Base flow	S	* Support aquatic & fringing vegetation, fish condition & Murray outcomes (maintain & improve diversity & condition of water-dependent native flora & fauna, water quality & ecosystem function)	Unmonitored	–	–
Macquarie– Castlereagh – Macquarie Marshes	10015-01	10	13/10/14 – 12/12/14	Base flow; fresh flow; wetland inundation	P	* Increase availability & access to fish habitat, fish movement, provide cues for spawning, recruitment & migration	AL (monitoring not part of LTIM)	Yes	NA
Vic Murray – Mulcra Island	10009-02	3.7609	12/08/14 – 22/12/14	Wetland inundation	S	* Benefit native fish populations	Unmonitored	–	–
Ovens – Ovens River	10004-01	0.05 0.02	04/04/15 – 05/04/15 30/04/15 – 30/04/15	Base flow	X	* Stimulate fish movement & allow passage between habitats	Unmonitored	–	–
QLD Border Rivers – Severn River	00111-17	0.3179	11/12/14 – 16/12/14	Bankfull	P	Support movement/migration of large-bodied fish, including Murray cod, golden perch, silver perch, eel-tailed catfish	Unmonitored	–	–
QLD Border Rivers – Severn River	00111-17	0.931	27/12/14 – 30/01/15	Bankfull	P	Support movement/migration of large-bodied fish, including Murray cod, golden perch, silver perch, eel-tailed catfish	Unmonitored	–	–

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QLD Border Rivers – Dumaresq–Macintyre River and fringing wetlands	00111-18	0.332 0.231	29/01/15 – 05/02/15 06/04/2015	Fresh	P	Support dispersal of fish and other aquatic biota, including Murray cod	Unmonitored	–	–
QLD Moonie – Lower Moonie River and fringing wetlands	00111-19	0.1968 0.324 0.2856 0.6086	30/12/14 – 05/01/15 27/01/15 – 01/02/15 27/02/15 – 05/03/15 04/04/15 – 11/04/15	Fresh	P	Dispersal and movement of fish and other aquatic biota	Unmonitored	–	–
QLD Condamine–Balonne	0011-21	17.244 0. 145	Late Jan – Early Feb May 2015	Fresh	S	Support dispersal and reproduction of aquatic organisms, particularly fish (Culgoa River)	Unmonitored	–	–
QLD Warrego – Upper Warrego and fringing wetlands	00111-22	0.3728	17/12/14 – 04/01/15	Fresh	P	Support movement and reproduction of fish, particularly small-bodied low-flow spawning fish, including Murray–Darling rainbowfish and carp gudgeon	Unmonitored	–	–
QLD Warrego – Upper Warrego and fringing wetlands	00111-23	0.2816 1.8873	27/12/14 – 28/12/14 09/01/15 – 15/01/15	Fresh	P	Fish migration especially large-bodied species, including golden perch	Unmonitored	–	–