2015–16 Basin-scale evaluation of Commonwealth environmental water – Fish

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Final Report

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2015–16 Basin-scale evaluation of Commonwealth environmental water – Fish

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

This report was prepared by The Murray–Darling Freshwater Research Centre (MDFRC). The aim of the MDFRC is to provide the scientific knowledge necessary for the management and sustained utilisation of the Murray–Darling Basin water resources. The MDFRC is a joint venture between La Trobe University and CSIRO. Additional investment is provided through the University of Canberra.

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

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1 Introduction

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. 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 Basin, 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 Basin. 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 Basin. 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 often play important roles in food web/ecosystem processes (Holmlund & Hammer 1999), and so evaluating and reporting fish response to flows is critical from the perspective of stakeholders.

Here we present the 2015–16 Basin Matter report for fish monitoring within the LTIM Project. This is the second 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 Basin. LTIM Basin-scale analyses are analyses of outcomes across multiple catchments or, in particular, multiple Selected Areas.

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 1 and Figure 2 help place the content of this year's report in the context of the broader Fish Basin Matter work plan (Stoffels *et al.* 2016a). Note that Fish Basin Matter outputs are planned to increase each year (Figure 2).

The general objectives for the 2015–16 LTIM Fish Basin Matter report were as follows (Stoffels *et al.* 2016a):

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

1. **Undertake a Basin-scale analysis of the response of fish spawning to flows**. This is the primary focus of this year's report, following the time line presented in the Foundation Report (Figure 1; Figure 2). This Basin-scale analysis of fish spawning focuses on six species, spanning a broad range of life-histories: golden perch (*Macquaria ambigua*), silver perch (*Bidyanus bidyanus*), Murray cod (*Maccullochella peelii*), bony herring (*Nematalosa erebi*), Australian smelt (*Retropinna semoni*) and carp gudgeon (*Hypseleotris* spp.). The specific objectives of this component were:
    a. Using metrics of flow dynamics standardised across Selected Areas, parameterise models of the probability of spawning as a function of various flow variables (e.g. rate of increase, mean discharge at the time of sampling) and temperature.
    b. Determine for each species the model providing the most parsimonious fit to the data. By 'parsimonious' we mean the model that, relative to other models in the candidate set, provided the best balance between having too many parameters and 'over-fitting' the model to the data, and having too few parameters leading to a biased description of the relationship between hydrology, temperature and spawning probability (Burnham & Anderson 1998). Development of such models is an essential step towards reporting on the spawning outcomes from flows at unmonitored sites throughout the Basin (Figure 1; Figure 2).

    Important note: The Basin-scale modelling of fish spawning response to flow variables will likely seem overly technical for a document that should be focusing on reporting on outcomes from Commonwealth environmental watering actions. To be clear, the motivation underlying the technical modelling work is, fundamentally, the long-term goal of scientifically defensible reporting. That is, it is very difficult to report on the impacts of Commonwealth environmental water in an objective, scientifically defensible way without predictive models. Such models facilitate the separation of Commonwealth watering action effects from the effects of 'background' (non-environmental water) hydrological variability (see Section 1.2). The modelling we have done this year puts us in a good position to begin defensible reporting on spawning outcomes from Commonwealth watering actions from 2018 onwards.
2. **Review technical reports for short-term (1 year or less) outcomes from Commonwealth environmental watering actions during 2015–16 and present a brief synthesis of those outcomes**. This brief synthesis is structured by the broad 'types' of flows delivered by CEWO: base flows; freshes; bankfulls; overbank flows; and wetland inundations.
3. **Present an analysis of how the states of fish populations and communities varied within and among Selected Areas over the first 2 years of LTIM**. We specifically, determine how the following vary through time, within 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.

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.

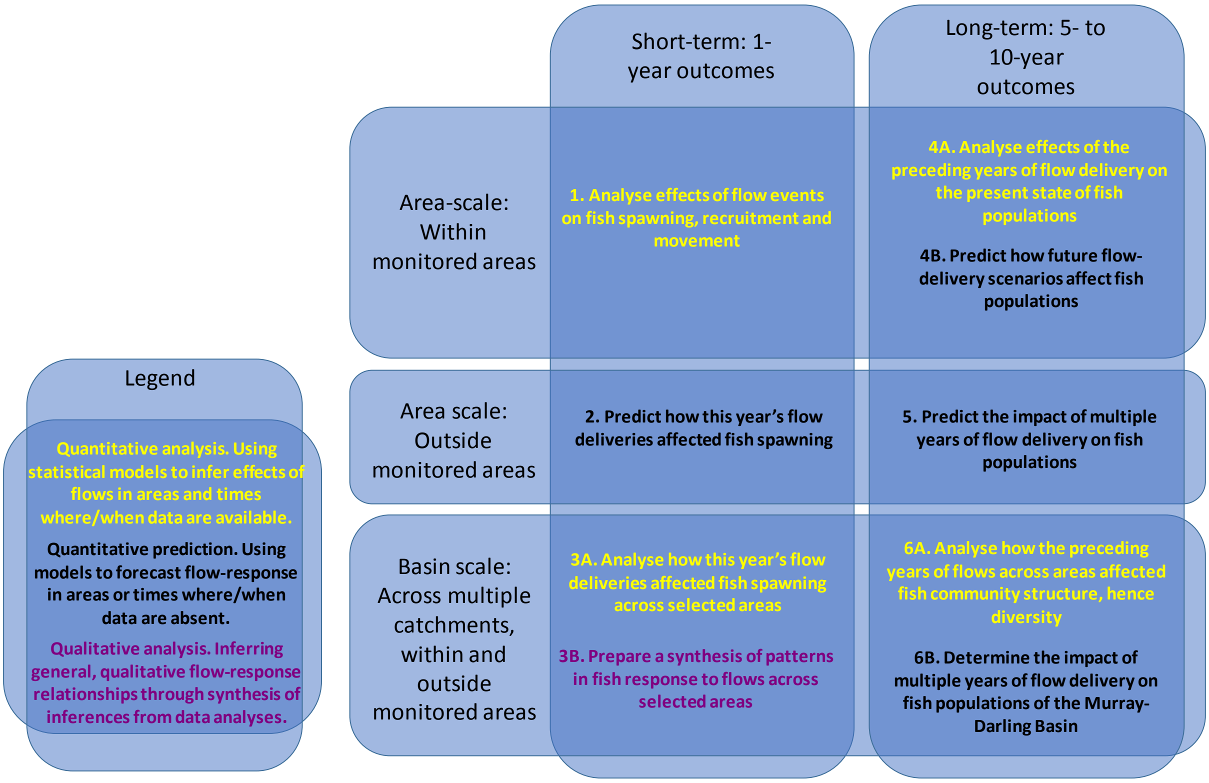

Figure 1. Fish analysis and prediction activities within LTIM fit into one of six groups, which are defined by the spatial and temporal scales of analysis/prediction. Activities are colour-coded by whether they involve analysis of data or prediction, and by whether the analysis or prediction is qualitative or quantitative.

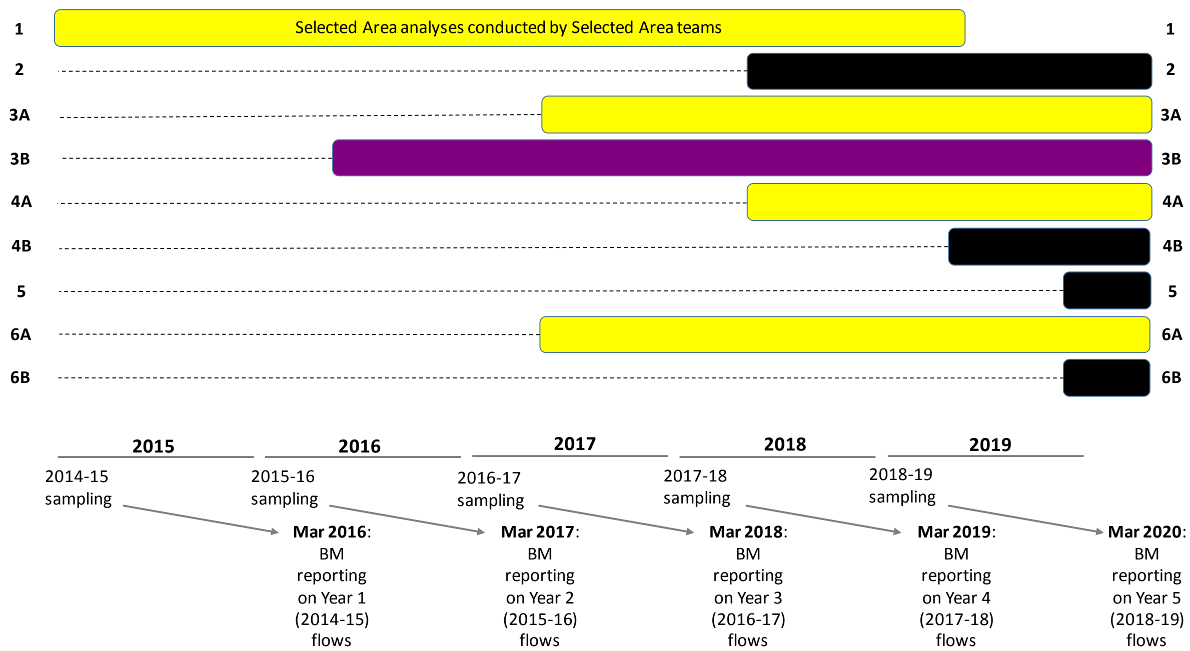

Figure 2. Gantt chart of analysis and prediction activities of Figure 1. Colour coding of bars follows that of Figure 1, and indicates the types of analysis/prediction involved.

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 some broader aims of LTIM. Indeed, a key objective of LTIM is to improve our capacity to predict ecological responses 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 to determine 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. Evaluate 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 Basin 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 Basin scale.

3. Assist 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 are 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 3.

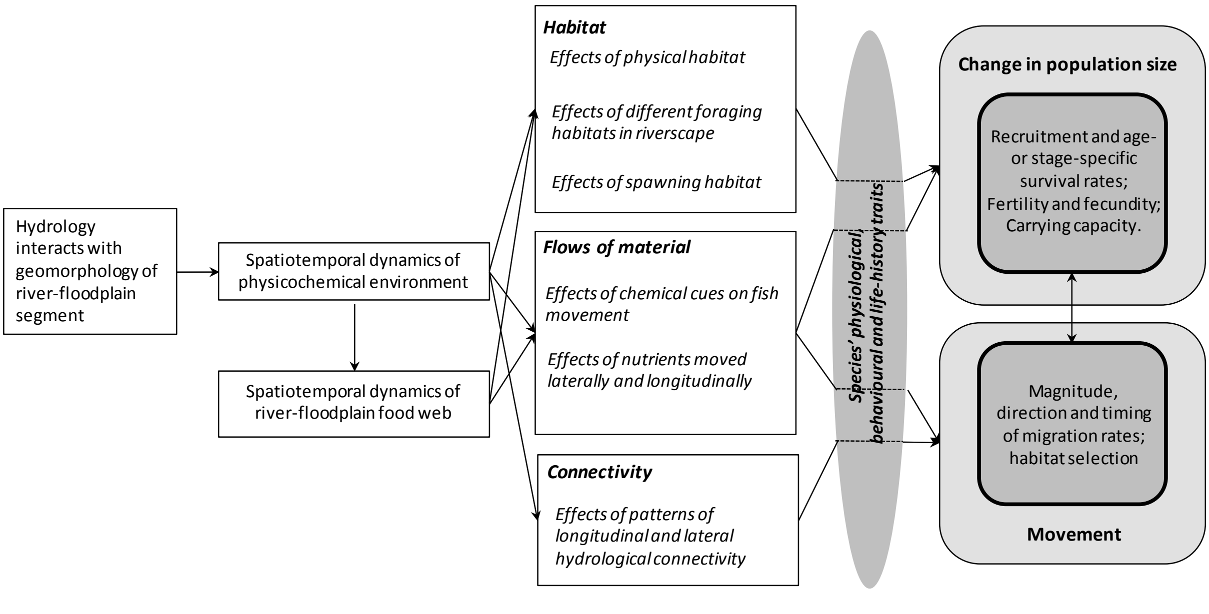

Figure 3. Conceptual diagram capturing the key mechanistic pathways by which flows change fish population size and drive dispersal. A flow will interact with the geomorphology of the river–floodplain landscape to affect the spatiotemporal dynamics of waterbodies. By 'spatiotemporal dynamics' we mean 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 3):
   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 & 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 3):
   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 of flows affecting 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 3); 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 will be 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 life span; spawning not tightly linked to flows, but data inconclusive at this stage).

Below we present diagrammatic conceptual models for four target species within LTIM: bony herring, golden perch, Murray cod and carp gudgeon. The primary purpose of each model is to serve as a visual representation of our expectations based on the accompanying literature review. Bony herring and golden perch are classified as periodic species; Murray cod is an equilibrium species and carp gudgeon is opportunistic. For each species, we have aimed to capture only the most prominent links between three types of flow (base flow; fresh; 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 4), 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 4). If base flows have an impact, then we propose that impact is on survival rates of juvenile and adult golden perch (Figure 4) 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 4). 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 & 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). Increased food availability may also result in higher fecundity.

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 4).

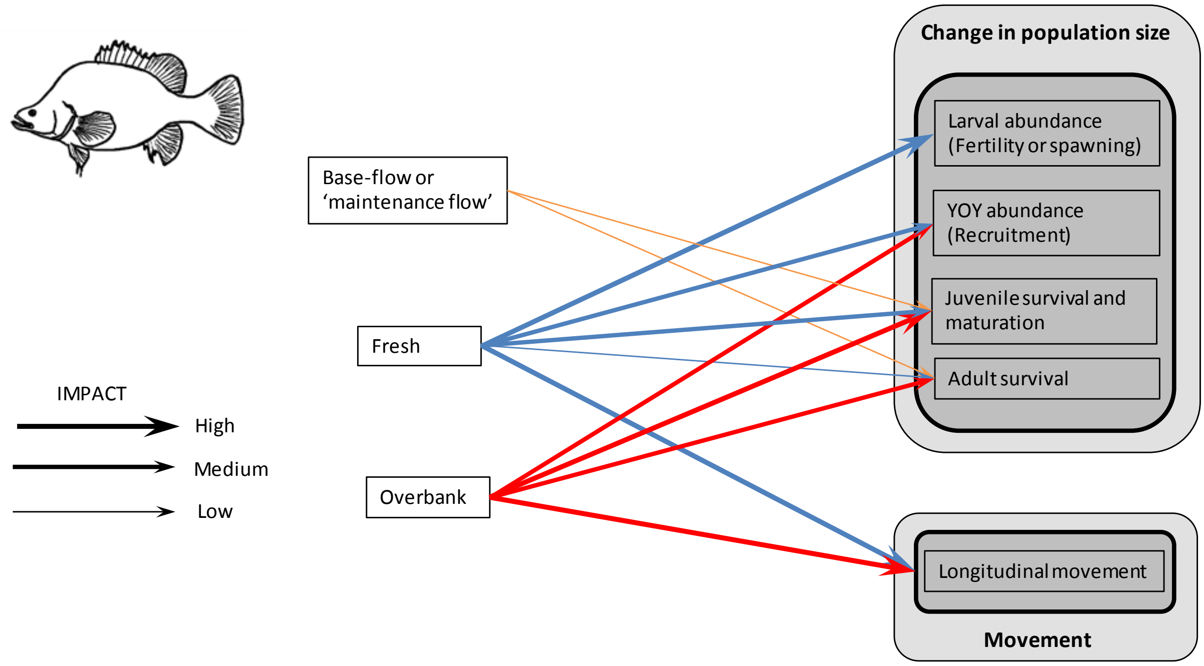

Figure 4. Conceptual model of how flows affect the population processes of golden perch, *Macquaria ambigua*, assuming the three flow types on the left are delivered under 'average' discharge conditions (i.e. not particularly dry or wet years). Only those processes that LTIM data-collection activities target are presented. The model is an adaptation of Figure 3, 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 otherwise significantly decline 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 5). 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 5).

Overbank flows

We expect the greatest impacts of flows on bony herring when there 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 there are large flows that increase lateral connectivity, then we expect to see high impacts on juvenile and adult survival rates (Figure 5).

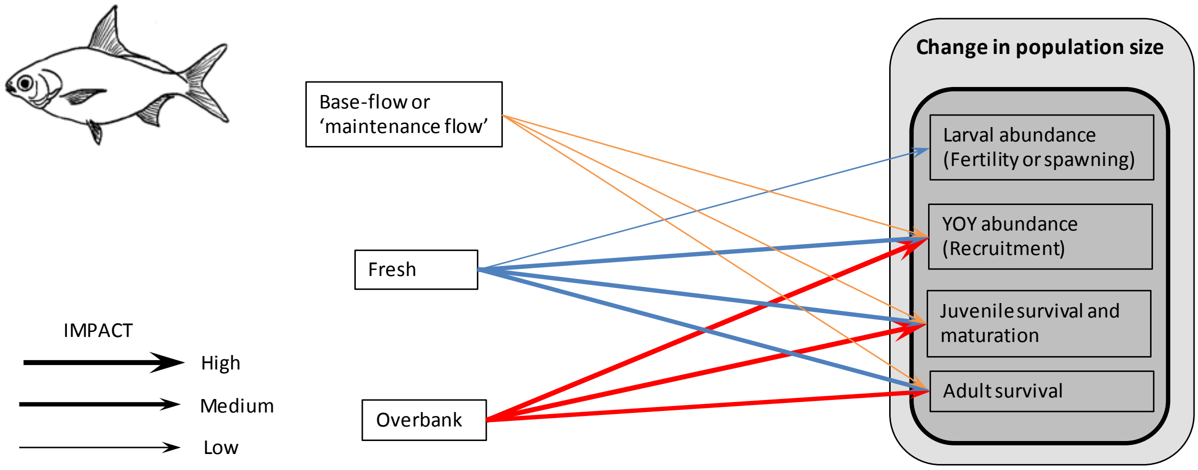

Figure 5. Conceptual model of how flows affect the population processes of bony herring, *Nematalosa erebi*, assuming the three flow types on the left are delivered under 'average' discharge conditions (i.e. not particularly dry or wet years). Only those processes that LTIM data-collection activities 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 3, 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 increasing habitat availability and, under cease-to-flow conditions, reducing the impacts of 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 (also see 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 the 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 6). It is possible that freshes and overbank flows increase foraging opportunities which, in turn, may increase condition and hence fecundity. It follows that, in theory at least, Murray cod spawning magnitude may increase during 'high-flow' years through increased fecundity.

We expect to observe medium impacts of flows on Murray cod recruitment and survival rates (Figure 6). 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 6).

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 6).

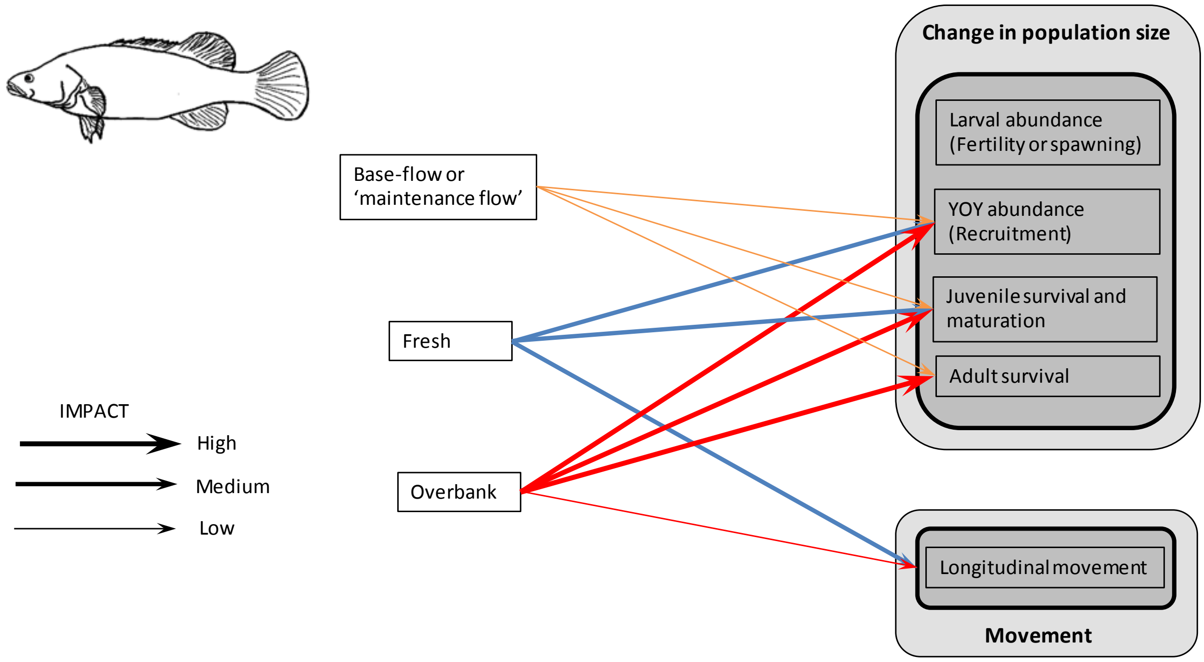

Figure 6. Conceptual model of how flows affect the population processes of Murray cod, *Maccullochella peelii*, assuming the three flow types on the left are delivered under 'average' discharge conditions (i.e. not particularly dry or wet years). Only those processes that LTIM data-collection activities target are presented. The model is an adaptation of Figure 3, 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. (2016), Southwell et al. (2016), Wassens *et al.* (2016), Watts *et al.* (2016), Webb *et al.* (2016), Ye *et al.* (2017) and Stoffels *et al.* (2016a). Here we briefly explain the methods underpinning this year's report; technical detail is kept to a minimum, but provides key references to which readers can refer for further information.

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 primarily aimed at informing area-specific evaluation questions. In certain instances, however, Category 3 methods are sufficiently similar to Category 1 methods to be used for Basin-scale analyses.

2.1.1 Spatial configuration of fish sampling

LTIM samples were collected within a hierarchy of spatial sampling units, following Gawne *et al.* (2013): 'zones' are nested within Selected Areas, and 'sites' are nested within zones. Zones and sites for fish sampling have the following characteristics.

A 'zone' was a subset of a Selected Area that represented a spatially, geomorphologically and/or hydrologically distinct unit at reach–segment scales as defined by Fausch *et al.* (2002). A Selected Area may comprise multiple zones, but each Selected Area contained a 'focal zone' from which samples for Basin-scale analyses were collected. The focal zone of each Selected Area was likely to receive Commonwealth environmental water at least once in the next 5 years and was associated with specific expected ecological outcomes within that same time frame. Aquatic habitats within focal zones were representative of the Selected Area as a whole.

Within zones, 10 channel sites were established for sampling. A site was defined as an 800 m reach of channel (Figure 7). Sites were selected to be representative of the zone as a whole, were randomly located, and their locations are fixed throughout the LTIM Project. Site locations have been fixed such that we do not conflate spatial and temporal sources of variation.

Within sites, a sampling grid was established to ensure individual samples could be sampled randomly with respect to spatial environmental heterogeneity, such that samples were representative of that site as a whole (Figure 7). Each 800 m site was subdivided by fixed transects spaced 50 m apart. Points of intersection between the transects and the riverbank defined the sampling grid (Figure 7).

The sample design specified in Figure 7 defines two key sampling locations: electrofishing (EF) units (16 in total) and passive-gear sample (PS) waypoints (34 in total). Use of these EF units and PS waypoints for larval sampling and annual censuses of population and community structure are explained below.

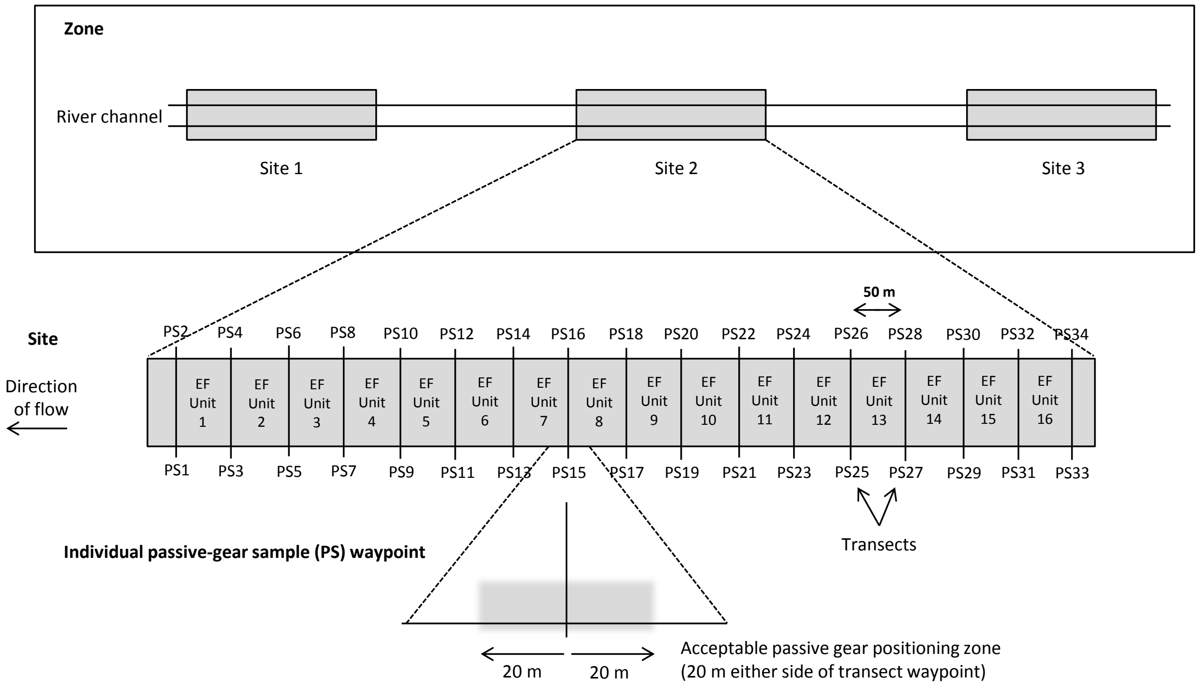

Figure 7. Diagram of the spatial configuration of sampling, showing sites nested within a zone, and individual sampling locations/units within sites.

2.1.2 Larval sampling

The primary focus of this year's report is a Basin-scale analysis of fish spawning. Larval sampling methods differ among Selected Areas and are a mix of Category 1 and 3 methods. The Category 1 larval sampling method currently in use is not the method presented in Hale *et al.* (2013). Instead, larval sampling under the current Category 1 larval method had the following specifications.

Sampling took place at 3 of the 10 sites within the focal zone of each Selected Area. Each site was sampled for larvae five times (five sampling 'events'; [Event 1, Event 2, …, Event 5]) within each flow delivery year (corresponds with a financial year; 1 July – 30 June) and, as much as practicable, all three sites were sampled on the same day within each event. Within each unique site–event combination, the standard method called for 10 light-trap and 3 drift samples.

The same modified quatrefoil light-traps (Humphries *et al.* 2002) were used at each Selected Area, to eliminate spatial bias. Mesh was fitted around the light traps to prevent larger fish from entering the trap and eating the sample (3 mm knot-to-knot). Each light trap was 'baited' with a yellow 12-hour light stick (Cyalume®, or equivalent manufacturer, but yellow in colour). The 10 light traps set within each of the 3 sites were set in the afternoon and retrieved the following morning. Within each site, during each event, the light traps were set at a random subset of 10 PS waypoints from the total of 34 (Figure 7). Abundances from light-trap samples were uploaded to the LTIM database as catch per unit effort (CPUE), with units of number of individuals, per trap, per hour within a site–event combination (i.e. variance across traps within sites was 'averaged away' prior to uploading).

The three drift samples within a site–event combination were one of two types:

a. If there was sufficient flow velocity within the focal zone, drift samplers were established to passively filter larvae from a moving water column.
b. If there was insufficient water velocity within the focal zone, three larval tows were obtained, whereby the drift net was pushed through the water column by boat, and larvae were actively filtered from the water column.

Irrespective of the whether the sample was active or passive, drift nets were constructed of 500 µm mesh, and had an opening diameter of 50 cm, tapering over 1.5 m to an opening of 9 cm, where a 'reducing bottle' was fitted. Volume through the net was estimated so that larval abundances in drift nets could be expressed as a density: number of individuals m^3. Volume sampled by the net is estimated as $\pi r^2 \cdot v \cdot t$, where *r* is radius in metres, *v* is mean velocity in m s^{-1}, and *t* is time set in seconds. Thus, for both active and passive drift samples, data uploaded to the LTIM database had CPUE units of mean number of individuals m^3. Again, each row in the LTIM database is a mean CPUE and disregards variation across the three drift samples within a site–event combination.

The data used for Basin-scale analysis of fish spawning is drawn from five Selected Areas: Lachlan river system, Murrumbidgee river system, Edward–Wakool river system, Goulburn River and the Lower Murray River. The larval sampling methods have evolved within each of these areas and have similar characteristics to the Category 1 methods describe above, but are essentially unique to each Selected Area. The reader is referred to individual Selected Area reports for details, and a brief summary of the larval data supporting the analysis of this year's report is presented here:

1. **Lachlan river system**: data from the Category 1 method only in 2014–15 and 2015–16.
2. **Murrumbidgee river system**: data from Category 1 method supplemented with:
   a. an additional three sites per event in both 2014–15 and 2015–16
   b. an additional sampling event, giving six in total in both 2014–15 and 2015–16.
3. **Edward–Wakool river system**: data from Category 1 only in 2014–15 and 2015–16.
4. **Goulburn River**: data from Category 1 method supplemented as follows:
   a. during 2014–15 and 2015–16, an additional site per event for drift samples (light trap samples from three sites only)
   b. during 2014–15, a total of 10 sampling events per site
   c. during 2015–16, a total of 11 sampling events per site.
5. **Lower Murray River**: data exclusively from Category 3 methods, as follows:
   a. no light-trap samples taken during any site–event combination; only drift samples (larval tows)
   b. during 2014–15 a total six sampling events at each of six sites
   c. during 2015–16 a total eight sampling events at each of six sites.

2.1.3 Population and community censuses

Category 1 annual censuses took place once each year during autumn and, unlike larval methods, follow Hale *et al.* (2013). Within the six Selected Areas, annual censuses consisted of intensive electrofishing for large-bodied species and fyke netting for small-bodied species.

Within each of the 10 sites, the entire 800 m site was electrofished. Within each electrofishing unit of a site (EF unit; Figure 7) two 'shots' of 90 seconds (s) 'on-time' was carried out. This resulted in a total of 2880 s (48 minutes on-time) for each site. No more than 180 s of shocking was allocated to each EF unit, such that electrofishing effort was spread out across the entire site, giving a random sample with respect to the (site's) environment. Within EF units, the location of shots was left to the discretion of the sampler. Abundances from electrofishing were calculated as number of individuals per second 'on-time' within each site and year.

Ten fyke net (fish trap) samples were also taken from within each site. Fyke nets were randomly positioned at PS waypoints and set overnight. Abundances from fyke nets were uploaded to the

LTIM database as mean numbers of individuals per net per hour within each site and year (variation across nets within a site–year combination was disregarded).

2.2 Data analysis

2.2.1 Spawning

Preparation of data

Time series of daily mean discharge (ML day^{-1}) were directly sourced from the LTIM Hydrology Basin Matter team. Table 1 presents the gauges for which hydrology series were obtained for 2014–15 through to 2015–16. Series for three variables were calculated for each of the gauges presented in Table 1: (1) 'background' (BG) daily discharges – the estimated discharge in the absence of any environmental water; (2) background discharges plus the contribution of Commonwealth environmental water (BG + CEW); (3) background daily discharges plus the contribution of all environmental water (BG + EW), where environmental water includes Commonwealth environmental water, state environmental water (e.g. Victorian Environmental Water Holder (VEWH) allocations), The Living Murray flows and certain inter-valley transfers.

We required a hydrological index that can be standardised across rivers having mean daily discharges that differ by orders of magnitude. Towards this end, we divided mean daily discharges at each gauge by the 'high fresh threshold' (HFT) discharge value at that gauge. The definition of HFT of a river reach is dependent on the definitions of other flow thresholds, so we present the definitions of key LTIM flow thresholds here (Stewardson & Guarino 2016):

- **Very low flows** are defined as flows that fall below the lowest flow in the unimpacted (defined below) monthly flow series or 2% of mean unimpacted flow, whichever is greater. This threshold corresponds to exceptionally low flows at the lower end of range that would normally occur in an unimpacted perennial river.
- **Medium low flows** are defined as flows that fall below the 95th percentile exceedance flow in the unimpacted monthly flow series or 10% of the mean unimpacted flow, whichever is greater. This flow threshold corresponds to a value that might typically be used as a minimum flow to maintain low flow habitats.
- **Low freshes** are defined as flow spells that raise water levels at least one-eighth of the height of the bank above the medium low flow level. This threshold corresponds to a slight increase in stage above base flow levels and would be a frequent occurrence in both the dry and wet seasons under unimpacted flow conditions.
- **Medium freshes** are defined as flow spells that raise water levels at least one-quarter of the height of the bank above the medium low flow level. This threshold corresponds to an increase in stage that wets the lower part of the bank, and would be a frequent occurrence in an unimpacted regime, by maintaining moist soils and contributing to a variable watering regime for this portion of the channel throughout the year.
- **High freshes** are defined as flow spells that raise water levels at least half of the height of the bank above the medium low flow level. Freshes of this magnitude would have occurred in most years in the unimpacted flow regime, and it would be common for freshes to exceed this threshold several times per year.

By transforming all discharge values by the HFT, we have placed all discharge values from different rivers on a common scale that should (approximately) quantitatively map to ecological effects in a similar manner across Selected Areas. Discharge values at each gauge were rescaled by the HFT for all three series (BG; BG + CEW; BG + EW). For clarity, we hereafter refer to 'discharge as a proportion of HFT' as 'standardised discharge'.

Time series of daily mean water temperature for focal zones were obtained from the LTIM River Metabolism database. All mean daily water temperature values were merged with the corresponding daily discharge values so that temperature variables could be included as predictors of spawning response. Mean daily water temperatures were only available for certain subsets of each year.

Once we had generated a data frame of the hydrology and temperature series corresponding to the LTIM sites where spawning was monitored, we then generated eight variables that may serve as predictors of spawning response:

1. **m1Flow$_i$** – the mean standardised discharge over 1 week preceding day i
2. **m3Flow$_i$** – the mean standardised discharge over 3 weeks preceding day i
3. **i1Flow$_i$** – the mean rate of increase in standardised discharge over 1 week preceding day i. Determined by fitting a linear regression to 7 daily standardised discharge values leading up to (and including) day i.
4. **i3Flow$_i$** – the mean rate of increase in standardised discharge over 3 weeks preceding day i. Determined by fitting a linear regression to 21 daily standardised discharge values leading up to (and including) day i
5. **m1Temp$_i$** – the mean daily water temperature over 1 week preceding day i;
6. **m3Temp$_i$** – the mean daily water temperature over 3 weeks preceding day i;
7. **i1Temp$_i$** – the mean rate of increase in mean daily water temperature over 1 week preceding day i. Determined by fitting a linear regression to 7 daily temperature values leading up to (and including) day i
8. **i3Temp$_i$** – the mean rate of increase in mean daily water temperature over 3 weeks preceding day i. Determined by fitting a linear regression to 21 daily temperature values leading up to (and including) day i.

All temperature and hydrology variables were then merged with the fish spawning data, ready for modelling. Our spawning analysis focused on six species: golden perch (*Macquaria ambigua*), silver perch (*Bidyanus bidyanus*), Murray cod (*Maccullochella peelii*), bony herring (*Nematalosa erebi*), Australian smelt (*Retropinna semoni*) and carp gudgeon (*Hypseleotris* spp.).

Modelling spawning probability

Generalised linear models (GLMs) were used to model spawning response as a function of the eight predictor variables. Specifically, we used logistic regression to model spawning probability of each of the six species as a function of the eight predictor variables:

$$S_{i,j} \sim Binomial(1, \pi_{i,j})$$

$$E_{i,j}(S) = \pi_{i,j} \quad \text{and} \quad var\left(S_{i,j}\right) = \pi_{i,j}(1 - \pi_{i,j})$$

$$logit\left(\pi_{i,j}\right) = f\left(\{predictors\}_{i,j}\right) + \beta_n \cdot area_j$$

where $S_{i,j}$ is either 0 (no spawning at the *i*th site–event combination for this species, at Selected Area *j*) or 1 (spawning of this species observed on the *i*th sample at area *j*). The predictors of the function *f* are the eight presented earlier.

At this stage of our model development within LTIM, 'area' was deemed a fixed factor. This is in accordance with our 5-year work plan in the Foundation Report, whereby at this stage we only wish to draw inferences about the specific areas yielding data for parameter estimates, not about sites through the Basin in general. Model structure will be altered next year, parameterising models to facilitate reporting of spawning outcomes from delivery of Commonwealth environmental water in unmonitored areas. To do this, the most basic step we can take is to consider area a random factor, but we may add further terms that increase our ability to scale response to unmonitored areas in a more meaningful way. For example, we could include adult stock density as a covariate, and determine whether the impact of flow on spawning probability is affected by adult abundance within an area. If we found it was, then our approach to modelling spawning response to managed flows in unmonitored areas would predict spawning outcomes under, say, low, medium and high adult stock density scenarios, thus ensuring uncertainty concerning adult abundance at the area scale is given full consideration in reporting.

For any given species, we only included data from Selected Areas where the species had been recorded spawning at some stage during the first 2 years of LTIM – data from areas yielding no larvae for a species were not included in parameter estimates. Arguably the two most parsimonious explanations of why larvae of a species were not recorded in an area are: (a) adults of that species are absent or occur at a low density within that area; (b) sampling intensity within that area is low which results in a low probability of detecting larvae. In future years, we hope to be able to disentangle these two effects but for now we weren't sure how to accommodate inter-area variation in detection probability, especially given the large variation in sampling methodology across catchments. Accordingly, we felt it wise to keep our first attempt at modelling spawning probability at the Basin scale as simple as possible. We focused on identifying the types of quantitative relations between spawning probability, flow and temperature variables we can expect, rather than trying to explain inter-area variation in the presence/absence of spawning.

Our model selection strategy was very simple:

- We first checked for collinearity among predictors using scatterplot matrices. For all species, we observed strong correlation between m1Flow and m3Flow, and between m1Temp and m3Temp. Accordingly, models included mean temperature and flow predictors over only a single time horizon (1 or 3 weeks), but not both. There was very little correlation among all other pairings of predictors.
- Boxplots of predictor values against $S_{i,j}$ values of a species helped to isolate predictors that may be having a clear positive or negative impact on spawning probability. These boxplots also helped us determine whether 1- or 3-week horizons for our mean flow and temperature predictors were most appropriate.
- For each species, at least three candidate models were then developed based on the preceding two steps of data exploration, and passed to the base generalised linear model function in R (R Core Team 2015). Using boxplots (and knowledge of the biology of the problem) we did not find it necessary to include more than four predictor variables in any model (note that four predictor variables can still yield one of our GLMs with 17 parameters).
- Akaike information criteria (AIC) were then used to determine which of the candidate models provided the most parsimonious description of the data. In addition – and because we fitted models that were nested versions of a so-called 'beyond optimal' model (Zuur *et al.* 2009) – we used chi-squared tests to determine which terms could be dropped from certain logistic models (see ?drop1 in R; R Core Team 2015). For ease of discussion, when we hereafter refer to a 'best model' we mean the most parsimonious model.
- We tested whether the final model significantly improved variance explained in $S_{i,j}$ compared with a null model (intercept only) using a chi-squared test. With respect to generalised linear modelling, the distribution of the difference between the null deviance and the residual deviance (null – residual) is approximately χ^2 with degrees of freedom: df_(proposed model) – df_(null model) = (n–(p+1)) – (n–1) = p, where p is the number of model parameters (Zuur *et al.* 2009).

Table 1. Gauges yielding hydrological time series used for fish Basin-scale analyses. 'Zone' refers to the name given to LTIM zones by Selected Area. 'Gauge' is the gauge name within the hydrology database managed by the LTIM Hydrology Basin Matter. 'Gauged' indicates whether the raw discharge time series are obtained from a specific gauge (1) or modelled/inferred based on data from those gauges (0). 'Site ID' is the unique LTIM site identifier. Columns 'Census' and 'Larvae' indicate whether, respectively, population/community censuses and/or larval data are collected from that LTIM site. Threshold definitions are provided within the body of this report. 'This gauge?' indicates whether the threshold values were modelled specifically for that gauge (1) or borrowed from the closest modelled gauge (0). NA = 'not available' or 'not applicable'.

							Thresholds						
Selected Area	**Zone**	**Gauge**	**Gauged**	**Site ID**	**Census**	**Larvae**	**Very low flow**	**Medium low flow**	**Low fresh**	**Medium fresh**	**High fresh**	**Bankfull**	**This gauge?**
Edward–Wakool	Zone1	Yallakool Offtake	1	NA	0	0	24	120	231	402	991.6478	3706.356	1
Edward–Wakool	Zone2	Wakool Offtake	1	NA	0	0	NA	NA	NA	NA	NA	NA	NA
Edward–Wakool	Zone3	EWZone3_Model	0	549	1	1	24	120	231	402	991.6478	3706.356	0
Edward–Wakool	Zone3	EWZone3_Model	0	553	1	1	24	120	231	402	991.6478	3706.356	0
Edward–Wakool	Zone3	EWZone3_Model	0	554	1	1	24	120	231	402	991.6478	3706.356	0
Goulburn	Zone2	McCoy's	1	700	0	1	311.5357	960	4436.214	12907.39	12907.39	57168.12	1
Goulburn	Zone2	McCoy's	1	703	0	1	311.5357	960	4436.214	12907.39	12907.39	57168.12	1
Goulburn	Zone2	McCoy's	1	698	1	1	133.3144	770.552	3456.82	9913.997	9913.997	43293.81	1
Goulburn	Zone1	Murchison	1	707	0	1	311.5357	960	4436.214	12907.39	12907.39	57168.12	1
Gwydir	Gingham–Gwydir	Pallamallawa	1	NA	0	0	39.10167	195.5083	470.5402	951.694	2838.697	12880.04	1
Gwydir	Gingham–Gwydir	Tyreel	1	NA	1	0	20.79922	103.9961	251.2095	509.2781	1523.377	6930.927	1
Gwydir	Gingham–Gwydir	Millewa	1	NA	1	0	1.131259	5.656293	51.81449	201.2363	1157.613	8978.986	1
Lachlan	Zone1	Hillston	1	639	1	1	37.23532	186.1766	446.2345	900.1559	2676.452	12106.9	0
Lachlan	Zone1	Hillston	1	643	1	1	37.23532	186.1766	446.2345	900.1559	2676.452	12106.9	0
Lachlan	Zone1	Hillston	1	647	1	1	37.23532	186.1766	446.2345	900.1559	2676.452	12106.9	0
Lachlan	Zone1	Whealbah	1	NA	0	0	NA	NA	NA	NA	NA	NA	NA
Lachlan	Zone1	Booligal	1	NA	0	0	NA	NA	NA	NA	NA	NA	NA
Lower Murray	Floodplain	Lock6	1	589	0	1	430.1759	2492.529	14615.77	47451.27	47451.27	233200.6	1
Lower Murray	Floodplain	Lock6	1	592	0	1	430.1759	2492.529	14615.77	47451.27	47451.27	233200.6	1

Selected Area	Zone	Gauge	Gauged	Site ID	Census	Larvae	Thresholds						This gauge?
							Very low flow	Medium low flow	Low fresh	Medium fresh	High fresh	Bankfull	
Lower Murray	Floodplain	Lock6	1	593	0	1	430.1759	2492.529	14615.77	47451.27	47451.27	233200.6	1
Lower Murray	Floodplain	Lock5	1	NA	0	0	NA	NA	NA	NA	NA	NA	NA
Lower Murray	Floodplain	Lock4	1	NA	0	0	NA	NA	NA	NA	NA	NA	NA
Lower Murray	Gorge	Lock1	1	586	1	1	689.323	900	11413.76	49610.56	49610.56	312787.9	1
Lower Murray	Gorge	Lock1	1	590	1	1	689.323	900	11413.76	49610.56	49610.56	312787.9	1
Lower Murray	Gorge	Lock1	1	591	1	1	689.323	900	11413.76	49610.56	49610.56	312787.9	1
Lower Murray	Gorge	Lock3	1	NA	0	0	NA	NA	NA	NA	NA	NA	NA
Lower Murray	Gorge	Lock2	1	NA	0	0	NA	NA	NA	NA	NA	NA	NA
Murrumbidgee	Carrathool	Carrathool	1	509	1	1	185.4229	927.1147	2044.943	3906.275	10860.11	45982.24	1
Murrumbidgee	Carrathool	Carrathool	1	515	1	1	185.4229	927.1147	2044.943	3906.275	10860.11	45982.24	1
Murrumbidgee	Carrathool	Carrathool	1	518	1	1	185.4229	927.1147	2044.943	3906.275	10860.11	45982.24	1
Murrumbidgee	Narrandera	Narrandera	1	522	0	1	205.2471	1026.235	2271.1	4347.913	12121.55	51466.21	1
Murrumbidgee	Narrandera	Narrandera	1	524	0	1	205.2471	1026.235	2271.1	4347.913	12121.55	51466.21	1
Murrumbidgee	Narrandera	Narrandera	1	526	0	1	205.2471	1026.235	2271.1	4347.913	12121.55	51466.21	1

2.2.2 Environmental context to long-term change – hydrology, water temperature and ecosystem metabolism

Within the 'Long-term (1–5-year) outcomes' section of this report (Section 4), we present a brief overview of inter-annual dynamics in hydrology, water temperature and ecosystem metabolism within the fish focal zones of the six Selected Areas. We present this overview of long-term environmental context for two reasons:

- From Year 3 onwards, the LTIM Fish Basin Matter will begin building quantitative models of the relationship between the gross hydrological and thermal properties of the fish focal zones, and fish population response (recruitment and survival of target species). At this early stage of LTIM – indeed at any stage of a long-term monitoring program – careful documentation of the inter-annual dynamics of potential drivers of population dynamics will provide clues concerning how models should be parameterised.
- For Basin-scale reporting purposes, the Fish Basin Matter team required a convenient, condensed graphical overview of the following, within the Category 1 fish focal zones of Selected Areas:
    - dynamics of daily discharge on a multi-year temporal scale, with daily discharge within a focal zone decomposed into the contributions of background flows, Commonwealth environmental water and total environmental water
    - gross inter-annual changes in the distribution of water temperatures experienced by fish populations
    - gross inter-annual changes in the distributions of primary productivity and ecosystem respiration.

We present two types of hydrograph:

1. hydrographs of daily discharge within all fish focal zones from the beginning of LTIM onwards (from July 2014), whereby the total discharge is decomposed into: BG; BG + CEW; and BG + EW, as detailed in Section 2.2.1,
2. time series plots of the proportionate contribution made to total discharge by (a) Commonwealth environmental water and (b) total environmental water. These series are presented from July 2014 onwards.

An overview of gross inter-annual changes in water temperature, gross primary production (GPP) and ecosystem respiration (ER) of fish focal zones is presented using boxplots.

Hydrology data were provided by the LTIM Hydrology team and GPP and ER data were sourced from the LTIM Monitoring Data Management System. Data for each discharge series presented in Section 4.2.1 come from the gauges where annual censuses have been conducted, within each Selected Area (Table 1). Where there was more than one gauge for each focal zone, means of daily discharge were obtained across those gauges.

2.2.3 State of fish populations

To determine how the states of fish populations varied within and among Selected Areas, we compared and contrasted the length structure, age structure and fish condition metrics among years within 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/`).

Age and length structure

Comparisons of age and length structure among Selected Areas 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). An ALK is a matrix whose *i,j*th entry is the probability that a fish of length-class *i* is of age *j* [$P(j|i)$]. 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 to 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 were as follows:

- Murray cod – 803 individuals (obtained from within LTIM Selected Areas and supplemented with individuals from the Campaspe and Loddon rivers and Gunbower Creek)
- golden perch – 553 individuals (obtained from within LTIM Selected Areas and supplemented with individuals from the Campaspe and Loddon rivers and Gunbower Creek)
- bony herring – 806 individuals (obtained exclusively within LTIM Selected Areas).

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,j*th 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,j*th 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 1. The final stage of ALK development was to transform the matrix such that row totals sum to 1, 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.

Condition

We determined how *relative* condition of individuals within a population vary through time as follows: within each Selected Area where the species under consideration was a focal species, we fitted a simple linear regression between *ln* mass (g) and *ln* length (mm) and extracted the residuals. Within a year, residuals will be skewed to more positive values if condition is 'above average' for that Selected Area, while the residuals will be more negatively skewed if condition is 'below average' for that Selected Area. At this stage of LTIM, we present boxplots of residuals by year to facilitate visual analysis of inter-annual changes in condition.

2.2.4 State of fish assemblages

For all analyses pertaining to community structure, data were first range standardised by re-scaling all abundance estimates to between 0 and 1. Range standardisation was carried out across all small-bodied species and across all large-bodied species separately, to account for differences in absolute abundance estimates from fyke net and electrofishing sampling techniques, which were used to estimate abundances of these two groups, respectively. As stated in the Standard Methods (Hale *et al.* 2013), small-bodied species comprised any species belonging to the families Retropinnidae, Eleotridae, Galaxiidae, Melanotaenidae, Atherinidae, Ambassidae and Poeciliidae. Large-bodied fishes are classified as belonging to the other families of the Basin. The range-standardised CPUE from site *k*, species *j* and year *i* is defined:

$$CPUE_{i,j,k}^{RS} = \frac{CPUE_{i,j,k} - \min(CPUE_{i,j,k})}{\max(CPUE_{i,j,k}) - \min(CPUE_{i,j,k})}$$

where the *j*s belong to one of two sets defining the domains of the minimum and maximum functions; the set of small-bodied fishes, or the set of large-bodied fishes. Range standardisations were carried out to put the very different CPUE units of these two sets of species (ind net^{-1} hour^{-1} *versus* ind s^{-1} on-time) on the same range [0,1]. In doing so, both large-bodied and small-bodied species exert equal influence on all community analyses, be they univariate (e.g. species evenness) or multivariate (e.g. Bray-Curtis similarity) analyses.

Univariate and multivariate analyses were graphical and comparisons were made among groups using 95% confidence regions/intervals. Univariate analyses involved comparing and contrasting mean species richness, mean Pielou's evenness and mean nativeness among years within Selected Areas and among Selected Areas. Mean (and standard errors (SEs), from which CIs are obtained) values of these statistics were calculated treating sites within years (n = 10) as replicates. Species richness refers to the number of species within an area. Pielou's evenness has range [0,1] and equals 1 when all species abundances of an assemblage are equal ($1/n$ if there are n species) and so, in conjunction with richness, helps provide a picture of how well represented each species is, within the local assemblage of a Selected Area. Nativeness is defined within the Fish Basin Matter as the proportion of total range-standardised CPUEs comprised of native species. Note that LTIM nativeness and Sustainable Rivers Audit nativeness are not quantitatively comparable as they are based on different sampling protocols.

Non-parametric multivariate analyses were used to determine how fish community structure varies among Selected Areas and years. Bray-Curtis similarities were calculated between samples (year–site combinations of mean CPUE) and differences among the six Selected Areas and years were visualised using non-parametric multidimensional scaling (NMDS). Confidence regions around group means were calculated using bootstrapping. The R package 'vegan' was used to undertake this analysis.

2.3 Synthesis of Selected Area outcomes

The qualitative synthesis is presented largely in tabular form. We reviewed short-term outcomes (movement, spawning and, to a lesser degree, recruitment outcomes) presented in technical reports (Dyer *et al.* 2016, Southwell *et al.* 2016, Wassens *et al.* 2016, Watts *et al.* 2016, Webb *et al.* 2016, Ye *et al.* 2017). The review focused on the six Selected Areas where LTIM monitoring is taking place.

3 Short-term (<1 year) outcomes

3.1 Highlights

These highlights are reported in more detail through Section 3.3 onwards.

- Probability of spawning in several species was significantly related to *standardised discharge variables* – discharge variables standardised by proportion of hydrological thresholds. This broad result is significant as it demonstrates that flow delivery rules to promote spawning can be developed that are not ‘river specific’. Flow delivery rules presented in units of discharge alone are not readily scaled to broader extents or different areas of the Basin, as the ecological effects of a fixed level of discharge will be river specific. Our demonstration that spawning response is linked to standardised discharge variables is a significant step forward with respect to ‘scaling-up’ the following activities:
    - scientifically defensible reporting of managed flow outcomes in unmonitored areas of the Basin
    - predicting likely outcomes from a set of possible watering actions in unmonitored areas of the Basin.
- Native fishes (golden perch, silver perch, Australian smelt, carp gudgeon, bony herring) have exhibited species-specific responses to hydrographs during the first 2 years of LTIM; no single, within-year watering action (i.e. timing, rate of increase, mean discharge, etc. of a managed flow) will be optimal if our objective is to maintain diversity of native fishes. This finding highlights the need to take a multispecies approach to planning watering actions to promote spawning.
- The probability of spawning in most species was heavily dependent on flow–temperature interactions, showing that timing of a watering action (within the spawning season) will affect spawning outcomes. No individual month is optimal for all species, and so watering actions within a year should be determined in light of watering plans and ecological objectives for the longer term.
- For golden perch, silver perch and Australian smelt, the rate at which discharge approaches the high fresh threshold had a significant, positive effect on the probability of spawning. Notwithstanding the constraints on flow delivery, rates of increase in standardised discharge of ~3% day^{-1} (3% of the high fresh threshold each day, for 1–3 weeks) will increase the probability of spawning in these flow-pulse-sensitive spawners, even at moderate mean discharge levels.
- Quantitative models of the relationship between specific flow variables and fish spawning are essential for: (a) deciphering the contribution of Commonwealth environmental water to fish spawning; and (b) deciding on which watering actions to deliver in any given year. After 2 years of LTIM, models of the probability of spawning as a function of specific flow and temperature variables are showing great promise. The Fish Basin Matter is now in a good position to begin:
    - identifying the relative contributions of background flows, Commonwealth environmental water and other environmental water on fish spawning, leading to scientifically defensible, transparent methods of reporting spawning outcomes
    - reporting on spawning outcomes across unmonitored areas of the Basin.
- In Selected Areas characterised by low mean annual discharge (e.g. Gwydir, Warrego), good evidence is emerging to show that *without* Commonwealth environmental water, water quality and fish assemblages of refuge pools would have significantly declined. The threatened olive perchlet (*Ambassis agassizii*) was recorded by LTIM monitoring, within refuge pools receiving Commonwealth environmental water base flows. River systems of the Basin characterised by low mean annual discharge likely benefit from managed base flows during dry climatic conditions.

3.2 Overview of watering actions with expected outcomes for fish

During the 2015–16 flow-delivery year, a total of 60 Commonwealth environmental watering actions were delivered with expected outcomes for fishes, summing to a total water volume of around 1566 GL delivered throughout the Basin. Of these watering actions, 42% were delivered as freshes; 7% as overbank flows; 23% as wetland inundations; and 28% as base flows. Annex A provides a summary of the Commonwealth environmental watering actions with expected outcomes for fish during 2015–16.

3.3 Fish spawning at the Basin scale

3.3.1 Golden perch

During the first 2 years of LTIM, golden perch larvae have been detected at three Selected Areas: Goulburn, Murrumbidgee and the Lower Murray. Within these three areas, over the 2 years, a total of 240 samples (unique site–event combinations) were taken and, of these, 27 yielded at least 1 golden perch larva.

The 'best model' (see Section 2.2.1) describing the probability of golden perch spawning was:

$$\mathrm{logit}(S_{i,j}) = -3.20 + 3.31 \cdot \mathrm{m1Flow}_{i,j} + 24.61 \cdot \mathrm{i1Flow}_{i,j} + \beta_4 \cdot \mathrm{Area}_{i,j} \qquad \text{(M1)}$$

Compared with the null model (containing only an intercept), the best model reduced null deviance by 12%. This reduction in deviance is relatively small; however, despite this relatively small difference between null and residual deviance (an indication of how well the model explains patterns in the data), model M1 explained a significantly greater amount of variance in $S_{i,j}$ compared with the null model (P = 0.001). Values of β_4 are area specific – and indicate how much the probability curve of each area departs from first Selected Area passed to the model – but at this stage of model development, there was little evidence to suggest that parameters of the model M1 varied significantly among Selected Areas.

The key features of the best golden perch model are as follows:

- Spawning probability of golden perch increased as a function of mean standardised discharge over the week preceding a sample (m1Flow), and further increased as a function of mean rate of increase in standardised flow over the week preceding a sample (i1Flow; Figure 8).
- Surprisingly, none of the temperature predictors improved the fit of the model to the data. This may be due to insufficient samples taken early in the spawning season, with sampling being too concentrated around specific flow peaks.
- There was little to no evidence of the quantitative nature of the relationship between flow predictors and spawning probability being altered across Selected Areas.
- The explanatory/predictive power of the best model is, at this stage of LTIM, quite low.

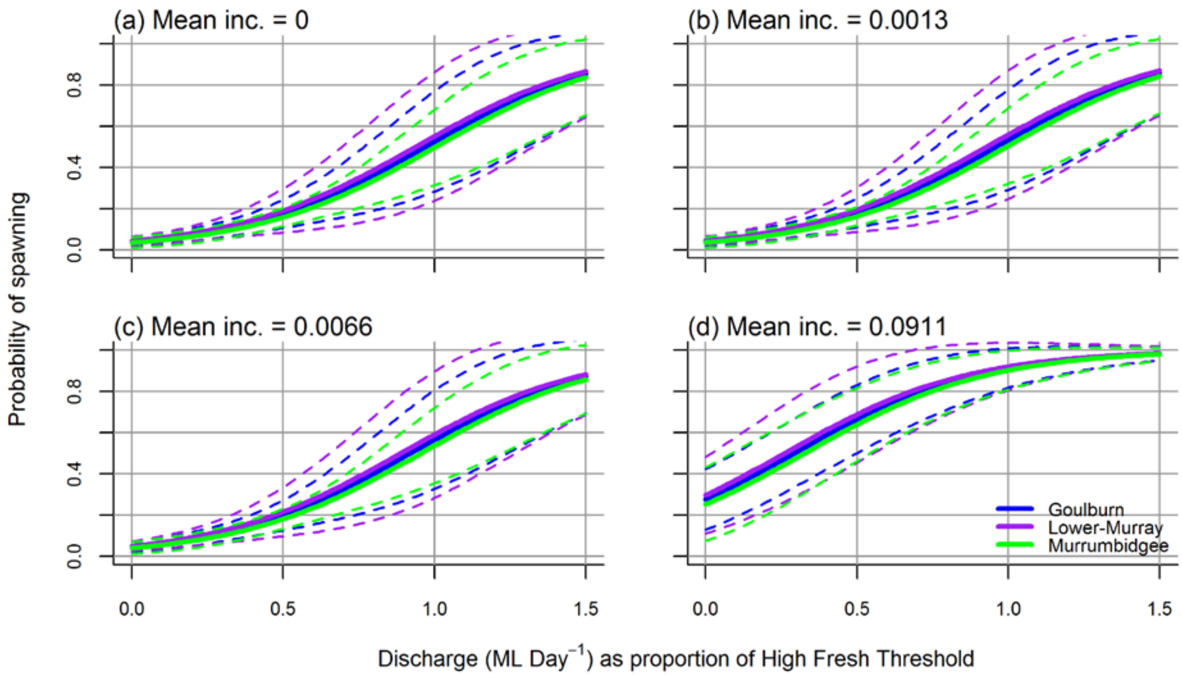

Figure 8. Probability of **golden perch** spawning as a function of mean standardised discharge (x-axis) and mean rate of increase in flow during the week preceding a sample. The different rates of increase correspond to (a) zero (stable water levels); (b) mean rate of increase across 2014–16; (c) the 75th percentile (3rd quartile) of rates of increase for 2014–16 data; and (d) the maximum rate of increase recorded during 2014–16 (for the three Selected Areas where golden perch larvae were recorded). Solid curves are fitted values generated by model M1. Dashed lines indicate ± SE around mean predicted value. Curves are plotted for the three Selected Areas where golden perch spawning was detected during 2014–16, but note the lack of a strong area effect.

3.3.2 Silver perch

During the first 2 years of LTIM silver perch larvae have been detected at three Selected Areas: Goulburn, Murrumbidgee and the Lower Murray. Within these three areas, over the 2 years, a total of 240 samples (unique site-event combinations) were taken, and of these, 33 yielded at least 1 silver perch larva.

The best model describing the probability of silver perch spawning was:

$$\text{logit}(S_{i,j}) = 6.28 - 37.01 \cdot \text{m3Flow}_{i,j} - 0.46 \cdot \text{m3Temp}_{i,j} - 630.43 \cdot \text{i3Flow}_{i,j} + 1.79 \cdot \text{m3Flow}_{i,j} \cdot \text{m3Temp}_{i,j} + 30.55 \cdot \text{i3Flow}_{i,j} \cdot \text{m3Temp}_{i,j} + \beta_7 \text{Area}_{i,j} \quad \text{(M2)}$$

Model M2 reduced null deviance by 39% and explained a significantly greater amount of variance in $S_{i,j}$ compared with the null model ($P < 0.001$). Values of β_7 are area specific.

The key features of the best silver perch model are as follows:

- The relationship between flows and silver perch spawning is more complex than that of golden perch (Figure 9). There is a strong and significant interaction between flows and temperature, with mean standardised discharge during the 3 weeks before a sample having a strong positive effect on spawning probability, *but only when water temperature exceeds 20–22 °C*. At colder water temperatures, increasing discharge may actually reduce the probability of silver perch spawning (Figure 9).
- Similar to golden perch, mean rate of increase in standardised discharge increased the probability of silver perch spawning (at the appropriate water temperatures; Figure 10). Unlike golden perch, however, mean rate of increase over a 3-week time horizon (rather than 1 week) was most strongly associated with spawning probability (Figure 10).

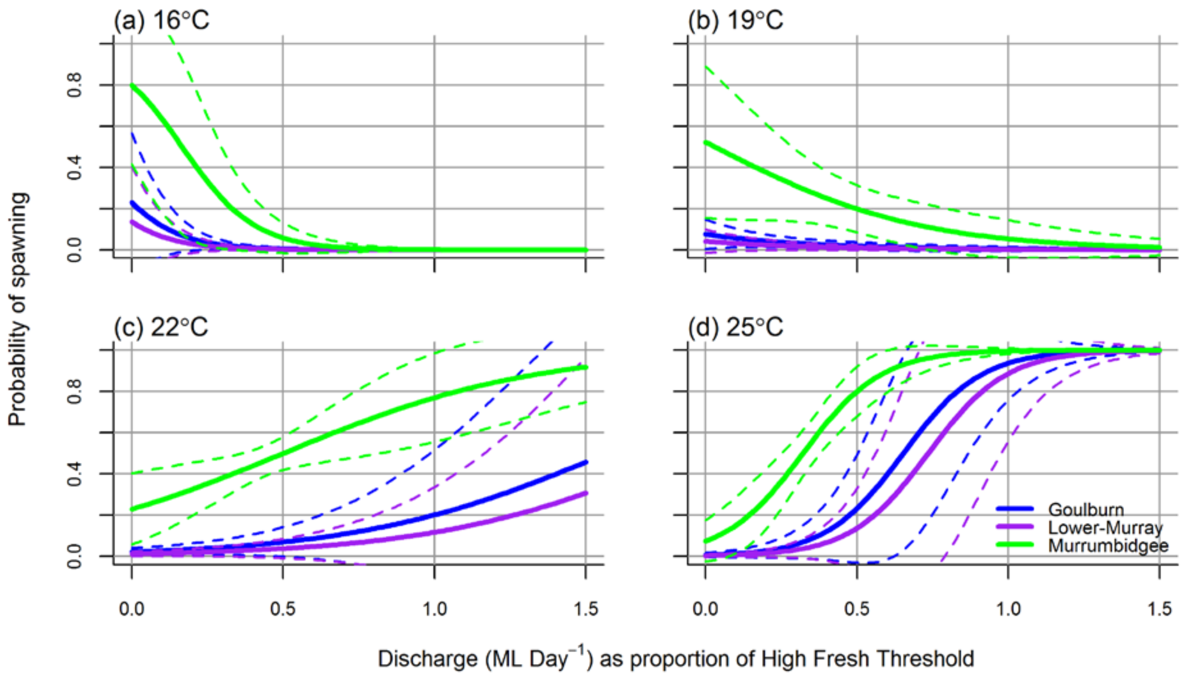

Figure 9. Probability of **silver perch** spawning as a function of mean standardised discharge (x-axis) and mean water temperature (different panels) during the 3 weeks preceding a sample. Solid curves are fitted values generated by model M2. Dashed lines indicate ± SE around mean predicted value. Curves are plotted for the three Selected Areas where silver perch spawning was detected during 2014–16.

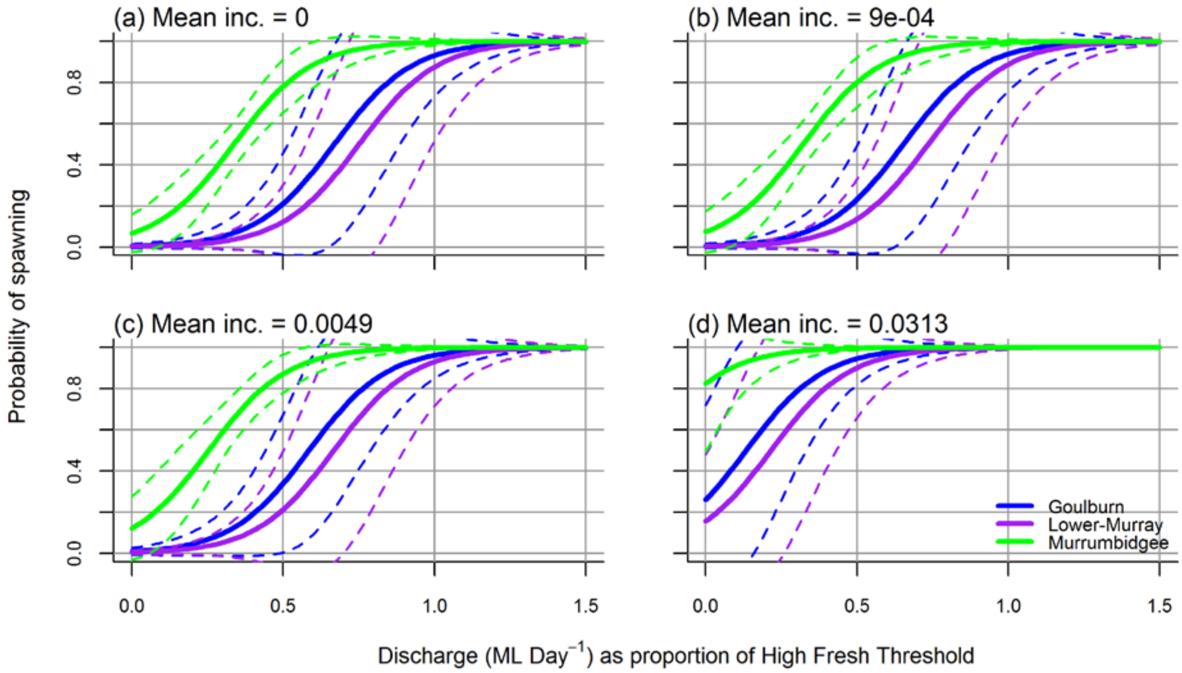

Figure 10. Probability of **silver perch** spawning as a function of mean standardised discharge (x-axis) and mean rate of increase in standardised discharge during the 3 weeks preceding a sample. The different rates of increase correspond to: (a) zero (stable water levels); (b) mean rate of increase across 2014–16; (c) the 75th percentile (3rd quartile) of rates of increase for 2014–16 data; (d) and the maximum rate of increase recorded during 2014–16 (for the three Selected Areas where silver perch larvae were recorded). Solid curves are fitted values generated by model M2. Dashed lines indicate ± SE around mean predicted value. Curves are plotted for the three Selected Areas where silver perch spawning was detected during 2014–2016. For these plots temperature was fixed at 22 °C.

3.3.3 Murray cod

During the first 2 years of LTIM, Murray cod larvae have been detected at all five of the Selected Areas monitoring fish spawning. Within these areas, over the 2 years, a total of 305 samples (unique site-event combinations) were taken, and of these, 131 yielded at least 1 Murray cod larva.

None of our candidate models provided a reasonable fit to the data. That is, we found no significant relationships between any temperature or flow variable and the probability of Murray cod spawning. Reasons for detecting no relationships are discussed in Section 3.3.6.

3.3.4 Australian smelt

During the first 2 years of LTIM, smelt larvae have been detected at all five Selected Areas monitoring spawning: Edward–Wakool, Goulburn, Lachlan, Murrumbidgee and the Lower Murray. Within these areas, over the 2 years, a total of 305 samples (unique site–event combinations) were taken, and of these, 165 yielded at least 1 Australian smelt larva.

The best model describing the probability of Australian smelt spawning had the same terms as the best model for silver perch:

$$\text{logit}(S_{i,j}) = 5.95 - 33.57\cdot\text{m3Flow}_{i,j} - 0.26\cdot\text{m3Temp}_{i,j} - 919.04\cdot\text{i3Flow}_{i,j} - 1.67\cdot\text{m3Flow}_{i,j}\cdot\text{m3Temp}_{i,j} - 45.37\cdot\text{i3Flow}_{i,j}\cdot\text{m3Temp}_{i,j} + \beta_7\text{Area}_{i,j} \quad \text{(M3)}$$

Model M3 reduced null deviance by 28% and explained a significantly greater amount of variance in $S_{i,j}$ compared with the null model ($P < 0.0001$). Values of β_7 are area specific.

Key features of the best Australian smelt model are as follows:

- The model had the same terms as the best silver perch model, but very different parameter values (Figure 11). There was a strong and significant interaction between flows and temperature, but in the opposite direction to those of silver perch, with mean standardised discharge during the 3 weeks before a sample having a positive effect on spawning probability, *but only when water temperature was less than 20–22 °C*. At warmer water temperatures, increasing discharge may actually reduce the probability of Australian smelt spawning (Figure 11).
- Similar to the case of golden perch and silver perch, mean rate of increase in standardised discharge increased the probability of Australian smelt spawning (at the appropriate water temperatures; Figure 12). Unlike golden perch, however, but concordant with the best silver perch model, mean rate of increase over a 3-week time horizon (not 1 week) was most strongly associated with spawning probability (Figure 12).

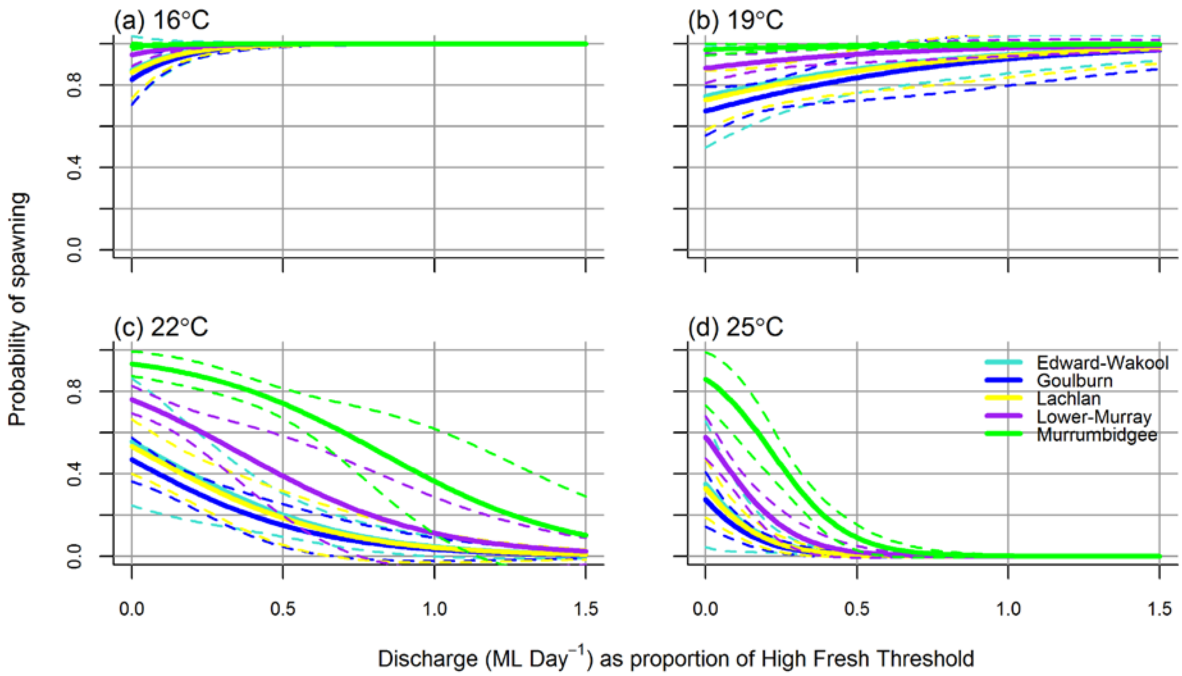

Figure 11. Probability of **Australian smelt** spawning as a function of mean standardised discharge (x-axis) and mean water temperature (different panels) during the 3 weeks preceding a sample. Solid curves are fitted values generated by model M3. Dashed lines indicate ± SE around mean predicted value. Curves are plotted for the five Selected Areas where fish spawning was monitored during 2014–16.

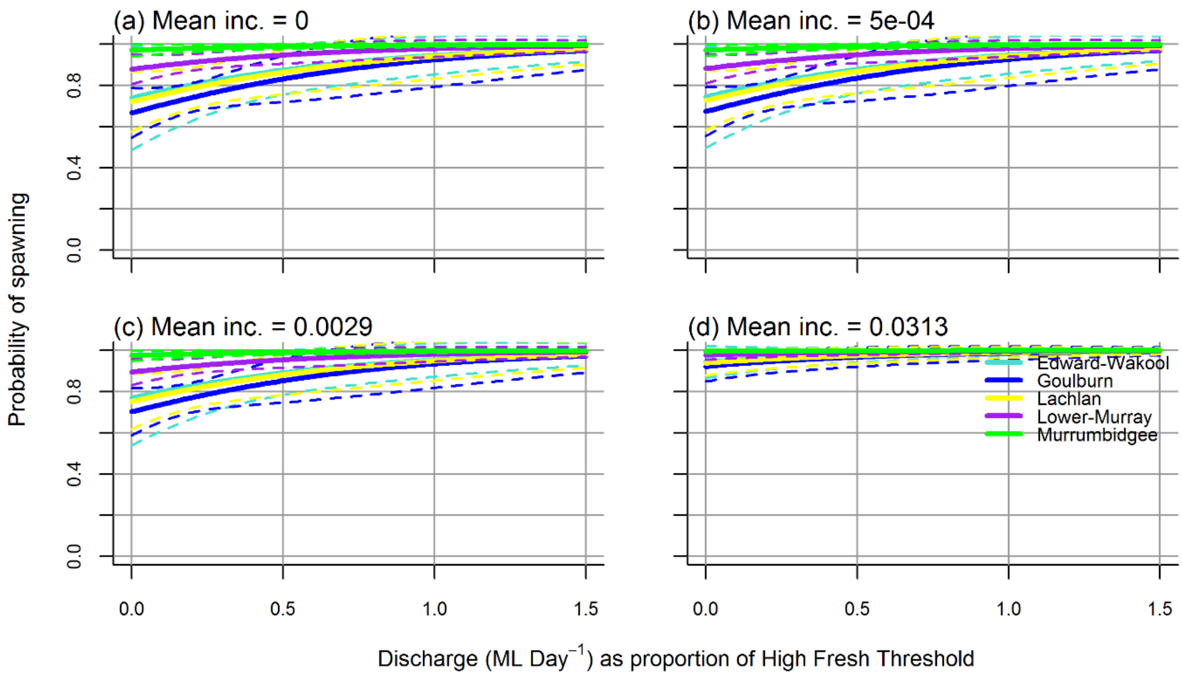

Figure 12. Probability of **Australian smelt** spawning as a function of mean standardised discharge (x-axis) and mean rate of increase in standardised discharge during the three weeks preceding a sample. The different rates of increase correspond to: (a) zero (stable water levels); (b) mean rate of increase across 2014–16; (c) the 75th percentile (3rd quartile) of rates of increase for 2014–16 data; and (d) the maximum rate of increase recorded during 2014–16 (for the five Selected Areas where smelt larvae were recorded). Solid curves are fitted values generated by model M3. Dashed lines indicate ± SE around mean predicted value. Curves are plotted for all five Selected Areas where LTIM larval monitoring during 2014–16. Curves generated with temperature fixed at 19 °C.

3.3.5 Bony herring

During the first 2 years of LTIM, bony herring larvae have been detected at two of the five Selected Areas monitoring spawning: Murrumbidgee and the Lower Murray. Within these two areas, over the 2 years, a total of 156 samples (unique site–event combinations) were taken, and of these, 72 yielded at least 1 bony herring larva.

The best model describing the probability of bony herring spawning was:

$$\text{logit}(S_{i,j}) = 5.37 - 71.07 \cdot \text{m3Flow}_{i,j} - 0.17 \cdot \text{m3Temp}_{i,j} + 3.14 \cdot \text{m3Flow}_{i,j} \cdot \text{m3Temp}_{i,j} + \beta_5 \text{Area}_{i,j} \qquad \text{(M4)}$$

Model M4 reduced null deviance by 46% and explained a significantly greater amount of variance in $S_{i,j}$ compared with the null model ($P < 0.0001$). Values of β_5 are area specific.

Key features of the best bony herring model are as follows (Figure 13):

- The best model was a simple one, including predictors of mean standardised flow and mean water temperature (and their interaction) over a 3-week horizon prior to sampling.
- Even though the model was simple, the effect of the flow–temperature interaction was somewhat complex; at relatively low flows, the effect of temperature on bony herring spawning differed strongly between areas, but increasing flows homogenised the response across areas (increasing the probability of spawning in the Murrumbidgee to a large degree, but slightly decreasing the probability of spawning in the Lower Murray).

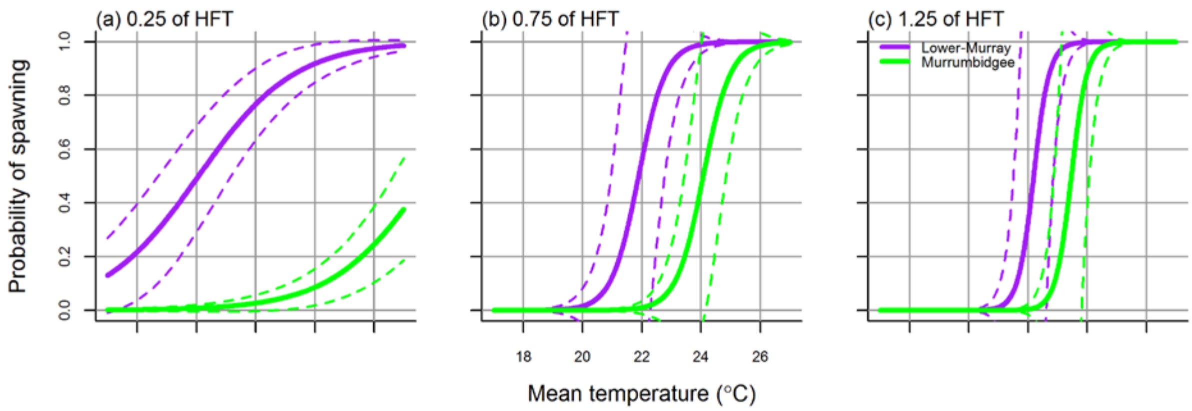

Figure 13. Probability of **bony herring** spawning as a function of water temperature (x-axis) and the mean standardised discharge during the three weeks prior to a sample (different panels). HFT = high fresh threshold (see body of document). Solid curves are fitted values generated by model M4. Dashed lines indicate ± SE around mean predicted value. Curves are presented for the two areas where bony herring spawning was detected.

3.3.6 Carp gudgeon

During the first 2 years of LTIM, carp gudgeon larvae have been detected at all five Selected Areas monitoring spawning: Edward–Wakool, Goulburn, Lachlan, Murrumbidgee and the Lower Murray. Within these areas, over the 2 years, a total of 305 samples (unique site–event combinations) were taken, and of these, 141 yielded at least 1 carp gudgeon larva.

The best model describing the probability of carp gudgeon spawning had the same terms as the best model for bony herring, but without the temperature–flow interaction:

$$\text{logit}(S_{i,j}) = -8.33 - 3.49 \cdot \text{m3Flow}_{i,j} + 0.49 \cdot \text{m3Temp}_{i,j} + \beta_4 \text{Area}_{i,j} \qquad \text{(M5)}$$

Model M5 reduced null deviance by 61% and explained a significantly greater amount of variance in $S_{i,j}$ compared with the null model (P = 0). Values of β_4 are area specific.

Key features of the best carp gudgeon model are:

- The best model confirms carp gudgeon's status as a low-flow spawner, with an increase in mean discharge over weeks prior to a sample lowering the probability of spawning, irrespective of temperature (hence the insignificant flow–temperature interaction; Figure 14).
- Spawning probability of carp gudgeon increased sharply around 18–22 °C, but an increase in flow not only lowered overall spawning probability, but resulted in spawning occurring at higher water temperatures (Figure 15).

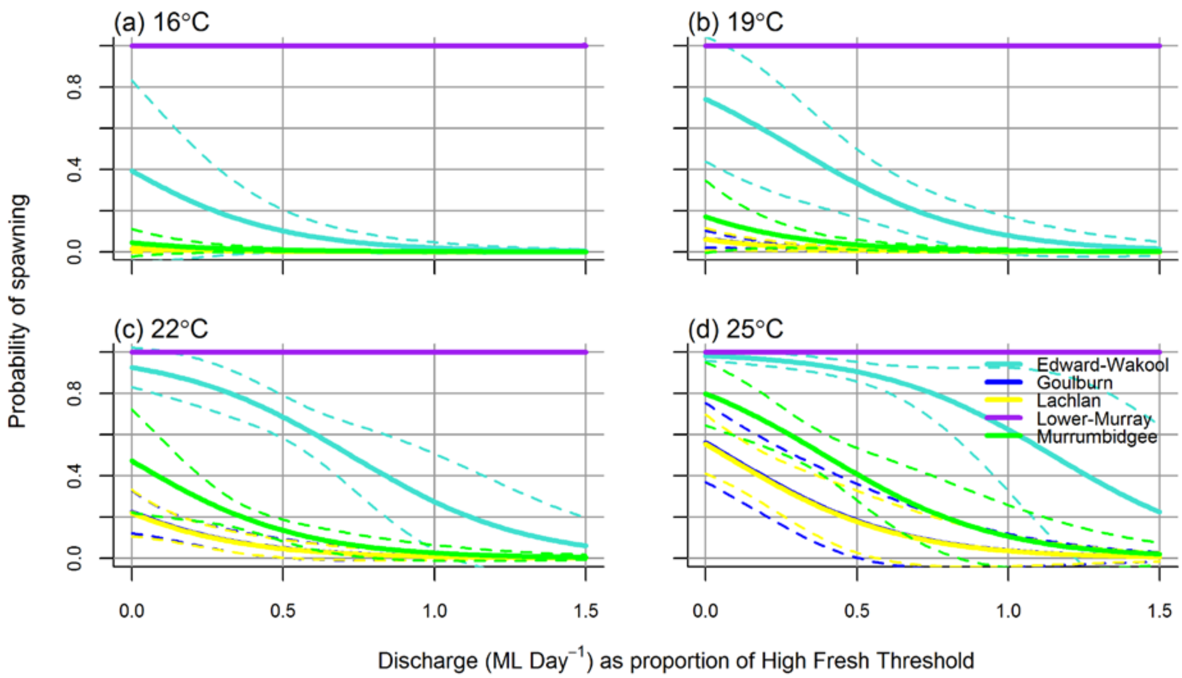

Figure 14. Probability of **carp gudgeon** spawning as a function of mean standardised discharge (x-axis) and mean water temperature (different panels) during the 3 weeks preceding a sample. Solid curves are fitted values generated by model M5. Dashed lines indicate ± SE around mean predicted value. Curves are plotted for the five Selected Areas where fish spawning was monitored during 2014–16.

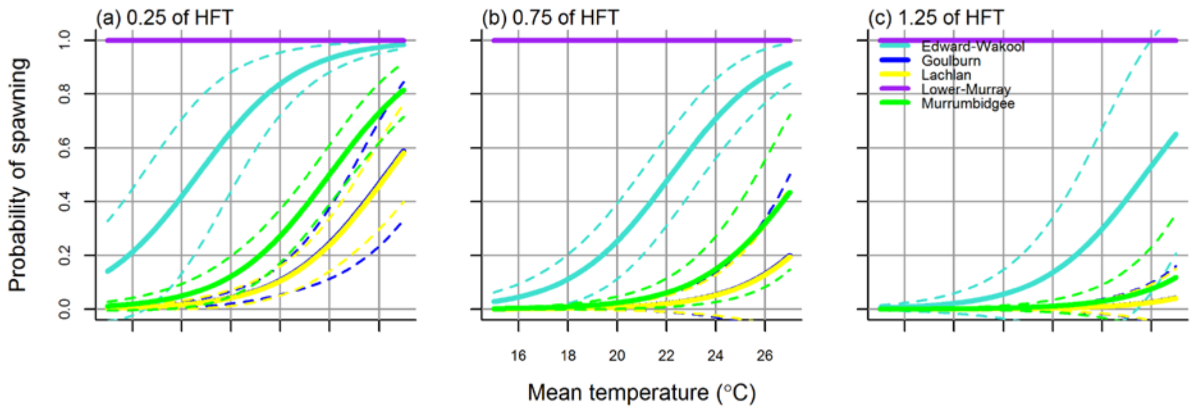

Figure 15. Probability of **carp gudgeon** spawning as a function of water temperature (x-axis) and the mean standardised discharge during the 3 weeks prior to a sample (different panels). HFT = high fresh threshold (see body of document). Solid curves are fitted values generated by model M5. Dashed lines indicate ± SE around mean predicted value. Curves are presented for all five Selected Areas where fish larvae were monitored.

3.3.7 Discussion: spawning at the Basin scale

Spawning: a function of flow–temperature interactions, but in a species-specific way

We were able to identify models that described a significant amount of variation in the relationships between spawning probability, flow and temperature for five of the six fishes studied. Of those five, three models contained significant flow–temperature interactions. For silver perch, Australian smelt and bony herring, the effects of flow variables were dependent on temperature. This was true irrespective of whether the flow variables were defined by rates of increase in discharge, or mean levels of discharge prior to a sample.

The significant and strong flow–temperature interactions have implications for managing environmental flows to increase the incidence of spawning in native fishes. For example, if we wish to deliver flows to enhance spawning of silver perch, those flows may have to be delivered after mean water temperatures exceed ~20 °C. The exact timing of mean river temperatures exceeding ~20 °C varies among rivers, but is generally around early to mid-October (e.g. Figure 16).

Importantly, however, the effect of the flow–temperature interaction is species specific. While temperature may be a critical consideration when deciding on the timing of a specific flow pulse to enhance silver perch spawning, the timing of such a pulse between September and December may have little impact on golden perch spawning. Flow pulses with a timing that benefits one species may be to the detriment of others. Here we presented evidence that a flow pulse may increase the probability of Australian smelt spawning when water is cool (<20 °C), but erode spawning probability at higher water temperatures – the exact opposite of what was observed for silver perch.

These models are in their earliest stages of development, but at this stage it appears that decisions concerning when and how to deliver an environmental flow may be associated with trading-off outcomes among species – no single type of environmental flow will enhance the spawning of all fishes. This principle has existed for some time (Humphries *et al.* 1999), but often as a simple trichotomy: a species may be a flow-pulse-dependent, low-flow-dependent or flow-independent spawner. LTIM data suggest that certain assemblages of fishes may comprise several flow-pulse-dependent spawners, each responding to flow pulses with different characteristics. We return to this issue in Section 3.5 (‘Adaptive management’).

Why were we unable to identify a suitable model of Murray cod spawning probability?

The LTIM data set yielded no significant, sensible models of Murray cod spawning probability as a function of flow and temperature; why? We offer two answers here, and note the implications for adaptive management in Section 3.5.

First, LTIM larval samples used for the Basin-scale analysis did not span a sufficiently broad range of environmental conditions. A case in point is temperature: Humphries (2005) and King *et al.* (2016) have demonstrated that temperature is a dominant driver of Murray cod spawning probability and magnitude, respectively. Humphries (2005) suggested cod were flow-independent spawners, with spawning beginning once water temperatures exceeded 15 °C during September, and all the way through to December. King *et al.* (2016) demonstrated that cod spawning magnitude (not just presence/absence) increases sharply beyond 15 °C and peaks at 19 °C. Examination of the LTIM data used for these analyses showed that the vast majority of our larval samples fell well outside these critical temperatures; the interquartile range of the water temperature data corresponding with larval samples fell entirely between 21.5 and 24.5 °C. The relatively narrow range of environmental predictors is a consequence of our sampling design, which calls for samples to be concentrated around a particular flow event.

Second – and related to the first answer, above – our choice of response variable (binary; presence or absence of larvae) is not well suited to (a) the narrow temporal domain of sampling and (b) the protracted, erratic nature of Murray cod spawning presence/absence. That is, given Murray cod start spawning earlier than the vast majority of our samples, and given their spawning presence/absence is somewhat erratic, our narrow range of cod larval samples contains a high noise:signal ratio on the presence/absence scale. It is possible that if we modelled spawning magnitude (like King *et al.* (2016)), then significant relationships with temperature and flow may have been elucidated.

We opted for a binary response variable due to the strong variation in larval sampling methodology among Selected Areas; it is difficult to standardise spawning magnitude across such disparate sampling designs. Nevertheless, we aim to explore approaches to modelling spawning magnitude in subsequent years of LTIM.

Caveat: uncertainty is high

All of the best models of spawning probability – perhaps with the exception of carp gudgeon – were characterised by high uncertainty. Although the best models provided a statistically significant fit to the data, they generally reduced null deviance in spawning probability by less than 50%. This uncertainty will decline each year, as more data contribute to model parameterisation and model parameter estimation. We return to this issue in Section 3.5.

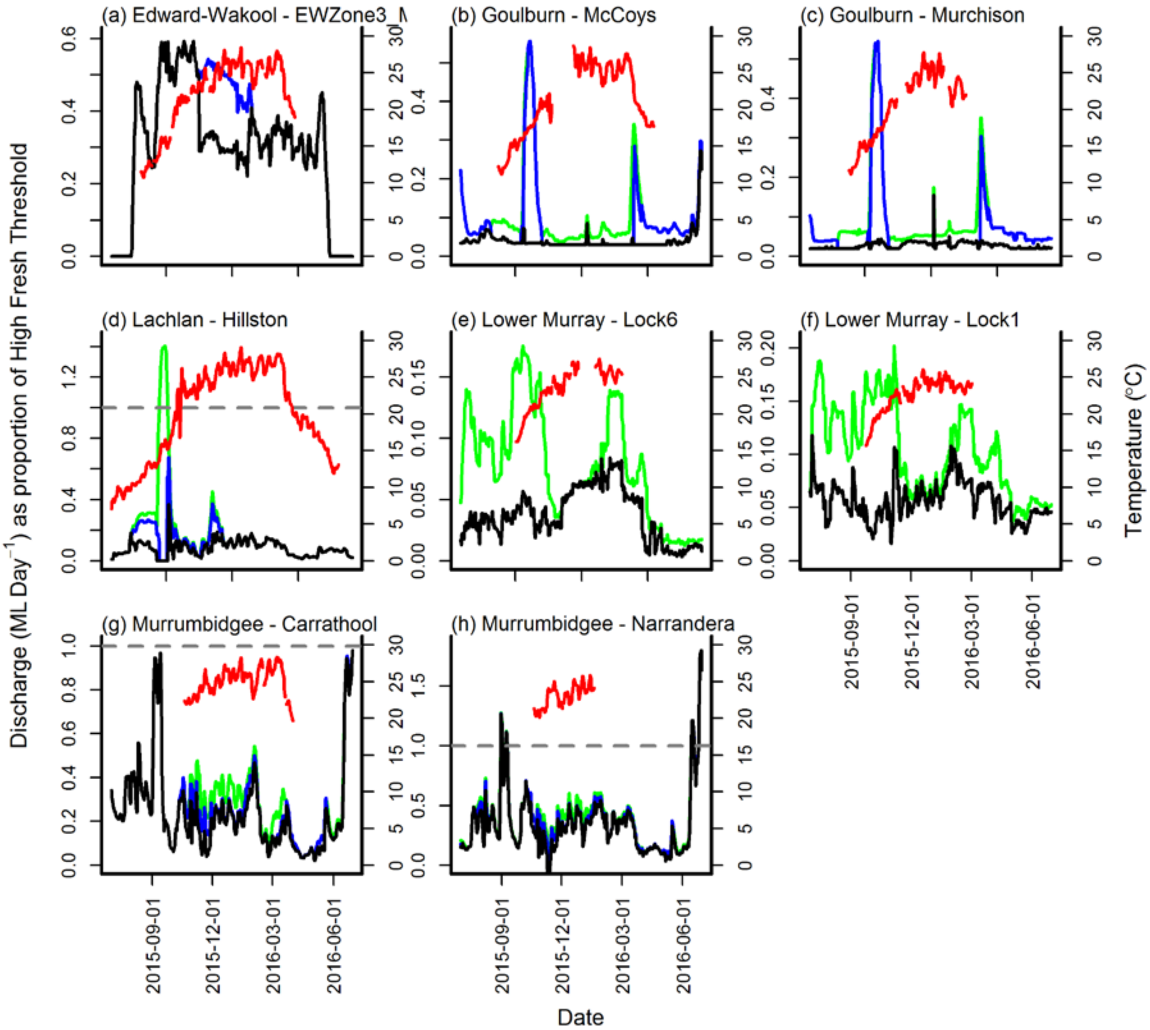

Figure 16. Hydrographs and temperature series during 2015–16 for the eight LTIM sites at which fish larvae were monitored for Basin-scale analysis. Discharge is presented as standardised discharge (see Section 2.2.2); dashed line indicates the high fresh threshold for that site. The black, blue and green lines indicate, respectively: background discharge (BG; discharge in the absence of any environmental water); background discharge + Commonwealth environmental water (BG + CEW); background discharge + all environmental water (BG + EW). Red line indicates temperature. In the Lower Murray, the contribution of CEW has been absorbed into EW, due to difficulties isolating the CEW component.

Progress towards determining how Commonwealth environmental water affects spawning

As we have highlighted in Section 1, undertaking a scientifically defensible evaluation of an intervention in a large complex experiment is a great challenge, and requires model development towards simulating the counterfactual. We are making good progress towards this goal and, to illustrate that progress, we provide an example evaluation of a Commonwealth environmental watering action in Figure 17.

Figure 17 presents the key steps involved in evaluating how a watering action has affected spawning probability; in this case, spawning probability of silver perch in the Murrumbidgee. First, we develop models of spawning probability, the fitted values of which are illustrated in Figure 17a and b. Second (Figure 17c), we decompose the hydrograph into its components, such that we may isolate the contribution of environmental water to the observed hydrology within a Selected Area over a defined period. Third, the different hydrological series (in this case, BG (black) and BG + EW (green)), and other important environmental covariates (temperature in this case) are passed to the spawning model to simulate spawning probability of spawning in the presence (green) and absence (black) of environmental water. In this instance, we can infer that, given the model and its assumptions, environmental water increased the probability of silver perch spawning in the Murrumbidgee for just under a month during the spawning season of 2014 (Figure 17d).

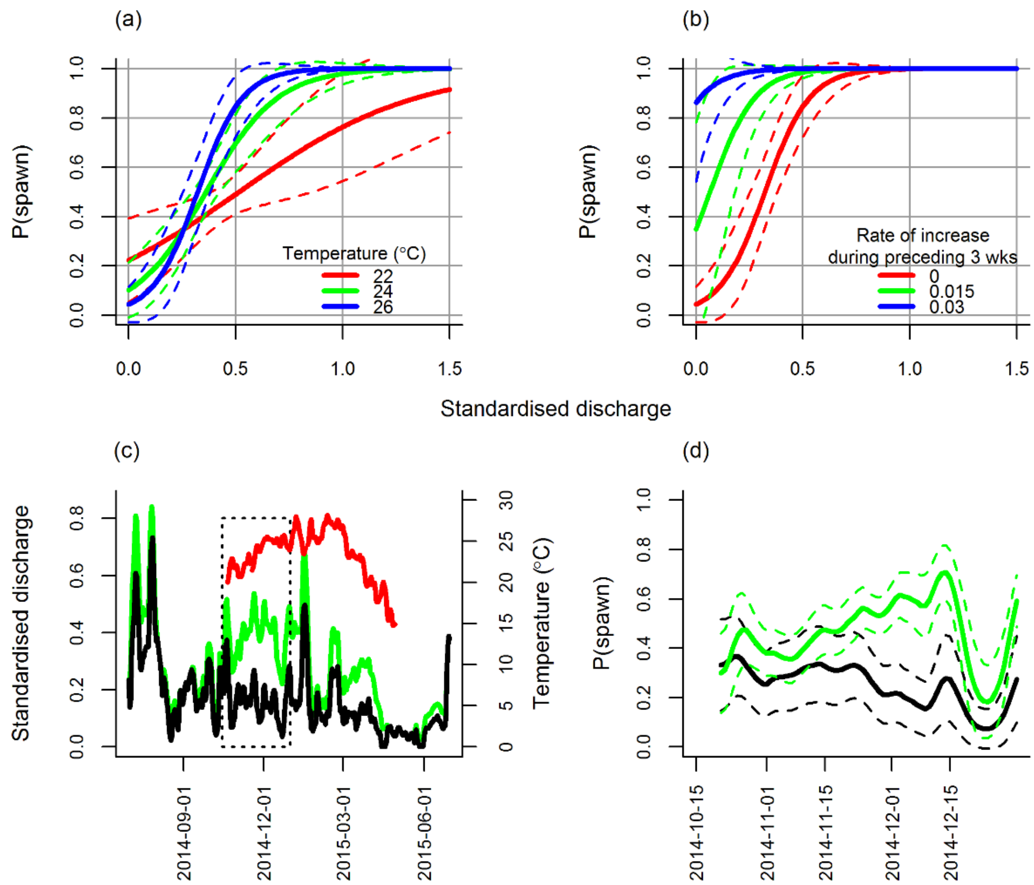

Figure 17. The key ingredients of evaluating the impacts of Commonwealth environmental water on the probability of silver perch spawning. In (a) and (b) the probability of silver perch spawning is presented as a function of mean standardised discharge, mean water temperature and mean rate of increase in standardised discharge over a 3-week time horizon prior to sampling. In (c), the hydrograph is decomposed into its components with the green series indicating the observed hydrological variability and the black being the modelled mean daily discharge in the absence of environmental water (in this case Commonwealth environmental water plus New South Wales water). The red series is mean daily temperature. The dashed box in (c) indicates the spawning period for which the counterfactual simulations are modelled in (d). In (d), we present modelled predicted probability (± SE) of silver perch spawning in the presence (green) and absence (black) of environmental water.

Note that we have not extended this modelling to undertake a full evaluation of Commonwealth environmental water's contribution to fish spawning across all Selected Areas. The primary reason for not doing this at this stage is that the models are not quite ready for a robust evaluation. Certain assumptions we have made when parameterising the models need to be carefully checked, and further data are required to reduce uncertainty. We will undertake a full evaluation of the contribution of Commonwealth environmental water to fish spawning in 2016-17.

3.4 Synthesis of outcomes within Selected Area reports 2015–16

Table 3 (at the end of Section 3) presents a summary of fish monitoring outcomes presented within the six LTIM Selected Area reports during 2015–16. We discuss noteworthy aspects of those outcomes below. Three types of watering actions were prominent during 2015–16: base flows, freshes and wetland inundations.

3.4.1 Base flows

Managed base flows may provide a critical contribution to meeting Basin Plan fish objectives. The base flows delivered within the Gwydir river system are a case in point. As shown in Figure 19 (see Section 4.2.1), Commonwealth environmental water can comprise the majority of total discharge within LTIM fish focal zones during dry periods. Within the Gwydir Selected Area there is good evidence that, without Commonwealth environmental water, key refuge pools supporting native fish biodiversity would have dried, water quality within those pools would have deteriorated, and longitudinal connectivity between those pools wold have ceased (Southwell *et al.* 2016). These flows have contributed to maintaining Gingham waterhole, within which olive perchlet (*Ambassis agassizii*), a threatened species, was recorded during 2015–16 LTIM monitoring.

Another good example of the value of managed base flows can be found in the Warrego system (CEWO 2016). Although the watering action associated with fish outcomes was listed as a 'fresh' (Table 3), the key hydrological outcomes for the fish community were essentially to: (a) promote longitudinal connectivity between the waterholes/refuges; and (b) enhance/maintain water quality within those waterholes. With respect to fish response, such hydrological outcomes are what we associated with base-flow delivery, so we cover fish outcomes from this action here, not under 'Freshes' below. During the 2015–16 delivery year, one of the key management actions was to open the gates at Boera Dam, allowing water to connect waterholes of the lower Warrego. It is clear that, without this action, waterholes would have not been connected and continued to dry. Following this watering action, strong recruitment of golden perch, bony herring and spangled perch (*Leiopotherapon unicolor*) was observed. Moreover, Hyrtl's tandan (*Neosilurus hyrtlii*), a relatively rare catfish, was recorded in the waterholes of the lower Warrego during 2015–16. The extent to which Commonwealth environmental water contributed to the observed recruitment and maintenance of rare fishes is currently unknown. However, given that environmental water is critical to the maintenance of connectivity and condition in this system, we may infer that without such flows, an important assemblage of self-recruiting, large-bodied native fishes would be threatened by drying.

Drawing such inferences within the Gwydir – and, to a lesser extent, the Warrego – were possible due to the strong hydrological modelling demonstrating that without managed flows, river segments would have ceased to flow entirely. Inferences concerning the ecological impacts of not delivering such flows could be strengthened by developing a quantitative understanding of how other factors, such as air temperature and duration of zero-flow events, affect water quality, waterhole morphology (e.g. depth, volume, etc.) and fish assemblages of refuge pools. Regardless, it is clear that river systems of the Basin characterised by low mean annual discharge may benefit immensely from managed base flows during dry climatic conditions.

3.4.2 Freshes

Within the Edward–Wakool river system, a fresh was delivered to the Yallakool Creek and the impacts on fish spawning, growth and recruitment were compared with those observed in a control system (Wakool Creek) that did not receive the fresh. The fresh had no detectable impact on fish spawning (with the exception of carp gudgeon), Murray cod recruitment or Murray cod growth

(Watts *et al.* 2016). Carp gudgeon spawning magnitude declined as a result of the fresh, which is concordant with our understanding of that species (Humphries *et al.* 1999; King *et al.* 2016), and concordant with our model of carp gudgeon spawning (M5; Section 3.3.6), which showed that high mean discharge reduces the probability of carp gudgeon spawning (Figure 14; Figure 15). Our understanding of how flows affect the recruitment and growth of Murray cod is extremely poor. It follows that we are not yet in a position to explain why Murray cod recruitment and growth appears insensitive to flow variability within the Edward–Wakool (Watts *et al.* 2016).

Within the Goulburn River, no spawning of golden or silver perch was detected during 2015–16. Hence, the fresh delivered within the Goulburn had no significant positive effects on spawning of golden or silver perch (Webb *et al.* 2016), despite positive effects of freshes on spawning in previous years. Webb *et al.* (2016) suggested the lack of a spawning response was due to the fresh being delivered too early in the spawning season, when temperatures were too low (~17 °C). This is a plausible explanation, although the Basin-scale spawning analysis did not identify temperature as being significantly correlated with spawning *within the spawning season*. It follows that there is currently much uncertainty around how flows and temperature interact to drive golden perch spawning. As suggested in Section 3.3.6, an 'adaptive monitoring' approach (Lindenmayer & Likens 2009, 2010) could be used to strategically assess monitoring approaches each year, towards fine-tuning sampling design to reduce specific sources of uncertainty.

In contrast with the spawning response within the Goulburn River, downstream movements of adult golden perch coincided with delivery of the fresh (Webb *et al.* 2016). The significance of such movements to processes that change population size (spawning, recruitment, survival) is poorly understood. However, given the timing of such movements broadly align with spawning events, one could suggest it is likely the movement is associated with spawning behaviour (Webb *et al.* 2016). However, the concomitant lack of detection of spawning itself further highlights the need to strengthen the monitoring of spawning in LTIM, such that we may better elucidate the significance of flow-induced movement to population growth/decline.

Results of the larval fish monitoring within the Lachlan river system add to the uncertainty around how flows affect spawning of fresh-cued spawners, particularly golden and silver perch. Within the Lachlan, Commonwealth environmental water was delivered as a fresh to induce golden and silver perch spawning, yet no golden perch nor silver perch spawning was detected (Dyer *et al.* 2016). Larval fish sampling intensity within the Lachlan was strengthened considerably during 2015–16 with NSW Fisheries supplementing the LTIM investment of five sampling events with a further three events (Dyer *et al.* 2016). Thus, in this case, low sampling effort is an unlikely explanation for the absence of spawning (a 'false negative'). Further, lack of a spawning response was unlikely due to low densities of adults in the Lachlan. Indeed, of the six Selected Areas using Category 1 LTIM methods (see Section 2.1), the Lachlan contains the second highest densities of adult golden perch (second to Lower Murray River; see Table 4 in Section 4.4). With respect to the hydrograph itself, Commonwealth environmental water – in conjunction with New South Wales water – resulted in a moderate–strong spring fresh that approximated the high fresh threshold for the Lachlan in September to early October, and was half that threshold at stages through to early December (Figure 16d). Thus, a qualitative appraisal of the hydrology of the lower Lachlan watering action yields little insight as to why it failed to induce a spawning response in golden and/or silver perch.

The absence of a spawning response of golden perch within the Lachlan during 2015–16 is difficult to explain when considering environmental factors and population state at short time scales, within the year of the flow delivery. However, if we expand the temporal scale at which we view the response, a possible explanation can be lost condition due to sustained low-flow conditions during 2014–15 and 2015–16, which may have resulted in reduced energetic investment by golden perch in reproductive tissue during 2016. This reduced investment may have, in turn, resulted in skipped spawning during spring 2016, irrespective of the presence/absence of a fresh. Our rationale underlying this hypothesis is explained below.

During the first 2 years of LTIM, the Basin experienced below average rainfall and runoff (www.bom.gov.au/water/nwa/). As we show below, condition of golden perch in several catchments declined during these dry years (see Section 4.3.2). In many fish species, loss of condition can lead to individuals reducing energetic investment in reproductive tissue – hence, lower spawning magnitude at the population level –and seasons where spawning is altogether skipped (Rideout *et al.* 2005; Jorgensen *et al.* 2006; Bunnell *et al.* 2007; Donelson *et al.* 2010; Pankhurst & Munday 2011). Research suggests that skipped spawning during prolonged sub-optimal conditions may be an adaptive trait that promotes survival of all stages over longer time periods – e.g. only spawn when larvae have best chance of spawning; don't allocate energy to reproductive tissue if it's going to lower your chance of making it through the next year (Jorgensen *et al.* 2006; Skjaeraasen *et al.* 2012). We have a poor understanding of the reproductive ecophysiology of Basin fishes, so we cannot be confident that lowered condition leads to skipped spawning in species like golden and silver perch. Nevertheless, research on other species shows that it is certainly a valid and interesting hypothesis explaining lack of spawning responses to freshes delivered during prolonged dry periods. As more data accrue within the LTIM Project, we will be able to test such hypotheses by determining the plausibility of models that include long-term antecedent hydrological conditions as predictors, as well as short-term hydrological variables.

The possibility that adult condition influences spawning responses represents the identification of another factor that may affect probability of spawning as a function of flow. Overall, there are now six factors that may affect spawning response to freshes (Table 2). These factors may interact and are likely to be not mutually exclusive.

Table 2. Summary of the factors currently considered as possible cues for spawning amongst flow-cued species such as golden perch and silver perch.

Factor	Description	Evidence
Temperature	Flows will not trigger spawning unless water is of an appropriate temperature	LTIM and literature
Rate of increase in discharge	Analysis of LTIM data reveals that rate of rise is associated with spawning	LTIM analysis
Adult condition	Evaluation of LTIM data and research on other species suggests adult condition may influence spawning behaviour	LTIM analysis and literature
Current velocity	Analysis of Goulburn R. spawning data indicates there is a relationship between spawning and maximum current velocity	Goulburn River, LTIM
Pre-conditioning fresh	Environmental flow management in the Goulburn R. was associated with spawning which was attributed to the allocation of water to a winter fresh that preceded the spawning fresh	Goulburn River, LTIM
Water source and chemical cues	Some species are known to respond to chemical cues in the water and these may be influenced by the water source.	Literature

The above discussion about how managed freshes affect spawning of fresh-cued spawners demonstrates a key point: although one may argue there is little uncertainty around how, say, golden perch spawn in response to flows within individual catchments (e.g. the Goulburn River), our ability to predict the spawning response of such species throughout the Basin remains lower than some might think. The Basin Plan has clear objectives concerning improving spawning of native fishes at the Basin scale, so there is a pressing need to ensure our tools for adaptively managing flows are not based on single catchments alone. This fact, coupled with the spatial uncertainty around how spawning is affected by hydrology, further underscores the importance of the Basin-scale objectives within the LTIM Project (see Section 1).

3.4.3 Wetland inundation

Wetland inundation within the Gwydir river system has had clear positive impacts on water quality within wetlands, as well as on lateral connectivity. Commonwealth environmental water contributed greatly to these lateral connectivity events. Fishes of high conservation concern, such as freshwater catfish (*Tandanus tandanus*), have been identified in some of the inundated wetlands, and thus Commonwealth environmental water is likely to be contributing to conservation outcomes for these species. Within wetlands of the Murrumbidgee river system that have received Commonwealth environmental water, native fish species richness increased during the first 2 years of LTIM.

3.5 Adaptive management

In light of our spawning analysis, we offer four recommendations:

1. Objectives underpinning watering actions to improve the state of fish populations should not be focused on single species within catchments. Our analysis shows that the spawning response of fishes to different hydrograph–temperature combinations may be species specific. It follows that aiming to optimise hydrograph–temperature scenarios to benefit a single species could: (a) reduce diversity in the long run; and (b) reduce the rate of learning about how species respond to different water regimes.
2. Rate of change in mean discharge over the 21-day period prior to sampling has a significant impact on the probability of spawning in silver perch, golden perch and Australian smelt. Notwithstanding the constraints on flow delivery, rates of increase in standardised discharge of ~3% day^{-1} (3% of the high fresh threshold each day, for 1–3 weeks) will increase the probability of spawning in these flow-pulse-sensitive spawners.
3. As part of the adaptive management process, adaptive learning will benefit from implementing some watering actions designed to help reduce uncertainty (e.g. around the influences of temperature) rather than just targeting an increasingly narrow time window thought to be 'optimal' for a particular process.
4. After 2 years of data collection, the spawning models show great promise. However, there is still considerable uncertainty in the model predictions. We will continue to work with CEWO and Selected Area teams to ensure sampling programs can reduce this uncertainty in future years as effectively and efficiently as possible.
5. The Basin Plan has clear objectives concerning improving spawning of native fishes at the Basin scale. Meeting this objective requires making effective watering action decisions within many and varied catchments of the Basin. LTIM Basin-scale analyses to date demonstrate that simple rules developed in a single catchment do not necessarily translate to multiple catchments. It follows that to make effective watering decisions we require either (a) good catchment-specific understanding of how fishes spawn in response to hydrology for the many catchments of the Basin, or (b) generalisable models, developed using data from multiple catchments, that capture the essential, general hydrological rules for inducing spawning. Strategy (a) is cost-prohibitive and is unlikely to ever eventuate. Strategy (b) is being undertaken by LTIM. The need to inform decisions at the Basin scale, coupled with the spatial uncertainty around how spawning is affected by hydrology, further underscores the importance of the Basin-scale objectives within the LTIM Project (see Section 1).

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 2015–16. Expected and observed ecological outcomes and influences were taken from the 2015–16 Selected Area annual reports (CEWO 2016; Dyer *et al.* 2016; Southwell *et al.* 2016; Wassens *et al.* 2016; Watts *et al.* 2016; Webb *et al.* 2016; Ye *et al.* 2017).

Water Action Reference	Surface water region/asset	Commonwealth environmental water volume (ML)	Dates	Flow component	Expected ecological outcome	Monitored site(s)	Observed ecological outcome	Influences
1516-EdWak-02	Yallakool River	13 004.1	04/09/15 – 30/01/16	Fresh and base flow	Provide areas of habitat for native fish, such as Murray cod, to move into and spawn, especially in areas where the flows will cover snags that are the preferred spawning and nesting sites of Murray cod. Maintain the growth and health of instream aquatic plants (such as common reed, pondweed and milfoil), that provide habitat for aquatic animals (like zooplankton and insects) which become food for small native fish, including gudgeons, smelt, hardyheads, as well as young cod and perch.	Numerous sites throughout Edward–Wakool Zones 1, 2 and 3.	It was hypothesised that larval abundance would be higher in Yallakool River, which received the bulk of environmental water. Data did not support this hypothesis. Larval abundance of all species showed no significant difference between Yallakool and Wakool rivers, with the exception of carp gudgeon, whose larvae were more abundant in the Wakool River, which did not receive environmental water and where discharge was much lower. No spawning or recruitment of golden or silver perch was observed. No significant impacts of the watering action on Murray cod growth or recruitment were observed. Although not listed as an expected outcome for 2015–16, extensive movement of golden	
1516-EdWak-01	Wakool River	1444.9	04/09/15 – 30/01/16	Fresh and base flow	As above, and improve knowledge of this part of the system by comparing the responses of Murray cod when environmental flows are provided to both the upper Wakool river and Yallakool creek systems over the same period of time.	Numerous sites throughout Edward–Wakool Zones 1, 2 and 3.		

Water Action Reference	Surface water region/asset	Commonwealth environmental water volume (ML)	Dates	Flow component	Expected ecological outcome	Monitored site(s)	Observed ecological outcome	Influences
							and silver perch was documented. When moving upstream into the environmental water experimental zones (Zones 1, 2 and 3, around fork of Yallakool and Wakool rivers), golden and silver perch displayed a tendency to move into the Wakool (low water delivery), not the Yallakool (recipient of the bulk of the water).	
1516-Gwyd-01	Gingham – Gwydir Wetlands	1350.00	09/01/16 – 11/02/16	Overbank – wetland inundation	Maintain water quality in wetlands. Support the longitudinal and lateral dispersal of native fishes.	Gwydir Wetlands: Eastern, Middle and Western dams. Gingham Wetlands: Bunnor Birdhide and Gingham Waterhole. Gwydir River: Allambie Bridge.	Maintenance and/or improved water quality in wetlands. Movement of small-bodied fish into wetlands and between waterholes. Also noteworthy was the recording of threatened/ endangered species: olive perchlet and freshwater catfish. Gingham Waterhole identified as a significant conservation unit within the Gwydir system, as it supports olive perchlet.	
1516-Gwyd-03	Gwydir – Mehi River (supplementary water)	964.00	09/11/15-11/11/15	Fresh	Maintain fish habitat and, in turn, maintain native fish diversity.	A total of 23 sites across the Gingham Watercourse, Gwydir River, Mehi River, Moomin Creek.	Although the state of the native fish community had declined since 2014–15, the authors of the Selected Area report suggested that this decline would have been worse without Commonwealth environmental water.	Drought conditions in the Gwydir system – watering actions aimed at maintaining

Water Action Reference	Surface water region/asset	Commonwealth environmental water volume (ML)	Dates	Flow component	Expected ecological outcome	Monitored site(s)	Observed ecological outcome	Influences
1516-Gwyd-04	Gwydir – Gwydir river system	2600	10/04/16 – 30/05/16	Base flow	Maintain fish habitat and, in turn, maintain native fish diversity.	A total of 23 sites across the Gingham Watercourse, Gwydir River, Mehi River, Moomin Creek.		populations in refuges.
1516-Lch-04	Lower Lachlan river channel	9378.5	11/11/15 – 15/12/15	Fresh	Support golden and/or silver perch spawning.	Category 1 sites within Zone 1.	No evidence for the watering action to have increased spawning of native fishes.	Very low larval fish sampling effort.
1516-Gbn-03	Goulburn – lower river channel	190 563.00	03/10/15 – 29/10/15	Fresh	Support spawning of native fish. Support dispersal of native fish.	Zones 1 and 2.	No spawning of golden or silver perch was detected during the spawning season of 2015. Downstream movements of golden perch coincided with flow releases, and may have been linked to spawning behaviour, but the dearth of evidence for spawning is a caveat to that interpretation.	Water temperature during this fresh was cooler (~17 °C) than in previous years, when water temperatures exceeded 20 °C.
1516-Gbn-02	Goulburn – lower river channel		09/07/15 – 02/10/15	Base flow	Support native fish condition.	Zone 1.	Not reported on at area scale.	
1516-Gbn-04	Goulburn – lower river channel		30/10/15 – 12/03/16	Base flow	Support native fish condition.	Zone 1.	Not reported on at area scale.	
1516-Gbn-06	Goulburn – lower river channel		06/04/16 – 30/06/16	Base flow	Support native fish condition.	Zone 1.	Not reported on at area scale.	

Water Action Reference	Surface water region/asset	Commonwealth environmental water volume (ML)	Dates	Flow component	Expected ecological outcome	Monitored site(s)	Observed ecological outcome	Influences
1516-SA-01	Lower Murray	556 000.00	01/07/15 – 30/11/15	Base flow	Increases in flow above regulated entitlement flows during spring–summer will promote the spawning and recruitment of golden and silver perch.	Gorge and floodplain zones.	Negligible spawning and recruitment of both golden and silver perch was observed in the Lower Murray during 2015–16. No significant change in the structure of the small-bodied fish assemblages, with opportunistic, low-flow species like carp gudgeon dominating. A significant change in the structure of the large-bodied fish assemblage compared with the previous year (2014–15), due to a decline in bony herring abundance, and an increase in the abundance of exotic goldfish.	Operation of Lake Victoria may have dampened the spring–summer flow pulses in the Lower Murray – pulses that may have induced spawning of golden and silver perch. Absence of favourable spring pulses in the Darling may have also contributed to low recruitment of golden and silver perch in the Lower Murray during 2015–16.
1516-SA-02	Lower Murray	242 000.00	01/12/15 – 01/07/16	Base flow		Gorge and floodplain zones.		
1516-Mbg-05	Murrumbidgee – Yanga National Park waterbird support	10 000.00	17/11/15 – 11/01/16	Wetland inundation	Support habitat requirements of native fish.	Mid-Murrumbidgee; Redbank; Nimmie-Caira.	Species richness was low in Redbank; only one of three spike rush wetlands receiving water in 2015–16.	

Water Action Reference	Surface water region/asset	Commonwealth environmental water volume (ML)	Dates	Flow component	Expected ecological outcome	Monitored site(s)	Observed ecological outcome	Influences
1516-Mbg-06	Murrumbidgee – Redbank	25 000.00	21/10/15 – 10/02/16	Wetland inundation	Support habitat requirements of native fish.		Overall, species richness has increased in the Nimmie-Caira since 2014–15. This increase in species richness may have been assisted by Commonwealth environmental water.	
1516-Mbg-03	Murrumbidgee – Nimmie-Caira	18 000.00	17/10/15 – 09/02/16	Wetland inundation	Support habitat requirements of native fish.		Native species richness increased in Waugorah Lagoon between 2014–15 and 2015–16. This increase in species richness may have been assisted by Commonwealth environmental water.	
1516-Mbg-02	Murrumbidgee – Yarradda Lagoon	1 394.30	02/09/15 – 20/12/15	Wetland inundation	Support habitat requirements of native fish.		Native species richness increased in Yarradda Lagoon between 2014–15 and 2015–16.	
1516-Warr-02	QLD Warrego – Lower Warrego River and fringing wetlands	859.29	17/01/16 – 19/01/16	Bankfull/ fresh	Support fish dispersal.	Five sites across Lower Warrego Basin.	Fish dispersal was not monitored but recruitment of native species (bony herring, golden perch, spangled perch) was observed.	Watering action listed as fresh but a base flow was essentially achieved, replenishing waterholes.

4 Long-term (1–5-year) outcomes

4.1 Highlights

- During periods of low runoff, Commonwealth environmental water has comprised the majority of total discharge through the LTIM fish focal zones at certain times of the year.
- There was a trend for areas with sustained low flows over the first 2 years of LTIM to exhibit reduced Murray cod recruitment and/or survival. More data and quantitative models will be required to confirm this trend, as well as identify watering strategies to best sustain populations across multiple years.
- At the Basin scale (across multiple Selected Areas), there was a trend for declining median condition of individuals within Murray cod and golden perch populations over the first 2 years of LTIM, particularly in areas experiencing sustained low flows. This does not imply Commonwealth environmental water isn't having a significant positive impact on fish condition, because it is possible that without water delivered in these areas, fish condition would have been worse. Again, predictive models will be critical to identifying the impact of Commonwealth environmental water on fish populations in the long term.
- We observed no decline in fish species richness, species evenness (a measure of how well represented (numerically) each species is in the local fish community) or nativeness within the Basin over the first 2 years of LTIM.
- Nativeness of the Basin's fish community was generally quite high, with the exception of the Goulburn River, where carp numerically dominate the large-bodied fraction of the community.

4.2 Environmental context – hydrology, temperature and river metabolism

4.2.1 Hydrology within LTIM fish focal zones

During the first 2 years of LTIM (2014–16), the Basin experienced below average rainfall and runoff (www.bom.gov.au/water/nwa/)rainfall and runoff are correlated to some degree, but often loosely due to the impact of soil moisture on mediating the fraction of rainfall leading to runoff). Throughout these 2 years, the contribution of Commonwealth environmental water – and environmental water in general – to discharge dynamics within LTIM fish focal zones was conspicuous (Figure 18). Indeed, at certain times of the year, environmental water may comprise the majority of total discharge through the fish focal zones during dry years (Figure 19). The time of year during which Commonwealth environmental water dominated discharge reflected ecological objectives within Selected Areas. For example, the late summer–autumn flows delivered within the Gwydir river system fish focal zone during both of these dry years reflect well the objective of maintaining water levels and water quality within refuge pools (Figure 19). The timing of these watering actions can be contrasted with those of the Murrumbidgee river system, Lachlan river system and Goulburn River Selected Areas, where freshes to induce spawning and movement have been objectives (Figure 19).

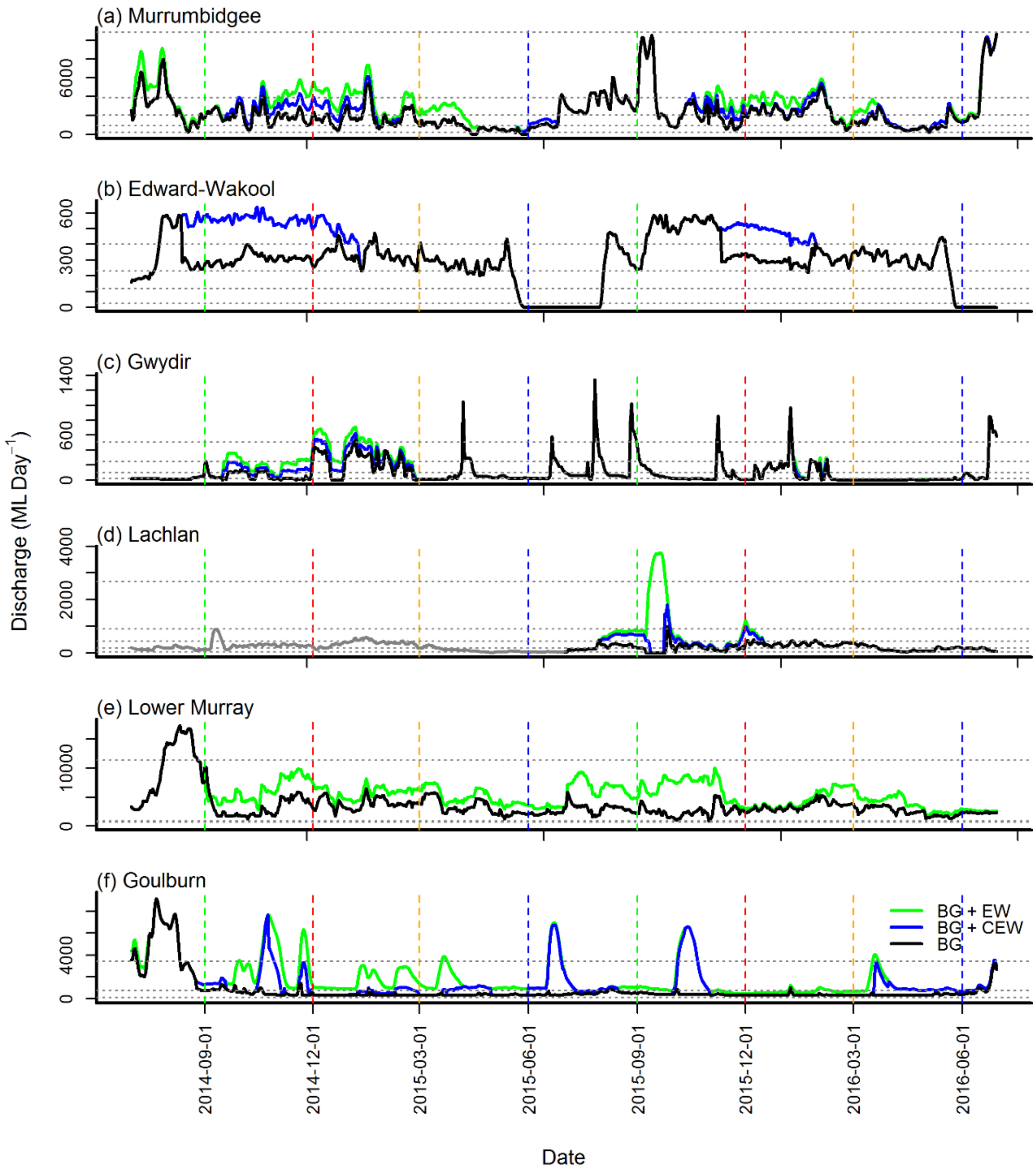

Figure 18. Long-term overview of the hydrological dynamics of the fish focal zones (see Methods Section 2.2.2) within the six LTIM Selected Areas with monitoring programs targeting fishes. Discharge within any given day has been decomposed into background flows (BG; black), background flows plus Commonwealth environmental water (BG + CEW; blue) and background flows plus all environmental water (BG + EW; green). The grey series within the Lachlan Selected Area is due to the discharge time series not having been decomposed into its components. Discharge time series are presented for the first 2 years of LTIM, providing a 'big-picture' overview of managed and background flows in the fish focal zones of LTIM. In the Lower Murray, the contribution of Commonwealth environmental water has been absorbed into EW, due to difficulties isolating the Commonwealth environmental water component. Horizontal dashed lines indicate flow thresholds. From the lowest threshold upwards, we have plotted: very low flows; low flows; low freshes; medium freshes; high freshes; bankfull (not all hydrographs contain all six thresholds, for example, the Goulburn plot contains (from the bottom up): very low flow, low flow and low fresh thresholds only).

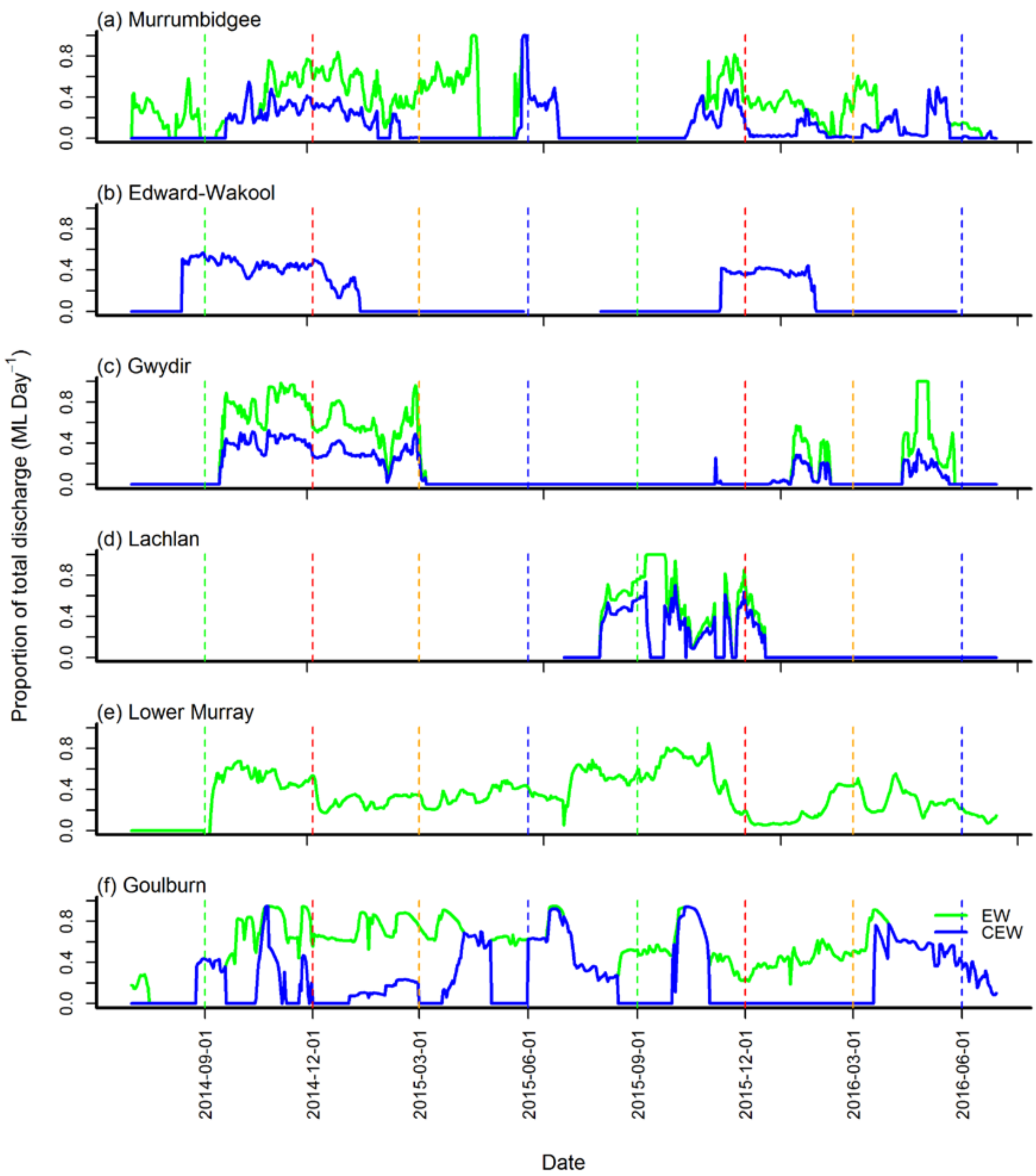

Figure 19. The proportion of total discharge in LTIM fish focal zones comprised of Commonwealth environmental water (CEW; blue) and all environmental water (EW; green).

4.2.2 Water temperature within LTIM fish focal zones

As ectotherms, the biochemical rates of fishes are dictated by water temperature (Fry 1971; Brett 1979; Brett & Groves 1979). It follows that water temperature exerts a significant influence on the fitness of individuals, which translates into an influence at the population level (Portner & Farrell 2008). Figure 20 presents the distributions of mean daily water temperature across the first 2 years of LTIM within each fish focal zone of Selected Areas. These data will assist in the interpretation of inter-annual variability in fish population states within Selected Areas. However, differences in temperature logging methods across standard areas confound comparisons across Selected Areas (note difference in the timing and duration of temperature logging in Figure 20).

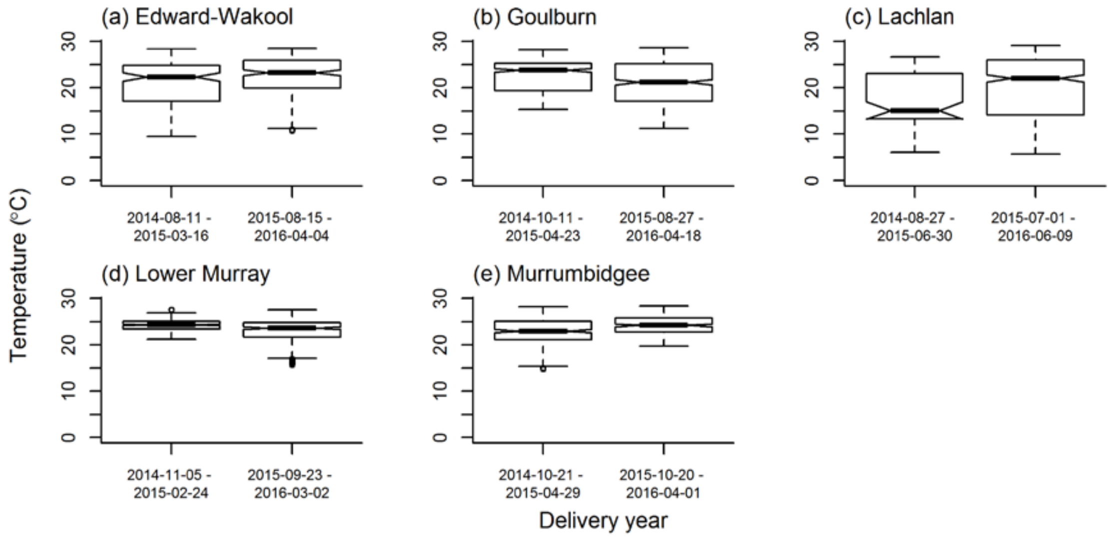

Figure 20. Boxplots of water temperatures within the fish focal zones of Selected Areas, during the first two years of LTIM. If notches in the sides of boxes do not overlap, a significant difference in median values can be reasonably inferred. Thick horizontal lines are medians; the box is defined by the 25th and 75th percentiles (lower and upper quartile, respectively); dashed lines have lengths of 1.5 times the spread (spread = difference between quartiles). Points outside this range are outliers.

4.2.3 River metabolism

Distributions of gross primary production (GPP) and ecosystem respiration (ER) vary substantially across years among and within Selected Areas (Figure 21 and Figure 22). A prevalent trend was that both GPP and ER were higher during the second year of LTIM (Figure 21 and Figure 22).

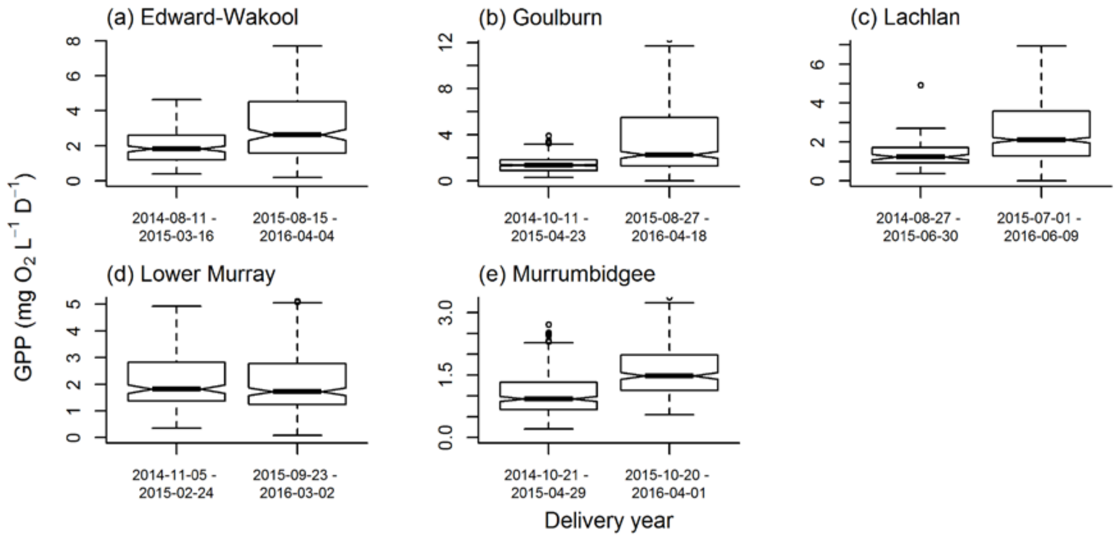

Figure 21. Boxplots of gross primary production (GPP) within the fish focal zones of Selected Areas, during the first 2 years of LTIM. If notches in the sides of boxes do not overlap, a significant difference in median values can be reasonably inferred. Thick horizontal lines are medians; the box is defined by the 25th and 75th percentiles (lower and upper quartile, respectively); dashed lines have lengths of 1.5 times the spread (spread = difference between quartiles). Points outside this range are outliers. These GPP data were characterised by

numerous extreme outliers, so they have been removed from the plot so as to not obfuscate visualisation of the bulk of the GPP distributions.

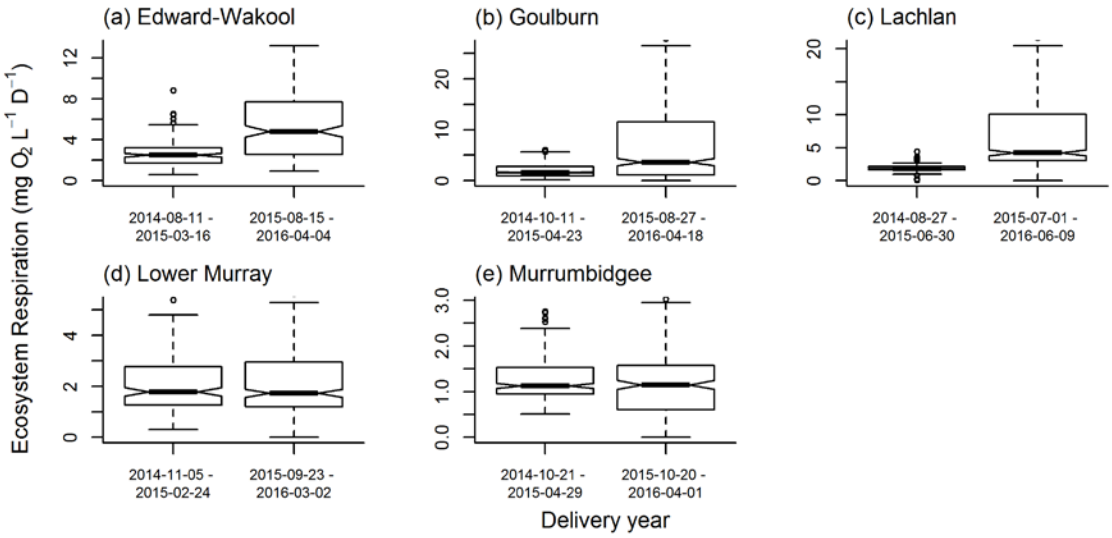

Figure 22. Boxplots of ecosystem respiration within the fish focal zones of Selected Areas, during the first 2 years of LTIM. If notches in the sides of boxes do not overlap, a significant difference in median values can be reasonably inferred. Thick horizontal lines are medians; the box is defined by the 25th and 75th percentiles (lower and upper quartile, respectively); dashed lines have lengths of 1.5 times the spread (spread = difference between quartiles). Points outside this range are outliers. These respiration data were characterised by numerous extreme outliers, so they have been removed from the plot so as to not obfuscate visualisation of the bulk of the ecosystem respiration distributions.

4.3 State of fish populations

4.3.1 Age structure

Bony herring

Bony herring is a focal species within five of the LTIM Selected Areas: Edward–Wakool river system, Gwydir river system, Lachlan river system, Lower Murray River and Murrumbidgee river system. We now have 2 years of population structure data for four of these five Selected Areas (bony herring was included as a focal species within the Lower Murray from 2015-2016). There appears to be little age-specific sampling bias for bony herring (Figure 23 – note the consistent reflected 'J-shape' across all areas, and most dashed lines have either 0 or negative slopes, typical of minimum-bias age-composition samples).

Within the Gwydir and Lachlan Selected Areas, recruitment (CPUE of 0+) of bony herring was significantly and substantially higher in 2016 than in 2015 (Figure 23b and c, respectively). In contrast, recruitment within the Edward–Wakool and Murrumbidgee was significantly lower in 2016 than in 2015 (Figure 23a and e, respectively).

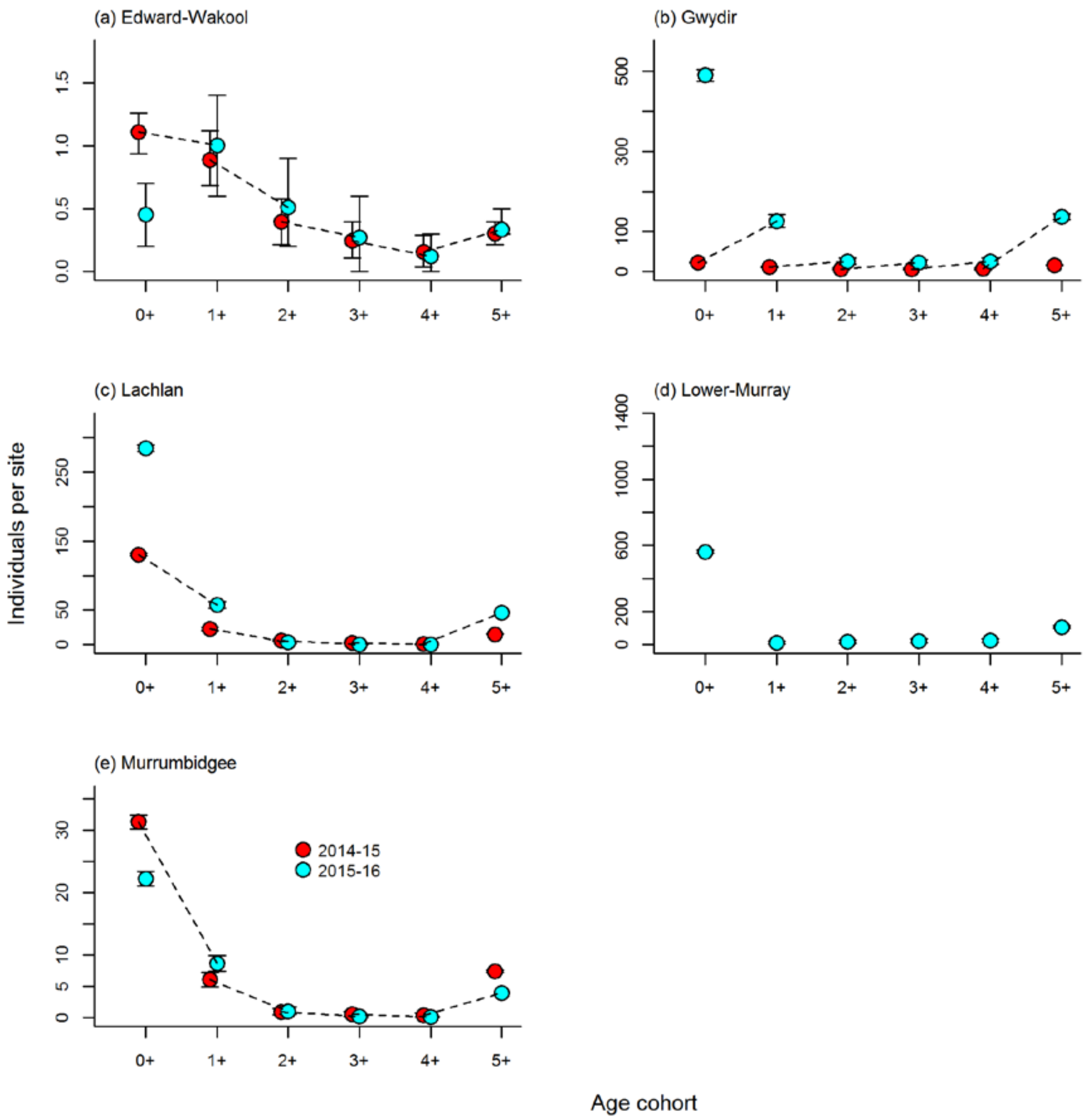

Figure 23. Mean (±95% CIs; vanishingly small for **bony herring** for most areas, given the very large length samples obtained by LTIM) catch per unit effort (CPUE; individuals per 2880 s of electrofishing) of six cohorts of bony herring, within four LTIM Selected Areas. Age composition has been inferred from length composition, using age–length keys (see Methods Section 2.2.3). Errors bars represent uncertainty associated with assigning ages to individuals based on their lengths. Age composition presented for the first 2 years of the LTIM Project (bony herring was not a target species within the Lower Murray during 2014–15). Dashed lines join CPUEs of age x–1 at year t–1 to age x at year t, and so give some visual indication of how a cohort increases or decreases across years (we have only been sampling for 2 years and so lines can only join two points).

In addition to increased recruitment within the Gwydir and Lachlan, there was also a significant increase in the abundance of 1+ and 5+ individuals within the Gwydir Selected Area (Figure 23b). We can offer two explanations for the increase in cohort abundance across years: (1) increased sampling efficiency in 2015 compared with 2014; and (2) immigration over the year in between the two samples. Examination of mean discharges within the Gwydir system at the time of annual censuses during 2015 and 2016 showed that discharge during the 2016 annual census was about 1/6 that of 2015. Moreover, there was a rapid decline in mean discharge over the months leading up to the 2016 annual census. Thus, it is likely that the increase in 1+ and 5+ bony herring during 2016 is merely due to a contraction of habitat volume and therefore an increase in density, but with no change in local population size overall.

We are not yet in a position to relate these ‘slow’ responses of fish population dynamics to flows. Doing so will require the development of quantitative models aimed at describing inter-annual changes in recruitment, to various characteristics of the flow regime over the year preceding each sample. Visual examination of the long-term hydrographs at each Selected Area (Figure 18) does not yield any obvious clues as to what characteristics of the observed flow regime—including water actions—might be driving these changes in bony herring population structure across years.

Golden perch

There was little change in golden perch population structure between the first and second years of LTIM monitoring (Figure 24). A notable feature of the golden perch population analysis was significantly higher golden perch recruitment within the Goulburn River in 2016 compared with 2015 (Figure 24b). We do not know the source of that recruitment at this stage. That is, the observed increase in 0+ abundance may indicate elevated natural recruitment in the Goulburn compared with 2015, or it may indicate increased stocking activity. We may have to negotiate annual stocking reports with state fishery authorities if we are to better understand factors driving recruitment of sportfish species (golden perch and cod).

Another notable feature of the golden perch populations was the general pattern of increasing abundance with age across all Selected Areas. There are two possible causes of this unusual population structure: (1) strongly episodic and relatively rare recruitment events; (2) sampling bias.

For certain species of fish, electrofishing efficiency may increase significantly and strongly with size of fish (e.g. Peterson et al. 2004). It is possible golden perch is such a species. Unfortunately, with respect to Australian freshwater fishes there has been little research on sampling bias and precision associated with different methodologies. Lyon et al. (2014) showed that electrofishing catch-probability of golden perch is low, with catch-probability increasing marginally with length. If we keep observing the same golden perch population structure across years, with no significant change in proportionate age composition, then it is likely electrofishing provides a biased age sample of golden perch.

Alternatively, we may observe such a population structure when population dynamics are characterised by strong, infrequent recruitment episodes. Selected Area experts have suggested that pulses of recruitment and juvenile survivorship have been detected using boat electrofishing, and that there is a good chance the pattern observed here does indeed reflect a strong recruitment event around 2010, during the last La Niña flood events. Given the Basin has just experienced another large-scale flood event (winter–spring 2016), LTIM annual censuses will provide further high-quality information concerning the nature of golden perch recruitment dynamics within the Basin. Reporting of the LTIM Fish Basin Matter during 2018–19 will capture recruitment pulses at the Basin scale, if they occur.

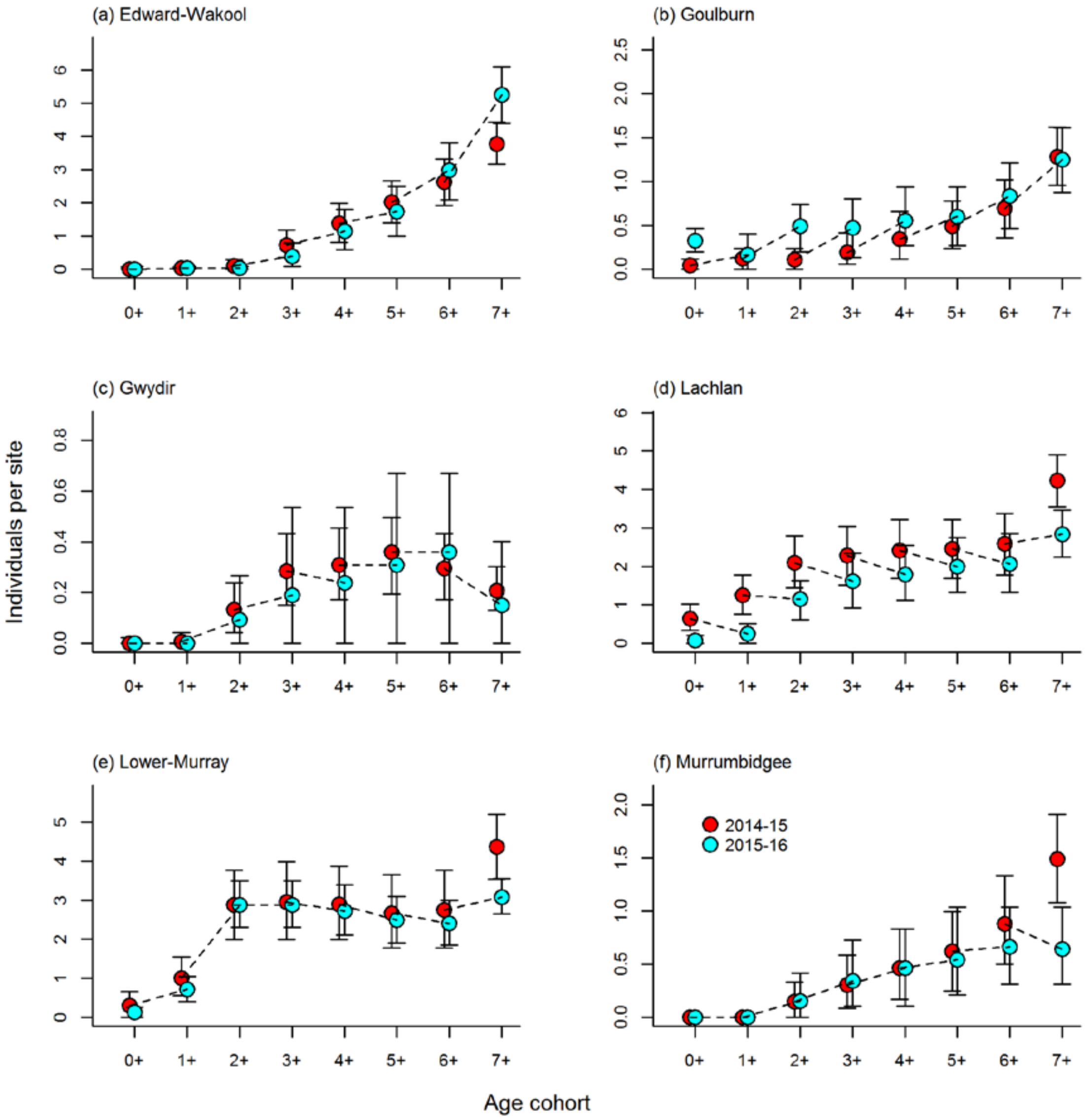

Figure 24. Mean (± 95% CIs) catch per unit effort (CPUE; individuals per 2880 s of electrofishing) of eight cohorts of **golden perch**, within six LTIM Selected Areas. Age composition has been inferred from length composition, using age–length keys (see Section 2.2.3). Errors bars represent uncertainty associated with assigning ages to individuals based on their lengths. Age composition presented for the first 2 years of the LTIM Project. Dashed lines join CPUEs of age x–1 at year t–1 to age x at year t, and so give some visual indication of how a cohort increases or decreases across years (we have only been sampling for 2 years and so lines can only join two points).

Murray cod

Recruitment of Murray cod (0+ abundance) during the 2015–16 period was variable in the Basin. Compared to the previous year (2014–15), recruitment was significantly higher within the Edward-Wakool, lower in the Goulburn, Lachlan and Murrumbidgee, with no significant change in the Gwydir and Lower Murray (Figure 25). As mentioned earlier, we will require quantitative models to decipher the influence of flows—and water actions, more specifically—on recruitment and survival of large-bodied fishes. We will begin development of such models during early 2018. At this stage, in the absence of such models, it may be worth noting that in the three areas where Murray cod 2015–16 recruitment was significantly lower than in 2014–15, mean discharge was also very low (around the

‘Low Flow’ and ‘Low Fresh’ Thresholds for extended periods of the year; Figure 18). Commonwealth environmental water was still delivered during this period (Figure 18; Figure 19). These observations raise at least two questions: (1) Murray cod have been considered a low-flow recruitment species, but only in the context of larval survival, not survival through to mid-late 0+ age (~5 – 10 cm total length); do sustained low flows over the summer-autumn period reduce recruitment through to late 0+? (2) If low flows reduce Murray cod recruitment, and given Commonwealth environmental water was delivered to reduce the impact of low flows during 2015–16, would Murray cod recruitment have been worse in the absence of these water actions? We aim to offer answers to such questions as annual reporting progresses and, in particular, as model development continues (when the data and models are available to predict the counterfactual scenario; Figure 2).

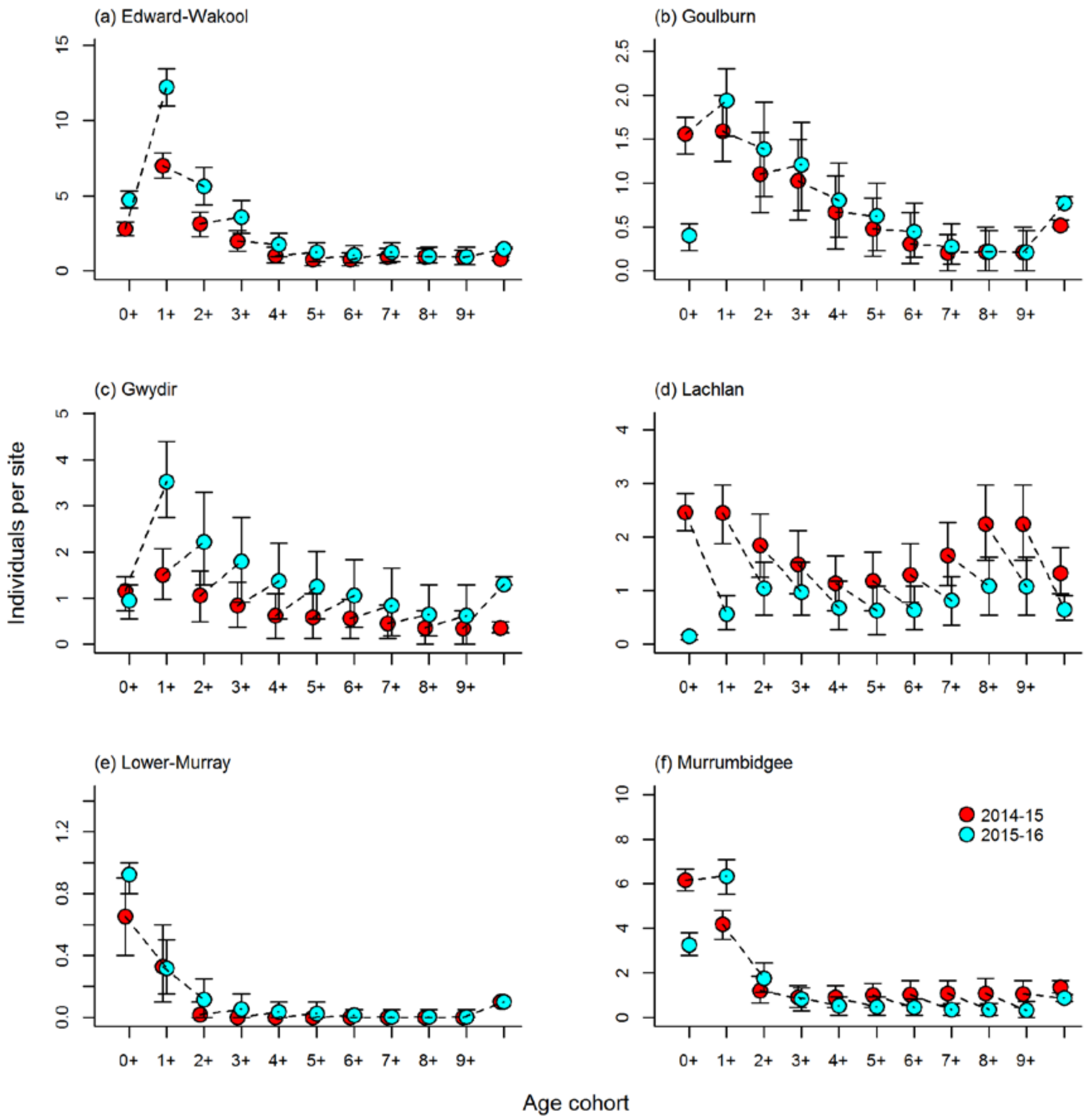

Figure 25. Mean (± 95% CIs) catch per unit effort (CPUE; individuals per 2880 s of electrofishing) of 11 cohorts of **Murray cod**, within six LTIM Selected Areas. Age composition has been inferred from length composition, using age–length keys (see Section 2.2.3). Errors bars represent uncertainty associated with assigning ages to individuals based on their lengths. Age composition presented for the first 2 years of the LTIM Project. Dashed lines join CPUEs of age x–1 at year t–1 to age x at year t, and so provide give some visual indication of how a cohort increases or decreases across years (we have only been sampling for 2 years and so lines can only join two points).

Recruitment aside, there is one other feature of the Murray cod analysis worth noting: Within the Lachlan there was general trend of low Murray cod survival across most age cohorts (Figure 25d). This observation again begs the question as to whether low flows negatively impact Murray cod survival rates, given the sustained low flows in the Lachlan (Figure 18). Although we do not yet have the models to answer these questions, very basic structural analysis has raised an interesting hypothesis to test.

4.3.2 Condition

With the exception of the Gwydir river system, bony herring condition did not appear to change significantly between 2014–15 and 2015–16 (Figure 26). A significant increase in bony herring median condition was observed within the Gwydir (Figure 26b). Coupled with the observation of increased abundance of adults within the Gwydir focal zone, it is possible that bony herring habitat improved within the Gwydir during 2016. The extent to which this increase in bony herring condition is due to flows – either natural or managed – is currently unknown.

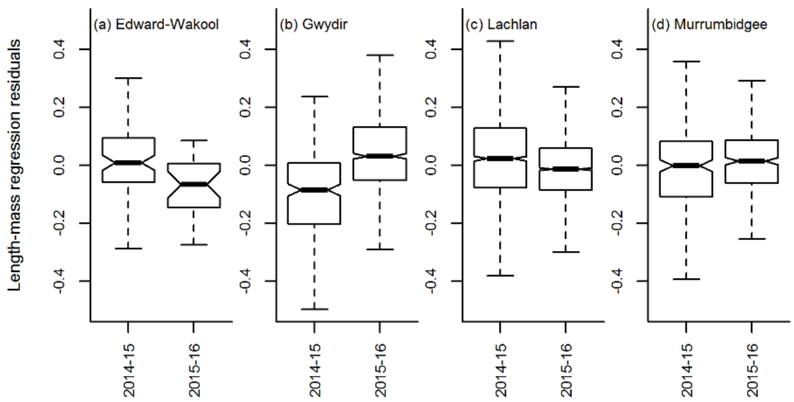

Figure 26. Variation in relative **bony herring condition** over years. Boxplots of year-specific residuals around a global regression of *ln* mass on *ln* length, within each Selected Area. Positive and negative values may be interpreted as 'above average' and 'below average' condition for that Selected Area, respectively. If notches of boxes do not overlap, a significant difference in median condition among years may be inferred. The bony herring is a target species at five Selected Areas. Only four are plotted here as it only became a target species within the Lower Murray from 2015–16. Thick horizontal lines are medians; the box is defined by the 25th and 75th percentiles (lower and upper quartile, respectively); dashed lines have lengths of 1.5 times the spread (spread = difference between quartiles). Points outside this range are outliers.

With respect to golden perch and Murray cod, mean condition of individuals in the population tended to decline between 2014–15 and 2015–16 (observed at five out of six Selected Areas for both species; Figure 27 and Figure 28). However, this trend was subtle. Indeed, for golden perch, decline in median condition was only significant in the Lachlan (Figure 27d), while for Murray cod, statistically significant decline was observed within the Edward–Wakool, Lachlan and Murrumbidgee (Figure 28a, d and f, respectively). At this stage, little can be inferred from this type of qualitative analysis concerning the role of flow variability and Commonwealth environment water in driving mean condition of fish populations. For example, this trend for declining condition in Murray cod and golden perch is occurring during a period of sustained low flows in many catchments of the Basin (2015–16). This does not mean Commonwealth environmental water isn't having positive impacts on fish condition, because it is possible condition would have been worse in the absence of Commonwealth watering actions.

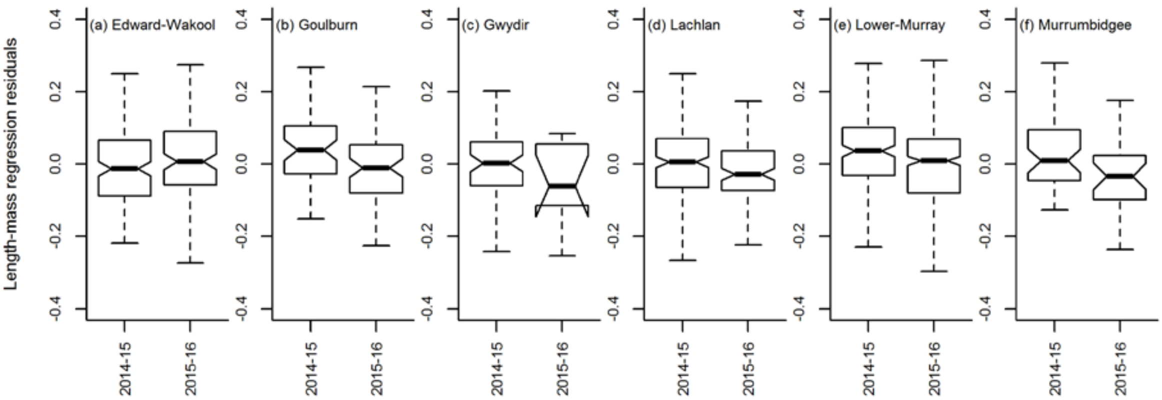

Figure 27. Variation in relative **golden perch condition** over years. Boxplots of year-specific residuals around a global regression of *ln* mass on *ln* length, within each Selected Area. Positive and negative values may be interpreted as 'above average' and 'below average' condition for that Selected Area, respectively. If notches of boxes do not overlap, a significant difference in median condition among years may be inferred. Thick horizontal lines are medians; the box is defined by the 25th and 75th percentiles (lower and upper quartile, respectively); dashed lines have lengths of 1.5 times the spread (spread = difference between quartiles). Points outside this range are outliers.

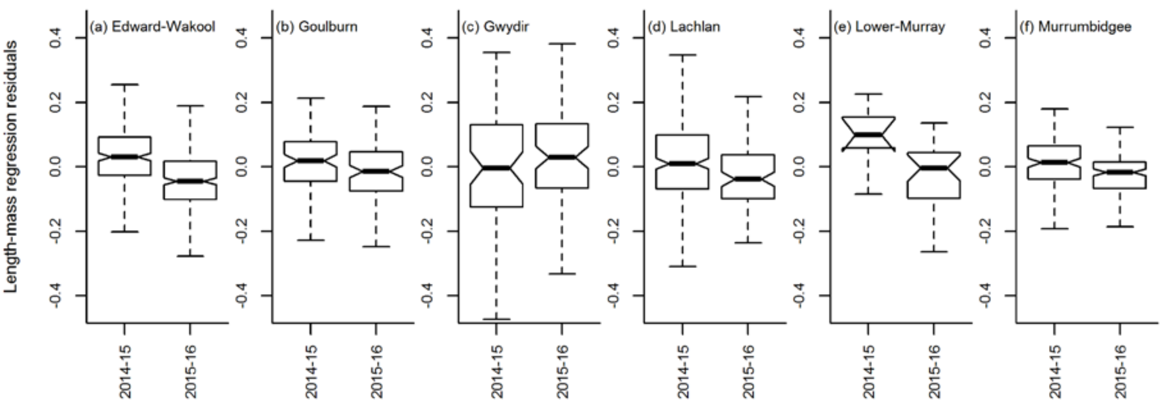

Figure 28. Variation in relative **Murray cod condition** over years. Boxplots of year-specific residuals around a global regression of *ln* mass on *ln* length, within each Selected Area. Positive and negative values may be interpreted as 'above average' and 'below average' condition for that Selected Area, respectively. If notches of boxes do not overlap, a significant difference in median condition among years may be inferred. Thick horizontal lines are medians; the box is defined by the 25th and 75th percentiles (lower and upper quartile, respectively); dashed lines have lengths of 1.5 times the spread (spread = difference between quartiles). Points outside this range are outliers.

4.4 Variation in the composition of fish assemblages

The structure of local fish communities within all six Selected Areas showed very little change across the first 2 years of LTIM. There was no significant change in the species richness (Figure 29a), species evenness (Figure 29b) or nativeness (Figure 29c) of the fish community within each area. Nativeness of the fish community was generally quite high, with the exception of the Goulburn River (Figure 29c), where carp numerically dominate the large-bodied fraction of the community (Table 4).

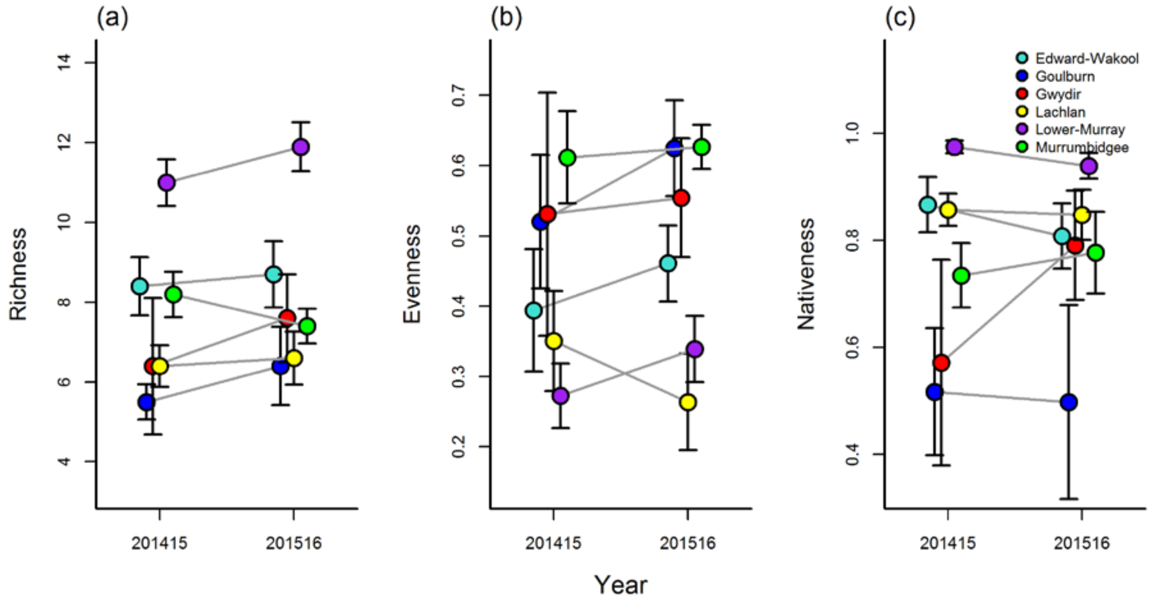

Figure 29. Mean (± 95% CIs) species richness (a), evenness (b) and 'nativeness' (c) of fish assemblages within each of six LTIM Selected Areas over the first 2 years of the LTIM Project. Means calculated across 'range-standardised' catch per unit effort (CPUE), where the range standardisation is conducted within only two groups: large-bodied species; and small-bodied species (see Methods).

The non-metric multidimensional scaling plot clearly shows there have been no significant changes in the structure of the Basin's fish community composition between 2014–15 and 2015–16 (Figure 30). This is also clearly reflected in Table 4, where the only species that exhibited significant changes in abundance across years were:

- carp gudgeon in the Murrumbidgee (increase)
- Murray cod in the Edward–Wakool (increase)
- rainbowfish (*Melanotaenia fluviatilis*) in the Gwydir (increase) and Murrumbidgee (decrease)
- bony herring in the lower Murray (decrease).

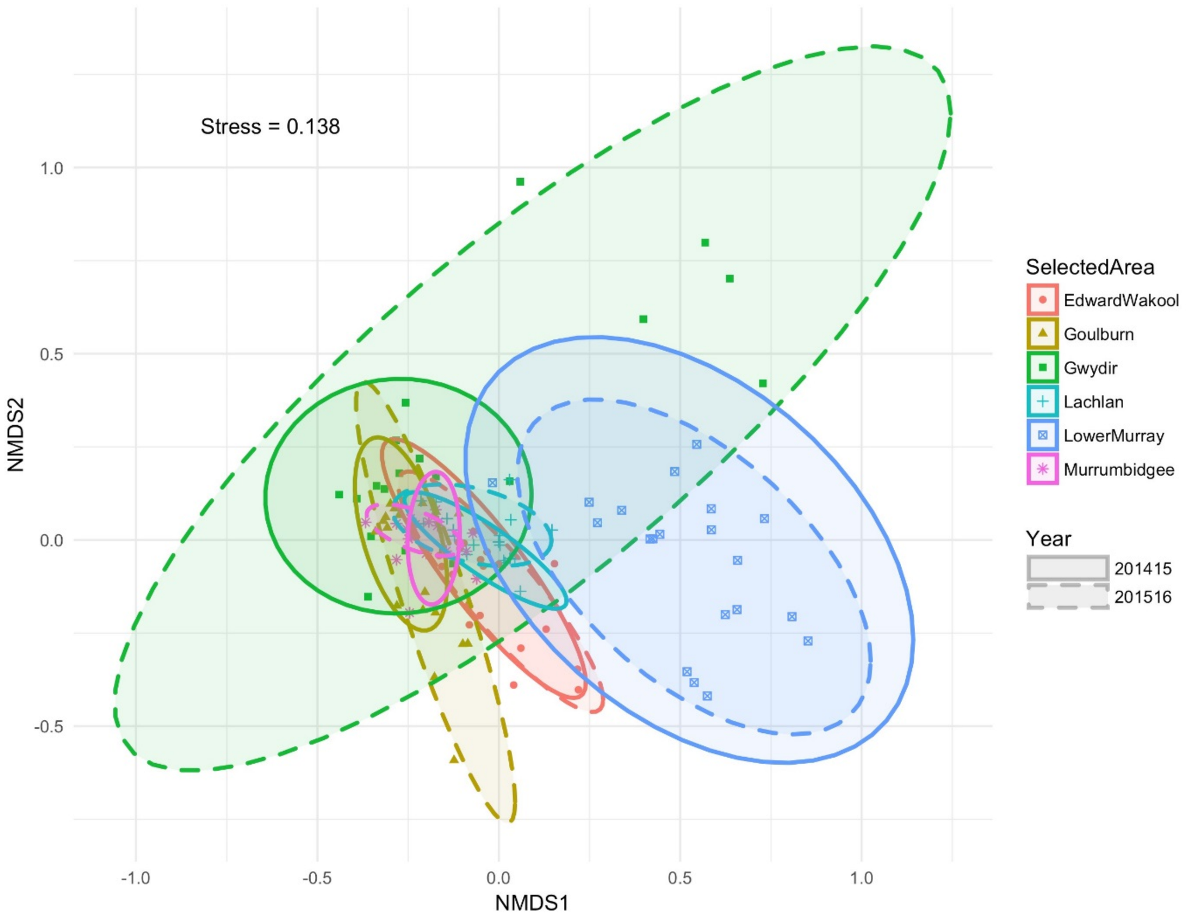

Figure 30. Non-metric multidimensional scaling (NMDS) plot of community composition differences among Selected Areas and between the first 2 years of LTIM. 95% confidence ellipses are presented.

Table 4. Mean catch per unit effort (CPUE, 95% CI magnitude) of all fishes captured by LTIM monitoring during the first two years of the program. CPUE units for large-bodied species are mean number of individuals per LTIM site hence per 2880 seconds of electrofishing 'on-time'. CPUE units for small-bodied species are number of individuals per fyke net per hour. Grey cells indicate a significant change in CPUE among years.

Year	Selected Area	*C. s. fulvus* Hardyhead	*C. carpio* Common carp	*Hypseleotris* Carp gudgeon	*M. peelii* Murray cod	*M. ambigua* Golden perch	*M. fluviatilis* Rainbowfish	*N. erebi* Bony herring	*R. semoni* Smelt	*C. auratus* Goldfish
2014–15	Edward-Wakool	0.031, 0.009	16.8, 1.8	2.086, 0.534	21, 2.436	10.7, 1.491	0.082, 0.024	3.1, 1.683	0.001, 0.001	2.1, 0.64
2015–16		0.018, 0.008	17.6, 0.562	1.234, 0.197	34.824, 2.325	11.6, 0.897	0.04, 0.011	2.7, 1.146	0.001, 0.001	3.8, 1.245
2014–15	Goulburn	0, 0	10.7, 1.62	0.011, 0.005	7.9, 2.014	3.299, 0.615	0.004, 0.001	0, 0	0.001, 0	0.8, 0.359
2015–16		0, 0	26.398, 9.139	0.025, 0.006	8.297, 1.932	4.709, 1.05	0.006, 0.002	0.302, 0.154	0, 0	2.2, 2.091
2014–15	Gwydir	0.072, 0.056	29.319, 10.298	0.936, 0.898	7.801, 2.914	1.6, 0.921	0.127, 0.069	71.026, 30.192	0.005, 0.002	4.8, 4.8
2015–16		0.688, 0.515	40.468, 18.624	2.919, 1.728	15.558, 6.867	1.34, 0.851	1.036, 0.317	826.351, 607.292	0.042, 0.036	12.587, 12.587
2014–15	Lachlan	0, 0	23.749, 4.981	0.028, 0.008	19.3, 3.29	18.011, 3.032	0, 0	177.279, 18.221	0, 0	1.1, 0.504
2015–16		0.001, 0.001	17.144, 2.794	0.105, 0.064	8.3, 1.438	11.8, 1.679	0, 0	392.548, 186.247	0, 0	2.2, 1.781
2014–15	Lower Murray	0.209, 0.109	12.6, 2.088	9.836, 3.133	1.1, 0.233	19.8, 2.577	0.187, 0.051	1597.4, 195.529	0.042, 0.032	1.8, 0.929
2015–16		0.337, 0.141	24.6, 2.701	10.425, 1.775	1.6, 0.34	17.3, 1.647	0.445, 0.156	742.7, 129.703	0.007, 0.004	11.8, 3.069
2014–15	Murrumbidgee	0.001, 0.001	11.2, 1.489	0.095, 0.013	19.892, 3.416	3.9, 0.722	0.186, 0.033	46.643, 6.953	0.013, 0.008	1.1, 0.407
2015–16		0, 0	6.3, 1.075	0.365, 0.096	15.5, 2.104	2.8, 0.611	0.071, 0.01	36, 3.804	0.002, 0.002	0.3, 0.153

Table 4 continued.

Year	Selected Area	*G. holbrooki* Mosquitofish	*B. bidyanus* Silver perch	*P. grandiceps* Flathead gudgeon	*M. macquariensis* Trout cod	*L. unicolor* Spangled perch	*T. tandanus* Freshwater catfish	*P. macrostomus* Dwarf flathead gudgeon	*P. fluviatilis* European perch/redfin
2014–15	Edward-Wakool	0.084, 0.046	0.5, 0.269	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0
2015–16		0.192, 0.112	0.5, 0.224	0.002, 0.001	0, 0	0, 0	0, 0	0, 0	0, 0
2014–15	Goulburn	0, 0	0.2, 0.133	0, 0	0.1, 0.1	0, 0	0, 0	0, 0	0, 0
2015–16		0, 0	0.504, 0.168	0, 0	0.4, 0.221	0, 0	0, 0	0, 0	0, 0
2014–15	Gwydir	0.028, 0.025	0, 0	0, 0	0, 0	11.779, 3.934	0, 0	0, 0	0, 0
2015–16		0.641, 0.442	0, 0	0, 0	0, 0	14.999, 7.529	0.766, 0.457	0, 0	0, 0
2014–15	Lachlan	0.096, 0.033	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0
2015–16		0.304, 0.099	0, 0	0.005, 0.003	0, 0	0, 0	0, 0	0, 0	0, 0
2014–15	Lower Murray	0.63, 0.247	0.4, 0.221	0.012, 0.009	0, 0	0, 0	0.6, 0.306	0.045, 0.015	0.1, 0.1
2015–16		0.718, 0.154	0.5, 0.224	0.024, 0.008	0, 0	0, 0	0.7, 0.26	0.056, 0.02	0, 0
2014–15	Murrumbidgee	0.204, 0.029	0.1, 0.1	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0

Note: species names are (left to right, top to bottom) *Craterocephalus stercusmuscarum fulvus; Cyprinus carpio; Hypseleotris* spp.; *Maccullochella peelii; Macquaria ambigua; Melanotaenia fluviatilis; Nematalosa erebi; Retropinna semoni; Carassius auratus; Gambusia holbrooki; Bidyanus bidyanus; Philypnodon grandiceps; Maccullochella macquariensis; Tandanus tandanus; Philypnodon macrostomus; Perca fluviatilis.*

4.5 Adaptive management

It is difficult to offer flow management suggestions to promote the long-term resilience of the Basin's native fishes at this early stage of LTIM; Basin-scale inferences from the first 2 years of data are still characterised by much uncertainty. As more data come to hand, and as models of long-term responses to flows are developed, suggestions towards enhancing the management and monitoring of the Basin's fishes will also improve. This year's Basin Matter analysis has raised an important issue that we briefly discuss here; more as 'food for thought' at this stage, rather than an explicit recommendation.

The first 2 years of LTIM have been characterised by low flows in many parts of the Basin (www.bom.gov.au/water/nwa/; noting this report covers data collected before the large-scale floods of winter–spring 2016). We have presented some evidence that these extended low-flow periods may erode condition and survival of Murray cod and golden perch populations. Suppose the models we develop over the next couple of years add some confirmation that multiyear low-flow periods erode the condition, recruitment and survival of large-bodied native fish populations. If this was the case, then the question arises: what types of watering actions during low-flow periods yield the greatest *long-term* (thinking beyond that watering year) outcomes for large-bodied native fishes? During the first 2 years of LTIM, freshes have been delivered to promote spawning (e.g. in the Lachlan) but, given the prevailing conditions at the time, perhaps those quantities of water may be better used to maintain flows above the low-flow threshold throughout summer; maintaining condition and survival rates of populations. Perhaps freshes are best delivered during years when we do not expect particularly dry summer–autumn periods.

Successful adaptive management of the Basin's flows will require making watering decisions in the short term in light of historical and projected future hydrological and climatic conditions. Current watering strategies within the Basin already incorporate this principle into watering decisions at multiples scales (MDBA 2014). However, a challenge to putting this principle into practice is the dearth of models that enable: (a) defensible inferences concerning flow impacts on indicators at multiple scales of space and time; and (b) forecasts of outcomes given possible delivery scenarios into the future. The Fish Basin Matter aims to develop tools for tackling this challenge during the first 5 years of LTIM.

5 Contribution to achievement of Basin Plan objectives

Within certain Selected Areas, the geomorphological and hydrological conditions enable us to infer impacts of managed water delivery relatively well. The Gwydir river system is a good example. In 2015–16, Commonwealth environmental water comprised the majority of discharge through river segments during critically dry periods. These watering actions contributed significantly to Basin Plan objectives of maintaining fish diversity and promoting dispersal of native fishes. In other areas, deciphering the impact of watering actions on Basin Plan fish objectives is not straightforward. Watering actions (freshes) in the Goulburn River promoted dispersal of native fish during 2015–16. The Fish Basin Matter is not yet in a position to provide robust reporting on the contribution of Commonwealth environmental water to the Basin Plan objectives of recruitment and survival. Importantly, however, the LTIM data are of high quality and, coupled with encouraging progress in model development (reported herein for spawning), assures strong capacity for reporting on outcomes from specific watering actions at multiple spatiotemporal scales from 2018 onwards.

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Annex A. 2015–16 Commonwealth environmental watering actions for fishes

Table A1. Watering actions that included Commonwealth environmental water in 2015–16. Note that many of these actions were implemented in conjunction with other environmental water (The Living Murray, state environmental water) but only the Commonwealth environmental water component is shown here.

Water Action Reference	Surface water region/asset	Commonwealth environmental water volume (ML)	Dates	Flow component	Primary (P), secondary (S) or unassigned (X) expected outcome	Expected ecological outcome
1516-Lch-04	Lower Lachlan river channel	9378.50	11/11/15 – 15/12/15	Fresh	P	(1) Support golden and/or silver perch spawning. (2) Support golden and/or silver perch movement.
1516-BrdR-01	QLD Border Rivers – Severn River (QLD)	22.22	31/01/16 – 01/02/16	Base flow	P	(1) Support movement of golden perch, silver perch, Murray cod and freshwater catfish.
1516-BrdR-02	QLD Border Rivers – Dumaresq–Macintyre River and fringing wetlands	409.30	26/07/15 – 07/08/15	Fresh	P	(1) Support movement of golden perch, silver perch, Murray cod and freshwater catfish.
1516-BrdR-03	QLD Border Rivers – Dumaresq–Macintyre River and fringing wetlands	234.90	26/08/15	Fresh	P	(1) Support movement of golden perch, silver perch, Murray cod and freshwater catfish.
1516-BrdR-05	QLD Border Rivers – Dumaresq–Macintyre River and fringing wetlands	243.50	07/11/15	Fresh	P	(1) Support movement of golden perch, silver perch, Murray cod and freshwater catfish.
1516-BrdR-04	QLD Border Rivers – Dumaresq–Macintyre River and fringing wetlands	137.10	01/02/16	Fresh	P	(1) Support movement of golden perch, silver perch, Murray cod and freshwater catfish.
1516-Moon-01	QLD Moonie – Lower Moonie River and fringing wetlands	200.98	28/08/15 – 02/09/15	Fresh	S	(1) Support dispersal of fish. (2) Refresh refuge waterholes.
1516-CndBal-01	QLD Condamine-Balonne – Nebine Creek	997.78	23/06/15 – 27/06/15	Fresh	S	(1) Refresh refuge waterholes.
1516-CndBal-02	QLD Condamine-Balonne – Lower Balonne floodplain system	9454.90	09/02/16 – 16/02/16	Fresh	S	(1) Support dispersal of fish. (2) Support spawning of fish.
1516-Warr-02	QLD Warrego – Lower Warrego River and fringing wetlands	859.29	17/01/16 – 19/01/16	Bankfull/ fresh	P	(1) Support fish dispersal.
1516-Mbg-06	Murrumbidgee – Redbank	25 000.00	21/10/15 – 10/02/16	Wetland inundation	P	(1) Support habitat of native fish.
1516-Mbg-05	Murrumbidgee – Yanga National Park waterbird support	10 000.00	17/11/15 – 11/01/16	Wetland inundation	S	(1) Support habitat of native fish.

Water Action Reference	Surface water region/asset	Commonwealth environmental water volume (ML)	Dates	Flow component	Primary (P), secondary (S) or unassigned (X) expected outcome	Expected ecological outcome
1516-Mbg-03	Murrumbidgee – Nimmie-Caira	18 000.00	17/10/15 – 09/02/16	Wetland inundation	P	(1) Support habitat of native fish.
1516-Mbg-01	Murrumbidgee – Hobblers Lake – Penarie Creek	5000.00	08/03/16 – 29/3/16	Fresh	S	(1) Support habitat of native fish.
1516-Mbg-02	Murrumbidgee – Yarradda Lagoon	1394.30	02/09/15 – 20/12/15	Wetland inundation	P	(1) Support habitat of native fish.
1516-Mbg-13	Murrumbidgee – Yanco Creek wetland inundation	18 263.00	21/07/15 – 13/08/15	Wetland inundation	S	(1) Support habitat of native fish
1516-Mbg-04	Murrumbidgee – Yanco Creek trout cod support flow	8075.00	15/10/15 – 11/11/15	Fresh	P	(1) Support dispersal of fish, esp. trout cod. (2) Support spawning of native fish, esp. trout cod.
1516-EdWak-02	Edward–Wakool – Upper Wakool River	1444.90	04/09/15 – 30/01/16	Base flow and fresh	P	(1) Compare spawning response of cod to that of Yallakool (1516-EdWak-01).
1516-EdWak-01	Edward–Wakool - Yallakool Creek	13 004.10	04/09/15 – 30/01/16	Base flow and fresh	P	(1) Compare spawning response of cod to that of Wakool (1516-EdWak-02).
1516-Gbn-02	Goulburn – lower river channel	190 563.00	09/07/15 – 02/10/15	Base flow	P	(1) Support condition of native fish.
1516-Gbn-03	Goulburn – lower river channel		03/10/15 – 29/10/15	Fresh	S	(1) Support spawning of native fish. (2) Support dispersal of native fish.
1516-Gbn-04	Goulburn – lower river channel		30/10/15 – 12/03/16	Base flow	P	(1) Support condition of native fish.
1516-Gbn-06	Goulburn – lower river channel		06/04/16 – 30/06/16	Base flow	P	(1) Support condition of native fish.
1516-Ovn-02	Ovens River – with benefit to Buffalo River en route from Lake Buffalo	20.00	25/04/16 – 26/04/16	Base flow	P	(1) Support dispersal of native fish.
1516-Ovn-01	Ovens River – with benefit to King River en route from Lake William Hovell	50.00	05/04/16 – 07/05/16	Base flow	P	(1) Support dispersal of native fish.
1516-Ldn-01	Loddon Reach 4 (with benefit to Reaches 1, 2, 3a, 3b and 5 en route)	1476.70	24/08/15 – 07/09/15	Fresh	P	(1) Support spawning of native fish. (2) Support movement of native fish.

Water Action Reference	Surface water region/asset	Commonwealth environmental water volume (ML)	Dates	Flow component	Primary (P), secondary (S) or unassigned (X) expected outcome	Expected ecological outcome
1516-SA-01	South Australian River Murray and Coorong	556 000.00	01/07/15 – 30/11/15	Base flow	P	(1) Increase spawning of native fish. (2) Increase abundance of native fish. (3) Maintain native fish diversity. (4) Extend spatial distributions of native fish.
1516-SA-02	South Australian River Murray and Coorong	242 000.00	01/12/15 – 01/07/16	Base flow	P	(1) Increase spawning of native fish. (2) Increase abundance of native fish. (3) Maintain native fish diversity. (4) Extend spatial distributions of native fish.
1516-Brock-01	Banrock Station – Herons Bend	20.41	10/11/15 – 27/11/15	Wetland inundation	X	(1) Increase spawning of native fish.
1516-Brock-04	Banrock Station – Banrock Bend	15.48	03/12/15 – 18/12/15	Wetland inundation	X	(1) Increase dispersal of native fish.
1516-Brock-05	Banrock Station – Wigley Reach Central	52.49	20/01/16 – 01/02/16	Wetland inundation	X	(1) Increase dispersal of native fish.
1516-Brock-02	Banrock Station – Wigley Reach Depression	571.91	10/11/15 – 18/01/16	Wetland inundation	X	(1) Increase dispersal of native fish.
1516-Brock-03	Banrock Station – Eastern Lagoon	1340.43	17/11/15 – 11/03/16	Wetland inundation	X	(1) Increase dispersal of native fish.
1516-Cmp-01	Campaspe – downstream of Lake Eppalock (Reach 4 with benefit to Reaches 2 and 3 en route)	1700.00	26/08/15 – 06/09/15	Fresh	P	(1) Stimulate fish dispersal.
1516-Cmpe-02	Campaspe – downstream of Lake Eppalock (Reach 4 with benefit to Reaches 2 and 3 en route)	1558.70	27/10/15 – 04/11/15	Fresh	P	(1) Stimulate fish dispersal.
1516-Brkn-01	Lower Broken Creek – Reach 3 with benefit to Reaches 1 and 2 en route	29 519.50	12/8/15 – 22/5/16	Base flow	P	(1) Operate fish ladders; support fish dispersal.
1516-Brkn-02	Lower Broken Creek – Reach 3 with benefit to Reaches 1 and 2 en route		18/8/15 – 30/11/16	Base flow	S	(1) Operate fish ladders; support fish dispersal.
1516-Brkn-04	Lower Broken Creek – Reach 3 with benefit to Reaches 1 and 2 en route		1/10/15 – 16/5/16	Base flow	S	(1) Operate fish ladders; support fish dispersal.

Water Action Reference	Surface water region/asset	Commonwealth environmental water volume (ML)	Dates	Flow component	Primary (P), secondary (S) or unassigned (X) expected outcome	Expected ecological outcome
1516-Brkn-03	Lower Broken Creek – Reach 3 with benefit to Reaches 1 and 2 en route		18/08/15 – 12/09/15 28/09/15 – 30/11/15	Freshes	S	(1) Operate fish ladders; support fish dispersal.
1516-Brkn-05	Lower Broken Creek – Reach 3 with benefit to Reaches 1 and 2 en route		25/10/15 - 09/11/15 29/11/15 – 31/12/15	Base flows	S	(1) Operate fish ladders; support fish dispersal.
1516-Mur-01	NSW and Vic Murray – River Murray to SA and Floodplain – River Murray Channel	99 400.00	22/06/15 – 24/07/15	Base flow and in-channel freshes	P	(1) Increase spawning of native fish. (2) Increase abundance of native fish. (3) Maintain native fish diversity. (4) Extend spatial distributions of native fish.
1516-Mur-03	NSW and Vic Murray – River Murray to SA and Floodplain – River Murray Channel, Barmah and Millewa	172 600.00	25/07/15 – 10/09/15	Overbank	P	(1) Increase spawning of native fish. (2) Increase abundance of native fish. (3) Maintain native fish diversity. (4) Extend spatial distributions of native fish.
1516-Mur-04	NSW and Vic Murray – River Murray to SA and Floodplain – River Murray Channel, Barmah and Millewa	63 900.00	11/09/15 – 03/10/15	Overbank	P	(1) Increase spawning of native fish. (2) Increase abundance of native fish. (3) Maintain native fish diversity. (4) Extend spatial distributions of native fish.
1516-Mur-05	NSW and Vic Murray – River Murray to SA and Floodplain – River Murray Channel, Barmah and Millewa	30 900.00	04/10/15 – 31/10/15	Overbank	P	(1) Increase spawning of native fish. (2) Increase abundance of native fish. (3) Maintain native fish diversity. (4) Extend spatial distributions of native fish.
1516-Mur-02	Mid-Murray – Gunbower Creek	13 606.00	01/07/15 – 30/06/16	Base flow	P	(1) Maintain diversity of native fishes. (2) Maintain condition of native fishes.
1516-Mur-08	NSW Murray – Barham Lake	115.00	19/01/16 – 07/03/16	Wetland Inundation	P	(1) Maintain habitat for freshwater catfish population.

Water Action Reference	Surface water region/asset	Commonwealth environmental water volume (ML)	Dates	Flow component	Primary (P), secondary (S) or unassigned (X) expected outcome	Expected ecological outcome
1516-Weir-01	NSW, Vic and SA Murray – Weir pool manipulation, Lock 15 raising	5249.00	01/07/15 – 30/12/15	Fresh (raising weir)	P	(1) Maintain recruitment of native fish. (2) Maintain condition of native fish. (3) Maintain survival of native fish.
	NSW, Vic and SA Murray – Weir pool manipulation, Lock 15 lowering		01/04/16 – 30/06/16	Fresh (lowering weir)	P	(1) Maintain recruitment of native fish. (2) Maintain condition of native fish. (3) Maintain survival of native fish.
1516-Weir-04	NSW, Vic and SA Murray – Weir pool manipulation, Lock 7 raising	2739.00	01/08/15 – 30/01/16	Fresh	P	(1) Maintain recruitment of native fish. (2) Maintain condition of native fish. (3) Maintain survival of native fish.
	NSW, Vic and SA Murray – Weir pool manipulation, Lock 7 lowering		01/01/16 – 30/05/16	Fresh	P	(1) Maintain recruitment of native fish. (2) Maintain condition of native fish. (3) Maintain survival of native fish.
1516-Weir-05	NSW, Vic and SA Murray – Weir pool manipulation, Lock 5 raising	4346.00	01/08/15 – 30/11/15	Fresh	P	(1) Maintain recruitment of native fish. (2) Maintain condition of native fish. (3) Maintain survival of native fish.
1516-Weir-06	NSW, Vic and SA Murray – Weir pool manipulation, Lock 2 raising	738.00	01/09/15 – 30/11/15	Fresh	P	(1) Maintain recruitment of native fish. (2) Maintain condition of native fish. (3) Maintain survival of native fish.
1516-Macq-01	Macquarie – Macquarie Marshes Nature Reserve and Core Wetlands	12 114.00	06/08/15 – 17/10/15	Fresh	P	(1) Support dispersal of native fish. (2) Maintain condition of native fish.
1516-Macq-02	Macquarie – Macquarie River System, including floodplain (Supplementary water)	2125.00	25/06/16 – 30/06/16	Fresh	P	(1) Support dispersal of native fish. (2) Maintain condition of native fish.
1516-Gwyd-01	Gwydir – Gwydir Wetlands	1350.00	09/01/16 – 11/02/16	Overbank	S	(1) Maintain refuge for fishes.
1516-Gwyd-03	Gwydir – Mehi River (Supplementary water)	964.00	09/11/15 – 11/11/15	Fresh	P	(1) Maintain native fish habitat. (2) Support fish dispersal. (3) Increase fish spawning. (4) Increase fish recruitment.

Water Action Reference	Surface water region/asset	Commonwealth environmental water volume (ML)	Dates	Flow component	Primary (P), secondary (S) or unassigned (X) expected outcome	Expected ecological outcome
1516-Gwyd-04	Gwydir – Gwydir river system	2600.00	10/04/16 – 30/05/16	Base flow	P	(1) Maintain waterholes/refuge for native fish.
1516-VicW-01	Mallee wetland Sites – Brickworks Billabong	200.00	01/10/15 – 30/11/15 9/03/16 – 3/06/16	Wetland inundation	P	(1) Increase abundance and distribution of Murray hardyhead.
1516-VicW-02	Mallee wetland Sites – Cardross Wetland inundations	476.61	9/09/15 – 24/12/15	Wetland inundation	P	(1) Increase abundance and distribution of Murray hardyhead.
1516-HattL-01	Hattah Lakes	5347.50	12/10/15 – 23/10/15	Wetland inundation	P	(1) Maintain habitat for small bodied fish, including golden perch.
TOTAL		**1 565 779**				