

# Long Term Intervention Monitoring Project

## Foundation Report: Fish

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# Final Report

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## Commonwealth Environmental Water Office

### Long Term Intervention Monitoring

#### Basin Matter - Fish foundation report

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# Table of Contents

<b>1</b>	<b>Why monitor fish response to flows?</b>	<b>4</b>
<b>2</b>	<b>Objectives and conceptual foundation</b>	<b>4</b>
2.1	Objectives and evaluation questions	4
2.2	Foundational concepts	6
2.2.1	Critical drivers of change in fish populations	6
2.2.2	A trait-based approach	8
2.2.3	Conceptual response to flows	9
<b>3</b>	<b>Approach</b>	<b>15</b>
3.1	Categorised methods and the balance between reporting on long- and short-term responses	15
3.1.1	Cat 1 annual census	16
3.1.2	Cat 1 larval sampling	17
3.1.3	Cat 2 fish movement	17
3.1.4	Cat 3 methods	17
3.1.5	Balancing the investment portfolio	18
3.2	Analysis and modelling approach	19
3.2.1	Analysis and modelling activities	19
3.2.2	Hydrological data requirements	28
3.2.3	Links with other basin matters	29
<b>4</b>	<b>Literature cited</b>	<b>30</b>
<b>5</b>	<b>Appendix A. Basin matter team</b>	<b>37</b>

# Basin Matter - Fish foundation report

## Preface

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

This report presents an overview of the conceptual and methodological foundation for fish monitoring within LTIM, and complements the overarching Logic and Rationale (Gawne et al. 2013) and Evaluation Plan (Gawne et al. 2014) of LTIM. The intended audience for this report is, first and foremost, the scientists of LTIM. Despite the somewhat technical nature of this report, it also serves to communicate to CEWO the scope of the fish evaluation during the first five years of LTIM. Throughout, we have tried to keep technical details to a minimum, while at the same time providing sufficient clarity such that the work-plan for the first five years is not ambiguous. Last, this report may also be read by scientists outside of LTIM; those scientists wishing to know more about fish monitoring within LTIM, and why the approach was adopted.

Below, this report is divided into three sections: In Section 1 we very briefly state why fish monitoring was included in LTIM. In Section 2 we present the key evaluation questions and objectives that underpin fish monitoring within LTIM. In this second section we also review the ecological concepts that provide the foundation for fish monitoring. We emphasise the critical population processes that drive changes in fish population size, and how flows may affect them. In Section 3 we present and justify our approach to answering the evaluation questions.

## 1 Why monitor fish response to flows?

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<sup>1</sup>). Flows affect riverine fish via direct and indirect causal pathways. Direct effects include the provision of spawning and dispersal cues for certain species; indirect effects include the provision of habitat. The links between flows and fish population processes make fishes a useful indicator of system response to managed flows and, within the context of the Basin Plan, biodiversity response to flows. Fishes have substantial socioeconomic value, and so evaluating and reporting fish response to flows is critical from the perspective of stakeholders.

## 2 Objectives and conceptual foundation

### 2.1 Objectives and evaluation questions

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

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<sup>1</sup> <https://www.legislation.gov.au/Details/F2012L02240>

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 objective** of the fish basin matter is to answer these questions. These questions, however, belie the broader aims of LTIM. Indeed, a key objective of LTIM is to improve our capacity to predict ecological response to flow events (hydrographs spanning 1 year or less) and regimes (hydrographs spanning multiple years) (Gawne et al. 2013; Gawne et al. 2014). Prediction within LTIM will facilitate the following three activities:

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

2. Decision-making. Good decision-making involves predicting the likely outcomes from a set of different management options (decisions), given certain antecedent conditions and a set of future environmental states (Clark et al. 2001; Conroy and Petersen 2013; Walters and Holling 1990). 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, hence demand for water by of end-users that may compete with the environment. Decisions in need of evaluation may involve flow events or regimes, hence concern predictions over one- or multi-year timeframes. Simulation models—be they statistical or 'process-based'—are a very useful tool for making these predictions (Shea 1998). Simulation models incorporate antecedent conditions, are accompanied by explicit sets of assumptions, and project outcomes bound by confidence intervals, thus improving our ability to characterise uncertainty and compare decisions (Clark et al. 2001; Polasky et al. 2011; Walters 1997).

3. Improve capacity to evaluate decisions in monitored areas. Even where monitoring is occurring, analysis of outcomes from adaptive management is rarely, if ever, 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 serve as poor references for the perturbation of interest (Konrad et al. 2011; Olden et al. 2014).

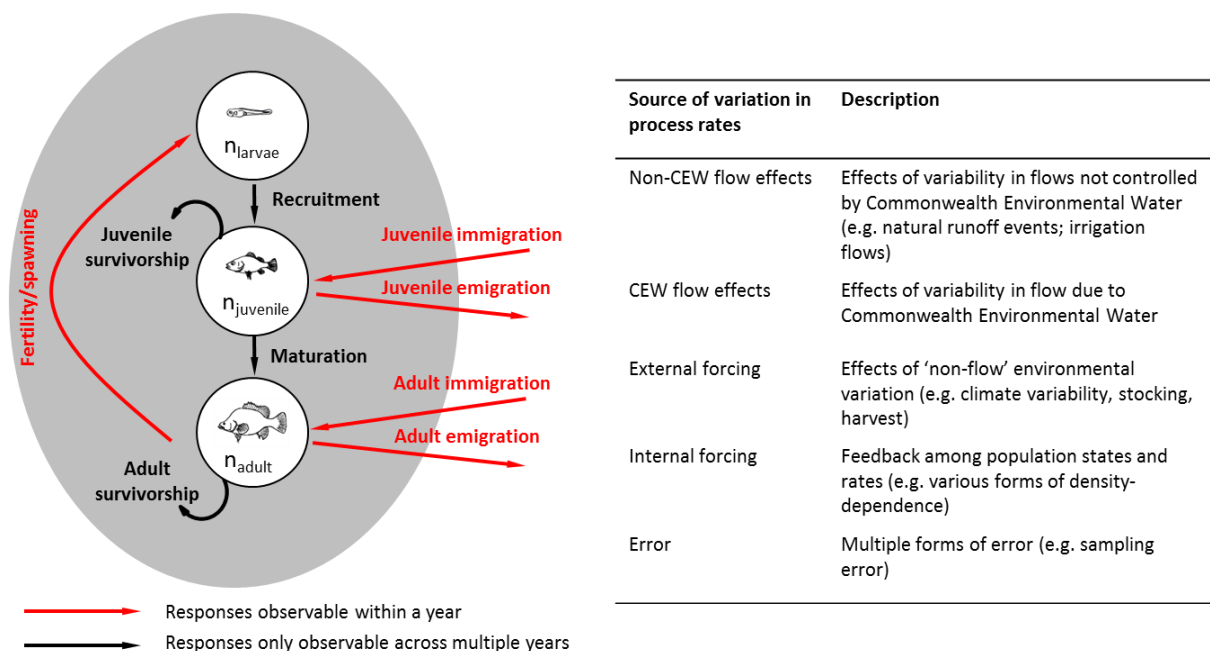
Time series analysis provides a way for determining the impact of perturbation in unreplicated ecosystem experiments (Box and Tiao 1975; Carpenter 1990). In turn, simulation models play a pivotal role in time series analysis, enabling us to contrast observed time series with what we predict would have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

It follows, therefore, that the **second 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. To meet these objectives, nine activities are proposed as part of the first five years of LTIM. These activities will be presented and explained in Section 3.

## 2.2 Foundational concepts

### 2.2.1 Critical drivers of change in fish populations

A basic conceptual model outlining the key processes and states involved in driving the temporal dynamics of a fish population is provided in Figure 1. This conceptual model is based on an axiom of animal population ecology: changes in animal abundance through time are a function of gains (births, immigration) and losses (deaths, emigration) (Caswell 2001; Williams et al. 2002). The purpose of Figure 1 is to illustrate that population dynamics are a function of how population state (the relative abundances of different cohorts) interacts with processes (arrows in Figure 1; measured as rates). The table on the right of Figure 1 also shows the potential drivers of changes in rates across years. Only a subset of these drivers comprises flow impacts.



**Figure 1.** Life-cycle graph of key processes that drive population dynamics of fishes within a river-floodplain segment. The model assumes three population stages (larvae, juveniles and adults) hence three state variables (circles). State variables,  $n_{larvae}$ ,  $n_{juvenile}$  and  $n_{adult}$ , indicate number of young-of-year, juveniles and adults, respectively, within a river segment. The arrows indicate the rates of processes that change these abundances through time. Segment-specific rate variables: Recruitment = rate of larval recruitment into juvenile stage; Maturation = rate at which juveniles mature to become adults; Juvenile and Adult Survivorship = survival rates of juveniles and adults; Fertility = fertility, or per-capita number of larvae produced. The rates are best viewed as either losses or gains. The maturation parameter is the rate at which juveniles transition to adults, and so

includes both age and size (growth) effects (Policansky 1983). Each rate is affected by several drivers (non-flow external forcing, internal forcing, error, flow effects) listed in the table on the right.

Here we briefly define the key processes that drive change in population size. Links to flow are presented in the subsection 'Conceptual response to flow'. Equations that explicitly translate these conceptual definitions into data-based, operational definitions will be developed later (e.g. Sakaris and Irwin 2010; Stratford et al. 2016; Yen et al. 2013).

- Here we define **recruitment** as the proportion of larvae produced each year that survive through to the juvenile stage. As such, recruitment here is just young-of-year (YOY) recruitment.
- **Juvenile survivorship** is the proportion of juveniles that survive and remain within the juvenile stage each year. If we take an age-structured view of the population, then juvenile survivorship encompasses the annual age-specific survival rates of ages from 0+ through to the average age at sexual maturity.
- The rate at which **juveniles mature into adults** determines the rate at which individuals in the juvenile stage transition into the adult stage. Maturation rate is a function of both age and size, hence growth rate (Policansky 1983).
- **Adult survival rate** describes the proportion of individuals in the adult stage that survive each year.
- We follow the terminology of Caswell (2001) here and define '**fecundity**' as the physiological maximum reproductive output and '**fertility**' as the realized reproductive output (number of individuals hatching into larval stage per female in the population). Fertility rate could equally be labelled 'spawning rate'. Fertility and recruitment combine to determine the number of 0+ individuals in the population each year.

It is important to emphasise that there are multiple sources of variation in the rates associated with these processes from one year to the next – flow variation and, in particular, releases of Commonwealth Environmental Water is just one of these. Statistically, these sources of variation are difficult to separate. However, understanding the sources of uncertainty in population response to management interventions is a critical component of any adaptive management plan (Conroy and Petersen 2013; Rose et al. 2015) (see table in Figure 1):

1. Background flow effects. We have distinguished two broad classes of flow impacts – those effects attributed to Commonwealth environmental water, and those effects due to flows from other sources (e.g. irrigation flows, natural flow variability). We have labelled the effects of non-CEW flows 'background' flow effects. Ideally, we wish to determine what Commonwealth environmental water has contributed to the processes in Figure 1.
2. Effects of Commonwealth environmental water. The effects of water actions—isolated from background flow (and other) drivers—on population processes.
3. Non-flow-related external forcing, such as the effects of thermal change, stocking and recreational harvest. For example, the fertility of certain species such as bony herring may be more closely related to temperature than to flow (Puckridge et al. 2010; Puckridge and Walker 1990).
4. Internal forcing, such as density-dependence of rates. Compensation, for example, might occur when high population density lowers recruitment or maturation.
5. Rates will always be subject to various forms of error or uncertainty. Examples include measurement error, which itself may be a function of the state of the environment (e.g. high flows reducing sampling efficiency), and inherent random variation in the critical rate, through time (Harwood and Stokes 2003; Regan et al. 2002).

### 2.2.2 A trait-based approach

One of the challenges for environmental monitoring is that it is unrealistic to collect data on all species simultaneously. However, despite this diversity, different species will often share traits, such as their fecundity, growth rates, sensitivities to pollution etc. Because traits are often correlated among species and one another, species can be classified into 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 and Rose 1992).

Three guilds are commonly recognized: equilibrium, periodic and opportunistic (Winemiller and 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 propose a guild-based approach is adopted in LTIM. By targeting species representing different guilds we hope to gain a fuller appreciation of how flow regimes affect multi-species communities, hence diversity, rather than just a single iconic species.

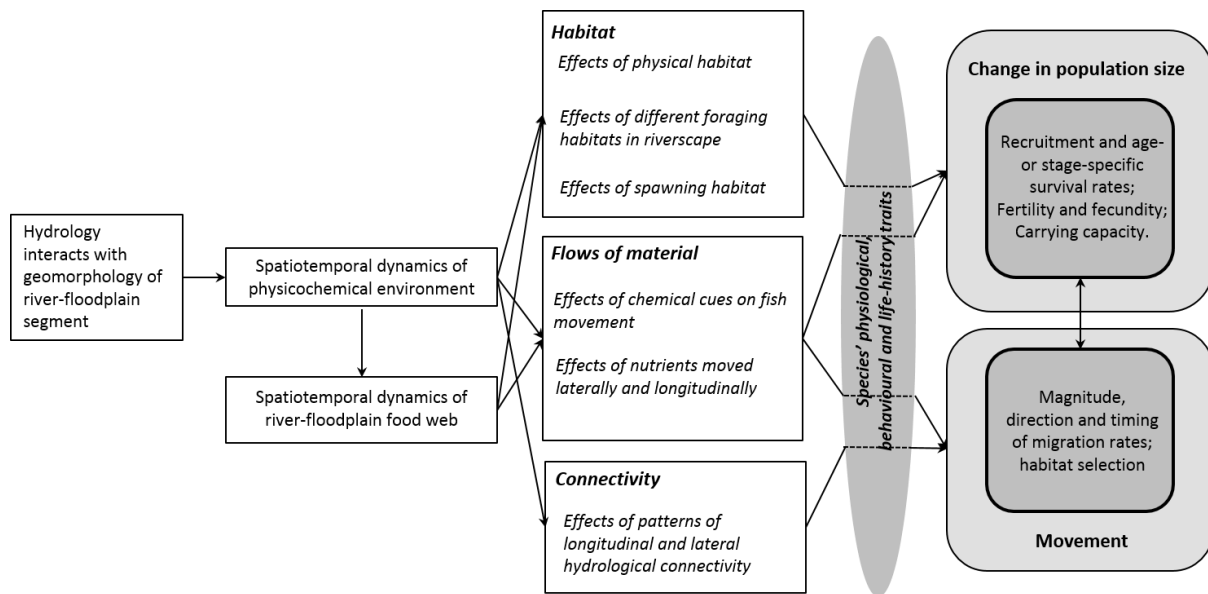
LTIM is taking place at seven 'selected areas' throughout the MDB. Within six selected areas (see Section 3) community samples will be obtained (sampling techniques do not target individual species), but many field procedures (e.g. length-mass estimates) will target four species within selected areas:

1. Equilibrium: Murray cod (large adult size; long-lived; non-flow spawner; greater investment in offspring);
2. Periodic: Golden Perch (large adult size; long-lived; flow-spawner; little investment per offspring) and Bony herring (medium adult size, medium longevity, spawning not tightly linked to flows);
3. Opportunistic: Carp-gudgeon (small adult size; short lifespan; spawning not tightly linked to flows, but data inconclusive at this stage).

If any of the above species are not abundant within a selected area, they will not be targeted for detailed population data. Bony herring, for example, will only be targeted at Gwydir, Murrumbidgee, Lachlan and Lower Murray, where they are abundant. Within each selected area we also aim to add an additional species to each of the guilds, such that we obtain detailed annual estimates of population state from up to six species within each selected area, but with the requirement that only three of them are common to all areas. This strategy should enable us to address spatial variation in population response to flows for at least some species (cod, golden perch, carp-gudgeon), while also improving our understanding of the dynamics of other species that may be only locally-abundant within a particular area.

Note that only certain of the above target species might spawn in response to flows. However, just because a species does not spawn in response to flows does not mean its vital rates are unlinked to flow events. For example, although the magnitude of Murray cod spawning appears unlinked to flows, we have little understanding of whether survivorship rates are affected by flow. One of our key objectives is integrating all population processes to obtain an understanding of whole-population dynamics. Accordingly, equilibrium and opportunistic species are included as target species in the annual census with a view to elucidating effects of flows on multiple processes; not just spawning.

Further, we appreciate that carp-gudgeon are a generalist species of little conservation concern, but in our view this does not invalidate its use as a useful indicator of long-term environmental change and certain flow impacts. This species was selected because it (a) represents the opportunistic life-history strategy; (b) is represented across all areas, so makes for a good ‘basin-wide’ opportunistic indicator; (c) yields large sample sizes with minimal effort using minimum-bias sampling gears; (d) due to its very high abundances it may be a key forage fish for higher vertebrates, hence a key player in the food web; (e) may exhibit responses to flows at the population level that strongly contrast with periodic and equilibrium species (Bice et al. 2014).



**Figure 2.** 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; population processes 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.

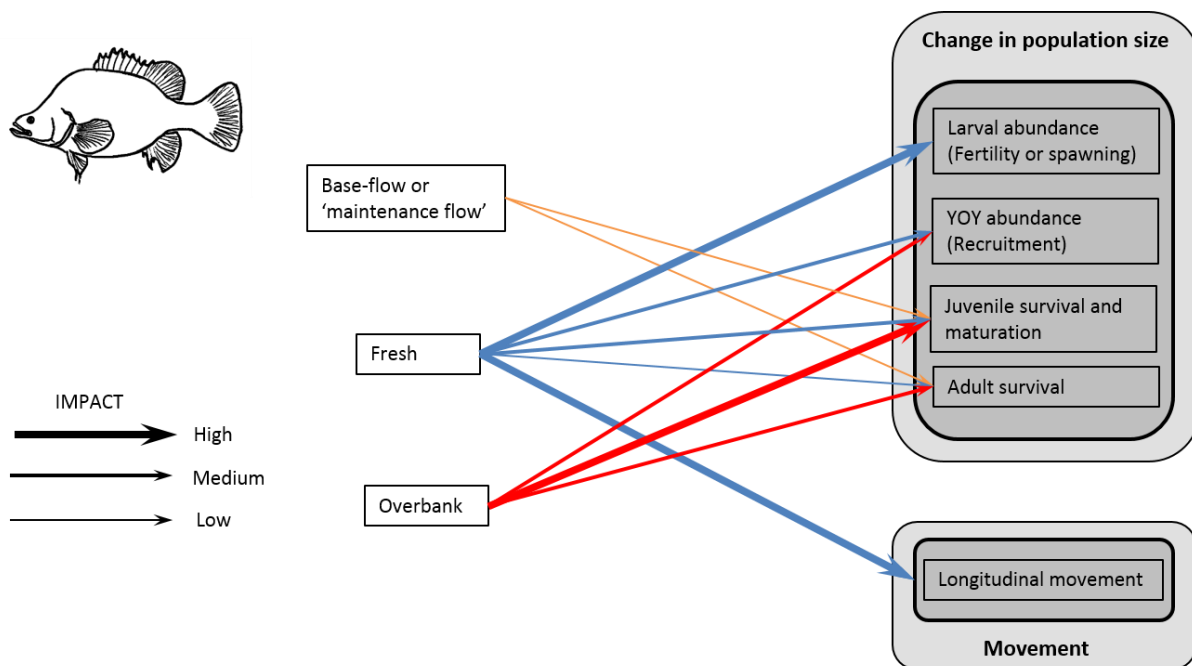
### 2.2.3 Conceptual response to flows

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 2.

1. Flows may affect fish population processes through the impact flow has on **habitat** (Figure 2):

- a. Flows may affect the **physical nature of habitat**, including both water chemistry (e.g. temperature, dissolved oxygen) and habitat hydrology (e.g. depth, velocity). Physical habitat is known to affect fish condition, survival and reproduction (Fry 1971; Gorski et al. 2010; Pichavant et al. 2001; Pichavant et al. 2000; Stoffels 2015; Wu 2009) 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 is known to strongly affect fish fitness generally (Clements et al. 2009; Jobling 1993), and although poorly studied, there is growing evidence spatiotemporal variation in river-floodplain food web structure affects fish population processes (Feyrer et al. 2006; Limm and 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** (Burgess et al. 2013; Gorski et al. 2010; Poizat and Crivelli 1997; Zeug and Winemiller 2007).
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 2):
  - a. Floods can mobilise dissolved materials that serve as important cues to changes in fish behaviour (Lewis 2002). In turn, recent work has highlighted the possibility for flows to affect fish movement—hence access to habitats that may affect population size—through the impact they have on **chemical cues** for fish dispersal (Stoffels et al. 2014).
  - b. Flows may affect fish population productivity without necessarily changing 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 (Baldwin et al. 2013; Baldwin et al. 2014; Hunt et al. 2012; Jardine et al. 2012).
3. Flows may also affect population size through another indirect pathway, by affecting the hydrological **connectivity** (Figure 2), hence movement of individuals throughout the river-floodplain landscape (Crook et al. 2013; David and Closs 2002; Jones and Stuart 2009; Koster and Crook 2008; Koster et al. 2014; Lyon et al. 2010; Stoffels et al. 2016).

Below we present diagrammatic conceptual models for four target species within LTIM: bony herring, golden perch, Murray cod and *Hypseleotris* spp. 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 are equilibrium species and *Hypseleotris* spp. are opportunistic. Our design principle for these species-specific conceptual models was to keep it very simple and focus on the data being collected as part of LTIM. One could probably imagine—and possibly even find scientific support for—literally hundreds of arrows linking flow effects to various ecosystem responses and, eventually, to fish population processes. However, such complexity would be misleading and create the impression we aim to test detailed, indirect cause-effect pathways, even when the data being collected are not fit for such a purpose. Accordingly, 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.



**Figure 3.** 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 (ie. not particularly dry or wet years). Only those processes that LTIM data-collection activities target are presented. The model is an adaptation of Figure 2, and so an explanation of broad mechanistic pathways can be found in the body of the document. Three types of flow are considered: base-flow or maintenance flow, fresh and overbank flows. These sources of hydrological variability are linked to fish population processes using lines of different colour.

## Periodic species – golden perch

### Base-flow

Generally we expect the impact of base-flows on golden perch to be low (Figure 3), 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 show in Figure 3). If base-flows have an impact, then we propose that impact is on survival rates of juvenile and adult golden perch (Figure 3), through provision of desirable physical and foraging (e.g. backwaters) habitats (Balcombe et al. 2006).

### Fresh

We propose that freshes may have high impacts on golden perch population processes, particularly spawning, recruitment and movement (Figure 3). Increases in discharge have been correlated with golden perch spawning and recruitment previously (Humphries et al. 2008; Humphries et al. 2002; King et al. 2016; King et al. 2009; Roberts et al. 2008; Zampatti and Leigh 2013), although certain studies have documented spawning and recruitment in the absence of notable peaks in the hydrograph (Ebner et al. 2009; Mallen-Cooper and Stuart 2003). Hydrology is not a 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 (Koster et al. 2014; O'Connor et al. 2005).

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

#### Overbank

Juvenile golden perch have been documented undertaking lateral movements of large magnitude during natural overbank flows (Balcombe et al. 2007; Stoffels et al. 2015; Stoffels et al. 2014). 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 and 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 high impact on survival rates of juvenile golden perch (Figure 3).

### Periodic species - Bony herring

#### Base-flow

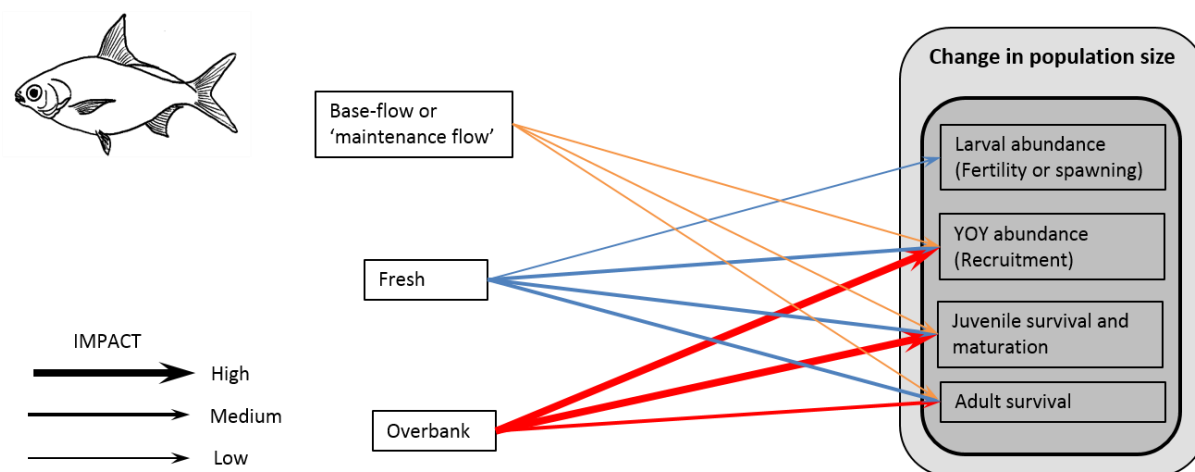
As is the case for golden perch we expect base-flows will have generally low impacts on bony herring. The exception would be during particularly dry years, when base-flows may play an important role in improving survival, which would have otherwise significantly declined due to low water quality. If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

#### Fresh

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 and Walker 1990; Pusey et al. 2004) (Figure 4). 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; Balcombe and Arthington 2009; Balcombe et al. 2012; Sternberg et al. 2008). 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 4).

#### Overbank

We expect the greatest impacts of flows on bony herring when those flows are large flows that inundate floodplains. Bony herring are known to exhibit lateral movements of great magnitude in response to overbank flows (Balcombe et al. 2007; Kerezszy et al. 2013; Puckridge et al. 2000; Stoffels et al. 2014; Stoffels et al. 2016). Floodplain habitats may be used for spawning and, in particular, foraging (Balcombe et al. 2007; Balcombe et al. 2005; Rolls and Wilson 2010). If we experience large flows that increase lateral connectivity, then we expect to see high impacts on juvenile and adult survival rates (Figure 4).



**Figure 4.** 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 (ie. 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 2, and so an explanation of broad mechanistic pathways can be found in the body of the document. Three types of flow are considered: base-flow or maintenance flow, fresh and overbank flows. These sources of hydrological variability are linked to fish population processes using lines of different colour.

## Equilibrium species – Murray cod

### Base-flow

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

### Fresh

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 temperature exceeds 15 °C (Humphries 2005; King et al. 2016; King et al. 2009; Koehn and Harrington 2006). Given our current understanding, we expect low impacts of freshes on Murray cod spawning (Figure 5).

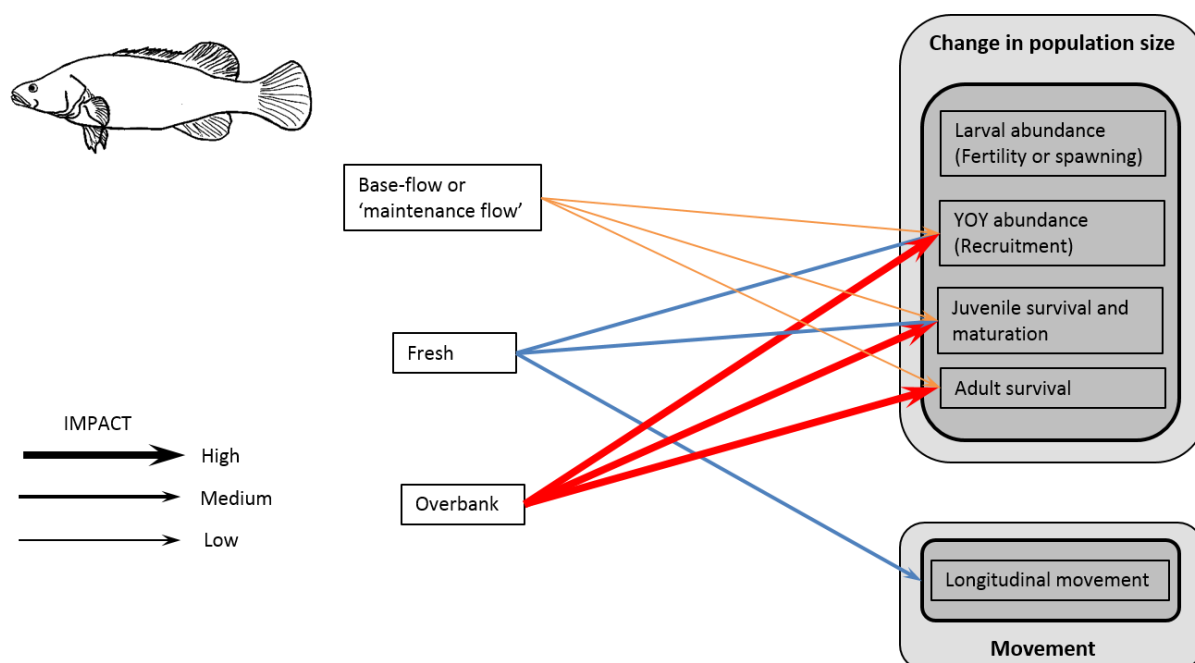
We expect to observe medium impacts of flows on Murray cod recruitment and survival rates (Figure 5). Although the evidence was weak, King et al. (2010) observed increased recruitment of cod following a large fresh within the Murray River (see also King et al. 2009). The effects of freshes on juvenile 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 and Stuart 2007), but they may exhibit quite large movements, which may be related to spawning behaviour (Koehn et al. 2009; Leigh and 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 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 5).

### Overbank

There is little evidence for Murray cod utilising floodplain habitat (Jones and Stuart 2007; Leigh and 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 (Baldwin et al. 2013; Baldwin et al. 2014; Bayley 1991; Hunt et al. 2012). Thus we propose overbank flows will have a high impact on recruitment and survival (Figure 5).



**Figure 5.** 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 (ie. not particularly dry or wet years). Only those processes that LTIM data-collection activities target are presented. The model is an adaptation of Figure 2, and so an explanation of broad mechanistic pathways can be found in the body of the document. Three types of flow are considered: base-flow or maintenance flow, fresh and overbank flows. These sources of hydrological variability are linked to fish population processes using lines of different colour.

## **Opportunistic species – *Hypseleotris* spp.**

### Preface

*Hypseleotris* is broadly considered a ‘flow generalist’ (Humphries et al. 1999; King et al. 2003; Reich et al. 2010). We aren’t 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

*Hypseleotris* 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 and 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 (Section 3).

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. The literature concerning flow impacts on *Hypseleotris* is generally scant and presents strongly discordant views. As such, we found it more convenient to present a brief review of the literature against each of the three flow types.

#### Base-flow

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 *Hypseleotris* were more abundant at sites with sustained higher flows (higher mean monthly flows), so we may find that *Hypseleotris* abundance fluctuates less, and is higher on average, in areas that receive less variable flow conditions.

#### Fresh

There is discordance in the literature concerning the impact of freshes on *Hypseleotris* abundance. Vilizzi (2012) presents evidence that, although *Hypseleotris* 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 *Hypseleotris* spawning (Humphries et al. 2002; King et al. 2003). The population-level impact of freshes is unknown for this species.

#### Overbank

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

## **3 Approach**

### **3.1 Categorised methods and the balance between reporting on long- and short-term responses**

LTIM methods are categorised as Category 1, 2 or 3 (Cat1, 2 and 3, respectively, hereafter (Hale et al. 2013)). Cat 1 methods are standardised and to be implemented across all six selected areas monitoring fish. Cat 2 methods are standardised but not implemented across all selected areas. Cat 3 methods are area-specific methods. No single category of methods covers all of the population processes that drive changes in population size. When developing the LTIM methods, key requirements were:

- to balance allocation of effort to detecting the response of individual processes to hydrology in the short-term, with the need to relate whole-population changes to flows in the long-term;
- while LTIM will, wherever possible, utilise data from other programs to facilitate answers to the evaluation questions, LTIM should not be *entirely dependent* on data from other programs to answer these questions for us.

With these key requirements in mind, four groups of sampling activities were developed for LTIM (details in Hale et al. 2013), which are explained in the sub-sections below.

### 3.1.1 Cat 1 annual census

This method involves intensively sampling the fish community annually within each selected area, each autumn, after the flow delivery season. Cat 1 censuses involve use of boat and backpack electrofishing, and fine-mesh fyke nets to sample the fish community (Hale et al. 2013). The method is designed to yield **a powerful time series** at the levels of the population and community. The method was designed to link inter-annual changes in population and community structure with characteristics of river flows that occurred between each annual sample (more on this in Section 3.2). This method was designed to detect **impacts of flows on whole-populations over the long-term** (5 years plus).

With respect to fish population structure, we seek samples with the following characteristics:

- The sampling intensity must be such that, at a minimum, the length-structure of the sampled population is precise. We know we have **high precision** of our estimate when further sampling effort does not change the structure of the sample (the shape of either the age-, stage- or length-distribution; Section 3.2). In addition to length-structure, we seek estimates of age- and stage-structure that are as precise as possible so that the suite of modelling options available to us remains broad.
- Ideally we'd obtain samples that have **minimal bias** with respect to size-, stage- and/or age-structure. That is, a sample from a site should, as much as practicable, reflect the actual population structure at that site. Of course, all fish sampling methods are biased, but if (a) that bias is kept constant in space and time through the use of standard methods; and (b) the biased samples are precise, then we still achieve reasonable power to detect changes in population structure in space and time.
- As much as possible, we seek samples of population structure that have **minimal confounding** by spatial and temporal changes in the environment. For example, if we have a sampling method for small-bodied fishes (e.g. rainbowfish) that is substantially more effective in clear than in turbid conditions, then this would be undesirable, as temporal changes in abundance may be more an artefact of sampling than an effect of flows, say. As is the case for bias, the objective is to devise a strategy that minimises confounding, acknowledging we cannot eliminate it.

The Cat 1 census was designed with these sampling objectives in mind (Hale et al. 2013). The random sampling scheme was implemented to minimise bias imposed by favouring certain habitats over others; sampling effort was increased over that utilised by SRA to dramatically improve precision; the method was standardised to ensure any (hopefully minimal) levels of bias and confounding were kept constant over areas, to facilitate more powerful multi-area inferences of flow impacts.

Although estimates of population structure from Cat 1 census data are the priority, we also designed the Cat 1 census to yield sound estimates of community composition. That is, we also sought

community structure estimates that essentially have the same characteristics as the population samples, but where we are interested in the community structure (species' relative abundances), rather than population structure.

Note that investigations of the precision of LTIM population and community samples are currently underway.

### **3.1.2 Cat 1 larval sampling**

Like the Cat 1 annual census, this method also involves developing a time series, but at a much finer temporal resolution. The method was designed to determine impacts of flows on fish spawning within an individual year, hence **targets response of a single population process to specific features of the hydrograph in the short-term** (1 year). Efficacy of larval sampling gears is heavily dependent on environmental conditions, so the emphasis of the methodology is not on standardisation of gears but on broader data requirements, which are:

- The objective underlying the larval method was to model the relationship between (a) probability of occurrence (at a minimum), or (b) density (ideally) of larvae, and characteristics of the spring-summer hydrograph, within a year. The method specifically targets flow-cued spawners.
- The larval sampling will take place within the 100 km zone where the Cat 1 censuses are taking place, such that we may treat area-specific abundance of adult flow-cued spawners as a covariate in multi-area modelling activities.
- The frequency of the samples must balance the need to minimise the risk of missing spawning events, and the need for samples to span as much of the spring-summer hydrograph as possible, hence as much of the domain of predictor variables as possible (rates of change in discharge, temperature, etc.).
- The requirements of precision, minimal bias and confounding that were stated for the Cat 1 census also apply here, too.

### **3.1.3 Cat 2 fish movement**

The Cat 2 fish movement method was designed to determine how flows affect the direction and magnitude of longitudinal movements (Hale et al. 2013). The method involves use of hydroacoustic tags to detect movements of target species at very high temporal and spatial resolutions. Like the larval method, by including the Cat 2 movement method in our portfolio we increase our capacity for **evaluating the response of a single population process to specific features of the hydrograph over the short-term** (1 year). Noteworthy, however, is the fact that this method also enables documentation of movements over several years, too, depending on the life of the tag.

### **3.1.4 Cat 3 methods**

In addition to the above standardised methods, there are also area-specific activities taking place aimed at monitoring the short- and long-term response of fish populations to flows, including:

- At the Lower Murray, Goulburn and Edward-Wakool, fish otoliths are being collected to determine the movement history of individual golden perch, silver perch and Murray cod, with the aim of linking fish movement to flows in certain parts of the basin. These selected area teams will be using otolith microchemistry to examine movement histories.
- Within the Edward-Wakool an extensive Cat 3 fish spawning study is taking place.
- Also within the Edward-Wakool, a Cat 3 method was developed for a more detailed investigation of how flows throughout the Edward-Wakool riverscape affect recruitment of Murray cod.

### 3.1.5 *Balancing the investment portfolio*

Each of the above four groups of monitoring activities has its trade-offs. For example, a great strength of the Cat 2 movement method is its sensitivity to flow impacts on fish movement. Once the array is established, it will automatically detect tagged fish moving in response to flow. By itself, however, it tells us little about how flows affect our fundamental objective; increased population size and/or persistence.

Fish spawning, as monitored using the Cat 1 larval method, may also be highly sensitive to flow impacts and so is a very useful short-term indicator of positive flow effects. However, evidence of spawning is not evidence of significant recruitment (Humphries et al. 1999) and so, by itself, spawning is not an indicator of flow impacts on population dynamics.

The Cat 1 annual census aims to monitor the effects of flows on survival rates, hence on the dynamics of populations. However, its weakness is that longer periods of data-collection may be required to achieve sufficient sensitivity to link flow events to population dynamics. As each year of data accrues we expect the sensitivity of population models to the effects of flow to increase. In addition, the Cat 1 annual census has limited ability to determine the effects of particular features of hydrographs.

Table 1 shows how the key monitoring activities, each with their strengths and weaknesses, are being spread within and among selected areas. As is the case with any sound investment strategy, our strategy in LTIM was to spread the risk of not being able to answer the core evaluation questions presented in Section 2.1. The distribution of effort outlined in Table 1 was aimed at achieving a good balance between investment in (a) short-term indicators based on single population processes; and (b) long-term indicators based on estimation of population response.

**Table 1.** Table highlighting data collected within each area. ‘Cat’ refer to category of sampling methodology (Hale et al. 2013). Filled cells indicate the sampling methods of the far left column are being implemented within that Selected Area. The four sampling categories themselves are briefly explain in the text, with more detail available in Hale et al. (2013).

	Goulburn	Edward-Wakool	Murrumbidgee	Lachlan	Gwydir	Lower Murray	Warrego-Darling
Cat 1 – Annual censuses							
Cat 1 – Spawning response							
Cat 2 – Movement response							
Cat 3 – Various indicators							

## 3.2 Analysis and modelling approach

### 3.2.1 Analysis and modelling activities

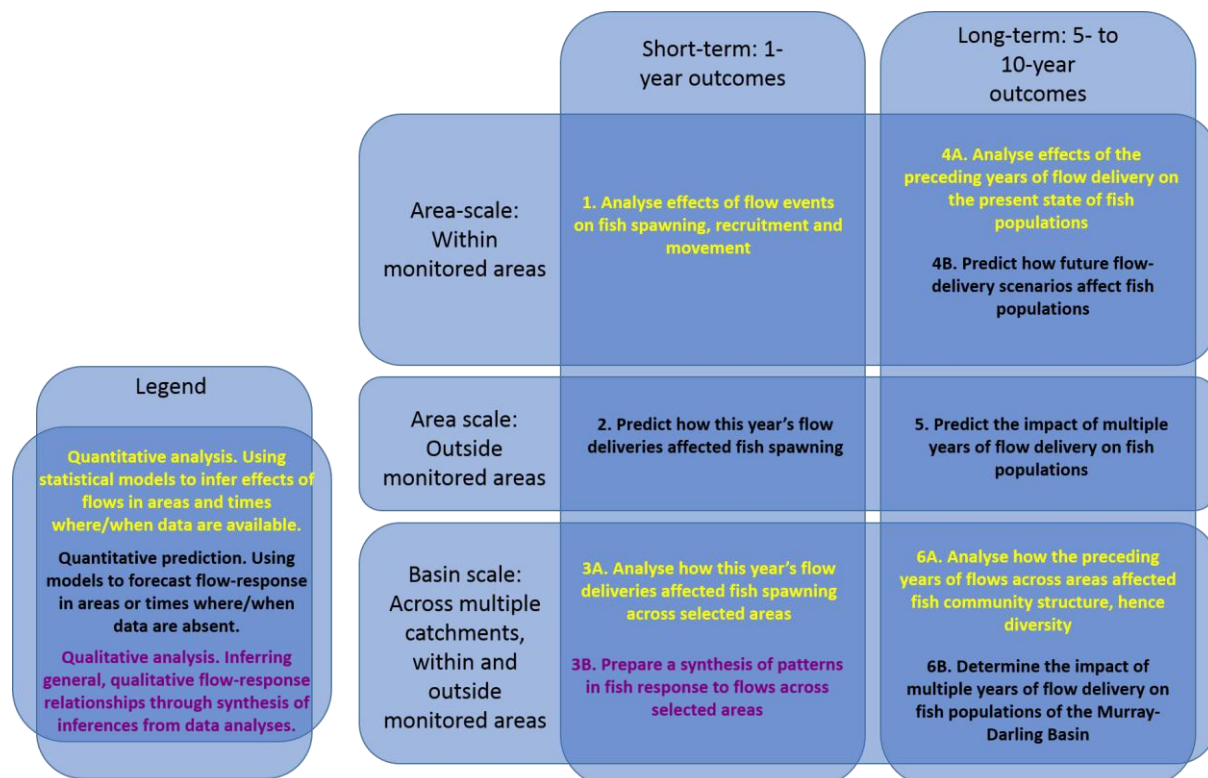
The broad evaluation questions of Section 2.1 were further decomposed (Figure 6) into specific activities. This decomposition was done to:

- inform development of methods;
- help to more specifically define scope;
- help delineate the analysis and prediction activities of different scientists working on fish monitoring within LTIM;
- devise a fish basin matter work-plan for modelling and analysis over the first 5 years of LTIM.

Three types of activity are proposed for evaluating flow outcomes for fish within LTIM (Figure 6):

- **Quantitative analysis.** This form of analysis involves using statistical models to infer impacts of flow in areas and times where/when data have been collected through monitoring.
- **Quantitative prediction.** Use of mathematical models to predict the effects of flows on fish in areas and/or times where LTIM data are unavailable at the time of prediction. The mathematical models used for prediction may be statistical models (Gelman and Hill 2006), or more mechanism-rich process-based models (Rastetter et al. 2003).
- **Qualitative analysis.** Inferring qualitative flow-ecology relationships through review and synthesis of selected area reports and the broader literature.

The nine activities can be classified into one of six groups, which are defined by the spatial and temporal scales of evaluation (Figure 6). These activities are explained below. Provides some definitions of expressions used throughout Section 3.2.



**Figure 6.** 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.

**Table 2.** Definitions of certain terms used throughout Section 3 of this report, which describes the analysis and modelling approach.

Spatial extent	Spatial scale has two primary components: grain and extent (Kotliar and Wiens 1990; Levin 1992; O' Neill 2001; Turner et al. 1989; Wiens 1989). We make no reference to grain in this report. Spatial extent refers to the area covered by samples.
Selected area	An LTIM selected area is a segment of a river and its floodplain within the MDB, chosen for monitoring ecological response to flows within LTIM. Spatial extent varies across selected areas. The extent of selected areas ranges between ca. 50 and 200 km.
Area-scale	Any prediction or analysis activity taking place at the 'area-scale' concerns ecological response within a river-floodplain segment up to 200 km in length. This aligns closely with Fausch et al.'s (2002) definition of 'segment-scale'.
Basin-scale	Any prediction or analysis activity that takes place at the 'basin-scale' concerns ecological response across multiple (more than one) river catchments. The LTIM basin-scale is analogous to Fausch et al.'s (2002) 'drainage-basin scale'. Basin-scale analyses do not necessarily imply analysis of flow response at the spatial extent of the entire MDB.
Basin matter team	The fish basin matter team is a group of scientists collecting and analysing LTIM data throughout the MDB, across seven selected areas; they comprise the authors of this document. Further details in Appendix A.
Selected area team	Selected area teams are groups of scientists responsible for monitoring and evaluation of ecological outcomes within each of the seven selected areas. Accordingly, there are seven selected area teams.

## 1. Analyse the effects of flow events on fish spawning, recruitment and movement, within LTIM selected areas.

Spatial scale and location. Area-scale and within monitored areas.

Temporal scale. Flow events over a year.

Analysis of data, or prediction? Quantitative analysis of LTIM data.

When will activity begin? This activity is carried out by selected area teams. Reporting against this activity will be carried out by selected area teams from 2016, when reporting on the 2014-15 flow delivery year.

Description. This activity involves determining how hydrographs within individual selected areas, within individual flow-delivery years, affected spawning, movement, and recruitment. Inferences will be gleaned from data collected using Cat 3, 2 and 1 sampling methods. Inferences will be provided in annual selected area reports and the approach to analysis may be area-specific. Annual basin matter reports will qualitatively analyse outcomes across areas as part of the annual synthesis (Activity 3B).

**Risks and their management.** We do not comment on risk management of Cat 3 methods, which are explained and justified in the work-plans corresponding to individual Selected Areas.

With respect to fish movement inferences arising from Cat 2 methods, the risk of not being able to determine the impacts of flow on fish movement is low. Of all the indicators used to determine impacts of flow on fishes, movement, as monitored with acoustic arrays, is the most sensitive.

A key risk to detecting larval response to flows is not having sufficient data points that span the hydrograph. Part of managing this risk is achieving expert consensus on the methodological approach, which was achieved at the 2016 annual forum. From a basin matter perspective, this risk will also be managed by combining data from all areas using multilevel regression methods, thus boosting inferential power (Gelman and Hill 2006).

## **2. Predict how this year's flow deliveries affected fish spawning (outside LTIM selected areas)**

**Spatial scale and location.** Area-scale, outside LTIM selected areas.

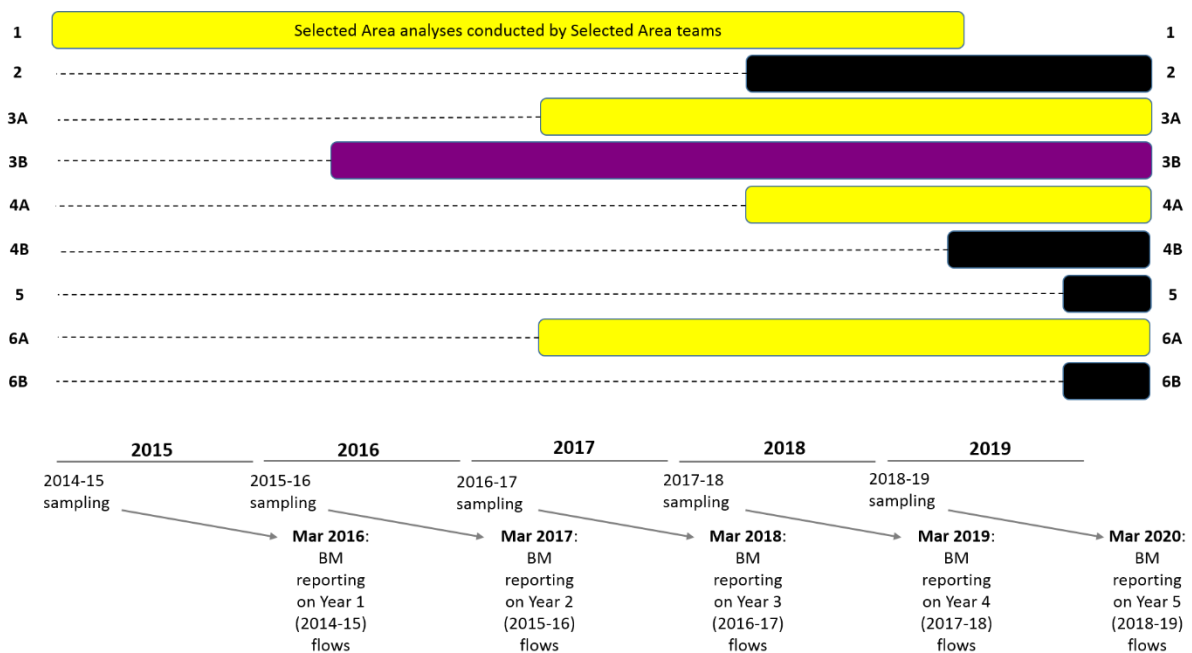
**Temporal scale.** Flow events over a year.

**Analysis of data, or prediction?** Quantitative predictions, where LTIM data have been used for parameter estimation.

**When will activity begin?** The first year of predicting spawning response to flows in unmonitored areas will be 2018, following three years of data collection for model parameterisation (Figure 7).

**Description.** Statistical models will be developed that predict either probability of occurrence, or larval abundance, as a function of key aspects of the hydrograph (e.g. rate of increase in discharge) and non-hydrological factors (e.g. temperature). The types of statistical models we will use are outlined in Activity 3A, below. Following parameter estimation, the models will then be used to simulate the possible spawning outcomes in response to flows in certain unmonitored areas of interest, where the appropriate environmental data exist. Data for parameter estimation will come from any categorised method of collecting fish larvae across six selected areas.

**Risks and their management.** Predictions are always possible, so the risk here is not whether a prediction can be made *per se*, but producing predictions that are very inaccurate, hence unhelpful. Inaccurate predictions can be avoided by ensuring sufficient data collection and model parameterisation precedes prediction. By suggesting delivery of this activity in Year 3 (2018) we have attempted to find the right balance between advancing evaluation of flow outcomes while reducing risk of unhelpful predictions.



**Figure 7.** Gantt chart of analysis and prediction activities of Figure 6.

### 3A. Analyse how this year's flow deliveries affected fish spawning across LTIM selected areas

Spatial scale and location. Basin-scale, drawing upon data from six LTIM selected areas.

Temporal scale. Flow events over a year.

Analysis of data, or prediction? Quantitative analysis using statistical models.

When will activity begin? The basin matter reports from 2017 onwards will include analyses of flow impacts on spawning across all areas (Figure 7).

Description. Unlike Activity 2, here we will use statistical models to analyse LTIM data and draw inferences concerning observed impacts of flows over the preceding year. Here we are concerned with actually happened, not what we predict would have happened under a set of assumptions. Using larval abundance data collected across all six areas we will use models to infer impacts of hydrology on spawning outcomes across the six selected areas. This analysis is considered a 'basin-scale' analysis because we will be concerned with inferences about response across multiple catchments throughout the Basin.

The statistical models that we plan on using are broadly referred to as multilevel or hierarchical regression models (Gelman and Hill 2006), and include generalised linear and additive models (Zuur et al. 2009). Such models have been used for determining flow impacts in the past (Webb et al. 2010), including impacts on spawning of riverine fishes (King et al. 2016).

Risks and their management. See risks to detecting spawning response in Activity 1. In addition, a risk associated with this activity is uncertainty in the statistical models that erode our ability to differentiate time series of larval abundance. Specifically, because we ultimately aim to isolate the effects of Commonwealth environmental water, we need to contrast the observed time series of larval abundance with that predicted to occur in the absence of Commonwealth environmental water (the 'counterfactual' time series; this type of analysis was briefly discussed at the beginning of Section 2). This risk is partly managed by LTIM's capacity to draw data together from multiple

selected areas, thus increasing the predictive power of models. Further, we have aimed to have sufficient data points that span the hydrograph each year, such that predictor variables have a domain that covers as much of the hydrological variability as possible.

### 3B. Prepare a synthesis of patterns in fish response to flows across selected areas

Spatial scale and location. Basin-scale, drawing upon inferences reported in all selected area annual reports.

Temporal scale. Flow events over a year.

Analysis of data, or prediction? Qualitative analysis through synthesis.

When will activity begin? From 2016 onwards (Figure 7).

Description. Basin matter reports will include a qualitative synthesis of outcomes across all selected areas, where inferences are simply gleaned from annual selected area reports.

Risks and their management. This is a review exercise and so there is essentially minimal risk. Risks associated with developing the data-based inferences that serve as input to this synthesis are dealt with under other activities.

### 4A. Analyse the effects of the preceding years of flow delivery on the present state of fish populations

Spatial scale and location. Area-scale, analysing LTIM data collected within selected areas.

Temporal scale. Flow events over multiple years, from the 2014-15 delivery season, up to the year of reporting.

Analysis of data, or prediction? Quantitative analysis of survival, recruitment and condition.

When will activity begin? The annual basin matter report will include analysis of the effects of flow on transition rates from 2018 onwards (Figure 7), following the 2014-15, 2015-16 and 2016-17 delivery years. As transition rates are estimated across years, this will give us 6 (areas) x 2 (inter-annual periods) = 12 rate estimates per cohort (which may be a 'stage' or an age) to be modelled as some function of flows, as of 2018.

Note, however, that we will be reporting on population structure and condition within all six selected areas from Year 1, 2016.

Description. This involves quantitative analysis of the links between flows and (a) changes in population composition and size and (b) mean individual condition (length:weight). The objective here is to use each year of LTIM census data (from 2014-15 onwards) to develop functions that link changes in population state to hydrographs, such that we may improve our understanding of how multi-year flow scenarios generate population-wide outcomes that accumulate over time. We will undertake this analysis within selected areas where quality data is being collected. If, however, we view each selected area as a sample from the Basin, then this activity could equally be considered a basin-scale analysis. Indeed, outputs from this activity are the key inputs to activities associated with answering Activities 5 and 6B (see below).

With respect to large-bodied species, the key parameters we wish to estimate are age- or stage-specific transition rates. Transition rates can be scalar values or functions that describe how a cohort transitions to the next cohort over an annual cycle. In the case of an age-structured approach, the transition rate for the 1+ cohort,  $\alpha_{1+}$ , can most simply be viewed as a ratio (Haddon 2011; Quinn and Deriso 1999):

$$C_{2+,t+1} = \alpha_{1+} C_{1+,t} \rightarrow \alpha_{1+} = C_{2+,t+1} \cdot C_{1+,t}^{-1}$$

where  $C$  is catch-per-unit-effort of a cohort. These transition rates will be proxies for survival, as they will not necessarily be bound on  $[0,1]$  (as survival rates should be), due to differences in electrofishing sampling efficiency across ages. Transition rates can then be modelled against aspects of the hydrograph. Multiple transition rates will be estimated and modelled against flow. Any significant relationships between flow and individual transition rates will greatly advance our understanding of flow impacts in Australia. In addition, we aim to integrate demographic rates using structured population models, such that we may improve our understanding of flow impacts on entire populations (Anderson et al. 2006; Caswell 2001; Sakaris and Irwin 2010; Shenton et al. 2012; Stratford et al. 2016; Yen et al. 2013).

If we wish to understand flow impacts on age- and stage-structure, we need to be able to infer age-structure from our sample. Due to heavy constraints on the number of individuals we are able to sacrifice for data, we will retain otoliths of a subsample of the large-bodied individuals captured (Hale et al. 2013). These length-age data will be coupled with annual length-structure samples to convert lengths to ages while taking full account of the uncertainty associated with undertaking such an exercise (Quinn and Deriso 1999 ch. 8).

It's worth noting here that if we don't wish to make any assumptions concerning the age- or stage-structure of the population, then we have two very solid alternatives: First, length-based matrix modelling approaches are available (Kirkpatrick 1984; Sauer and Slade 1987). In such a case we would be aiming to model transition rates of CPUE in length cohorts as a function of flows. Second, we may model temporal changes in the length-composition of the populations using functional regression (Stewart-Koster et al. 2014; Yen et al. 2015).

With respect to mean individual condition within populations, a time series of population-wide mean condition can be generated by reducing population-wide condition to a single scalar value using mixed-effects regression (Stoffels et al. 2015). These scalar values can then be entered as responses in functional regressions that model changes in condition as a function of flow (Yen et al. 2015).

Populations of our small-bodied target species are mostly comprised of 0+ individuals (MEPs; personal communication). Therefore, there is little to be gained from utilising structured population models to project the dynamics of those populations. Instead, we will utilise standard time series models (Box et al. 2008; Gelman and Hill 2006), where the key data requirement is precise estimation of population-level CPUE within an area, within each year.

***Risks and their management.*** This activity, and those that are dependent on it (Activities 4B, 5 and 6B), are the most challenging activities within LTIM's fish basin matter. They are challenging because they involve understanding how multiple fish population processes, each interacting with multiple flow events, are integrated to drive population dynamics. Noting that we are managing the basin-matter-wide risk through a balanced investment portfolio (see Section 3.1), we suggest there are four sources of risk associated with this activity: insufficient age-length data; insufficient flow variation for parameter estimation; stocking effects and large-scale movement of target species.

**Insufficient age-length data.**—If an age-structured modelling approach is taken, then such an approach is dependent on methods used to estimate age composition of the fish population. Although these methods are very well developed (Aanes and Volstad 2015; Fridriksson 1934; Gascuel 1994; Kimura 1977; Kimura and Chikuni 1987), they are dependent on having good samples of otoliths from the particular sub-populations for which demographic parameters are sought. That is, we require large sample sizes of otoliths from within selected areas. Exactly how large will depend on an analysis of how great variability in growth is both (a) between selected areas; and (b) within

areas, through time. These analyses will take place in due course, as more LTIM data comes to hand, but for now we have requested (Hale et al. 2013):

- 100 otoliths from Murray cod and golden perch during the first five years of LTIM, from all six selected areas;
- 100 otoliths from bony herring from four selected areas every year.

We perceive no significant risk with respect to bony herring, but there is a risk that 100 otoliths for the remaining two large-bodied species yields projections with undesirable confidence intervals (see Section 3.2.1).

We will manage this risk by working with MEPs to source as much age-length data as possible from Murray cod and golden perch populations within selected areas. These data may come from historical data collections from selected areas, or be supplemented by other projects currently taking place within selected areas.

**Insufficient flow variation for parameter estimation.**—We wish to estimate the effect of spring-summer hydrographs on transition rates. Essentially, different hydrographs can be viewed as different experimental treatments and—as is the case with any experiment—if our treatments don’t span a broad range of hydrograph types, then we obtain a very narrow view of how flow affects transition rates.

Compounding this potential risk is the fact that five years is not a long time when it comes to estimating the key demographic parameters of an animal population (Caswell 2001). It would be wrong to hide this fact, and we feel it is necessary to state it here for the sake of transparency. The objective of achieving predictive capacity within LTIM is ambitious, worthwhile and is essentially state-of-the-art (Stewart-Oaten and Bence 2001; Wolkovich et al. 2014). Hence this risk is something to be aware of, but not something that should cause us to abandon the objective. *One could suggest this risk is best managed by managing our expectations.* During 2016-17 we aim to undertake precision analyses to ensure that LTIM methods are fit for the purposes of estimating parameters of predictive models. If these analyses confirm the methods are appropriate, then we have managed this risk as well as possible. From there we must await sufficient LTIM data to accrue so that we meet the objective of prediction and population-level evaluation in the long term.

**Stocking.**—Murray cod and golden perch are regularly stocked as 0+ individuals throughout the catchments where LTIM monitoring is taking place. It is likely, therefore, that inter-annual changes in 0+ abundance will reflect at least two signals: natural recruitment and stocking (Crook et al. 2015). We will manage this risk in two ways. First, with the assistance of the MEPs we aim to collate as much information as possible on stocking intensity, timing and location, so that these data can be included as variables in any model aiming to disentangle flow impacts on recruitment. Second, if we have little confidence that 0+ CPUE data is informative with respect to flow impacts, then we can focus our efforts on transition rates, say, from 0+ upwards. We would undertake such analyses under the assumption that, once in the population, a stocked fish is subject to the same flow impacts as naturally-recruited individuals.

**Movement.**—With respect to golden perch, in particular, there is growing evidence that individuals may have extremely large ranges, especially as juveniles. In estimating transition rates we must assume that individuals remain within a selected area over—at a minimum—two annual censuses, such that flow-transition functions reflect the hydrology of that area. Sites within areas span 100 km segments, and so if most individuals are moving distances greater than 100 km every year, then estimated transition rates will not necessarily be due to environmental conditions within the monitored area.

Cat 3 and 2 LTIM methods to monitor movement will greatly improve our understanding of movement rates and magnitudes of large-bodied target species. It follows that our risk management strategy will be dependent on what these Cat 3 and 2 data yield. It may be, for example, that once golden perch achieve a certain size they establish a home range (Crook 2004a; b), and transition rates from that size onwards are largely a function of environmental conditions within an area. In this instance we would focus on estimating flow-transition functions for those cohorts that are most likely to remain within an area for 2 or more years.

Alternatively, if individual golden perch really are as mobile as some suggest, then one could suggest our sample from a 100 km segment is a reasonable approximation of the catchment-wide population, in which case the hydrological data used to develop flow-transition functions is sourced from a spatial scale exceeding that of the selected area.

In any case, golden perch are only one target species among several large- and small-bodied fishes. It follows that, basin-matter wide, golden perch movement does not pose an unmanageable risk to this particular analysis activity.

#### **4B. Predict how future flow-delivery scenarios affect fish populations**

Spatial scale and location. Area-scale, within selected areas.

Temporal scale. Flow events over multiple years, projecting population response over a five-year time horizon.

Analysis of data, or prediction? Quantitative prediction of changes in population state.

When will activity begin? 2019, following four years of flow delivery (Figure 7).

Description. This activity involves using models developed as part of 4A to project how target fish populations will respond to multi-year flow management scenarios over a 5-year time horizon. This will be carried out within selected areas, where quality data are available, hence in areas of the Basin where the uncertainties of our projections can be minimised.

Risks and their management. The risks of Activity 4A apply here, too.

#### **5. Predict the impact of multiple years of flow delivery on fish populations (outside LTIM selected areas)**

Spatial scale and location. Area-scale, outside LTIM selected areas.

Temporal scale. Flow events over multiple years, projecting population response over a five-year time horizon, from 2014-15 through to 2018-19 flow delivery years.

Analysis of data, or prediction? Quantitative prediction of changes in population state.

When will activity begin? As this activity involves generalising the area-specific models developed for Activity 4B, we have allowed one year after that activity proceeds to generalise parameter estimates. Hence this activity will take place in 2020 (Figure 7).

Description. The models developed as part of Activity 4a will facilitate projections of population response to flows in areas that are not in the set of LTIM selected areas. These projections will be made only in areas where good environmental data exist (e.g. appropriate hydrology data). By 'multiple years' we mean from the 2014-15 delivery year onwards. Improved capacity to predict the response of fish populations to flows delivered to unmonitored areas of the Basin is a core objective of LTIM (Gawne et al. 2013), set in response to the needs of the CEWO.

*Risks and their management.* The salient risk associated with this activity is imprecise parameter estimation, and so the risks of Activity 4A apply here.

## 6A. Analyse how the preceding years of flows across areas affected fish community structure

*Spatial scale and location.* Basin-scale, utilising community structure data from six LTIM selected areas.

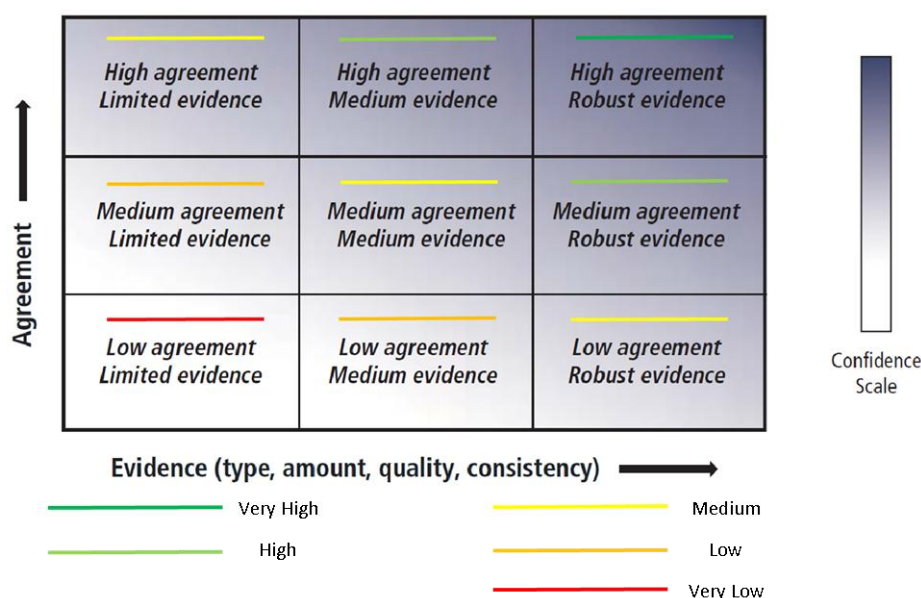
*Temporal scale.* Flow events over multiple years.

*Analysis of data, or prediction?* Quantitative analysis of changes in community structure.

*When will activity begin?* This activity involves routine analyses and requires two years of data collection at a minimum, so this activity will proceed from the second year of reporting onwards (2017 onwards; Figure 7).

*Description.* For this quantitative analysis activity the aim is to use standard multivariate analysis techniques (Anderson 2001; Anderson et al. 2008) to determine how coarse gradients in flow dynamics across selected areas affect magnitudes and directions of change in fish community composition. It is considered a basin-scale analysis because each selected area is essentially considered a treatment in a broader basin-wide flow-gradient study.

*Risks and their management.* We anticipate no substantial risks associated undertaking this analysis activity.



**Figure 8.** The IPCC matrix for qualitative assessment of uncertainty concerning predictions at large spatial scales. In the case of LTIM, evidence strength (x-axis) increases when predicted fish response to flow is associated with narrow confidence bands and agrees with general observed trends obtained from data from either LTIM or other monitoring programs. Agreement (y-axis) increases when observed and predicted trends match across multiple catchments, increasing the confidence of flow-related outcomes at the spatial extent of the Basin.

## 6B. Determine the impact of multiple years of flow delivery on fish populations of the Murray-Darling Basin

Spatial scale and location. Basin-scale, drawing inferences about impacts of flows on fish populations both within and outside of LTIM selected areas.

Temporal scale. Flow events over multiple years.

Analysis of data, or prediction? Quantitative analysis and prediction of changes in population state.

When will activity begin? This activity requires the first five years of LTIM data. Accordingly, we will report against this activity in the final report of the first five years of LTIM, during 2020 (Figure 7).

Description. Although considered a quantitative prediction activity in Figure 6, this activity really involves both prediction and analysis. It is just as challenging as Activity 4A, and uses models developed by 4A. CEWO have requested an evaluation of how watering actions throughout the Basin have affected fish populations. Undertaking this activity in the final year (Figure 7) will be a two-step process:

First, using models of population response to flow, developed as parts of Activity 4A, we will make predictions of the outcomes within a certain number of catchments throughout the MDB. To be included in this Basin-wide analysis, catchments must (a) have yielded good hydrological data over the first five years of LTIM; and (b) must also be yielding annual censuses of fish population structure either as part of LTIM or another program. The predictions of population outcomes will encompass the first five years of watering actions within LTIM.

Second, we will use both LTIM data and fish population data collected under the Basin Authority's monitoring program to compare *observed* changes in fish populations from 2014-15 through to 2018-19 with those changes *predicted* to occur from fish flow-response models. If observed changes over this five year period match what we would expect on the basis of modelled flow impacts then we may infer flow impacts throughout the Basin.

Any inferences of Basin-scale impacts made using this approach will be assigned a confidence level using the framework of the Intergovernmental Panel on Climate Change (Mastrandrea et al. 2010). In the case of LTIM, evidence strength (x-axis; Figure 8) increases when predicted fish response to flow is associated with narrow confidence bands and agrees with general observed trends obtained from data from either LTIM or other monitoring programs. Agreement (y-axis; Figure 8) increases when observed and predicted trends match across multiple catchments, increasing the confidence of flow-related outcomes at the spatial extent of the Basin.

Risks and their management. The risks of Activity 4A apply here also.

### 3.2.2 Hydrological data requirements

Fish response models will be dependent on:

1. A time series of discharge for the zone within which fish sampling is taking place (the zone within which the ten basin-matters monitoring sites are located).

Additional hydrological information would improve our ability to understand how flow management affects population processes:

2. A time series of wetted area (channel and floodplain) (a) within the monitoring zone and (b) over some area upstream of the monitoring zone. The spatial extent (e.g. the river and its floodplain for 20 km upstream of zone) of the wetted area data upstream of the monitoring

zone is yet to be determined. We would use these data to test hypotheses concerning the impact of extent of floodplain inundation on transition rates;

3. In addition to wetted area within the river-floodplain landscape, data on the volumes of water returning from the floodplain into the channel. Such return flows may play an important role in driving recruitment and survivorship of fishes, by providing a spatial subsidy of energy to in-channel food webs. It is currently not known how feasible these data might be.

Each of these time series essentially needs to be decomposed into two parts: time series within and without Commonwealth Environmental Water.

Temperature is being logged within each area, and temperature is an essential additional important input to models.

### **3.2.3    *Links with other basin matters***

There is an *a priori* objective to link fish response to flows with ecosystem metabolism dynamics (river metabolism basin matters are being lead by Dr Mike Grace). There is currently much global interest in the role that ecosystem energetics plays in driving fish population dynamics, so LTIM presents a great opportunity to test the hypothesis that fish productivity in river-floodplain systems is carbon-limited.

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## 5 Appendix A. Basin matter team

The basin matter team is as follows:

Rick Stoffels, Nick Bond, Carmel Pollino (CSIRO and La Trobe University; MDFRC): Basin matters leadership; analysis and prediction at the basin-scale.

Gavin Butler (NSW Fisheries): Scientist leading monitoring within the Gwydir and Warrego-Darling Selected Areas.

Ben Broadhurst (University of Canberra): Scientist leading monitoring within the Lachlan Selected Area.

Jason Thiem (NSW Fisheries): Scientist leading monitoring within the Murrumbidgee Selected Area, as well as certain aspects of monitoring within the Edward-Wakool Selected Area.

Nicole McCasker and Keller Kopf (Charles Sturt University): Scientists leading recruitment and spawning monitoring within the Edward-Wakool Selected Area.

Wayne Koster (Arthur Rylah Institute). Scientist leading fish monitoring within the Goulburn Selected Area.

Brenton Zampatti and Qifeng Ye (SARDI). Scientists leading fish monitoring within the Lower Murray Selected Area.