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Monitoring of environmental flow outcomes in a large river basin: The Commonwealth Environmental Waterholder's Long-Term Intervention in the Murray Darling Basin, Australia

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Abstract

The Murray-Darling Basin in south-eastern Australia contains over 70,000 square kilometres of wetlands and floodplains, many of which are in poor condition. In response, Australian governments have committed to a major restoration program, the Murray-Darling Basin Plan that includes management of 2,750Gl of environmental water to protect and restore aquatic ecosystems. The restoration is being undertaken within an adaptive management framework that includes monitoring the outcomes of environmental flows in seven river valleys. This paper provides an overview of the five-year monitoring project and some preliminary results. Monitoring design considered the Basin Plan's environmental objectives, conceptual models of ecosystem responses to flow and an outcomes framework linking flow responses to the environmental objectives. Monitoring indicators includes ecosystem type, vegetation, river metabolism and fish. Responses are evaluated to identify the contribution of environmental flows to Basin Plan environmental objectives, and continual improvements in management. The program is unique in that it seeks to monitor long-term outcomes of environmental flows at the river basin scale. Despite many challenges, the monitoring has become a key part of the adaptive management of environmental flows in the Murray-Darling Basin.

Keywords

Adaptive management, floodplain-river, wetland, restoration, fish, vegetation, metabolism,

1. Introduction

Environmental flows are widely used to protect or restore river ecosystems whose flow regimes have been modified to meet growing human demands. Across the world, programs such as those in the Everglades (Osborne, Fitz, & Davis, 2017), Colorado River (Lovich & Melis, 2007), and the European Water Directive (Hering et al., 2010) have sought to protect environmental values through the allocation of environmental water. In the Murray-Darling Basin (Basin) in south-eastern Australia, a major restoration project, the Murray-Darling Basin Plan (Plan), is being undertaken to protect and restore water dependent ecosystems, in part, through the allocation of environmental flows (Hart, 2016).

The management of environmental flows at basin scales is important because some ecological processes operate at basin scales (McCluney et al., 2014). Managing environmental, social and economic objectives at the basin scale are increasing (Taft & Evers, 2016). There is, however, limited experience of managing environmental flows at basin scales because many large-scale environmental flow programs are achieved via releases from individual dams (Olden et al., 2014). As a consequence, the management of environmental flows at the basin scale has been identified as an emerging challenge (Poff, Tharme, & Arthington, 2017).

Monitoring the outcomes of environmental flows is a key step in the adaptive restoration of rivers, wetlands and floodplains (King et al., 2015). Monitoring outcomes of environmental flows, when undertaken, varies widely. The types of questions asked range from short-term testing of hypotheses (Melis, Walters, & Korman, 2015) through to long-term changes in condition (McDonald et al., 2017). There is also considerable variation in the selection of indicators (Doledec, Forcellini, Olivier, & Roset, 2015) and the scale over which outcomes are monitored (Walters, Korman, Stevens, & Gold, 2000). This variation reflects diverse objectives, rivers, environmental flows and outcomes. This variation in conjunction with uncertainty around large-scale outcomes of environmental flows (Konrad, Warner, & Higgins, 2012) means that the design and implementation of basin-scale monitoring of environmental flows should be undertaken within an adaptive management framework (Westgate, Likens, & Lindenmayer, 2013).

This paper describes the major steps in designing the Long-Term Intervention Monitoring (LTIM) of environmental flows in the Murray Darling Basin, Australia. The outcomes of the first two annual evaluations are also presented. The Australian Water Act (2007) established the Commonwealth Environmental Waterholder (CEWH) and Waterholder's Office (CEWO) to manage the Commonwealth Government's environmental water holdings with the objective of contributing to achievement of the Murray Darling Basin Plan (Plan) environmental objectives. The Plan is required to establish an adaptive management framework. In response, the CEWO developed a monitoring, evaluation, reporting and improvement (MERI) framework (CEWO 2013b) which provided the starting point for development of the LTIM project. The project's two primary objectives were to enable the CEWO to report on the outcomes of environmental water allocations, including their contribution to achievement of Plan objectives and to develop new knowledge in support of adaptive management.

Approaches to monitoring the outcomes of environmental flows are highly variable (Walters, Korman, Stevens, & Gold, 2000, Doledec, Forcellini, Olivier, & Roset, 2015). There are three characteristics of the LTIM project that make it unique. The first is that it was designed within a legislated objective hierarchy that started with basin-scale objectives and targets to which environmental flows were expected to contribute. Second, in line with Plan objectives, the LTIM project is designed to quantify both area scale outcomes (river reaches (100kms) and associated wetlands and floodplains) and their contribution to achievement of basin-scale objectives; i.e. achieve outcomes beyond the immediate influence of the environmental flow. There are three pathways by which outcomes may be significant at the basin scale: i) small-scale outcomes may be significant in their own right, ii) combine with other outcomes or iii) propagate to be significant at the Basin scale (Gawne et al., 2018). The third characteristic of the LTIM project is that it seeks to quantify both short (<1y) term outcomes of discrete flow events, and examine longer term (1-5y) responses to the flow regime that may include multiple, varied environmental flows (Gawne et al., 2016, 2017). Environmental flow monitoring is often focussed on discrete flow events (Olden et al., 2014) and while there are instances of long-term monitoring (Lamouroux & Olivier, 2015; Robinson, 2012), considerable uncertainty remains concerning environmental flow's capacity to achieve sustained changes in condition, particularly at the basin scale over long time frames (Thompson, Bond, Poff, & Byron, 2018).

2. Methods

2.1 The Murray-Darling Basin

The Murray Darling Basin (Basin) covers just over 1 million km^2 in S.E Australia, or 14% of the total area of the continent (Crabb, 1997). The Basin spans four states and the Australian Capital Territory and is comprised of 25 river valleys (Stewardson & Guarino, 2018). According to the Australian National Aquatic Ecosystem (ANAE) mapping project, the Basin contains over 200,000 aquatic ecosystems, including approximately 8000 lakes and 34,000 floodplain wetlands (Brooks, 2017). The ecological character of these systems varies widely across the Basin with a-seasonal flows in the northern Basin, being dominated by monsoonal floods and annual discharge varies between 1% and 10 times the long-term average. In contrast, in the southern Basin, flows are seasonal with floods occurring in late winter and spring and annual discharge varying from 30% to 3 times the long-term average. The Basin's variable ecosystems and flow regimes support a broad range of flow dependent species and ecological communities. These include a large number of nationally and internationally significant plant and animal species, including 95 species listed as threatened under national or State legislation (Leblanc, Tweed, Van Dijk, & Timbal, 2012).

Water resources within the Basin have been extensively developed with around 42% of annual runoff (31,000Gl) being diverted. Regulating the Basin's variable water resources has required infrastructure development ranging from a series of large headwater dams, channels, floodplain levies, in-channel weirs and a plethora of minor regulatory structures across the Basin (Steinfeld & Kingsford, 2013).

The development of Basin water resources has been associated with declining condition of water dependent ecosystems (Walker, 1992) and declining water security (Connell & Grafton, 2008). In response, the Commonwealth Government passed the Water Act (2007) which required establishment of the Murray-Darling Basin Authority (MDBA) and development of the Plan that seeks to ensure a 'healthy and working' Basin 'that includes healthy and resilient ecosystems'. A key component of the Plan was the identification of a sustainable diversion limit (SDL) based on the water required to sustain environmental values (Swirepik et al., 2016). The Plan identified that 2,750 GL (annual long-term average) of surface water was to be recovered for environment use to achieve an Environmentally Sustainable Level of Take (ESLT) (Basin Plan 2012). The recovered water is managed by the Commonwealth Environmental Waterholder (CEWH), to contribute to the achievement of Plan objectives, targets and annual watering priorities identified by the MDBA.

The CEWO currently holds 2,106 GL of environmental water (annual long-term average as at 31 December 2017) to allocate to achieve biodiversity, ecosystem function and resilience outcomes. The CEWO entitlements are not evenly distributed among the river valleys with holdings highest in the Warrego River (24% of mean annual discharge), 14% in the Condamine-Balonne and Murrumbidgee Rivers, but less than 3% of mean annual discharge in 12 of the 25 rivers. Environmental flow entitlements are also held by the State and Territory governments, the MDBA and other smaller environmental entities.

2.2 Project Scope

The LTIM project objective is to evaluate the contribution of Commonwealth environmental water outcomes to achieve Plan environmental objectives within the context of a working Basin (Basin Plan 2012, Section 5.03). These are to:

(a) protect and restore water-dependent ecosystems of the Basin;

(b) protect and restore the ecosystem functions of water-dependent ecosystems; and,

(c) ensure that water-dependent ecosystems are resilient to climate change and other risks and threats.

The evaluation had two functions, the first being to enable the CEWH to report on the outcomes of environmental flows across the Basin and the second was to support the adaptive management of the Commonwealth's environmental water. The project is designed to evaluate the outcomes of those decisions and the contribution of those outcomes to achievement of Basin Plan objectives and not water allocation decisions. The diversity of rivers, ecosystems, environmental water holdings and delivery methods all needed to be considered in the monitoring design. It was clear that even with the resources available, monitoring all environmental flows delivered by the CEWH was not feasible. As a result, it was decided to focus activities on Commonwealth environmental water at seven 'Selected Areas' (Figure 1).

The Selected Areas were regions containing high value aquatic ecosystems that broadly represent water dependent ecosystems across the Basin and are also likely to receive multiple allocations of environmental flow over the project's five-year life. The LTIM selection process also sought Areas that would complement existing monitoring programs; this meant that important wetlands such as Hattah Lakes and Macquarie Marshes were not included in LTIM as they already had monitoring programs in place.

At the end of each water year (July to June), the monitoring data are used to inform an evaluation of outcomes at each Selected Area. The outcomes also consider ways that flow management could deliver improved outcomes in the future as part of the process of adaptive management. The Selected Area evaluations provided one of the major inputs to the Basin evaluation. The Basin scale assessment evaluated outcomes from all environmental water delivered over the course of the year to identify the overall contribution of Commonwealth environmental flows to achievement of the Plan's environmental objectives.

2.3 Conceptual Framework

The LTIM project design was based on a collective understanding of the contribution environmental flows would make to achievement of Plan objectives. This required the integration of four major inputs to predict the likely ecological outcomes of environmental water use:

1. *An objectives hierarchy* of Environmental Water Plan objectives (EWP objectives). An objectives hierarchy recognises the nested nature of complex systems in which management actions, each with their own small-scale objectives, contribute to large scale

objectives or goals. The objectives hierarchy communicates why interventions are undertaken and the relationships between management interventions and large-scale objectives for environmental water managers, practitioners and scientists (Kingsford, Biggs, & Pollard, 2011). The hierarchy started with the Plan's objectives. The MDBA then refined these to focus on specific biotic groups and functions within the Plan and these were then translated into targets within the Basin Watering Strategy (MDBA, 2014). The LTIM project took this hierarchy and adapted it to support the requirements of the evaluation (Figure 2). Level 1 objectives were taken directly from the Plan, while Level 2 objectives were drawn from the Basin Watering Strategy and arranged to ensure consistency with the observed ecological hierarchy (Dale & Beyler, 2001).

2. *A suite of conceptual models* that use the best available science (Ryder et al., 2012) to link EWP objectives to changes in flow. Having established the objectives hierarchy, conceptual models were developed to describe our understanding of the potential role of Commonwealth environmental water in achieving those objectives. The models sought to build on earlier work undertaken in other monitoring and assessment programs including the Integrated Monitoring of Environmental Flows in the Basin (Chessman & Jones, 2001) and the Victorian Environmental Flows Monitoring and Assessment Program (Webb, Stewardson, Chee, et al., 2010) and were based on a literature review (MDFRC, 2013). Two series of conceptual models were developed. The first described causal linkages between flow and Area-scale objectives. The second series described the way that achievement of Area-scale objectives would contribute to achievement of basin-scale objectives.

The conceptual models included only relationships believed to influence outcomes (Gross, 2003) and two broad types of indicators; effect indicators that support reporting of progress against objectives and causal indicators that support evaluation and adaptive management.

3. *The major flow types* described in the Plan (MDBA, 2011) and their ecological role. The Plan classifies the hydrology of the Basin in terms of five environmentally significant flow types. The role of four of the five flow types (base flows, freshes, bank full and overbank flows) is described in terms of their influence on biodiversity, ecosystem function, resilience and water quality. In some instances, infrastructure such as pumps, weirs and regulators may be used to mimic one of the flow types identified (Figure 3). For these events, the watering objective or the flow type being simulated would be used to inform development of an appropriate outcome. The role of each of the major flow types is summarised in Table 1.

4. *Water availability*. The large variation in Basin flow regimes, regulation infrastructure and water license conditions affect the type of environmental flows that can be delivered and their characteristics (e.g. magnitude, duration). This in turn affects the ecological outcomes of environmental flows over the one-to-five-year timeframe. The CEWO flow management strategy (CEWO, 2013a) identifies a range of annual water availability scenarios. These range from very low water availability, in which the foci include protecting refuges and avoiding irretrievable damage; through to very high-water availability, in which the foci include supporting reproduction and recruitment (CEWO, 2013a). The water availability

scenarios were used to conceptualise the expected outcomes over 1-5 years, ranging from a sequence of dry to very dry years through to a sequence of wet years (Figure 4).

These inputs are used to develop a generic set of expected outcomes over both less than 1 year and one to five-year periods. The expected outcomes informed development of the Outcomes Framework (below).

2.4 Outcomes Framework

The four conceptualisations (Objective hierarchy, Conceptual models, Flow types, and Water availability) were used to develop the Outcomes Framework that summarised the broad outcomes expected from the allocation of environmental flows over an annual and one to five-year time frame. The temporal dimension could be summarised in Table form (Table 2). Alternatively, the Outcomes Framework can be represented diagrammatically to illustrate both the temporal and spatial scale over which long-term and large-scale outcomes are expected (Figure 5).

These models were important to the LTIM project as they supported identification of indicators (Niemeijer & de Groot, 2008) and the evaluation of monitored outcomes, but they also provided a useful resource for water managers, and an information source to support communication with non-technical audiences (Gross, 2003).

2.5 Reference – options and choice of modelled approach

Assessment of the outcomes of an environmental flow is dependent on having an appropriate benchmark (control or reference) against which to compare the intervention data (Angelopoulos, Cowx, & Buijse, 2017). The difficulties associated with identification of an appropriate benchmark has resulted in less than 20% of environmental flow studies including control sites (Gillespie, Desmet, Kay, Tillotson, & Brown, 2015). The LTIM project considered three options: benchmark sites for each environmental flow; a gradient design for each Selected Area; and a modelling approach, all of which were evaluated against two main criteria.

Benchmark sites would need to be independent from but similar to the treatment site in terms of flow regime, regulation (Gillespie, Desmet, Kay, Tillotson, & Brown, 2015) and condition (Thompson, King, Kingsford, Mac Nally, & Poff, 2017). It appeared likely that these sources of variation between sites would reduce capacity to identify the influence of the environmental flow at the treatment site, as previously found in another long-term environmental flow project in the Basin (Humphries et al., 2008). The second criterion was consistency. It was important that the approach could be consistently and successfully applied across the Basin to the variety of ecosystem types that would be monitored (e.g. ephemeral wetlands, permanent rivers). While there were certainly some systems for which appropriate benchmark sites could be identified, there were many where this was not the case (e.g. the junction of the Darling and Warrego Rivers is unique in the Basin).

Gradient design is an alternate to the use of benchmark sites (King et al., 2015). This utilises multiple watering events as replicates of a larger experiment examining responses along a gradient of one or more environmental flow characteristics (e.g. timing, duration). This approach was not pursued as variation in the types of environmental flows allocated each year at each selected Area posed risks in terms of the limited number of data points they would generate along the gradient, thereby reducing the power of the analysis.

The final approach considered, and subsequently adopted, was to develop models to predict the counterfactual scenario – what the outcomes would have been in the absence of environmental flows, effectively creating an artificial benchmark. This approach was considered to have several advantages. The approach was feasible, could be applied consistently across the Basin, allowed monitoring to focus on those areas receiving environmental water and that, once developed, the models would be available to support both the evaluation of outcomes at areas that were not monitored and the planning of future environmental flows. Models were available to support area-scale evaluations at some Areas, however, development of models to support basin-scale evaluation are reliant on data generated by the LTIM project and so will not be available until the latter stages of the project in 2018 and 2019. The approach to modelling varies among the indicators but includes both Bayesian hierarchical modelling which provides a great deal of flexibility and sensitivity in detecting ecological responses (Webb, Stewardson, & Koster, 2010) and intervention analysis (Box, Jenkins, Reinsel, & Ljung, 2015) that uses time-series data to model population dynamics.

2.6 Indicators and sampling method development

The development of an objective hierarchy and conceptual models identified a range of potential indicators that met some of the key requirements for indicators. All indicators were believed to be sensitive to environmental flows and would respond in a predictable manner (Dale & Beyler, 2001). In order to support achievement of the LTIM project objectives, three types of indicators needed to be identified: short-term effect indicators (to support both reporting and adaptive management objectives); short-term causal indicators (that help to explain variation in outcomes in support of adaptive management); and long-term effect indicators (to support both reporting and adaptive management objectives). Selection of the final suite of indicators was based on feedback from a series of workshops held in each Selected Area and a subsequent prioritisation process that considered each indicator's alignment with Area priorities, Basin reporting obligations and value to adaptive management. This process identified nine priority indicators (Table 3) to be monitored at all seven Selected Areas. Additional indicators were selected at a subset of Selected Areas as they are an important objective within the Area and contribute to the Area's diversity (Table 2). Details of the sampling methods are included in the Area monitoring plans available on the CEWO website (CEWO, 2017). The outcomes of these monitoring activities and the basin-wide indicators were synthesised to provide a list of the species believed to have benefited from Commonwealth environmental water across the Basin.

The information generated by the monitoring and evaluation process is aggregated in order to report against environmental objectives (Table **2**). For example, reporting on "Biodiversity" used information from three of the Basin-wide indicators; Ecosystem Diversity, Vegetation Diversity and Fish. In addition, Area specific monitoring and monitoring of collaborative watering by other projects, also contributes information on biodiversity indicators including frogs and turtles.

3. Results

3.1 Hydrology

The first two years of LTIM were similar in climatic conditions, with dry conditions and low water availability scenarios identified for most catchments across the Basin. During dry conditions, environmental water is used in many instances to support threatened species and maintain refuges, communities and functions. In the first year of LTIM (2014-15) Commonwealth environmental water contributed to two large scale floodplain watering actions, one each in Hattah Lakes and the Gwydir River system. In 2015-16 a similar volume of water was delivered to a larger number of wetland and floodplain systems with reduced extents and shorter durations for individual inundation events.

In the 2015-16 watering year, a net total of 1662 gigalitres of Commonwealth environmental water was delivered to three quarters of the Basin's catchments across 115 individual watering actions (Table 4). Over 70% of the total volume was allocated to the Lower Murray (828 gigalitres) and the Central Murray (390 gigalitres) catchments. While the majority of water was delivered as in-channel river flows (base flow or freshes), around a quarter was delivered out of the river channel as infrastructure assisted wetland watering and a small number of bank-full and overbank flows. There were also attempts to maximise the ecological benefits of environmental water by augmenting natural flow events.

3.2 Biodiversity

Three major lines of evidence were used to evaluate the contribution of Commonwealth environmental water to meeting biodiversity objectives at a Basin-scale (Hale 2017):

1. Maintaining the ecological character of internationally important wetlands listed under the Ramsar Convention – over the period 2014 – 2016, Commonwealth environmental water was delivered to half of the Basin's 16 Ramsar wetlands. There is strong evidence to suggest (from LTIM and other monitoring programs) that environmental water protected and restored the critical components, processes and services of at least four of these sites (Barmah Forest, Central Murray Forests, Hattah–Kulkyne Lakes and Macquarie Marshes). Improved condition was recorded for inundation dependent vegetation communities, and the provision of habitat and breeding opportunities for fish, waterbirds and frogs.
2. Supporting protected threatened species and communities – between 2014 and 2016, 35 species listed under national or State legislation as vulnerable or endangered were recorded at sites that received Commonwealth environmental water. While presence does not constitute evidence that a species benefited, there was good evidence that Commonwealth environmental water supported several species at multiple locations and / or important refuge sites.
3. Maintaining condition between natural flood events – while large scale ecological responses such as booms in floodplain productivity or mass waterbird breeding are facilitated only by large-scale natural floods, there is evidence to suggest that environmental water is essential for maintaining key habitats in dry periods (Bino et al. 2015, Howard et al. 2017). From 2014 to 2016, Commonwealth environmental water contributed all or most of the water for inundation of several floodplain wetland systems that would otherwise remained dry, maintaining condition of long-lived vegetation and refuge habitat for biota.

3.3 Ecosystem Function

The outcomes framework (see Table 2) provides two sub-objectives for ecosystems function: connectivity and process, the latter associated with stream metabolism (primary production of decomposition). Commonwealth environmental water contributed to both lateral and longitudinal hydrological connectivity in the first two years of LTIM. In 2015-16 Commonwealth environmental water comprised all of the barrage flows at the Murray Mouth, some 561 gigalitres. It is most likely that without this contribution, the river mouth would have remained closed for the first half of 2015. In addition, instream freshes and baseflows from Commonwealth environmental water flowed through 20,000 kilometres of river channel, connecting waterholes and facilitating the movement of native fish and other biota.

The majority of environmental water is delivered as in-channel flows, and monitoring detected little effect of this water on stream metabolism. There was, however, some evidence of positive effects of environmental water on primary productivity and ecosystem respiration from lateral movement of water into wetland and floodplain systems. This included 3 – 5 fold increases in these processes above baseline values in the Lower Murray River (Grace 2017).

3.4 Resilience

Contributions to resilience were considered through effects on ecosystem diversity, hydrological connectivity, maintaining refuges and improving condition of communities and biota, making them more resilient to unfavourable future conditions. Commonwealth environmental water contributed to maintaining refuges in a dry landscape both in wetlands (largely through wetland watering assisted by infrastructure) and by maintaining in-channel waterholes. The latter was particularly important in the intermittent streams of the northern Basin, where maintaining refuges was considered a priority for environmental water and was the target of a number of watering actions.

Inundation by environmental water contributed to improving the condition of vegetation, fish, waterbirds and other biota. In particular, fish condition across the Basin in 2014-2016 exhibited species-specific trends. The condition of Bony herring (*Nematalosa erebi*: Günther), remained consistent in most Selected Areas, but increased in condition between 2014-15 and 2015-16 in the Gwydir River system. The median condition of Golden perch (*Macquaria ambigua*: Richardson) and Murray cod (*Maccullochella peelii*: Mitchell), however, were at or below average across most Selected Areas, with a statistically significant decline observed in Murray cod within the Edward-Wakool, Lachlan and Murrumbidgee Rivers. This result may reflect the dry conditions i.e. it is possible condition would have been worse in the absence of Commonwealth environmental water (Stoffels et al. 2017).

4. Discussion

The first two years of the LTIM project successfully identified the influence of Commonwealth environmental water on flow regimes across the Basin and associated short-term bio-physical responses. Some of the responses were as expected, including increases in vegetation diversity at the site and landscape scale, and positive responses by frogs and some species of waterbird. Other responses were not expected, including the lack of metabolic responses to in-channel freshes and declines in fish condition at some Selected Areas.

In future, additional data and development of quantitative models will improve capacity to identify the ways that either the environmental flow's characteristics or the context within which it was delivered influenced outcomes. In the case of vegetation and frogs, this information will inform adaptive management with the aim of improving responses to environmental flows, while for metabolism and fish the information will identify whether metabolism may have been reduced and fish condition undergone a greater decline without the environmental flows. The capacity to answer these questions depends on the development of models to predict counterfactual outcomes. Answering these questions will enable better quantification of the flows required to protect fish condition, in part through maintenance of key ecosystem processes such as metabolism.

The inclusion of both short-term and long-term responses in the monitoring program is showing promise with short-term responses being observed and long-term patterns being recorded, both of which will guide future investigation of the influence of flow on ecological outcomes.

4.1 Areas of Improvement.

Increasing our confidence in identifying the outcomes of environmental flows remains a challenge. This is particularly important given the contested nature of the Plan, and the need to build stakeholder confidence. One of the key areas requiring improvement is hydrology which underpins evaluation of all the other outcomes (Konrad et al., 2012). There are two areas where improvements would make significant reductions in uncertainty and improve capacity to scale results from Areas to the entire Basin. The first is improvements in inundation information. Currently, inundation data are compiled from a range of different sources some of which are known to include inaccuracies. Development of a consistent approach to monitoring inundation would better inform environmental watering decisions and improve understanding of the hydraulic conditions experienced by sites in the lead up to sampling. This would improve our ability to explain more of the variation in monitored responses. The second improvement would be a consistent process for development of a counterfactual scenario for both in-channel flows and over-bank inundation. Development of a consistent approach is recognised as important if we are to compare outcomes across multiple management interventions (Gillespie et al., 2015).

For those indicators for which models will be developed (fish, vegetation and metabolism) it is anticipated that the models will enable much stronger and transparent inferences to be drawn from the evaluation. For other indicators, the project is currently reliant on opportunistic identification of benchmarks, including the system prior to being watered or nearby systems that do not receive water, or in their absence, expert judgement. Changes in the system through time (e.g. temperature) or differences in the condition or type of nearby systems reduces capacity to make inferences about the influence of flow. It is anticipated that additional data, improved understanding and in some instances model development (e.g. (Wassens, Hall, Osborne, & Watts, 2010) will improve capacity to infer the role of environmental flows in both short-term and long-term population or process dynamics.

The importance of basin-scale restoration has been recognised (Poff & Matthews, 2013) and responds to the notion that a basin-scale approach is required to consider critical ecological processes that operate at this scale (McCluney et al., 2014). The ability of managers to allocate or coordinate environmental flows at the basin scale is currently limited by our understanding of basin scale processes or the scale at which populations respond to changes in flow. The design of the LTIM program was based on our understanding of flow responses which is still very much at the site scale with some insights into Area scale responses. The design of the LTIM program with sites nested with Areas and multiple Areas selected across the Basin should, over time, start to identify interdependencies in terms of responses to environmental flows. This is particularly true as the CEWO seek to coordinate delivery of environmental water to multiple sites across Areas. If, as anticipated, these coordinated watering actions provide an opportunity to compare outcomes from both isolated and connected watering actions, then new insights into the influence of large scale processes on smaller-scale outcomes will emerge. These comparisons should both inform improvements to environmental flow management and also identify limitations in the current design of the LTIM project. In line with the principles of adaptive management, these findings will inform adaptations of the project that will allow incorporation of large scale processes into environmental flow decisions and their subsequent monitoring and evaluation through modification of the indicators or the sampling design.

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Table 1. General description of the role of different flows types on rivers, wetlands and floodplains.

Flow Type	Ecosystem Type		
	River	**Wetland**	**Floodplain**
No Flow	Cease to flow. Disturbance that influences biodiversity and function.	No surface water. Disturbance that influences biodiversity and function.	No surface water. An important determinant of floodplain character.
Base Flow	Flow that protects refugia, sustains water quality, productivity and biodiversity. Provides limited longitudinal connectivity.	-	-
Fresh	In-channel disturbance maintains littoral habitat, scours biofilm and provides longitudinal connectivity. Will affect water quality and ecosystem functions but the effects vary.	-	-
Bankfull	In-channel disturbance. Influences in-channel and riparian habitat, provides longitudinal and limited lateral connectivity. Sediment transport influences long-term channel form.	Only inundates wetlands connected at bank full. Influence on all water-dependent species habitat, provides some lateral connectivity, major stimulus for metabolism. Maintain permanent wetlands as refugia.	-

Flow Type	Ecosystem Type		
	River	**Wetland**	**Floodplain**
Overbank	In-channel disturbance. Major influence on in-channel and riparian habitat, provides longitudinal and lateral connectivity, major stimulus for other functions. Sediment transport influences long-term channel form.	Major influence on ecosystem diversity, provides connectivity, major stimulus for metabolism. Maintain permanent wetlands as refugia.	Major influence on ecosystem diversity and habitat, provides connectivity, important for ecosystem function.

Table 2. Summary of contribution of Commonwealth Environmental Water Office (CEWO) watering in 2014-16 to Basin Plan objectives. Columns 1 to 4 describe the objectives hierarchy and expected outcomes from environmental flows over periods <1year and 1-5 years.

Basin Plan objectives	Basin outcomes		5-year expected outcomes	1-year expected outcomes	Measured 1-year outcomes 2015–16	Measured 1–2- year outcomes 2014–16
Biodiversity (Basin Plan S. 8.05)	Ecosystem diversity		None identified	None identified	Total of over 200 000 hectares of mapped wetland inundated. 65% of the different aquatic ecosystem types.	67% of the different aquatic ecosystem types inundated with Commonwealth environmental water.
	Species diversity	Vegetation	Vegetation diversity	 Reproduction Condition	Presence of some native species likely to be dependent on inundation by Commonwealth environmental water. Decrease in exotic taxa.	Presence of some native species likely to be dependent on inundation by Commonwealth environmental water. Decrease in exotic taxa.
			Growth and survival	Germination Dispersal	Increased total cover and dominance of inundated vegetation communities and mostly higher species richness (though highly dependent on a range of intrinsic and extrinsic factors).	Greater vegetation cover in plots/transects subjected to at least some wetting during this period.
		Macro-invertebrates				
		Fish	Fish diversity	Condition	Comparatively high level of nativeness in fish assemblages.	Comparatively high level of nativeness in fish assemblages. Golden perch, silver perch, Australian smelt, carp gudgeon and bony herring exhibited species-specific responses to flows.
				Larval abundance	Spawning by golden perch and bony bream.	Spawning by golden perch and bony

Basin Plan objectives	Basin outcomes		5-year expected outcomes	1-year expected outcomes	Measured 1-year outcomes 2015–16	Measured 1–2- year outcomes 2014–16
				Reproduction		bream.
			Larval and juvenile recruitment			
		Waterbirds	Waterbird diversity		Foraging habitat provided at a number of locations, including several large wetland complexes, particularly for shorebirds and other wading species.	Different foraging habitats provided for the full range of waterbird guilds across the 2 years
			Waterbird diversity and population condition (abundance and population structure)	Survival and condition		
				Chicks	Some evidence of breeding of waterbird species and small-scale colonial nesting in Barmah–Millewa.	Some evidence of small-scale breeding at several locations: Hattah, Barmah–Millewa, Murrumbidgee.
				Fledglings	Fledgling recorded in nesting birds at Hattah Lakes.	Fledgling recorded in nesting birds at Hattah Lakes.
		Other vertebrate diversity		Young	Limited breeding.	Breeding of frogs at several locations across the 2 years.
			Adult abundance		Foraging habitat provided in several areas.	Foraging habitat provided in several areas.
Ecosystem Function (Basin Plan S. 8.06)	Connectivity			Hydrological connectivity including end of system flows	Evidence of lateral and longitudinal connectivity in a number of river systems. Maintained an open Murray Mouth.	Evidence of lateral, longitudinal connectivity in a number of river systems Maintained an open Murray Mouth.
				Biotic dispersal and movement	Evidence of longitudinal fish movement in the Gwydir river system and lateral movement at Hattah Lakes.	Evidence of longitudinal fish movement in the Gwydir river system and lateral movement at Hattah Lakes.

Basin Plan objectives	**Basin outcomes**		**5-year expected outcomes**	**1-year expected outcomes**	**Measured 1-year outcomes 2015–16**	**Measured 1–2- year outcomes 2014–16**
				Sediment transport		
	Process			Primary productivity (of aquatic ecosystems)	Little evidence, under dry conditions, of effects on these processes.	Little evidence, under dry conditions, of effects on these processes.
				Decomposition		
				Nutrient and carbon cycling		
Resilience (Basin Plan S. 8.07)	Ecosystem resilience		Population condition (individual refuges)	Individual survival and condition (individual refuges)	Refuges in the Warrego and Gwydir were maintained/improved by Commonwealth environmental water.	A number of permanent wetlands inundated with environmental water over the 2 years.
			Population condition (landscape refuges)			
				Individual condition (ecosystem resistance)	Some evidence of improved condition of vegetation communities and fish populations with a high degree of nativeness.	Some evidence of improved condition of vegetation communities and fish populations with a high degree of nativeness.
			Population condition (ecosystem recovery)			
Water quality (Basin Plan S. 9.04)	Chemical			Salinity		
				Dissolved oxygen		Evidence from the Edward–Wakool of maintained dissolved oxygen.

Basin Plan objectives	Basin outcomes		5-year expected outcomes	1-year expected outcomes	Measured 1-year outcomes 2015–16	Measured 1–2- year outcomes 2014–16
				pH		
				Dissolved organic carbon		
	Biological			Algal blooms		

Table 3. The main indicators and a brief summary of the sampling method for each with references that provide more detail. Some indicators are categorised as short term, but are also used to support long-term documentation of responses through aggregation (hydrology, connectivity, ecosystem diversity) or aggregation and trend analysis (vegetation diversity).

Indicator	Sites	Time	Type	Method	Reference
Hydrology	All	Short	Cause & Effect	Analysis of flows at 109 gauges against five flow thresholds.	Stewardson and Guarino, 2017
Hydrological connectivity	All	Short	Cause & Effect	GIS analysis of maximum inundation extents.	Mueller et al., 2016, Thomas et al., 2015
Ecosystem diversity	All	Short	Effect	GIS analysis of wetland types inundated.	Brooks 2017, Hale et al., 2014
Vegetation diversity	All except Lower Murray	Short	Effect	On-ground monitoring of species presence, functional group, projected foliage cover and abundance (% cover).	Brock & Casanova, 1997, Hale et al., 2014
Channel metabolism	All except Gwydir	Short	Cause & Effect	Open water dissolved oxygen and temperature logged data are analysed using the Bayesian Stream metabolism Estimation (BASE) model	Giling, Grace, Thomson, Mac Nally, & Thompson, 2014
Water quality	All	Short	Cause & Effect	Discrete water quality samples collected at channel metabolism sites.	Hale et al. 2014
Fish populations	All	Long	Effect	Annual fish census using a combination of active (electro-fishing) and passive (nets) techniques.	Hale et al. 2014
Larval fish	Edward, Gwydir,	Short	Effect	Larval fish are sampled fortnightly over breeding season using a combination of	Hale et al. 2014

	Lachlan, Murrumbidgee			methods.	
Fish movement	Edward, Goulburn, Lower Murray Gwydir	Short	Effect	Monitoring is undertaken using tagged (acoustic) native fish.	Hale et al. 2014

Table 4. Summary of Commonwealth Environmental Water Office (CEWO) watering actions by valley for 2015-16 (see Gawne et al. 2017 for further explanation).

Valley	Number of actions	Commonwealth environmental water volume (GL)	Total active environmental volume (GL)	CEW volume as % of total	Flow components							
					Cease to flow	Baseflow	Fresh	Base flow and fresh	Bankfull	Overbank	Wetland inundation	Fresh and wetland
Barwon–Darling	3	7.6	7.6	100			3					
Border Rivers	6	1.2	1.2	100		1	5					
Broken	5	29.5	30.3	97		4	1					
Campaspe	2	3.3	9.8	34			2					
Central Murray	12	399.9	NA	NA		1	1	1		4	5	
Condamine–Balonne	2	10.5	10.5	100			2					
Edward–Wakool	4	32.2	34.5	93				4				
Goulburn	6	190.6	228.2	84		4	2					
Gwydir	4	8.1	13.2	61		1	1			2		
Lachlan	4	36.0	48.0	75			4					
Loddon	1	1.5	3.9	38			1					
Lower Murray	48	817.7[a]	NA	NA		2	5				40	1
Macquarie	2	14.2	55.1	26			2					
Murrumbidgee	13	108.3	200.8	54			2				11	
Ovens	2	0.1	0.1	100		2						
Warrego	1	0.9	0.9	100					1			
Total count	115				0	15	31	5	1	6	56	1
Component volume as % of total					0.0	62.3	6.1	7.9	0.1	16.8	6.8	0.1

[a] This volume includes water delivered in the Central Murray so total Commonwealth environmental water is less than sum of Central Murray and Lower Murray volumes.

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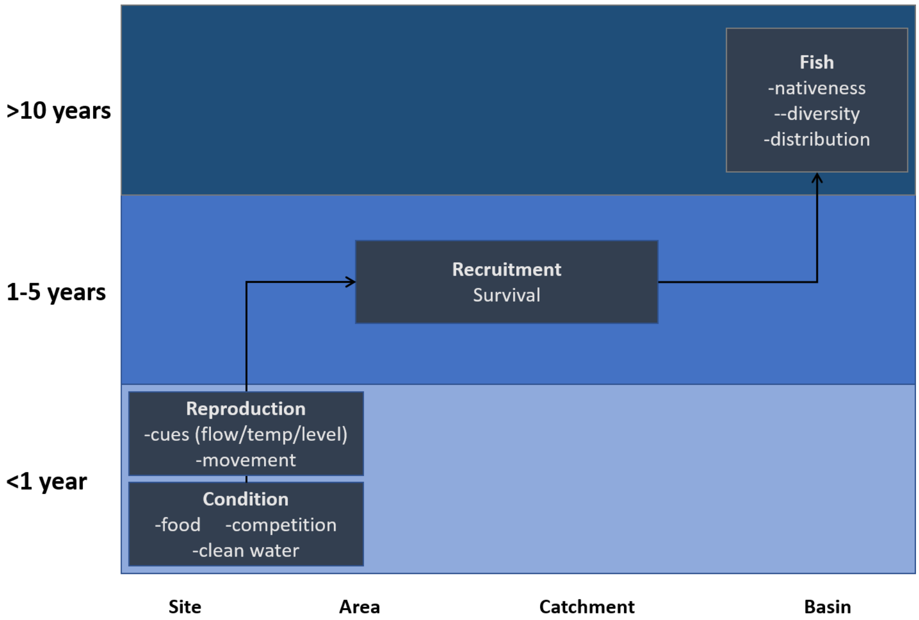
Figure 3. Five flow types and their influence on different parts of the river channel, wetlands and floodplains (MDBA 2011).

Figure 4. Level 2 and 3 objectives and associated generic cause-effect diagrams influenced by four different annual flow conditions. Each circle represents a year in a river valley with dry or very dry (orange circles), median (yellow), wet (light green) and very wet (green) years.

Figure 5. An illustration of the spatial and temporal relationships between elements of the fish objectives hierarchy. The boxes represent aspects of the Level 3 fish objective for which conceptual model had been developed.



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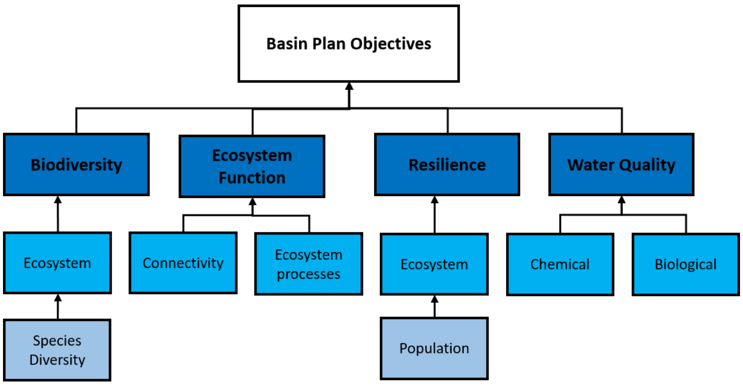

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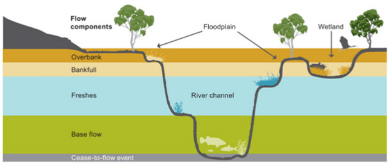

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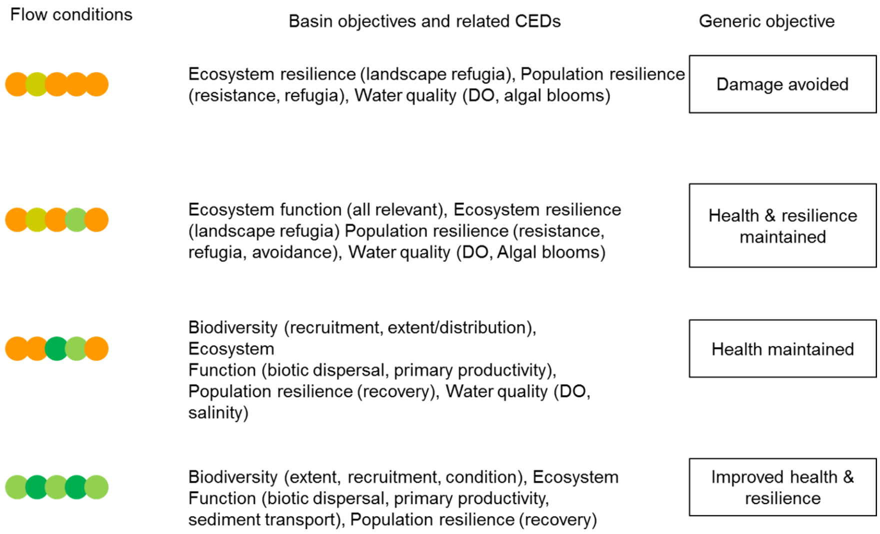

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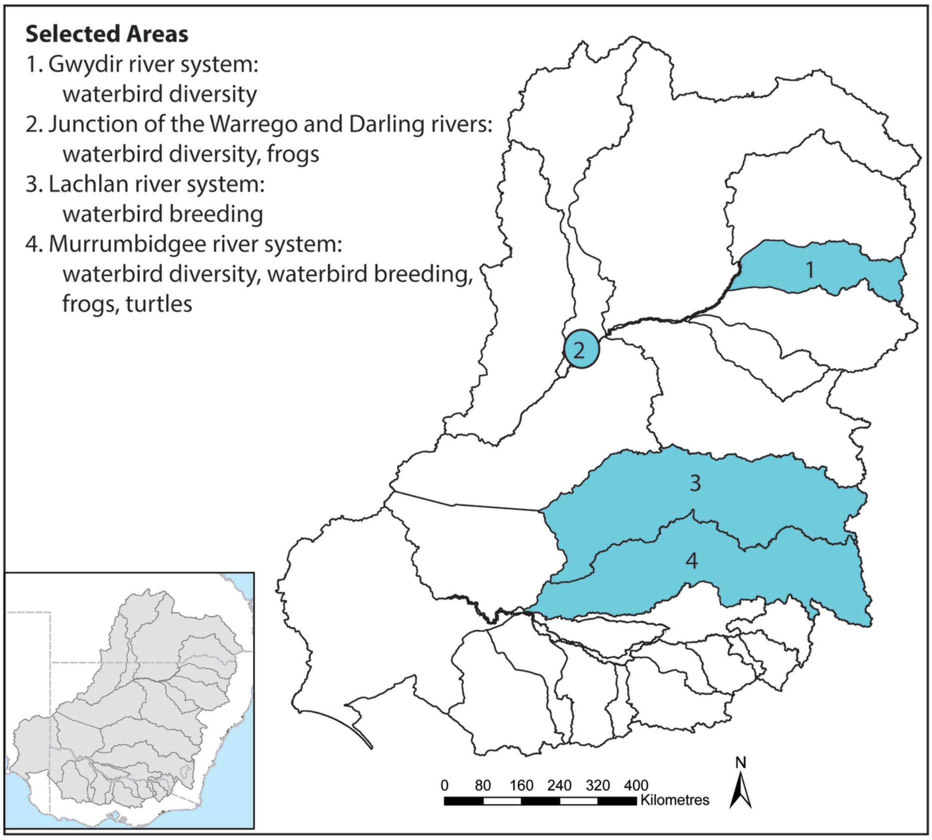

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