2015–16 Basin-scale evaluation of Commonwealth environmental water – Stream Metabolism and Water Quality

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Final Report

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2015–16 Basin-scale evaluation of Commonwealth environmental water – Stream Metabolism and Water Quality

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

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

Contents

List of tables

List of figures

1 Introduction

1.1 Context

This report seeks to evaluate the influence of environmental water on stream metabolism, which refers to the transformation of organic matter and is comprised of two key ecological processes – primary production and decomposition – which generate and recycle organic matter, respectively. Gross Primary Productivity (GPP) is the rate of biomass creation through photosynthesis and estimated by oxygen production, and is usually simplified to ‘Primary Production’ throughout this report.[1] The abbreviation ‘GPP’ is retained. Ecosystem Respiration (ER) is the amount of organic matter decomposed, estimated by oxygen consumption, under aerobic conditions.

In seeking to achieve healthy and resilient ecosystems with rivers and creeks regularly connected to their floodplains and, ultimately, the ocean (Basin Plan section 5.02.2), the Basin Plan recognises the importance of these processes and has included objectives concerning ecological productivity (section 8.05.2(c)) and the protection and restoration of the ecosystem functions of water-dependent ecosystems.

These objectives reflect best available science, including major river conceptual models that state that patterns of production are a major influence on ecosystem character and condition. These models describe the critical role that flow plays in determining patterns of productivity.

Stream metabolism has been included as an ecological indicator to be evaluated at the whole-of-Basin scale (i.e. a ‘Basin Matter’) within the Commonwealth Environmental Water Office (CEWO) Long Term Intervention Monitoring (LTIM) Project because of its inclusion as an environmental objective in the Murray–Darling Basin Plan, but also for the following reasons:

- Australian aquatic ecosystems are characterised by their cycles of ‘boom and bust’. These cycles are built of changes in productivity associated with flood and drought. This is also recognised in the Basin Plan objectives that state that the Basin’s rivers should support episodic periods of very high production.
- Stream metabolism is sensitive to changes in flow, particularly changes in hydrological connectivity between the river and floodplain.
- Monitoring processes provides insight into the mechanisms driving patterns of change in biota. Included within this is our current belief that food abundance is critically important in the recruitment of both young native fish and waterbirds which are often targets of environmental watering.

These characteristics mean that understanding river metabolic responses to environmental flows both enables feedback on how environmental flows are influencing a critical environmental function (in line with the Basin Plan objectives) and, in conjunction with an evaluation of habitat availability, contributes to understanding fish and waterbird population responses.

[1] Strictly speaking, Gross Primary Productivity is the *rate* of biomass accrual through photosynthesis while Primary Production is the amount of biomass created. They are numerically equivalent. The Whole Stream Metabolism method estimates GPP from the diel oxygen curve, hence results and plots are presented as GPP not Primary Production.

1.2 Objectives of the Stream Metabolism and Water Quality Basin Matter

This component of the LTIM Project's Basin-scale evaluation of Commonwealth environmental water will address the following short-term (1-year) questions:

- What did Commonwealth environmental water contribute to patterns and rates of decomposition?
    - Decomposition is measured as the rate of ecosystem respiration. The hypothesis is that rates of ecosystem respiration will increase in response to the delivery of environmental water. Increased rates of decomposition that do not contribute to hypoxia facilitate energy movement through ecosystems and have the potential to increase energy and nutrient supply to riverine food webs.
- What did Commonwealth environmental water contribute to patterns and rates of primary production
    - The hypothesis is that rates of primary production will increase in response to the delivery of environmental water. Increased rates of primary production that do not contribute to blooms of cyanobacteria will increase the energy and nutrient supply to river food webs.
- What did Commonwealth environmental water contribute to pH and dissolved oxygen levels and to salinity and turbidity regimes?

The long-term questions are essentially the same for metabolism and water quality, except that the focus is on long-term patterns of metabolism and water quality. In the case of metabolism, the relevant objective is that 'water-dependent ecosystems are able to support episodically high ecological productivity and its ecological dispersal' and so the above questions will seek to identify the contribution of Commonwealth environmental water to long-term patterns of productivity. For water quality, the long-term questions will focus on the frequency, intensity and duration of adverse water quality events; that is, events where the allocation of Commonwealth environmental water can influence the occurrence or severity of these events.

These questions stem from the relevant Basin-scale objectives set out in the Basin Plan and as defined in Table 2 of Gawne *et al.* 2014:

- stream metabolism/ecosystem function – 'to protect and restore the ecosystem functions of water-dependent ecosystems'
- water quality – 'to ensure water quality is sufficient to achieve the above objectives for water-dependent ecosystems, and for Ramsar wetlands, sufficient to maintain ecological character'.

Estimates of river metabolism are derived from daily measurements of changes in dissolved oxygen, temperature and light in open water (Figure 1). The open water measurements average out all metabolic activity occurring in the channel and these data are then used to generate estimates of gross primary production, ecosystem respiration and the re-aeration coefficient per litre of water (Figure 1.2). The estimates of gross primary production and community respiration can then be scaled up to provide an estimate of reach scale metabolism using an estimate of the volume of water in the monitored reach (Figure 1.3). See the *Stream Metabolism and Water Quality foundation report* (Grace 2015) for more detail on the method.

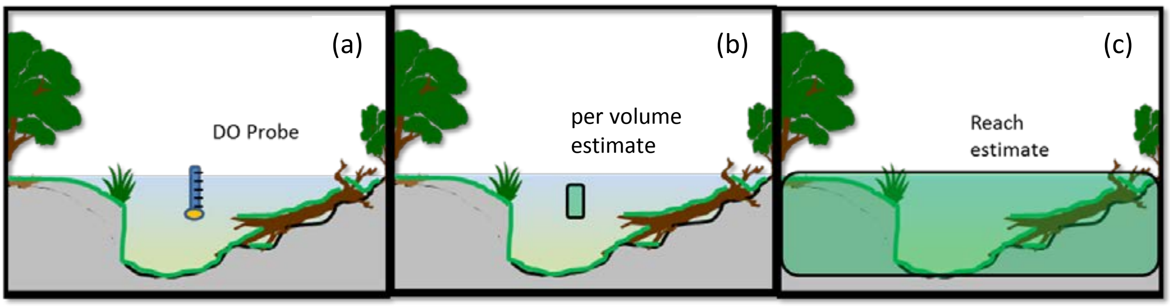

Figure 1. Illustration of the three steps in generating a reach-scale estimate of stream metabolism: (a) monitoring open water dissolved oxygen (DO); (b) using data to develop a per unit volume measure; and (c) scaling up to the reach.

1.3 Conceptual understanding – influence of flow

There are four ways by which flow may influence river metabolism. These influences are not mutually exclusive and metabolic responses to changes in flow may involve interactions among the various responses. The next four subsections provide a brief summary of these influences.

1.3.1 Available habitat

Flow interacts with channel morphology to create habitat for algae and macrophytes, with the habitat characteristics influencing the species present, their abundance and distribution. As an example, in a clear water system where light penetrates to the streambed, the area of illuminated streambed represents the available habitat for attached algae (Figure 2). An increase in flow increases the amount of habitat available for these algae. The increase in flow may also mean that other components, such as plant stems and wood, may also become available as habitat. Even in turbid systems in which floating algae dominate, an increase in flow may be associated with an increase in channel width which also represents an increase in the amount of habitat available for floating algae.

The relationship between flow and algal habitat can be quite complex as increases in flow are not always associated with predictable changes in habitat availability; for example:

- The relationship between the area of inundated streambed and discharge is not linear, and small changes in discharge may be associated with large increases in the area inundated.
- Increases in discharge may reduce the amount of illuminated streambed due to depth or changes in turbidity.
- Changes in discharge may create or destroy slackwater habitats that are important for floating algae.

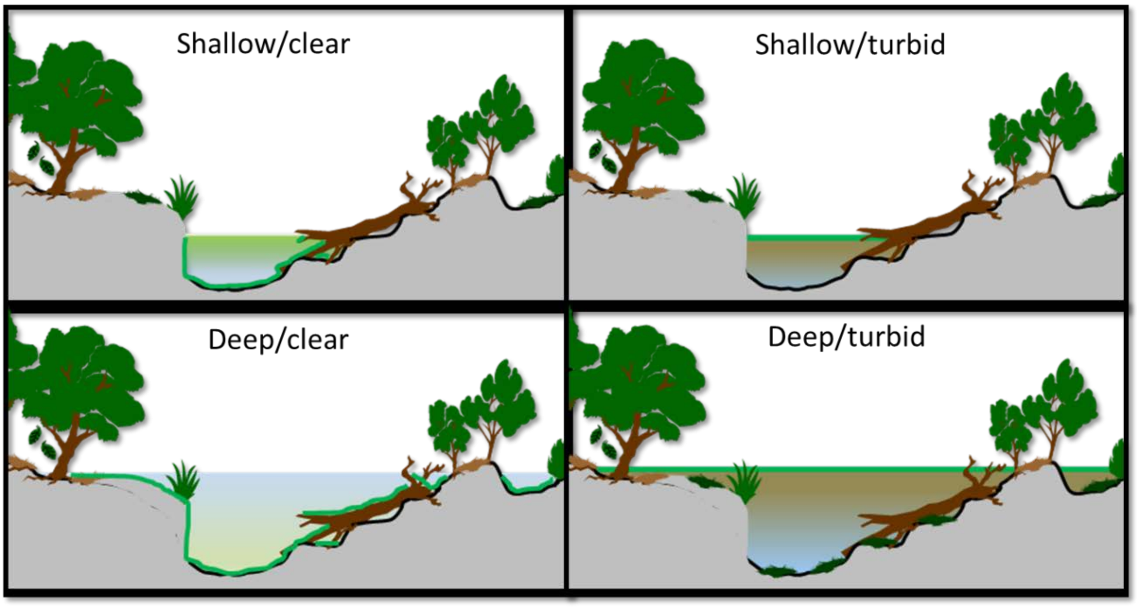

Figure 2. Conceptual model of increased flow and turbidity effects on stream metabolism through their influence on habitat (Habitat Model). In shallow/clear systems, light penetrates to the riverbed, but there is less habitat than when flows increase (deep/clear). In turbid systems, light may not penetrate to the riverbed, meaning that primary production is confined to the 'bathtub ring' and floating algae. In these systems, increases in flow may lead to an increase in the size of both the illuminated water column and inundated sediment (deep/turbid)

When new habitat is created or existing habitat is changed, the algal community takes time to respond because the response may include colonisation or growth from very small numbers. The time taken to respond will depend on other conditions including temperature, light and nutrients, but usually occurs with 2-4 weeks.

1.3.2 Entrainment

Primary production requires nutrients, notably nitrogen (N) and phosphorus (P), in bioavailable forms (Borchardt 1996; Boulton & Brock 1999). When water column nutrients are all consumed, photosynthesis may be severely inhibited. Conversely, the microbial population undertaking ecosystem respiration requires cellular detritus from dead plants and animals (organic matter) as a food supply and, during this process, nutrients (N and P) are regenerated. Once the supply of organic matter is diminished, nutrient regeneration is reduced. The two processes of primary production and ecosystem respiration are therefore closely linked. Figure 3shows that when discharge levels increase, more nutrients and organic matter can be transported into the stream, potentially alleviating nutrient and organic matter limitation. Fuß *et al.* (2017) recently demonstrated that both the quantity and quality (chemical composition) of the dissolved organic matter in flowing waters had major impacts on ecosystem respiration in 33 streams in Austria; the nature and amount of this organic matter was, in part, determined by land use. In addition, land use, and specifically agricultural activities, were closely linked to effects on primary production, mediated by nutrient delivery. It concluded that organic carbon was the link between catchment activities and stream metabolism.

Flow and, in particular, lateral connectivity have long been recognised as important in facilitating the exchange of organic matter and nutrients between rivers and associated wetlands and floodplains (Junk *et al*. 1989; Tockner *et al*. 1999; Baldwin *et al*. 2013). The amount of nutrients and organic carbon added will depend on how high the water reaches up the bank (whether it inundates benches) and whether backwaters, flood runners and the floodplain itself are reconnected to the main channel (Thoms *et al*. 2005; McGinness & Arthur 2011; Southwell & Thoms 2011).

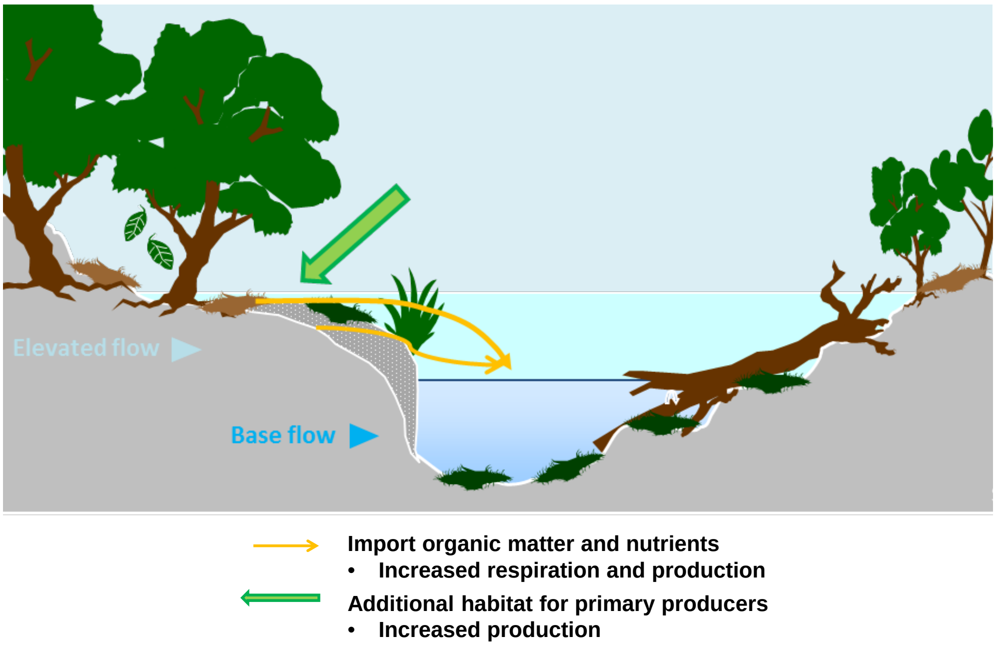

Figure 3. Conceptual model of increased flow effects on stream metabolism through increased nutrient and organic matter delivery from riparian and floodplain habitats (Entrainment Model).

1.3.3 Mixing or resuspending material

There are several situations in which changes in flow can entrain material that has accumulated within sinks found in river channels. Examples of these sinks include:

- organic matter in areas of low flow
- nutrients within sediments (where oxygen from the overlying water does not reach)
- nutrients and organic matter in stratified pools.

Within the channel, organic matter may accumulate in areas of low flow, such as slackwaters or the bottom of deep pools (Figure 4). In these areas, low flow limits the supply of oxygen and nutrients, slowing rates of decomposition. When flows increase, the accumulated material may be resuspended or mixed, relieving the limitation and this is often associated with a significant increase in metabolic activity (Baldwin & Wallace 2009).

In rivers exemplified by the Darling, where low water velocities combined with structures, such as weir pools, cause water impoundment with potentially long residence times, it is extremely likely that extended periods of thermal stratification will occur (Oliver *et al.* 1999). The stratification leads to a depletion of oxygen levels at the bottom of the pool and this results in the release of phosphate and ammonia from the sediments. The first flush that breaks down stratification may lead to the transportation downstream of large concentrations of these bioavailable nutrients and accumulated organic matter, which may then engender significant decomposition in the water column over subsequent days and weeks, leading in some instances to depletion of oxygen in the water column (Baldwin & Wallace 2009). This occurred in the Darling River in 2004 and was associated with fish kills (Ellis & Meredith 2004).

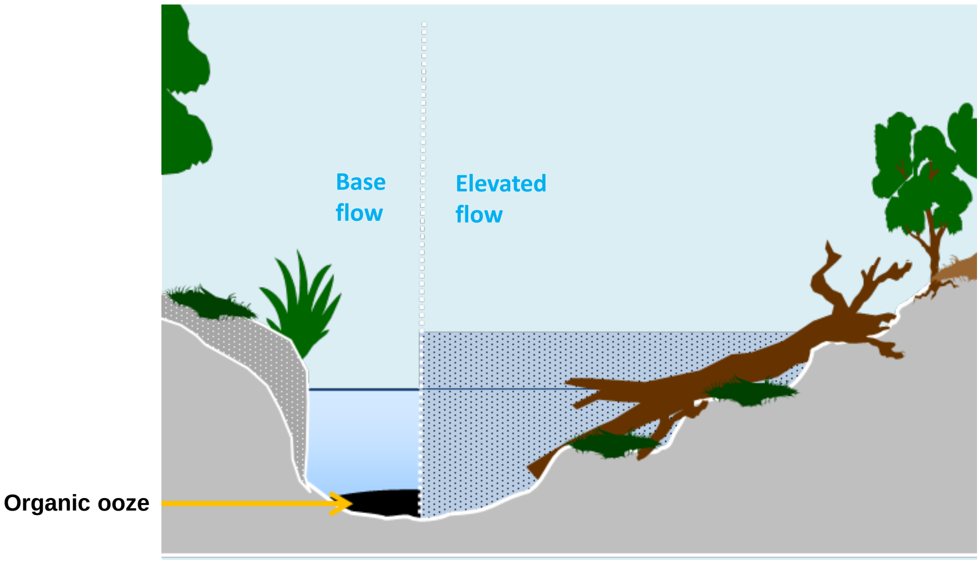

Figure 4. Conceptual model of increased flow effects on stream metabolism through resuspension of soft bottom sediments (Mixing Model).

1.3.4 Disturbance – scouring of existing biofilms

Biofilms – which grow on any surface, including sediments, plants or wood – can provide a substantial proportion of the primary production and respiration in a stream. Flow events with sufficient stream power (resulting from higher water velocities) to cause scouring of these biofilms (Ryder *et al*. 2006) can 'reset' primary production to very low rates which are then maintained until the biomass of primary producers is re-established (Uehlinger 2000). Over a period of weeks, this can lead to higher rates of primary production if those biofilms that were washed away were 'old' and not growing substantially, or even starting to decline (senesce) (Figure 5).

Reductions in flow may also disturb biofilms through desiccation. The drying of the biofilms kills much of the microbial community and the slime in which the algae and bacteria are imbedded dries, shrinks and cracks. When the surface is then inundated, the dried biofilm often sloughs off, leaving an altered community.

Floating communities of algae and bacteria are also subject to disturbance by changes in flow (Reynolds *et al.* 1991; Reynolds 1992; Reynolds & Descy 1996). Phytoplankton abundance is influenced by the residence time of water within the reach which in turn is affected by discharge and the relative volume of slackwaters within the reach. As discharge increases, existing slackwaters may be flushed out and the overall area of slackwaters may change, either increasing or decreasing. The flushing of slackwaters will lead to reductions in floating algae. The longer term effects will depend on populations building up in newly created slackwaters

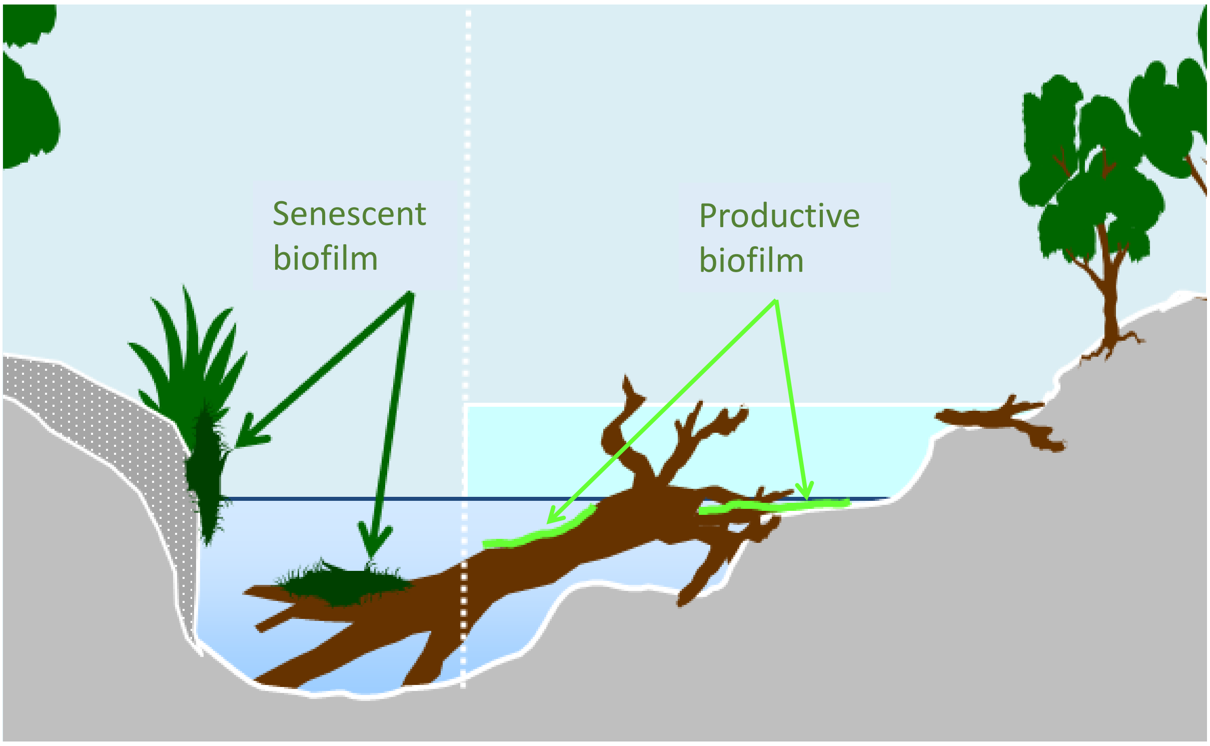

Figure 5. Conceptual model of increased flow effects on stream metabolism through scouring of biofilms (Disturbance Model).

1.4 Conceptual understanding – flow types

The discussion in section 1.3 describes how flow changes may influence stream metabolism. This information can be used to make predictions of how the allocation of environmental flows to different flow types is likely to influence stream metabolism. The response to a given environmental flow is complicated by the fact that several of the processes described in the sections above may occur during the same flow. Our understanding of how these processes interact is currently limited; however, it will improve as the LTIM monitors more environmental flows and builds the capacity to evaluate both flow responses per unit volume and at the reach scale. The following sections describe the influence of the major flow types included in the Basin Plan to illustrate how we believe flow can affect metabolism in multiple ways.

1.4.1 Cease to flow

The effects of cease-to-flow events on metabolism may be complex due to interactions between changes in habitat availability, accumulation of material and food-web changes. Toward the later stages of drying, metabolism is likely to increase as consumers are lost and material accumulates in still water. Cease-to-flow events are often associated with declines in water quality (Figure 6). Ultimately, flow cessation may lead to drying, which is a disturbance that will ultimately lead to major reductions or cessation of metabolism. While the cease to flow and subsequent drying will affect metabolism, subsequent inundation may be associated with an increase in metabolism in response to release of nutrients from dried sediments and dead or accumulated organic matter.

Figure 6. An algal bloom within a still pool of the drying Ovens River during the millennium drought.

1.4.2 Base flows

Base flows are often dominated by algal production as inputs of terrestrial organic matter are reduced due to the limited lateral connectivity and the increased distance between the water and riparian vegetation. Flow influences the amount of available habitat and also interacts with factors including substrate availability (sediment type, wood, macrophytes), nutrient availability and light availability (season, weather and turbidity) to determine productivity. Allocating environmental water to enhance base flows can influence the amount of available habitat, but also prevent cease-to-flow conditions associated with declines in water quality.

1.4.3 Freshes

Metabolic responses to freshes are complicated because they integrate three different processes:

1. Entrainment (Section 1.3.2) of organic material and nutrients from adjacent habitats has the capacity to influence metabolism, increasing the use of entrained organic matter. This model was proposed by Tockner *et al.* (1999) in a modification of the flood pulse concept (Junk *et al.* 1989).
2. Disturbance (Section 1.3.4) – the increase in discharge may both flush out slackwater areas where floating algae accumulate and also scour attached biofilms. Both of these influences may reduce metabolism in the short term, but may end up leading to higher rates if the disturbed biofilms had become senescent prior to the fresh.
3. Available habitat – increasing discharge may create additional habitat for primary producers; however, utilisation of this new habitat takes time as the algae or plants need to colonise and then grow. This response is also likely to be variable depending on the time of year (influence of light and temperature) and the influence of the change in flow on turbidity (source of water, disturbed sediments) and the amount and type of habitat inundated.

If the fresh entrains significant amounts of organic matter, one would expect a fresh to be associated with an increase in decomposition and a decline in primary production per unit volume. The amount of organic matter entrained will depend on antecedent flow conditions, condition of stream-side vegetation and the area of bank/riparian habitat inundated. The algal response will depend on the change in current velocity, slackwater habitat and factors that influence algal growth (e.g. nutrients, light and temperature). As noted above, the complexity of these interactions means we expect responses to freshes to be variable.

1.4.4 Bankfull

Metabolic responses to bankfull may be similar to those described for freshes if they are of short duration. The effects of longer periods of bankfull discharge will depend on river morphology and riparian vegetation. In general, deeper water limits light penetration and this reduces habitat for attached biofilms and tends to favour floating algae. Floating algae can only accumulate if algae are retained in the reach and this is influenced by the interaction between flow and channel morphology. Many rivers have low retention when running at bankfull with limited slackwater or backwater habitats to retain algae. Retention also influences the fate of external organic matter that may enter the river, increasingly the likelihood that it will be transported downstream. As a consequence, bankfull discharge events may be associated with changes in overall metabolism that may be less important than the changes wherein the metabolism takes place (attached versus floating) and the extent to which the organic material is retained in the reach.

1.4.5 Overbank flows

Overbank flows are associated with large increases in metabolism for a number of reasons, including:

- inundation of accumulated organic matter and associated nutrients
- lack of consumers
- increases in the amount of available habitat – large areas of shallow water, macrophytes and plant material
- changes in water quality as a result of subsidies coming from the floodwater and their settlement on the floodplain in slow-flowing water.

While all these factors may contribute to an increase in metabolism, every overbank flow is different and the type of metabolic increase, magnitude and fate of the organic matter will all vary in response to a number of factors, including land use, sediment loads, flow paths and hydraulics, antecedent flow conditions, duration and timing of the overbank flow.

1.5 Challenges in evaluating the contribution of environmental water to stream metabolism at the Basin scale

This metabolism evaluation seeks to identify the influence of Commonwealth environmental water on rates of stream metabolism on the basis of rates per unit volume and also at the reach scale.

Despite evidence of the importance of patterns and rates of metabolism to river ecosystems, there is currently some uncertainty around the influence of water flow due to the absence of larger flows (natural and associated with watering actions) in years 1 and 2 of LTIM (2014–16). This affects our capacity to evaluate the extent to which environmental water influences stream metabolism. As the LTIM Project generates data, it is anticipated that this uncertainty will substantially decrease and the evaluation process will greatly improve.

Initially, in the absence of these data, this evaluation will be based around the use of conceptual models and comparisons of stream metabolic rates from before, during and after the watering action. One of the challenges with this approach is that comparisons are usually confounded by the passage of time and associated changes in season, temperature and water quality. It is anticipated that additional data generated by the LTIM Project over several years will help by developing models which will provide:

- the capacity to generate reach estimates of metabolism
- the reference against which observed outcomes are measured. This will overcome the issues associated with comparing rates before, during and after a watering action
- an evaluation of extended watering actions (e.g. base flows, wetland inundations) for which there is currently no suitable reference
- expanded capacity to enable evaluation of the outcomes of water regimes rather than individual actions which will enable better alignment with Basin Plan objectives, the hydrology evaluation and Category 1 fish evaluation.

These data and the associated models will both improve the evaluation and enable the evaluation of a greater range of watering actions. The situation is summarised in Table 1. In this, the second year of the Basin-scale evaluation of Stream Metabolism and Water Quality, the models are not available due to limited data availability. The lack of models restricts the scope of the evaluation in terms of both the types of flow that can be evaluated and the underlying processes (Section 1.3).

As a consequence, the evaluation will, as in 2014–15, focus on the outcomes of freshes and water returned from wetland or floodplain inundation and whether they were associated with entrainment or resuspension.

This report also examines water quality data, especially in the context of drivers of ecosystem function and the avoidance of poor water quality as exemplified by low DO concentrations.

Table 1. Summary of the relevant conceptual models and their proposed inclusion in this evaluation. The development of a quantitative model will improve the rigour of all evaluations by providing a robust counterfactual prediction (i.e. determining the marginal benefit of environmental water). The three data requirements are: hydrology – the contribution of Commonwealth environmental water to flows in the channel; hydraulic – the influence of Commonwealth environmental water on key hydraulic outcomes, including average depth and channel width; and metabolism – the metabolism estimates derived from records of dissolved oxygen.

Flow	Relevant models	Data requirements	Included in evaluation	Comment
Cease to flow	Habitat, Mixing Model	Hydrology, hydraulic, metabolism	Year 1 (2014–15)	Not included in the evaluation as the Commonwealth Environmental Water Office (CEWO) does not have the capacity within channels to create cease-to-flow events
Base flow	Habitat	Hydrology, hydraulic, metabolism	Year 3 (2016–17)	Evaluation of base flows' influence on metabolism is reliant on hydraulic information not available to the first 2 years' evaluations
Fresh	Habitat, Entrainment, Disturbance, Mixing Model	Hydrology, hydraulic, metabolism	Year 1	Fresh flows can be evaluated on a per unit volume without hydraulic information; hydraulic information will enable reach estimates to be generated
Bankfull	Habitat, Entrainment, Disturbance	Hydrology, hydraulic, metabolism	Year 3	Short bankfull flows can be evaluated on a per unit volume without hydraulic information; hydraulic information will enable reach estimates to be generated
Wetland inundation	Entrainment	Hydrology, hydraulic, metabolism	Year 1	The effects of wetland inundation can be evaluated if monitoring takes place above and below the point where flows are returned to the channel.
Overbank	Habitat, Entrainment,	Hydrology, hydraulic, metabolism	Year 1	Overbank flows can be evaluated on a per unit volume without hydraulic information; hydraulic information will enable reach estimates to be generated.

2 Methods

2.1 The Stream Metabolism Basin Matter approach

The approach to evaluating stream metabolism to flows within the Basin Matter analysis is described in the foundation report (Grace 2015). The key points are summarised here.

All Monitoring and Evaluation (M&E) Providers deploy loggers at their Selected Areas to record changes in dissolved oxygen, light and temperature over the course of 24 hours. Details about the locations and methods for each site are included in the Selected Area evaluation reports. The field data are then analysed using the same statistical model ('BASEv2' – BAyesian Single-station Estimation) to compute volumetric estimates of metabolism (per cubic metre) to ensure a consistent approach to estimating rates of primary production and ecosystem respiration. The model was updated during 2016 in accordance with methodological recommendations contained within Song *et al.* (2016). These volumetric estimates can be converted into reach-scale estimates with the appropriate hydraulic information which is not available this year, but we anticipate it will be available for Year 3 (2016–17).

Quantification of the effects of environmental flows on metabolism requires a prediction of rates in the absence of the environmental water. Ultimately, the LTIM Project will develop quantitative models that will provide these predictions. Currently, however, there are no quantitative models that enable prediction of the metabolic rates expected at a specified flow, either with, or in the absence of, environmental watering. This leaves two potential approaches:

1. The use of monitoring at times or places where there is no environmental flow. The Edward–Wakool river system is fortunate in having several rivers that provide opportunities for comparisons between similar systems with and without environmental flows. In other systems, comparisons are made through time. There are limitations associated with these comparisons because many factors vary through time (e.g. daylight, temperature, nutrients) that confound our ability to identify the influence of flow.
2. Conceptual models describing the relationship between flow and metabolism (Section 1.3) provide a starting point for making predictions to support evaluation. These conceptual models will be interrogated as far as possible with data collected during the first few years of the LTIM Project, although, as noted above, this is complicated due to the influence of flow on multiple processes.

The limitations of these two approaches restrict the capacity to evaluate the influence of environmental flows on metabolism. Model development is dependent on having at least 3 years of data from the monitoring across the Selected Areas. It is anticipated that the models will:

- estimate the rate of stream metabolism in the absence of environmental watering at the reach scale for reaches that are monitored
- predict both environmental flow and non-flow rates of stream metabolism at the reach scale for reaches that are not monitored
- support estimation of Basin-scale changes to stream metabolism in response to environmental watering.

Work undertaken in the first 2 years of the LTIM Project has identified many of the drivers of metabolism and this analysis will inform the development of the statistical model. It will also inform key decisions about whether one model will be able to be used across the Basin or whether different models may be needed for northern and southern systems.

For this report, the models to predict metabolism were not available and neither were hydraulic data required to generate reach-based estimates. As a consequence, the evaluation is heavily reliant on the area evaluation of metabolism based at the Selected Areas and a broad conceptual evaluation of watering actions that had expected outcomes for metabolism at unmonitored sites.

The LTIM Stream Metabolism monitoring sites are shown in Figure 7.

2.2 The Water Quality Basin Matter approach

Collection of water quality data to address both the short- and long-term questions was typically performed when accessing the sites for other purposes (e.g. dissolved oxygen (DO) logger downloading and maintenance). Hence, data collection for pH, turbidity, salinity (electrical conductivity), and nutrient and chlorophyll-a concentrations was sporadic and typically at frequencies of every 2–6 weeks. The lack of continuous monitoring (except for DO and temperature collected using the loggers acquiring metabolism data) is a constraint imposed by the overall project budget. Hence, it is extremely difficult to attribute the effects of watering actions on any parameter other than DO. However, aggregated water quality data *are* useful to help explain patterns of metabolism at catchment and Basin scales.

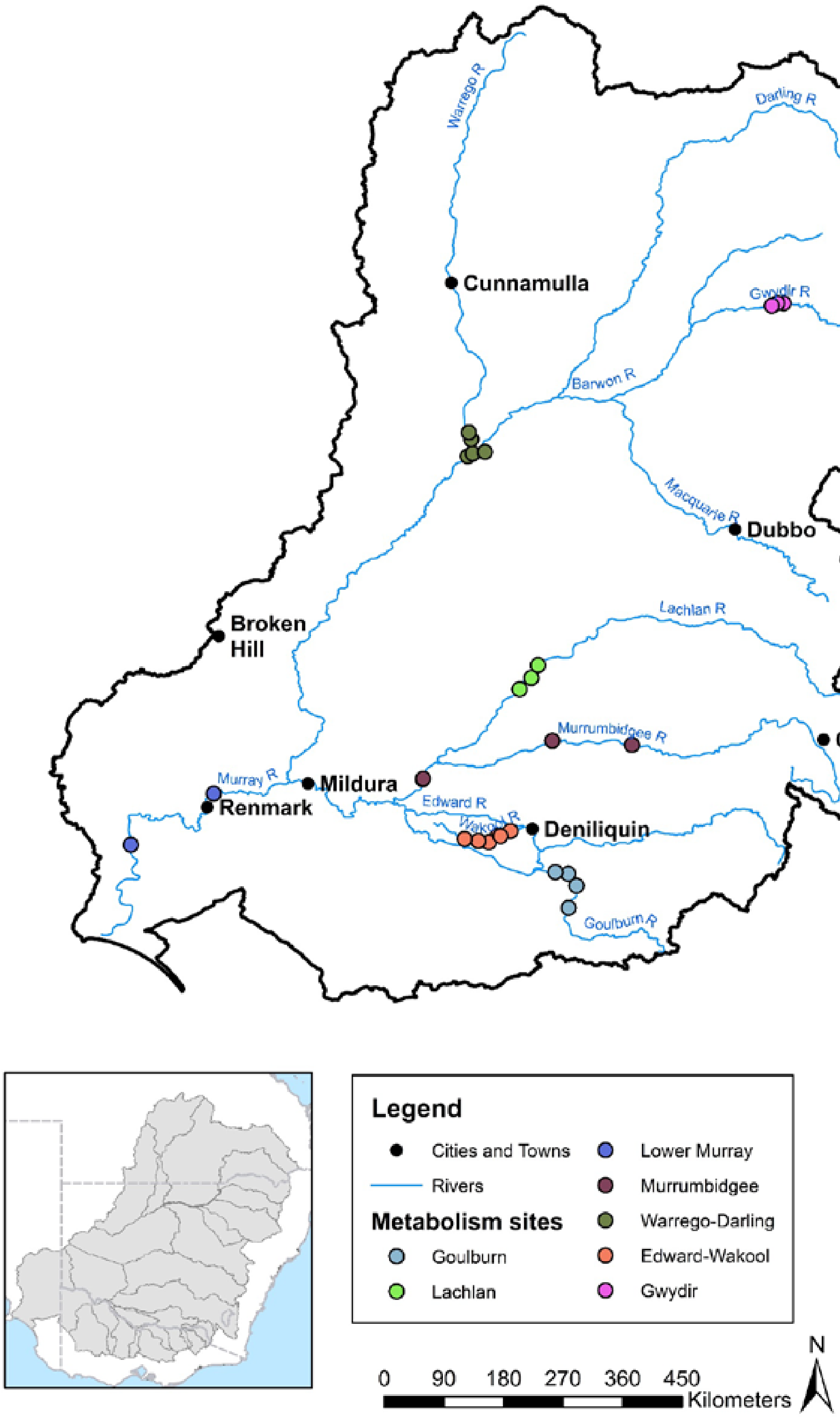

Figure 7. Location of LTIM Stream Metabolism monitoring sites.

3 Synthesis of Selected Area outcomes

3.1 Highlights

Commonwealth environmental water is likely to have had a beneficial influence on stream metabolism and water quality in 2015–16:

- in the Central Murray, Goulburn, Lachlan and Macquarie rivers through provision of base flows
- in the Lower Murray River via weir pool manipulations and base flows
- on dissolved oxygen in the Edward–Wakool river system and water outcomes in refuge pools in the Gwydir river system.

3.2 Synthesis of Selected Area outcomes

3.2.1 Overview of watering actions with expected outcomes for Stream Metabolism and Water Quality

In 2015–16, CEWO contributed to 10 watering actions within Selected Areas[2] to achieve expected outcomes associated with stream metabolism (including actions with expected outcomes for nutrient cycling and/or ecosystem function) (Table 2). Five of these watering actions were allocated to base flows for a combined volume of 74.4 gigalitres (GL), almost of which (97%) was delivered in the Goulburn River. CEWO also delivered five fresh flows – two in the Goulburn (109.9 GL) and three in the Barwon–Darling (7.6 GL) for a total of 117.5 GL. One overbank watering action was also undertaken in the Gwydir that delivered 1350 megalitres (ML) into wetlands (see Table 4). A further 21 watering actions using Commonwealth environmental water focused on water quality as a key outcome (Annex A; watering actions included in Table 2 were not repeated in this annex).

[2] This information was collated from the CEWO watering action acquittal reports provided in December 2016 and then updated according to the March 2017 Hydrology Report Card and the Watering Action Acquittal Report – Northern Unregulated Catchments 2015–16 (provided April 2017). There were several watering actions in the Lower Murray that targeted salt and nutrient movement (i.e. to facilitate meeting Water Quality objectives) and these are included in Annex A.

Table 2. Summary of 2015–16 watering actions targeting stream metabolism and generic ecosystem functioning in Selected Areas.

Selected Area	Dates	Flow component type	Commonwealth environmental water volume delivered (GL)	Monitored site(s)	Expected ecological outcome	Observed ecological outcomes	Influences
Goulburn River (lower river channel)	01/07/15 – 08/07/15	Fresh	10.661	McCoy's Bridge	Support ecosystem function	Prior to commencement of data collection in August 2015.	
Goulburn River (lower river channel)	09/07/15 – 02/10/15	Base	10.549	McCoy's Bridge	Support ecosystem function	Small increases in rates of primary production (GPP) and ecosystem respiration (ER).	Increased rates due to increasing water temperatures and longer days coupled with possible enhanced nutrient and organic carbon availability.
Goulburn River (lower river channel)	03/10/15 – 29/10/15	Fresh	99.139	McCoy's Bridge	Support ecosystem function	Rates depressed by large dilution effect but increasing on the receding limb of the hydrograph.	Eventual rate increased due to increasing water temperatures and longer days coupled with possible enhanced nutrient and organic carbon availability.
Goulburn River (lower river channel)	30/10/15 – 12/03/16	Base	0.915	McCoy's Bridge	Support ecosystem function	Rates generally increased over this period.	Unable to distinguish effects of watering action from seasonal changes.
Goulburn River (lower river channel)	15/03/16 – 05/04/16	Base	26.961	McCoy's Bridge	Support ecosystem function	Rates depressed by significant dilution effect. Increases in ER but not GPP on falling hydrograph.	Lack of response in GPP on the falling hydrograph likely due to cooler water temperatures and shorter days.
Goulburn River (lower river channel)	06/04/16 – 30/06/16	Base	33.356	McCoy's Bridge	Support ecosystem function	Any effects of this watering action were after completion of 2015–16 monitoring.	
Gwydir	10/04/16 – 30/05/16	Base	2.600	Pallamallawa	Support fundamental ecosystem function processes	No data available.	

Selected Area	**Dates**	**Flow component type**	**Commonwealth environmental water volume delivered (GL)**	**Monitored site(s)**	**Expected ecological outcome**	**Observed ecological outcomes**	**Influences**
					of nutrient and carbon cycling and primary production.		
Barwon–Darling (Mungindi to Menindee)	01/07/15 – 30/09/15	Fresh	2.702	Toorale	Nutrient and sediment cycling from inundation of lower level benches (Darling River at Toorale and downstream).	No discernible changes in very low rates of GPP and ER.	Naturally low metabolic rates due to cool temperatures and relatively short daytime photoperiods.
Barwon–Darling (Mungindi to Menindee)	28/01/16 – 01/03/16	Fresh	3.481	Toorale	Nutrient and sediment cycling from inundation of lower level benches (Darling River at Toorale and downstream).	No data available.	
Barwon–Darling (Mungindi to Menindee)	01/06/16 – 30/06/16	Fresh	1.457	Toorale	Nutrient and sediment cycling from inundation of lower level benches (Darling River at Toorale and downstream).	No data available.	

[1] As reported by the Commonwealth Environmental Water Office (CEWO).

[2] As reported by the Monitoring and Evaluation (M&E) team for each Selected Area in Selected Area reports for 2015–16.

3.2.2 Base flows

Currently there is limited capacity to evaluate base flows as hydraulic information was not available and there is no quantitative model to provide a prediction of what would have happened in the absence of the environmental flow. It is anticipated that a quantitative evaluation will be possible in Year 3 (2016–17). An evaluation based on the conceptual models (see Section 1.3) is, however, possible.

Environmental flows that increase base flows are likely to influence the amount of habitat available for primary producers (Section 1.3.1). Any increase in available habitat is likely to increase the supply of organic carbon, the energy source driving and sustaining aquatic food webs and essential nutrient recycling via ecosystem respiration. In flowing systems in which environmental flows have had a significant influence on base flows, it is likely that there will have been an associated effect on metabolism. The systems where Commonwealth environmental water increased base flows included the Central Murray, Goulburn, Lachlan and Macquarie rivers (Stewardson & Fiorino 2017). Given their duration (multiple weeks), these watering actions are likely to have provided base levels of organic carbon and nutrients – the quantities of these essential components are determined by primary producer biomass and the amount of organic carbon available.

The situation in impounded rivers is likely to be different, as changes to base flows may not affect the amount of habitat, but may influence habitat type (still water versus flowing water) and the effect of this change on metabolism is not clear. In 2015–16, however, the allocation of Commonwealth environmental water to base flows through the Lower Murray River were associated with weir pool manipulations which promoted lateral connectivity and the possibility of entrainment (Section 1.3.2). The effects of water level manipulations in the Lower Murray on (a) stream metabolism and (b) biofilm community composition and succession were examined in two papers prepared for the South Australian Department of Environment, Water and Natural Resources by Wallace and Cummings (2016a, b). Murray River weir pools were raised by 0.45 m and 0.50 m, while the Chowilla Environmental Regulator was used to increase the water height in the anabranch system by 1.5 m. As a result of these watering actions, primary production (GPP) and ecosystem respiration (ER) increased by a factor of up to 2–3 above baseline values, while there was an even larger (5-fold) increase in ER, but not GPP, in the Chowilla Creek anabranch (Punkah Creek) and associated wetlands. These increases were attributed to changed resource (organic carbon, nutrients) availability associated with the water level rise and then fall. Water level manipulations in the weir pools also induced longer term changes in biofilm community composition. It might be expected that enhanced biofilm community turnover and succession would result in enhanced GPP, but this was not observed here. Watering actions in this region, including spring flooding, have previously been shown to introduce a large amount of organic carbon from the floodplains of the Lower Murray into the main river channel (e.g. Wallace & Furst 2016). The impacts of such organic carbon delivery on metabolism in the river channel will also depend on the relative volumes of water.

Using watering actions to maintain a base flow in the reach can also be important in avoiding adverse water quality outcomes. This is exemplified by Zone 2 in the Edward–Wakool river system Selected Area where very low flow resulted in dissolved oxygen concentrations below that at which fish health is compromised. This may also have been important in the Warrego–Darling river system and Gwydir river system.

3.2.3 Freshes

Fresh flows were allocated in the Goulburn River and Gwydir river system Selected Areas in 2015–16. Allocation of environmental water to provide freshes may have significant environmental benefits through enhancing rates of primary production and ecosystem respiration, although these benefits may arise from a variety of mechanisms (see Section 1.2.3). In the Goulburn River, monitoring revealed freshes were associated with no change or a depression in rates of GPP and ER per unit volume, which is most likely the result of dilution. The effect of freshes on reach-scale metabolism remains uncertain as the total amount of dissolved oxygen – hence, organic carbon fixed and consumed at the reach scale – depends on scaling the rates up to the reach using an estimate of the volume of water present in the reach. It is intended that the Year 3 (2016–17) Basin Matter report will quantify the amount of organic carbon produced in a stream reach of 1 km under both base flow conditions and with the introduction of freshes. This will then enable assessment of the benefits of those freshes that are still constrained within the river channel. It is anticipated that the amount of carbon produced will be determined by nutrient availability and the light climate during and immediately after the fresh. From a conceptual point of view, it is not clear what the overall outcome would have been in the Goulburn as the counteracting forces of a decrease in the rate per unit volume may have been offset by the overall increase in water within the reach, and the longer the fresh lasted and the warmer the water, the more likely it is that the fresh would have increased overall metabolism.

The fresh delivered in the Gwydir was may also have had an effect on metabolism, but the evaluation is subject to the same uncertainties outlined for the Goulburn. From a water quality perspective, it appears likely that the Gwydir fresh influenced water quality, particularly in refuge pools.

3.3 Unmonitored area outcomes

Over the 2015–16 watering period, CEWO contributed to 16 watering actions to achieve expected outcomes associated with stream metabolism (including actions that targeted nutrient cycling and/or ecosystem function) in unmonitored sites. These actions are summarised in Table 3.

Based on results from years 1 and 2 (2014–16) of the monitored areas, it is anticipated that environmental watering actions confined within the defined river channels (e.g. the Campaspe and Ovens river systems) will not result in significant changes to metabolic rates on a volumetric basis. It is still hypothesised, based on the Entrainment Model, that in the southern Basin, metabolic rates are largely determined by low nutrient concentrations (and specifically, low concentrations of 'bioavailable' phosphorus for GPP and labile organic carbon for ER).

One of the environmental outcomes expected from watering actions in the Ovens River (Table 3) is improved primary production through the disruption of biofilms (Section 1.3). As shown in the hydrograph at Wangaratta (Figure 8), with the exception of a small natural fresh in early December 2015, discharge was very low throughout summer to mid–autumn. At this site, Commonwealth environmental water contributed none of the total streamflow volume. Given the low and relatively constant flows during the period when primary production might be highest due to higher temperatures and longer days of more intense sunlight, disturbance of biofilms is considered unlikely. It would be informative to investigate whether flows of the magnitude experienced in early December (around 2000 ML/day) are capable of scouring old biofilms – and hence enabling growth of new, more active biofilms.

Table 3. Summary of 2015–16 watering actions targeting stream metabolism and generic ecosystem functioning at unmonitored sites.

Valley name (Water Action Reference)	Dates	Commonwealth environmental water delivered (ML)	Flow component type	Location	Expected ecological outcomes
Lachlan (10039)	03/08/15 – 15/10/15	24 059	Fresh	Lachlan – Great Cumbung Swamp	Contribute to ecosystem functions.
Moonie (111-27)	28/08/15 – 02/09/15	201	Fresh	QLD Moonie – Lower Moonie River and fringing wetlands	Contribute to natural flow events to support key ecosystem functions and aquatic habitats.
Border Rivers (111-26)	26/07/15 – 07/08/15	409	Fresh	QLD Border Rivers – Dumaresq–Macintyre River and fringing wetlands	Contribute to nutrient and sediment cycling (from inundation of upper channel areas, some anabranch channel and near-stream wetlands).Other fish and hydrological objectives.
Border Rivers (111-26)	26/08/15	235	Fresh	QLD Border Rivers – Dumaresq–Macintyre River and fringing wetlands	Nutrient and sediment cycling (from inundation of upper channel areas, some anabranch channel and near-stream wetlands). Other fish and hydrological objectives.
Border Rivers (111-26)	07/11/15	244	Fresh	QLD Border Rivers – Dumaresq–Macintyre River and fringing wetlands	Nutrient and sediment cycling (from inundation of upper channel areas, some anabranch channel and near-stream wetlands). Other fish and hydrological objectives.
Border Rivers (111-26)	02/02/16	137	Fresh	QLD Border Rivers – Dumaresq–Macintyre River and fringing wetlands	Nutrient and sediment cycling (from inundation of upper channel areas, some anabranch channel and near-stream wetlands). Other fish and hydrological objectives.
Murrumbidgee (10035-09)	17/11/15 – 11/01/16	10 000	Wetland inundation (via the most direct path to Tarwillie Swamp to minimise incidental inundation of vegetation that has achieved its required flooding regime in recent years)	Murrumbidgee – Yanga National Park waterbird support	Support ecosystem functions.

Valley name (Water Action Reference)	Dates	Commonwealth environmental water delivered (ML)	Flow component type	Location	Expected ecological outcomes
Murrumbidgee (10035-15)	08/03/16 – 29/03/16	5000	Fresh Planned deliveries (150–300 ML/day) to inundate Hobblers Lake and Penarie Creek	Murrumbidgee – Hobblers Lake – Penarie Creek	Provide winter refuge habitat and drying habitat into spring–summer 2016–17.
Murrumbidgee (10034-03)	21/07/15 – 13/08/15	18 263	Wetland Inundation Supplementary take targeting up to 1300 ML/day at offtake and use of Colleambally Catchment Drain from 1 August.	Murrumbidgee – Hobblers Lake – Penarie Creek	Support ecosystem functions, such as dispersal of biota and transfer of nutrients that relate to longitudinal and lateral connectivity.
Gwydir	09/01/16 – 11/02/16	13 500	Overbank	Gwydir – Gwydir Wetlands	Allow for sediment transport, nutrient and carbon cycling
Gwydir	09/11/15 – 11/11/15	964	Fresh Take supplementary water during natural flow events as announced by Water NSW	Gwydir – Mehi River (supplementary water)	Support in-stream ecological function and nutrient cycling, contributing to the health of in-stream habitat and maintaining water quality.
Macquarie	06/08/15 – 17/10/15	12 114	Fresh Pulse 1 – 1000 ML/day at Marebone Weir (800 ML/day Macquarie River and 200 ML/day Marebone Break and Bulgeraga Creek – target 300–500 ML/day at Pillicawarrina) Pulse 2 – 1000 ML/day at Marebone Weir (600 ML/day Macquarie River and 400 ML/day Marebone Break and Bulgeraga Creek – target 600–700 ML/day at Pillicawarrina)	Macquarie – Macquarie Marshes Nature Reserve and core wetlands	Provide refuge habitat for fish and other aquatic species. Increase hydrological connectivity along the Macquarie River and into the Southern and Northern Marshes to Carinda. Depending on the level of water extraction by unregulated irrigators downstream of Carinda, the action may contribute water to the Barwon–Darling River, thus improving connectivity in the Basin. Allow for sediment transport, nutrient and carbon cycling.
Macquarie	25/06/16 – 30/06/16	2125	Fresh The timing, magnitude and duration of the flow was dependent on the announcement of a supplementary event	Macquarie – Macquarie river system, including floodplain (supplementary water)	Allow for sediment transport, nutrient and carbon cycling. Plus, contribute to many other habitat, hydrological and biota-driven objectives.
Ovens (10004-02)	05/04/16 – 07/04/16	50	Release at same time as Lake Buffalo entitlement if a bulk release occurs, otherwise when advised by North East Catchment Management Authority (NECMA)	Ovens River with benefit to King River en route from Lake William Hovell	Improve primary production through the disruption of biofilms.

Valley name (Water Action Reference)	Dates	Commonwealth environmental water delivered (ML)	Flow component type	Location	Expected ecological outcomes
Ovens (10004-02)	25/04/16 – 26/04/16	20	Release with a bulk release if one occurs, otherwise when advised by NECMA	Ovens River with benefit to Buffalo River en route from Lake Buffalo	Improve primary production through the disruption of biofilms.
Lower Murray	12/10/15 – 23/10/15	5348	Wetland	Hattah Lakes	Promote exchange and cycling of nutrients and carbon between the river and the lakes.

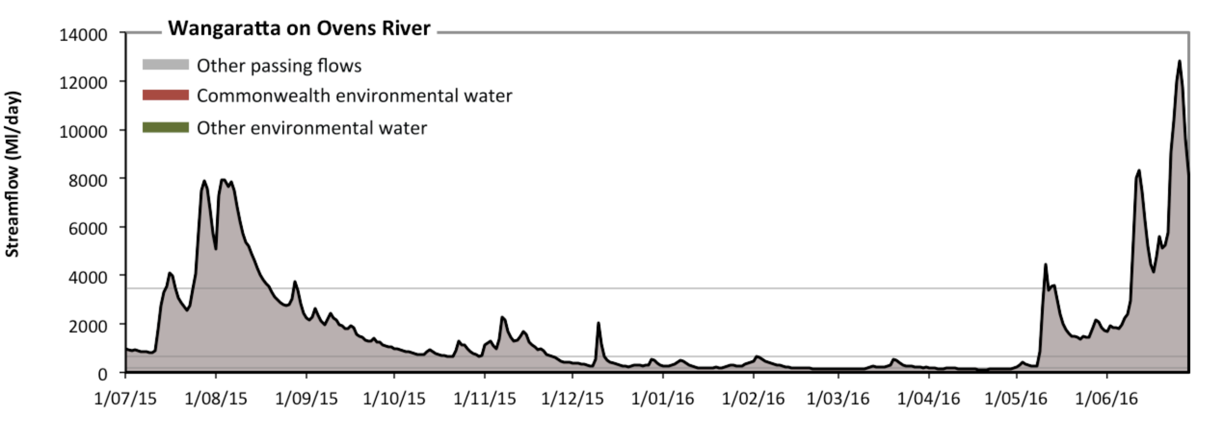

Figure 8. Contribution of environmental water delivery at Wangaratta on the Ovens River. Horizontal lines indicate thresholds for very low flows, low flows, low freshes, medium freshes and high freshes (from lowest to highest).

Based on the small amount of data now available from the Junction of the Warrego and Darling rivers and Gwydir river system Selected Areas, it is anticipated that primary production rates, in particular, will be constrained in the unmonitored sites due to high turbidities. There is not yet sufficient information on flow–metabolism relationships to determine whether Commonwealth environmental water will attenuate the high turbidity and therefore facilitate primary production or suppress photosynthesis further. Hopefully, more extensive data sets from the Warrego–Darling system and the Gwydir sites in 2016–17 and beyond will enable further insights into relationships between discharge, light availability and ensuing primary production. It is highly likely that nutrient concentrations will be sufficient to initiate significant primary production should the light climate be conducive to such growth.

For watering actions targeting stream metabolism and water quality in unmonitored sites, it is expected that water returning to the main river channel after inundating wetlands and floodplains (e.g. Macquarie River) is likely to affect water quality and rates of primary production and ecosystem respiration. On this basis, it appears likely that the watering actions undertaken in the Macquarie River would have been associated with increases in metabolism based on the Entrainment Model.

The magnitude of the effects of these watering actions will be influenced by a number of factors. Timing will influence the temperature and amount of light and, as noted earlier, these are both major drivers of metabolism responses. Duration of inundation will also have an influence as longer duration inundation events provide more time for growth of key primary producers, such as algae. Finally, the area inundated and its associated vegetation community will influence the amount and type of organic matter and nutrients available for entrainment.

3.4 Synthesis of water quality findings

The Basin Plan objective in relation to water quality and salinity is to maintain appropriate water quality, including salinity levels, for environmental, social, cultural and economic activity in the Murray–Darling Basin. More specifically, for water-dependent ecosystems, the objective is to ensure water quality is sufficient to protect and restore ecosystems, their associated ecosystem functions and to ensure they are resilient to climate change and other risks and threats. In terms of an evaluation of the management of Commonwealth environmental water, there are three considerations:

1. the extent to which watering actions undertaken to achieve biodiversity, ecosystem function or resilience outcomes influenced water quality

2. the effectiveness of watering actions undertaken to ameliorate threats from acute water quality events, including cyanobacterial algal blooms, oxygen-depleted blackwater and acidification
3. the effectiveness of watering actions undertaken to achieve long-term improvements in water quality, including the export of salt.

Within this context, the available data did not detect any water quality issues and there was no additional monitoring to assess water quality risks arising from the implementation of watering actions in 2015–16. The watering actions undertaken in the Lower Murray River were effective in exporting salt and nutrients which would be expected to contribute to 1–5-year improvements in water quality in the Basin.

A review of water quality data from across the seven Selected Areas provides an important baseline that will inform the evaluation of watering actions undertaken in future years of the LTIM Project. Annex C of this report lists the nutrient data from samples collected from the Selected Areas during 2015–16. Of particular importance to stream metabolism are the concentrations of the bioavailable forms of nitrogen (N) (nitrate+nitrite = 'NOx' and ammonia/ammonium) and phosphorus (P) (filterable reactive P (FRP) which is usually equated to phosphate). The Edward–Wakool, Murrumbidgee, Goulburn and Lower Murray sites in particular had very low median FRP concentrations (around 3–5 µg P/L; Table C5) which almost certainly constrained primary production. FRP was also relatively low in the Lachlan. Median FRP was much higher in samples from the Gwydir and especially the Warrego–Darling samples, so it will be instructive to contrast metabolism from these two Selected Areas with the other five Selected Areas to assess the impact of nutrients. Bioavailable N concentrations (ammonia and nitrate; Tables C3 and C4, respectively) varied widely across the Selected Areas. It is anticipated that low bioavailable N may help limit primary production where P is also low or favour N-fixing cyanobacteria if P concentrations favour significant growth. It is expected that nutrient availability will perhaps be the dominant determinant of metabolism (especially primary production) across the southern Basin.

Dissolved organic carbon (DOC) concentrations (Table C6) also showed some variability between Selected Areas. DOC can be correlated with ER, as ER involves breakdown of organic matter. However, it must be stressed that the relationship between these two parameters is not straightforward as the lability ('quality' – related to chemical composition) of the organic carbon is just as important. DOC can be a reasonable estimate of organic matter but can also reflect the carbon remaining after all the labile fractions have been consumed. Continued assessment of lability of the DOC (and total organic carbon) samples, through techniques including fluorescence excitation and emission matrices (Watts *et al*. 2015), is essential to tease these factors apart.

3.5 Adaptive management

Based on the information from the first 2 years of the LTIM Project, it appears that, in line with the Entrainment Model, rates of primary production and ER are unlikely to respond to base flows or freshes on a per unit volume basis when constrained within the river channel. It does appear likely that stream metabolism did respond to those watering actions that achieved significant floodplain or wetland inundation; for example, in the Lower Murray, based on the Entrainment Model (Section 1.3.2).

It is hypothesised that the lack of response to base flows and freshes is largely determined by the limited opportunities for entrainment that occur when water remains in-channel. Results suggest, however, that delivery of water from alternative sources (e.g. Chowilla into the Lower Murray, flows from Copeton Dam rather than other sources into the Gwydir, attenuating high turbidity) can induce higher metabolic rates. Nutrient increases may also be mediated through rewetting dried areas, as seen in the Murrumbidgee. In addition, there is a limited amount of evidence to indicate that higher nutrient concentrations do stimulate primary production and ER (one site in the Edward–Wakool

Selected Area, Entrainment Model). There is emerging evidence that increasing nutrient concentrations will enhance what appear to be 'low' rates of primary production and ER on a world scale, although what now constitutes 'average' ranges for metabolic parameters across the globe is an open question as more data sets slowly emerge with rates similar to those found during this LTIM Project.

In many instances, the management of Commonwealth environmental water will be limited to freshes and base flows due to either the volumes of water available or delivery constraints within the system. In these instances, three options emerge in terms of future management:

1. When planning environmental flows, consideration of the trade-off between magnitude and duration may be influenced by consideration of metabolism outcomes. Two options may be worth considering:
   - If shortening the duration of the flow would significantly increase the extent of lateral connection, then it may be worth increasing magnitude and reducing duration.
   - If, however, there is limited scope to achieve significant lateral connectivity, then a longer smaller flow is likely to have a greater influence on metabolism as it will enable colonisation and accumulation of primary producers and decomposers. There will obviously be a balance here between promoting such biota and leaving the system too stable which may lead to declines due to senescence.
2. If stream metabolism is a priority outcome either in its own right or in order to achieve outcomes for fish or waterbirds, then opportunities to connect the river to potential sources of nutrients and organic matter should be explored. These may include upstream opportunities or through the use of infrastructure to inundate and then return water to the main channel.

3. Focus on other outcomes – environmental flows play a variety of roles in rivers and, if stream metabolism outcomes are unlikely within the operational constraints, this requires that flow management focus on other outcomes, such as provision of habitat or connectivity.

From a water quality perspective, Commonwealth environmental water has the capacity to influence water quality as evidenced by the outcomes in the Gwydir and Edward–Wakool. In the Edward–Wakool, Commonwealth environmental water is believed to have had a beneficial effect by preventing the development of the low dissolved oxygen conditions found in a nearby site which did not receive water.

3.6 Selected Area summary outcomes

The following subsections provide a high-level summary of the outcomes reported at each of the Selected Areas. They are all derived from the Selected Area reports and the relevant report should be consulted if further detail is required.

3.6.1 Data collection

The stream metabolism data set collected for Year 2 (2015–16) is summarised in Table 4. For each monitoring site in the seven Selected Areas, the table includes the total number of days for which metabolic parameters were calculated and the number of days for which the model fitted to the experimental data using the BASE model met or failed the criteria for subsequent analysis. These two criteria – $R^2 \geq 0.90$ and coefficient of variation for GPP< 50% – were established during the LTIM Project meeting of Selected Area (Stream Metabolism Matter) leaders in Sydney, 21–22 July 2015. With BASEv2, an additional criterion was also used which stipulated the model fit parameter PP_{fit} must be in the range 0.1 to 0.9. Values of PP_{fit} outside this range indicate that the 'best fit' to the data is still an implausible model. The addition of this extra criterion was an outcome from the LTIM Project meeting of Selected Area (Stream Metabolism Matter) leaders in Sydney, 19–20 July 2016.

It is emphasised that this method of data collection and analysis using the BASEv2 model is *only* appropriate for flowing waters, not wetlands. Analysis of wetland metabolism is much more difficult as water column stratification and heterogeneity in response mean multiple (as many as 6–10) loggers need to be deployed in a single wetland. Consequently, single measurements of metabolism in wetlands are considered as assays of the immediate vicinity of the dissolved oxygen probe rather than being indicative of whole wetland metabolism.

Table 4. Summary of stream metabolism data records 2015–16.

Catchment	Logger site	Period of record		Days with metabolism data (no.)		
		First date	Last date	Pass	Fail	Total
Edward–Wakool	Barham Bridge	15/08/15	04/04/16	106	91	197
Edward–Wakool	Hopwood	18/08/15	03/04/16	130	89	219
Edward–Wakool	Llanos Park2	15/08/15	04/04/16	52	163	215
Edward–Wakool	Noorong2	15/08/15	04/04/16	77	132	209
Edward–Wakool	Widgee, Wakool River1	19/08/15	04/04/16	144	72	216
Edward–Wakool	Windra Vale	15/08/15	03/04/16	136	83	219
Goulburn	Darcy's Track	29/08/15	22/02/16	43	112	155
Goulburn	Loch Garry Gauge	05/09/15	30/03/16	47	94	141
Goulburn	McCoy's Bridge	27/08/15	18/04/16	92	101	193
Goulburn	Day Road	24/10/15	18/04/16	39	105	144
Lachlan	CC	25/06/15	24/05/16	100	227	327
Lachlan	LB	25/06/15	09/06/16	223	123	346
Lachlan	WA	26/06/15	25/05/16	100	187	287
Lachlan	WB	8/07/15	23/05/16	112	185	297
Lower Murray	LK1DS_265km	23/09/15	03/03/16	117	36	153
Lower Murray	LK6DS_616km	23/09/15	03/03/16	92	41	133
Murrumbidgee	McKennas	20/10/15	01/04/16	145	13	158
Murrumbidgee	Narrandera	20/10/15	19/01/16	90	0	90
Gwydir	GW2	29/09/15	20/04/16	7	4	11
Gwydir	GW3	29/09/15	20/04/16	0	12	12
Gwydir	GW4	29/09/15	20/04/16	4	8	12
Warrego–Darling	Akuna	28/08/15	16/12/15	8	73	81
Warrego–Darling	Yanda	28/08/15	16/12/15	4	66	70

3.6.2 Site summaries

Edward–Wakool river system

This section is derived from the draft Edward–Wakool river system Selected Area evaluation report (Watts et al. *2016).*

There were four Commonwealth environmental watering actions in the Edward–Wakool system although none of these specifically targeted ecosystem functions. Two affected the study reaches assessed for stream metabolism during 2015–16, while the other two were related to the operation of Tuppal Creek and the Colligen–Niemur system. The Wakool River was to be maintained between 50–100 ML/day from 4 September 2015 to 30 January 2016 and Yallakool Creek was to be maintained between 450–500 ML/day from 10 November 2015 to 30 January 2016 (Figure 9). Only the Tuppal Creek watering action directly targeted water quality (Annex A). The scheduled metabolism monitoring program concluded in early April.

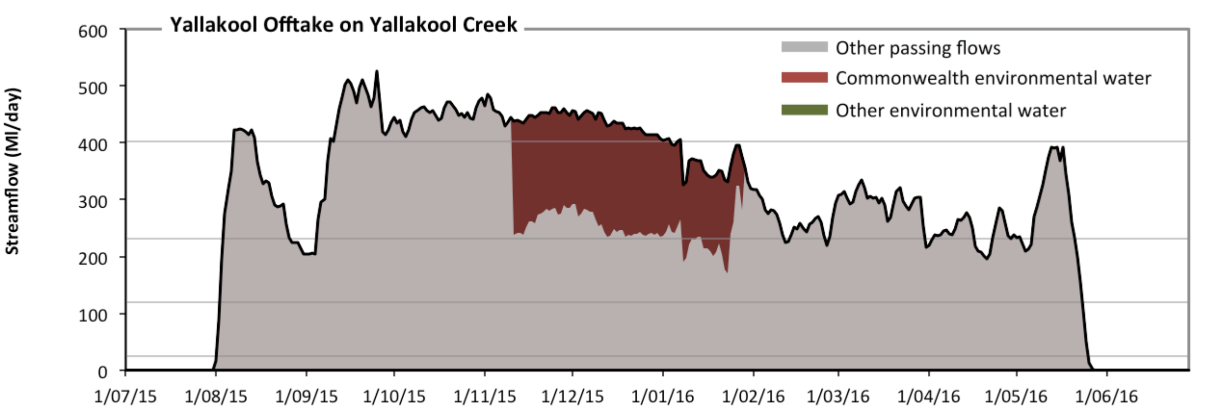

Figure 9. Contribution of environmental water delivery at Yallakool Offtake on Yallakool Creek. Horizontal lines indicate thresholds for very low flows, low flows, low freshes and medium freshes (from lowest to highest).

Although intended to achieve positive outcomes for fish by restricting flow variability during the spawning period, this constancy in flows (as exemplified in Figure 9) precluded detection of significant GPP and ER responses to watering actions. Median GPP values ranged from 1.37 to 4.09 mg O_2/L/day across the six monitoring sites. However, the 'real' range in median values is almost certainly smaller than this as the site with the highest GPP (Zone 3 upstream) had no data that met acceptance criteria over the period August–October 2015, when rates would be lower due to seasonal effects. To illustrate the narrowness of this range, during an algal bloom in March 2016, GPP rates reached 13 mg O_2/L/day, clearly indicative of a highly productive ecosystem. ER rates were generally higher than GPP, indicating a net heterotrophic ecosystem. The range in median values was again inflated by Zone 3 upstream (10.6 mg O_2/L/day) – without this site, median values were 2.7–6.4 mg O_2/L/day.

The effects of small variations in discharge (especially from October 2015 through to February 2016) on metabolic rates (the desired outcome) were masked by daily variability associated with weather and seasonal changes in these rates (changing temperatures and amounts and intensities of sunlight). In the absence of flow variation, seasonal changes in GPP and ER were observed. It is expected that longer, warmer days as spring becomes summer will increase the daily rates of primary production. Higher growth rates of primary producers, including benthic algae, will lead to more production of organic carbon and some of this will fuel increased rates of ecosystem respiration. The absence of significant flow change meant that scouring of extant biofilms was unlikely (Disturbance Model).

As noted in the Year 1 (2014–15) report (Grace 2016), the benefit of the constant and elevated flows was the maintenance of sufficient dissolved oxygen (DO) to avoid low DO levels. The one reach with only small flows (Zone 2, the upper Wakool River site at Widgee) experienced significantly lower DO in the water, with concentrations regularly dropping below 5 mg/L between mid-October 2015 and January 2016. These low DO concentrations were attributed to both the low flow and the higher respiration rates. This point emphasises the 'Goldilocks' nature of metabolic rates: *sufficient* primary production and ER are required to ensure the production of basal food resources but if rates are too high then this might be the result of algal blooms (primary production, as seen in the early autumn) or cause anoxia, with resultant fish deaths. A better understanding of the 'ideal target range' for metabolism should emerge as the LTIM Project continues into Year 3 (2016–17) and beyond.

Goulburn River

This section was derived from the Goulburn River Selected Area evaluation report (Webb et al. *2017).*

There were six watering actions during 2015–16 (two freshes and four base flows[3]) for a total of 181 581 ML (Table 2), all of which had expected outcomes of maintaining/improving water quality and ecosystem function (stream metabolism). In general, the onset of increased flow led, initially, to decreases in metabolic rates, almost certainly due to dilution. This was exemplified in the March 2016 flow event at Loch Garry; ER in particular declined as the stream discharge increased substantially.

Data from the four monitoring sites was available for the period late July – August 2015 through to February–April 2016. As illustrated in Figure 10for McCoy's Bridge, delivery of the first fresh occurred in the first week of July when no metabolism data were available. The second fresh was delivered over three weeks from 3–29 October 2015. The third fresh was delivered in March 2016 with the remaining watering actions being base flows.

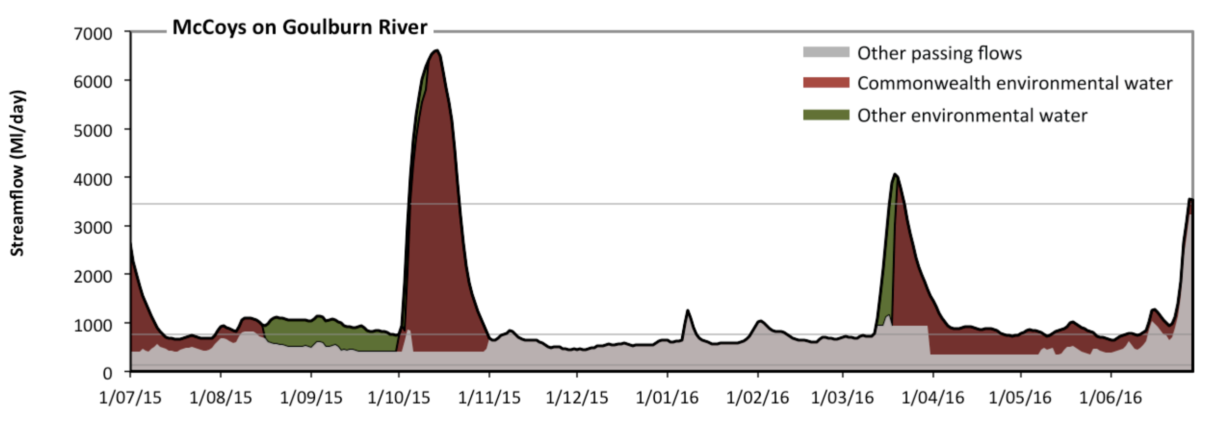

Figure 10. Contribution of environmental water delivery at McCoy's Bridge on the Goulburn River. Horizontal lines indicate thresholds for very low flows, low flows and low freshes (from lowest to highest).

Delivery of the second fresh was associated with an initial decrease in GPP. This is consistent with the increased flows either diluting the resident phytoplankton or disturbing the biofilms. This would suggest that the low freshes delivered in the Goulburn were not entraining organic matter or nutrients, but were diluting or disturbing primary producers.

When considering the oxygen load (mass transported per unit time), there was a positive effect of flow rate on total amounts of oxygen produced by GPP and consumed by ER. It is expected that if flows introduce nutrients there will be a post-flow lag of perhaps 10–20 days before significant increases in GPP may occur (shorter response times are expected for ER as bacterial populations increase in size more quickly than algal populations). Bayesian modelling showed that the total oxygen consumption in the river reach (based on ER) increased with flow and was best fitted to a model using a lag time of 2 days – this time frame is consistent with an increasing population of bacteria. This means that the total amount of organic matter processed in the reach increased with discharge. Using the October 2015 fresh as an example, even though the fresh event suppressed GPP and ER on a per litre basis, because of the additional discharge during this event, an additional

[3] The March 2016 event is listed as 'base flow', although it very clearly is a significant flow event. Consequently, the six watering actions are more correctly described as three freshes and three base flows.

2.8 tonnes of organic carbon was created per day by GPP and an additional 6.4 tonnes of organic carbon was respired. This corresponds to a doubling of primary production at the reach scale and a tripling of ER.[4] The fate of the processed organic matter is not clear as the bacteria may have used it for respiration, growth or reproduction and any additional biomass may have been either retained or exported from the reach.

As noted in Year 1 (2014–15), the rates of both GPP and ER were in the lower range of normal behaviour for river systems worldwide and almost all variability observed occurred within these 'low' ranges. 'Low' GPP is linked to both very low nutrient concentrations and relatively high turbidity measurements – although what defines 'low' and 'high' turbidity is highly dependent on the location in the Basin.

Of some concern were the short periods of low to very low average dissolved oxygen (DO) concentrations at several sites. Most notably, the mean daily DO was as low as 1.6 mg O_2/L on 2 December 2015 at the Day Rd site (and was just 2.3 mg O_2/L the preceding day). It recovered to over 7.6 mg O_2/L the following day. The origin of this very low DO event remains unclear as the Victorian Surface Water Monitoring Partnership DO logger at the Goulburn Weir outlet was out of commission over this period. It is highly likely the low DO originated in either the weir or further upstream. DO concentrations of less than 4 mg O_2/L can be deleterious to aquatic ecosystem health; hence, the origin needs to be identified. There was no significant flow event in the weeks leading up to this short (3-day) period of very low DO. Other short periods of DO drops were seen at McCoy's Bridge (twice) and once at Darcy's Track. There was some evidence that these events can be traced to low DO in some tributaries. If this is the case, the base flow watering actions would have helped ensure their influence was minimised within the main channel of the Goulburn River.

Lachlan river system

This section was derived from the Lower Lachlan river system 2015–16 technical report (Dyer et al. *2016).*

Four watering actions, totalling 36 0021 ML, were undertaken in the Lachlan River, as shown in Figure 11, only one of which was delivered with an expectation of specific ecological outcomes but not in the main channel (10033-01: 11 November to 15 December 2015, targeting water quality improvement as one objective, Annex A). The other three events targeted wetlands, including Booligal Wetlands and the Great Cumbung Swamp. All four watering actions were freshes, with the first starting in early August and ending in mid-September. This first fresh was followed by a large translucent environmental flow (16 September to 8 October 2015) which was the dominant feature of the hydrograph that spring. The next two freshes sought to deliver water to Booligal Wetlands, while the fourth was delivered in two pulses to promote fish outcomes and improve water quality. This last watering action represented a significant proportion of flow in the river at the time, but peak discharge was less than half that recorded during the translucent flow.

No data were available to evaluate the watering actions undertaken in August and October or the translucent flow. Data were available for the subsequent two watering actions; however, the data contained large gaps and some unreliable metabolism estimates meant that only around a third of

[4] As this analysis has been performed for this Basin Matter report, it was assumed there was a 1:1 ratio between oxygen and organic carbon. Daily loads of organic carbon created and consumed were based on the measured discharges and metabolic rates over the period 2– 31 October 2015. It was assumed (quite reasonably) that the base flow would have been around 800 ML/day in the absence of the fresh. Estimated GPP and ER rates during a nominal base flow in October were the average of 14 days prior to, and 14 days after, the October period. Nominal average GPP and ER loads under assumed base flow would have been 2.4 and 3.0 tonnes organic carbon per day for GPP and ER, respectively.

the data collected could be used in the evaluation (compliance rates were 31–38% at three of the four sites).

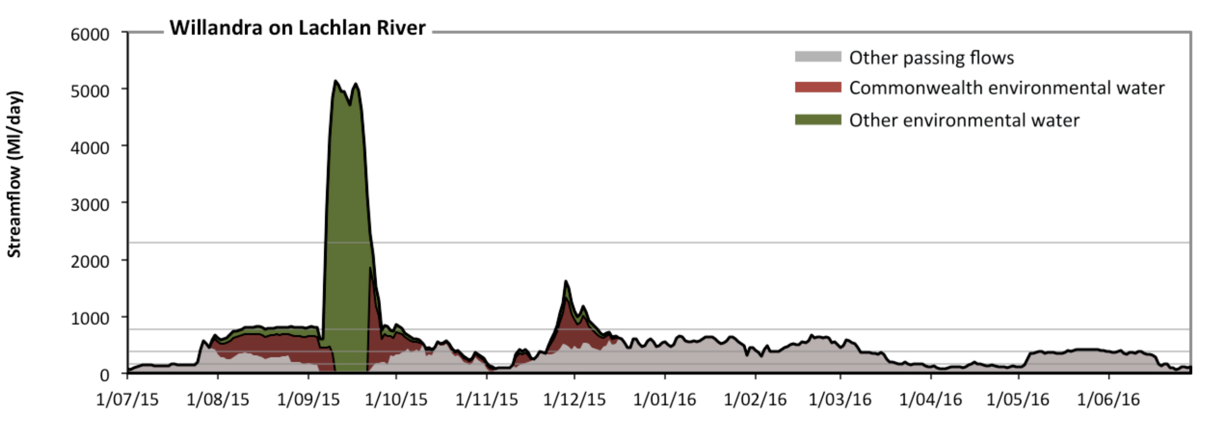

Figure 11. Contribution of environmental water delivery at Willandra on the Lachlan River. Horizontal lines indicate thresholds for very low flows, low flows, low freshes, medium freshes and high freshes (from lowest to highest).

From the available data, it appears that rates of GPP and ER during 2015–16, in this section of the Lower Lachlan river system, were very similar to those observed in the other southern Basin Selected Areas (Goulburn River and Edward–Wakool river system) and were consistent with the rates reported in 2014–15.

In considering the likely effect of the August fresh on metabolic rates, the first conceptual model considered is the Entrainment Model (Section 1.3.2). This fresh increased the magnitude and prolonged the duration of a small fresh in the system. As this was the first increase in discharge for some time, there may have been organic matter stored within the limited zone of inundation, which may have stimulated metabolism. Temperature and light may have been limiting, however, given the time of year. Data from other small in-channel freshes have not revealed that these types of pulses affect metabolism through the entrainment process. It appears unlikely, therefore, that this process influenced rates of metabolism. The fresh was quite prolonged, lasting around 5 weeks. It is possible that the fresh increased the area of bed illuminated and this may have led to increases in metabolism undertaken by biofilms. There is currently no data to determine how likely this effect may have been.

The translucent fresh, which caused a 3 m water level rise, is likely to have influenced metabolism through two processes, both entrainment and disturbance (Section 1.3). The larger area of inundation is likely to have entrained material from riparian areas and increased temperature and light would contribute to the likelihood that metabolic rates would have responded. In addition, material is likely to have been transported from upstream which may also have promoted metabolic rates. The translucent fresh is also likely to have disturbed sediments, small wood and organic matter and their associated biofilms. This disturbance may be associated with a short-term decrease in rates of metabolism, but longer term increases. On balance, it appears likely that the translucent fresh affected metabolism in the Lachlan River.

The available data did not detect any influence of the freshes delivered in November and December. This is not surprising given the relatively small magnitude of the freshes that led to 1.5 m depth increases in the U-shaped river channel, which was not large enough to inundate any significant in-channel features (Dyer *et al.* 2016). It is also likely that much of the material resident within the channel would have been entrained by the earlier translucent fresh, with insufficient time for significant amounts of fresh organic material to accumulate. The lack of change in metabolism is similar to results observed in other areas when small freshes have been delivered.

Although the detection of possible links between flow events and altered (increased) nutrient concentrations is very much constrained by the small number of water quality samples collected as part of the LTIM Project, there were no clear patterns in water chemistry associated with delivery of environmental flows.

Lower Murray River

This section was derived from the Lower Murray River Selected Area 2015–16 annual report (Ye et al. 2017). (Note that there is additional information in this section related to the export of material to the Murray Mouth)

As shown in Annex A, there were two watering actions – one following immediately after the first – in the South Australian section of the Lower Murray River that specifically targeted water quality (export of salt and nutrients). Both were classified as base flow actions, running from 1 July to 30 November 2015 and the second from 1 December 2015 to 30 June 2016. The hydrograph, highlighting Commonwealth environmental water is shown in Figure 12, for Lock 6. In addition to these two actions targeting the main river, there were an additional 39 actions, totalling nearly 11 GL of water, involving inundation of wetlands. These wetland actions have the potential to influence main river channel metabolism through return flows and the supply of organic carbon, nutrients and perhaps entrained algal populations. Much of the environmental water in July and August 2015 was return flows from Barmah–Millewa Forest and the large flow in the Goulburn River (see Figure 10above). Ye *et al.* (2017) also noted the 2015–16 was a relatively dry year.

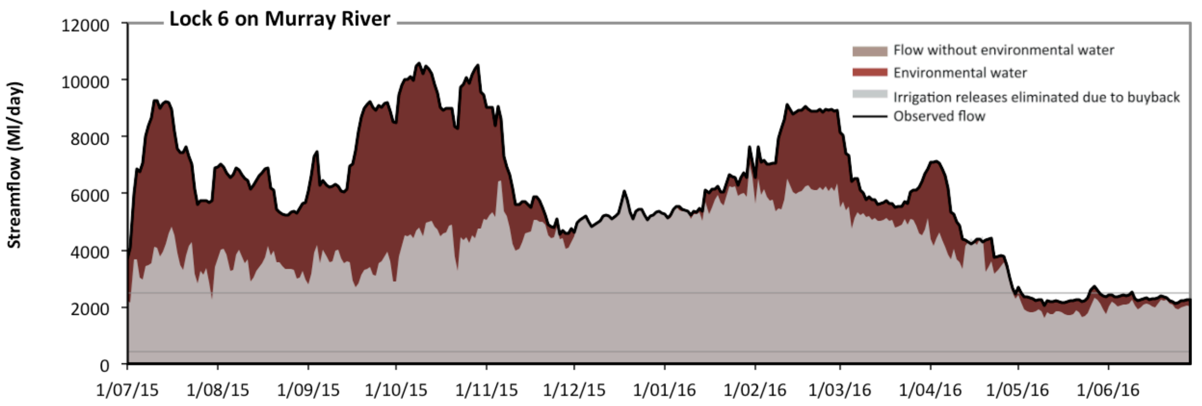

Figure 12. Contribution of environmental water delivery at Lock 6 on the Lower Murray River. Horizontal lines indicate thresholds for very low flows and low flows (from lowest to highest).

As noted in the Year 1 (2014–15) report, metabolic activity gradually increased over the sampling period (associated with warmer temperatures and more hours, and great intensity, of sunshine). Despite the variation in discharge (e.g. Figure 12)), the measured GPP and ER rates at both sites (Lock 6 and Lock 1) over the period September–December 2015 were largely constrained to the range 1–2 mg O_2/L/day. Rates for both parameters increased to 2–4 mg O_2/L/day from January until the conclusion of monitoring in early March 2016. Unfortunately, a faulty probe in Lock 6 resulted in missing data from mid-December to mid-January, making it impossible to ascertain whether the increase in rates at that site was continual or a step change. Metabolic rates (most notably ER) from Lock 1 were affected by large excursions to very high values that were subsequently attributed to biofouling of the probe (a phenomenon not observed in previous years at this site). Ye *et al.* (2017) noted that there were no changes in water quality parameters at this time that would offer an alternative explanation.

Below Lock 6, enhanced metabolic activity (but within a small range) from early October to early November 2015 was attributed to the raising of the water level in Weir Pool 5 supported by

Commonwealth environmental water, in turn reflecting the increased connection between the river and the floodplain. These enhancements to rate are however, relatively small (<1 mg O_2/L/day) and Ye *et al.* (2017) recognised the need for water level effects to be disentangled from seasonal effects. However, as noted above for the Goulburn River, large increases in flow coupled with even very small increases in GPP will lead to significantly more organic carbon being fixed in the river channel and therefore available for respiration or as a food source. It is planned that the magnitude of these increases in produced (GPP) and respired (ER) organic carbon during and after flow events will be included in the Year 3 Basin Matter report (2016–17). As noted in the Year 1 (2014–15) report, return flow from Chowilla Creek is also associated with increased metabolism and provides organic matter critical to the sustenance of the aquatic food webs in the Lower Murray River (e.g. see Baldwin *et al.* 2016).

As found in Year 1, rates of primary production and ER at both sites were in close balance, resulting in nearly zero net production, indicating that the organic matter produced via in situ primary production was also being consumed. The exception to this was during late February 2016 when higher rates of primary production resulted in positive net ecosystem production which were attributed to enhanced phytoplankton growth in lower turbidity waters. This assertion was supported by higher chlorophyll-a concentrations at that time.

Ye *et al.* (2017) notes that Commonwealth environmental water contributed to a median velocity in weir pools of around 0.1 m/s during winter and spring. This is insufficient to resuspend fine sediments and mix potentially nutrient-rich sediment pore waters into the overlying water column (Section 1.3). Due to the cohesive nature of fine sediments and the apparently 'smooth' benthic surface, water velocities much greater than 0.2 m/s are required for such resuspension (Gordon *et al.* 2004).

During the 2015–16 monitoring period, oxygen concentrations were maintained at acceptable levels (>50% dissolved oxygen saturation). There was no evidence of significantly depressed dissolved oxygen concentrations which might have arisen due to the large overland flows in the mid-Murray in September and October 2015. Likewise, these flows, which totalled around 100 GL, did not have any significant effect on metabolic rates in the Lower Murray, suggesting that any entrained organic carbon or nutrients from this inundation were either consumed in transit to the Lower Murray, or had little impact on such rates.

Based on weekly water quality monitoring in the Lower Murray River by SA Water and the coupled hydrodynamic–biogeochemical model used previously for the region downstream from Lock 1 (including Lake Alexandrina), it was determined that Commonwealth environmental water had little effect on salinity, dissolved nutrients, chlorophyll-a and particulate matter during 2015–16.

Murrumbidgee river system

This section was derived from the Murrumbidgee river system Selected Area evaluation report (Wassens et al. *2016).*

As in 2014–15, there were no Commonwealth environmental watering actions specifically targeting in-channel responses of ecosystem function, nutrient cycling or stream metabolism in the Murrumbidgee River during 2015–16. Commonwealth environmental water was allocated to 13 watering actions, 2 of which (Figure 13) were in-channel freshes delivered for fish (10035-15, late March; and 10035-03, 15 October to 11 November) and riparian vegetation outcomes (10035-15, late March). Eleven additional actions and the previously mentioned fresh in late March were used for wetland inundation and overbank flows. Watering actions delivered in July and September had only a minor influence on flows at Narrandera and no influence on flows at Carrathool (Figure 13). The series of watering actions undertaken from mid-October increased discharge at Carrathool to the medium fresh level several times and maintained flows above the low fresh level until mid-

February. Metabolism was monitored at the Category 1 site at Carrathool (mid October 2015 – early April 2016, Table 3) and the Category 3 site (upstream) at Narrandera (mid October 2015 – mid January 2016).

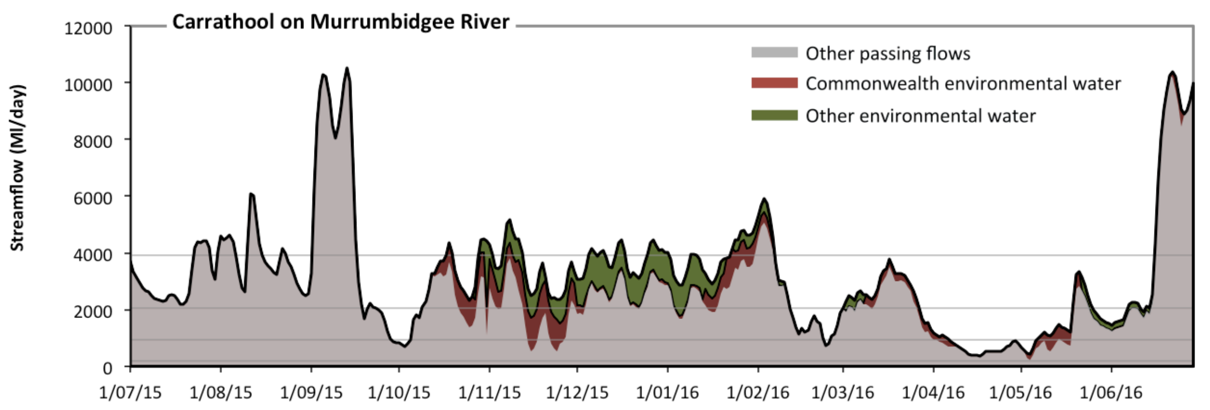

Figure 13. Contribution of environmental water delivery at Carrathool on the Murrumbidgee River. Horizontal lines indicate thresholds for very low flows, low flows, low freshes and medium freshes (from lowest to highest).

During 2015–16, primary production and ER in the Murrumbidgee River varied with time at both sites, with little evidence of a strong relationship between flow and metabolism. Peak values of these parameters occurred during both (relatively) high and low flows. Mean (and median) values were typical of, if not slightly lower than, other rivers in the Basin.

Consideration of the pattern of discharge over the monitoring period suggests that neither the Entrainment Model nor the Disturbance Model would have been expected to apply in the Murrumbidgee River in 2015–16. The river experienced a significant fresh in early September that would likely have removed organic matter and nutrients stored within the channel. The subsequent watering actions were smaller and would not inundate any new areas. The Disturbance Model is also unlikely to be relevant as discharge underwent frequent variations that would have regularly disturbed biofilms in the zone that was wetting and drying. This regular disturbance would likely dampen any variation in metabolism that might have occurred with only an occasional disturbance event. It is possible that the increased channel depth arising from the additional flows may have influenced either the area of slackwater or illuminated bed which would affect biofilm metabolic rates; however, the data to evaluate these possibilities are not available. Within this context, it is not surprising that the data revealed no influence of flow on rates of metabolism.

Modelling of relationships between water level and either primary production or ER, across both years of data, showed that GPP decreased 1 day after an increase in flow in 2014–15 while ER showed a similar response in 2015–16 but only at Narrandera. No statistically significant relationships were found at the Carrathool site. Ecological explanation of these relationships (and in particular, the 1-day lag phase) is not yet clear, although it may simply be due to dilution effects of the additional water. Depression of rates by dilution are most pronounced for systems where benthic metabolism (rather than water column metabolism) dominates. As additional data are collected, it is expected that more of these types of relationships will be revealed along with insights into the underlying drivers.

Rates of metabolism were relatively consistent between the two monitored zones. There was an apparent overall increase in GPP and decline in ER at the Narrandera site during 2015–16 that shifted net ecosystem metabolism toward primary production (P:R ratio >1) compared with 2014–15. This finding is consistent with the higher water column chlorophyll-a concentrations (indicating conducive conditions for phytoplankton growth).

From a water quality perspective, there were no indicators of adverse conditions under any of the flow levels.

Gwydir river system

This section was derived from the Gwydir river system Selected Area annual evaluation technical and synthesis reports (Southwell et al. *2016a).*

During 2015–16, a year of above-average temperatures and below-average rainfall, environmental water (from both Commonwealth and state resources) was used to provide small flow pulses, protect refugial waterholes from poor water quality and maintain longitudinal connection within the Gwydir river system. As a result, the Gwydir River had 38% connection (i.e. 38% of days were above the relevant connection threshold at both gauges). Without environmental water, the durations of very low (or no) flow periods (<39 ML/day) would have greatly exceeded durations expected in an average 'natural flow' year. There were three specific watering actions in the Gwydir river system but only one, a base flow of 2600 ML in April–May 2016, was designated to support fundamental ecosystem function processes of nutrient and carbon cycling and primary production in the river channel. The other two were a fresh of 1350 ML for supporting instream ecological function and nutrient cycling (November 2015) and an overbank flow for 'habitat quality' (January–February 2016). At the stream metabolism monitoring site at Pallamallawa, Commonwealth environmental water made up 7% of the total discharge (Figure 14).

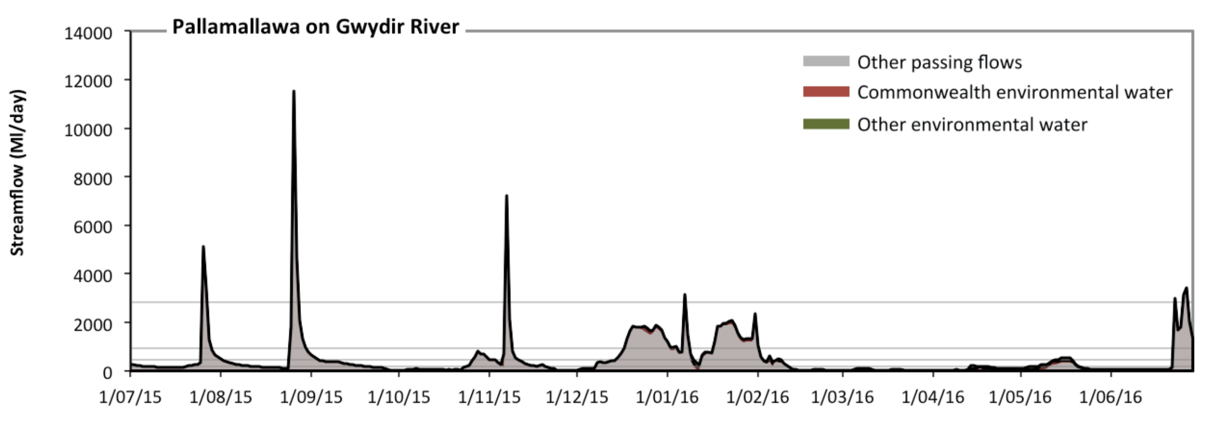

Figure 14. Contribution of environmental water delivery at Pallamallawa on the Gwydir River. Horizontal lines indicate thresholds for very low flows, low flows, low freshes, medium freshes and high freshes (from lowest to highest).

Only very short periods of data were collected for stream metabolism determinations at the three sites; GW2 (Pallamallawa), GW3 and GW4 (typically 12 days at each site, Table 3). Data collection was somewhat constrained by periods of flowing water. Consequently, it is very difficult to determine relationships of primary production and ER with discharge against a background of daily and seasonal variations, especially given that there were only 11 of a possible 36 days that met acceptance criteria for data meta-analysis.

Within these data constraints, rates did appear to be higher during the 'wet' period of early 2016 arising from the environmental watering. The increased rates of GPP and ER are coincident with higher carbon and phosphorus availability. These nutrients may have been transported with the environmental water or released in situ from recently rewetted sediments, consistent with the Entrainment Model (Section 1.3.2).

All sites and sampling occasions were net heterotrophic as the rates of ecosystem respiration exceeded primary production, reflecting the importance of the microbial loop in breakdown of organic material and recycling of nutrients.

During environmental water delivery periods (from Copeton Dam), mean daily turbidity (and electrical conductivity) were significantly lower than recorded in waters originating from catchment runoff events. The lower turbidities provide a more conducive environment for primary production, thereby emphasising the importance of water source in the metabolic functioning of the Gwydir. It is anticipated that a much larger data set in Year 3 (2016–17) will enable more quantitative assessment of the role of water source (e.g. from Copeton Dam versus more turbid waters from the catchment) in enhancing or suppressing ecosystem function. It will be most informative to note the effect of timing and magnitude of releases from Copeton Dam: it may be that the first fresh would have a large positive effect on metabolism if delivered during late spring into summer. Subsequent flows would then have smaller effects as the residual organic carbon and nutrients on the floodplain – built up over months perhaps – have already been transported to the main channel. Natural or planned flows during winter – early spring would have a much smaller effect on metabolism due to colder temperatures and shorter days constraining primary production.

Junction of the Warrego and Darling rivers

This section was derived from the Junction of the Warrego and Darling rivers Selected Area annual evaluation synthesis and technical reports (Southwell et al. *2016b).*

During 2015–16, a total of 7640 ML of Commonwealth environmental water was delivered in the Barwon–Darling valley, with three watering actions specifically targeting stream metabolism amongst other objectives (Table 2). At Louth, on the Darling River downstream from Bourke, Commonwealth environmental water contributed 1% of the total streamflow volume and affected stream flows for 6% of the 2015–16 (Figure 15). The Darling River within the Selected Area was connected for 61% of days during 2015–16, dominated by a single long connection event of 163 days early in the watering year and then 37 days in February–March 2016. The 2015 connectivity was driven by two consecutive flow events containing Commonwealth environmental water (July–October 2015 with 3547 ML of Commonwealth environmental water from the Queensland Border Rivers and Moonie and Upper Barwon Rivers as well as localised entitlements at Toorale. In November 2015, 1208 ML of Commonwealth environmental water from Queensland Border Rivers and the Gwydir River entered the Selected Area. The 37 days of connectivity commenced in mid-February, resulting from 13 955 ML of Commonwealth environmental water from the Queensland Border Rivers and Upper Barwon, Condamine–Balonne and Warrego rivers in January–March 2016.

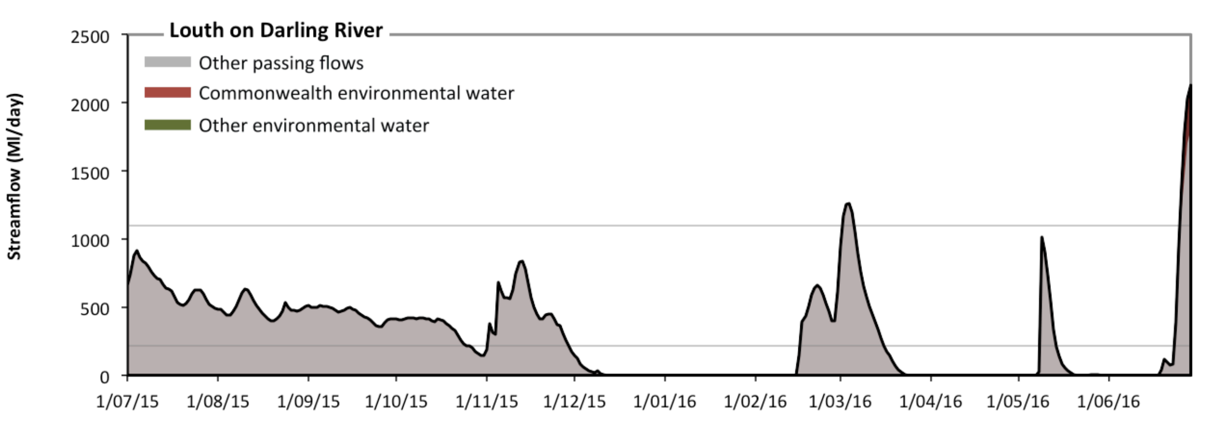

Figure 15. Contribution of environmental water delivery at Louth on the Darling River. Horizontal lines indicate thresholds for very low flows and low flows (from lowest to highest).

There was no Commonwealth environmental water allocated to the Warrego River in 2015–16. The hydrograph at Cunnamulla showed no flow apart from sharp peaks in the period mid-January to March 2016 and in late June 2016 (Figure 16). The peak on 17–19 January resulted from local rainfall around Cunnamulla and flowed into the Darling in January–March 2016. Downstream flows were insufficient to trigger Commonwealth environmental water at Toorale.

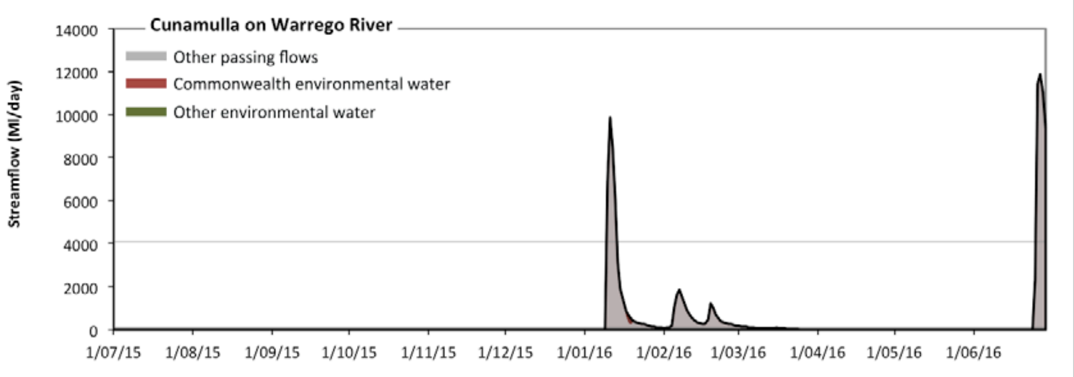

Figure 16. Contribution of environmental water delivery at Cunamulla on the Warrego River. Horizontal lines indicate thresholds for very low flows, low flows and low freshes (from lowest to highest).

The Darling upstream monitoring station (including stream metabolism and water quality) is located near Yanda homestead; all Commonwealth environmental water derived in the upstream tributaries of the Darling pass through this reach. The monitoring station near Akuna homestead is located downstream of the confluence of the Warrego and Darling rivers. Issues with power supply and instrument failure (turbidity and biofouling) at both sites meant that data sets were partly discontinuous in the 2015–16 watering year. Metabolism was measured during three periods: (1) variable flow (28 August to 28 September 2015); (2) flow peak (29 October to 29 November 2015); and (3) low constant flow (10–17 December 2015).

All three periods at both stations were net heterotrophic (P:R < 1) throughout the study period except the upstream station (Yanda) during period 1. Weak positive relationships were recorded at both stations between increased discharge and higher rates of primary production and ER. Both upstream and downstream stations recorded the lowest rates of GPP during period 1 when temperatures were cooler and flows were low but fluctuating. Rates of GPP and ER generally increased between station 1 and 2, with the highest rates of GPP and ER recorded in the downstream station during period 2, suggesting that increased discharge may have led to increased rates of production and respiration, driven by a reduction in water column turbidity and increase in chlorophyll (Appendix F in Southwell *et al.* 2016b).

Despite nutrient concentrations (especially bioavailable phosphorus) that frequently exceeded water quality guidelines, thereby indicating the potential for excessive plant/algal growth, primary production rates were similar to other Selected Areas, typically ranging from <1 mg O_2/L/day during late winter – early spring, up to around 4 mg O_2/L/day during the latter two flow periods. It is interesting to speculate what might have occurred during and after the February–March 2016 flow period (Figure 15), but that data were not collected.

The lack of a greater response of primary production to warmer temperatures, longer days and high nutrient concentrations is almost certainly due to the very high extant turbidities, which greatly reduce the viable light climate for phytoplankton and benthic algal growth. Mean daily turbidities were in the range 21–305 nephelometric turbidity units (NTU) (generally well above the Australian and New Zealand Environment Conservation Council (ANZECC) water quality guidelines).

Interestingly, Southwell *et al.* (2016b) points out that many water quality parameters had their highest recorded values at approximately 500 ML/day, suggesting that this may be a key threshold for the inundation of in-channel bars that subsequently affect water quality in the Darling River under relatively low flow conditions. Further increases in discharge reduce turbidity, dissolved oxygen and chlorophyll-a concentrations, which were attributed to dilution effects. The authors point out the benefits of relatively small magnitude flows above this nominal 500 ML/day threshold (highest discharge of 971 ML/day) for ameliorating, or perhaps even preventing, potential water quality problems, including any hypoxia linked to outbreaks of the floating water plant *Azolla*, which can completely carpet the river surface (which frequently occur in this reach of the Darling River, especially in the weir pools).

3.6.3 Overview of stream metabolism at monitored sites within Selected Areas

The metabolic parameters primary production and ER for the seven Selected Areas during 2015–16 are presented in Figures 17 and 18, respectively. The data are stratified into season (spring, summer, autumn and winter) to briefly evaluate any seasonal patterns. The data are also summarised in Annex B of this report. As noted with the smaller 2014–15 data set, the typical trend was that both primary production and ER increased when moving from spring into summer. This is entirely consistent with longer (more hours of sunlight and more intense sunlight), warmer (higher cellular metabolic rates) days during summer. As algae double in number every 1–2 days, the highest algal populations are often found in late summer rather than earlier in the season. One graphic example of this was the formation of the cyanobacterial *Chrysosporum ovalisporum* bloom in the Murray–Edward–Wakool system in late summer through early autumn. Moving from summer into autumn, there was no common pattern between the Selected Areas for primary production or ER. The Edward–Wakool results showed higher rates in autumn due to the prevailing bloom through most of that sampling period. In most other areas, metabolic rates decreased as light intensity and average water temperature dropped and daylight hours diminished. There was insufficient data from three Selected Areas (Lower Murray, Gwydir and Warrego–Darling) to comment on any trends over this seasonal change. As stressed in the Year 1 (2014–15) Basin Matter report (Grace 2016), this information is extremely important for the LTIM Project as it will enable predictions of the counterfactual – what would the metabolic rates be if there was no added environmental water. The effects of added environmental water can then be modelled knowing the background behaviour of each river system.

For comparison on a global scale, a compendia of stream metabolism data collected worldwide (but mostly featuring the United States of America; USA) indicate that primary production and ER values are typically in the range 2–20 mg O_2/L/day (Bernot *et al*. 2010; Marcarelli *et al*. 2011) – assuming an average water depth of 1 m to enable conversion of areal units to the volumetric units used in this report. Hence, the LTIM Project data fall towards the bottom end of this range. Anecdotal descriptions of as yet unreleased United States Geological Survey data from a large number of sites across the USA over many years suggest that the LTIM data are not unusually low after all, but confirmation of this finding awaits official release of these data which may be a year or two away. Again, as further data become available over subsequent years, it will be very informative to determine whether these Selected Area rates are consistent between years or whether 2014–15 and 2015–16 were unusually low (or high) for the Basin. A recent study by Hall *et al.* (2016) of 14 larger rivers in the western USA revealed a wide range of primary production rates (0.2–26.2 mg O_2/L/day). However, for 10 of these 14 rivers, rates were <5 mg O_2/L/day, putting them in the same range as the rates typically found (Figure 17) from this LTIM Project. It was suggested that the rates at the lower end of this range were constrained mainly by low bioavailable[5] nutrient concentrations or, in the cases of the Colorado River and the Green River at Gray Canyon, by very high turbidities (turbidity > 100 NTU) limiting the euphotic depth and inhibiting photosynthesis. Further comparison of LTIM results with this data set is tempered by the fact that in the US study, typically only a few days of metabolism data were collected from each of the rivers – in stark contrast to the extensive LTIM data set which covers several seasons across multiple years.

[5] 'Bioavailable' refers to those forms of nitrogen (N), carbon and phosphorus (P) most readily taken up by organisms. This typically equates to phosphate for P and the combination of ammonia, nitrate and nitrite for N.

Consequently, questions relating to whether these rates are low on a global basis mean that food webs (and hence native fish populations) are resource/energy limited will remain a key focus of annual reports towards the end of the LTIM Project. This will also require access to appropriate international data sets.

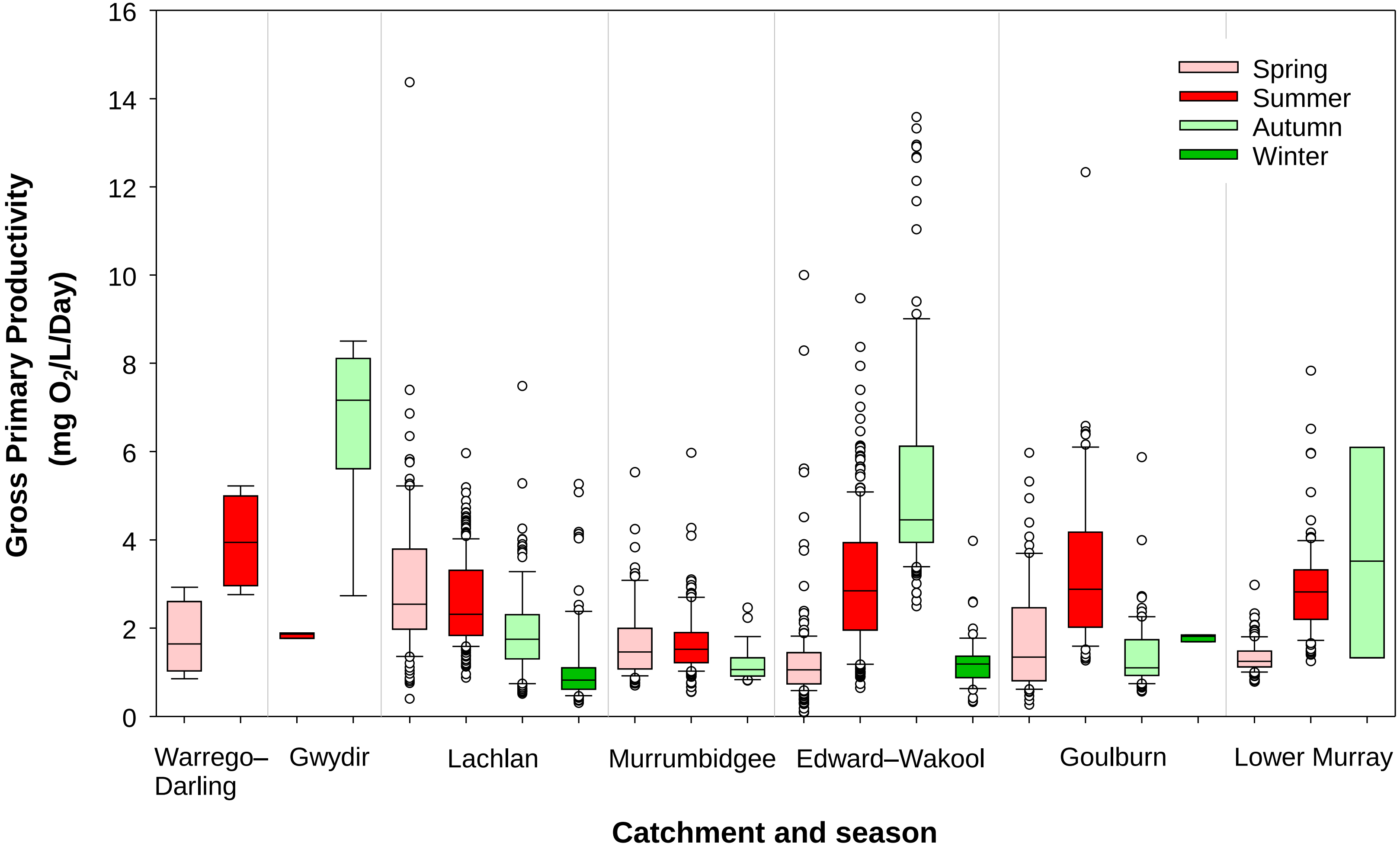

Figure 17. Box plot representing the seasonal dependence of gross primary productivity (GPP) in the five Selected Areas for which data are available. Within each area, results from individual loggers (sites) have been composited. The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. 'Whiskers' above and below the box indicate the 90th and 10th percentiles. Values beyond this (outliers) are plotted as individual circles.

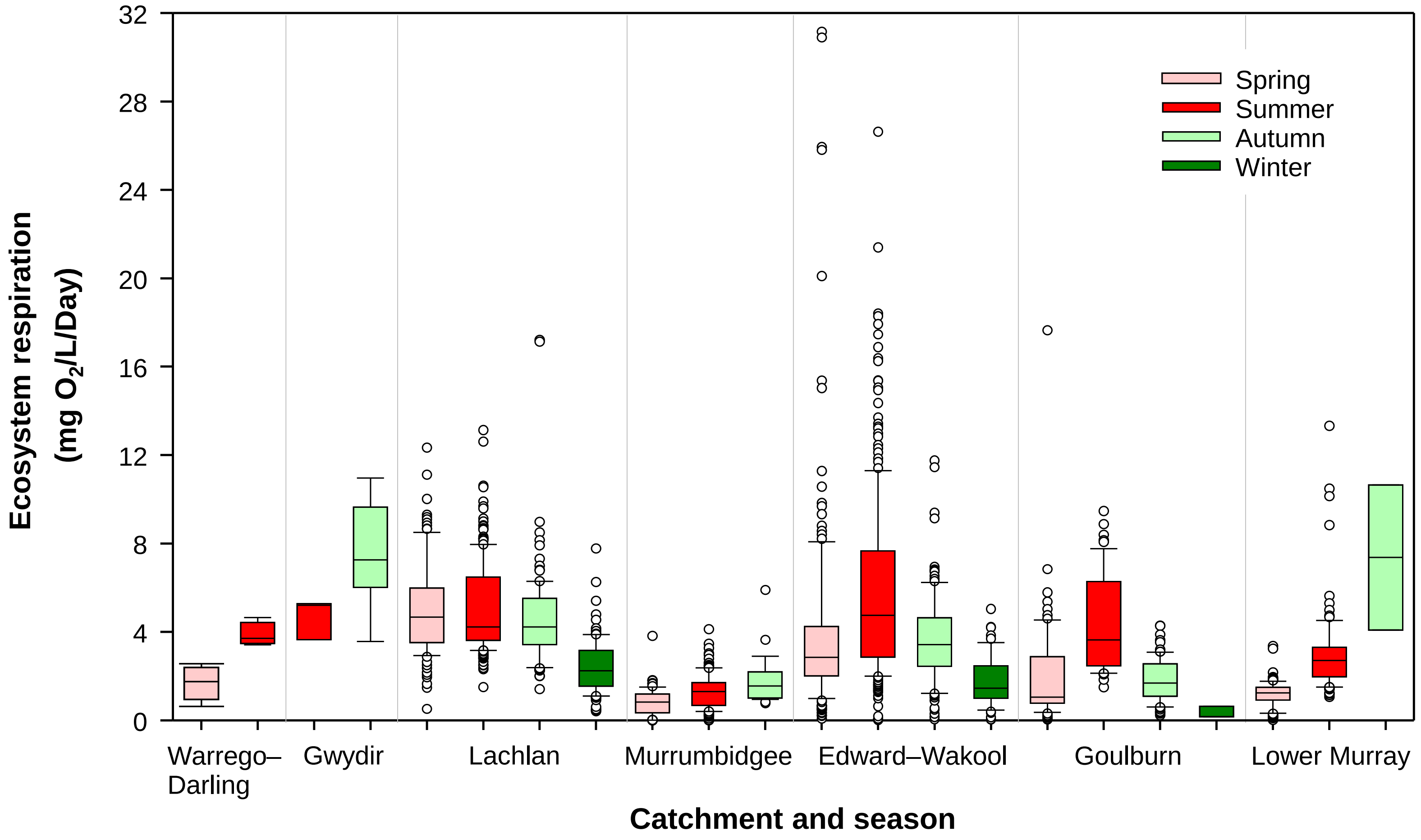

Figure 18. Box plot representing the seasonal dependence of ecosystem respiration (ER) in the five Selected Areas for which data are available. Within each area, results from individual loggers (sites) have been composited. The boundary of the box closest to zero indicates the 25th percentile, a line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. 'Whiskers' above and below the box indicate the 90th and 10th percentiles. Values beyond this (outliers) are plotted as individual circles.

4 Expected 1–5-year outcomes

The relevant Basin Plan long-term objective for stream metabolism is water-dependent ecosystems able to support episodically high ecological productivity and its ecological dispersal. Within this context, the metabolism objective is similar to the hydrological connectivity objective that seeks to protect and restore more natural patterns of lateral and longitudinal connectivity. Like hydrological connectivity, there is no presumption that metabolism responses will lead to a long-term metabolic legacy per se. Rather, the legacy will be manifest further up the food chain with improvements in the condition of fish and waterbird populations. As a result, the outcomes of each watering action contribute to long-term patterns of productivity and, given it is the second year of monitoring, considering 1–5-year outcomes is still very speculative.

A potential exception to the above is suggested by the Basin Plan objective; specifically, that the capacity of water-dependent ecosystems to support episodically high productivity may vary – that is, ecosystems in good condition may show a stronger response to boom times than systems in poor condition. There is little evidence to test this idea and, as a consequence, the underlying processes are not known, but may include variations in a system's ability to retain nutrients, the composition of the decomposer and primary producer communities or the influence of starting condition on the system's response to change. Over time, the LTIM Project monitoring data will provide valuable insight into this hypothesis which would help guide future water management toward short-term improvements in condition that would underpin longer term outcomes during episodes of high ecological productivity.

Monitored outcomes of freshes and base flows in the first 2 years (2014–16) did not detect any significant changes in rates of gross primary productivity or ER with the addition of environmental water, although individual positive responses of specific actions occurred at specific sites. It should be noted that it is possible that environmental flows created additional habitat for primary producers and decomposers and that this will have had an influence on metabolic rates. The data required to evaluate this possibility were not available again this year, but it is expected that this will be included in future evaluations (e.g. it will be available for the Year 3 (2016–17) Goulburn River assessment).

It appears likely that unmonitored watering actions that inundated wetlands and floodplains were associated with increases in primary production and decomposition. It would appear from these results that using environmental flows to connect rivers to sources of nutrients and organic carbon (Entrainment Model) will make a contribution toward achievement of the Basin Plan objective.

5 Expected Basin-scale outcomes

5.1 Stream metabolism

With essentially no long-term data on stream metabolism across the Basin prior to the short-term monitoring projects in 2011 and onwards into the first 2 years of the LTIM Project, it is difficult to determine whether the 2014–15 and 2015–16 results provide typical rates of primary production and ER in these waterways and whether there is any longer term trend. As noted above, rates were lower in the Murrumbidgee than recorded a decade ago, but it is uncertain whether these differences are perhaps due to differences in sites, methodology and/or analysis methods, rather than a real decline. It will be interesting, and hopefully informative, to contrast these first two 'drier' years with the very wet period in late 2016, especially in the southern Basin. It is anticipated that this comparison will be a major feature of the Year 3 (2016–17) Basin-level evaluation.

As found in 2014–15, there was significant variability in rates, even in the absence of major flow changes, and a general seasonal trend towards higher values for GPP and ER moving from spring into summer.

Several comments have already been made throughout this report on comparisons with metabolic rates from elsewhere in the world. As more international data become available, especially from the few studies published that have looked at lowland rivers, it *might* be the case that the 2014–15 and 2015–16 rates *are* 'typical' for waterways across the Basin and comparable with rates in similar biogeographic zones elsewhere. One important difference when comparing systems between Australia and many aquatic systems elsewhere is the higher turbidities found in Australian streams (due to the fine colloidal nature of the soils), which would be expected to inhibit primary production. These high turbidities persist for very long periods, often near permanently, meaning that primary production is dominated by plant growth in the shallow, littoral regions where light inhibition is minimised (the 'bathtub ring' effect; Bunn *et al.* 2006). This is in distinct contrast to many international clear-water rivers and streams where there can be prolific benthic plant growth (macrophytes and benthic algae).

It is the interplay of increasing nutrient concentrations and increasing light penetration into the water column (through lower turbidities) that should give rise to higher rates of primary production. If ER is driven largely by autochthonous production, then increased primary production should also result in increased ER, both from algal detritus and photosynthetically derived algal exudates. Conversely, if an external source of organic matter is the dominant carbon supply mechanism, then the link between primary production and ER will be relatively weak and mediated through the flow events introducing both nutrients and organic carbon into the river channel. As noted by Fuß *et al.* (2017), as well as several others, the lability (palatability) of the organic carbon to microbial communities is also very important, as the same concentration of dissolved organic carbon can have very different effects on respiration rates depending on whether it is labile or refractory. Insights into this point are being obtained through the Edward–Wakool Selected Area, using fluorescence excitation–emission matrices.

Hence, it is still *expected* that watering actions that reconnect backwaters, flood runners and the floodplain should increase both primary production and ER but the types of watering actions delivered over the first 2 years did not provide the opportunity to confirm this expectation. It is also expected that the monitored waterways in the Selected Areas will broadly represent stream metabolism across the Basin. Thus, it is believed likely (again without evidence to support or refute the statement) that higher trophic levels across the Basin, including native fish populations, may be constrained by the availability of food supplies. The inability to examine the veracity of this hypothesis is largely due to the absence of significant flow events during the first 2 years of the LTIM

Project. Hopefully the much wetter start to the 2016–17 will facilitate interrogation of the data to examine this point.

More extensive stream metabolism data from both the Gwydir river system and Junction of the Warrego and Darling rivers Selected Areas in 2016–17 and beyond (rather than the small data sets available from 2015–16) may help disentangle the effects of nutrient concentrations on metabolism in these Australian lowland rivers, as phosphorus concentrations are much higher in these two waterways than in the other five Selected Areas (Annex C, Table C5), thereby decreasing the likelihood of nutrient limitation.

Consequently, despite much of the uncertainty described above, the following key points can be made regarding managing future watering actions and achieving improvements in stream metabolism to boost food resources for the aquatic food webs in the Basin:

1. Freshes that remain in channel and do not rewet significant areas of dry sediment are unlikely to boost rates of primary production and ecosystem respiration due to nutrient limitation.
2. The first fresh following winter to inundate dry sediment has the greatest potential to enhance metabolic rates, but this is also dependent upon timing as freshes in winter – early spring will result in lower primary production due to colder temperatures and shorter hours of lower intensity sunlight than freshes that are delayed until late spring – summer. Subsequent freshes may have a much lower effect as standing stocks of organic carbon and nutrients in wetlands and on the floodplain have been depleted by the earlier flow event and have had insufficient time to rebuild. It should be noted, however, that some sediments may not have the opportunity to accumulate much organic matter due to their shape or associated riparian vegetation.
3. Inundation of wetlands may entrain nutrients and organic matter which have the potential to enhance metabolism within the river channel, but this requires water to return from the backwaters and wetlands to the river.
4. Return water from wetlands and the floodplain may also constrain primary production within the river channel due to high turbidities. It is likely that such effects may be more pronounced in the northern half of the Basin, due to the very fine colloidal soil particles.
5. In regions of the Basin where light limitation (rather than nutrient limitation) is constraining primary production, then the introduction of clearer water from dams higher in the catchment may promote primary production even though there may be an actual decrease in bioavailable nutrient concentrations.
6. In catchments where a mix of water sources is available, metabolic responses to flow may change significantly depending on the source of that flow. The example of the effect of Chowilla on the metabolism in the Lower Murray (see Sections 3.2.1 and 3.5) is a case in point here. Another example may prove to be the proportion of flows coming from the Border Rivers, the Condamine–Balonne and the Bogan River for metabolism in the Darling River below Bourke.

These points can be refined and altered as new data comes in over years 3–5 of the LTIM Project (2016–19).

5.2 Water quality

Although the data were too sparse to provide any detailed insights into the effects of watering actions on pH, turbidity and salinity (electrical conductivity), it is worth noting that there were no generalised water quality problems associated with these parameters in 2015–16. It is likely that these findings are also representative across the Basin. Localised conditions (e.g. drying down of streams into isolated pools) may result in development of poor water quality through concentration of salts but this phenomenon was not observed at the larger scale. Depending on the size of the event, subsequent rewetting may lead to a first flush with very poor water quality (high salt content, low dissolved oxygen).

Commonwealth environmental water may provide benefits for dilution of poor-quality water (the counterfactual was observed in the Edward–Wakool where the one site that did not receive Commonwealth environmental water developed low dissolved oxygen). In terms of the benefits of increasing loads of nutrients and phytoplankton to receiving waters low in these commodities, the modelling from the Lower Murray suggests that export increases are primarily through increases in discharge rather than increases in concentration.

6 Contribution to achievement of Basin Plan objectives

This section provides a brief overview of the extent to which the management of Commonwealth environmental water contributed to the ability of water-dependent ecosystems to support episodically high ecological productivity and its ecological dispersal. The data from the Selected Areas did not detect any significant change in stream metabolism in response to watering actions that provided base flows and freshes within river channels. Although there are as yet no firm data, it is likely that watering actions that achieved significant wetland or floodplain inundation and then returned water to the main channel (Gwydir, Warrego–Darling and Macquarie) would have been associated with increases in metabolism. It is anticipated that increasing the number of days over which metabolic data are collected in the Gwydir will enable future investigation of the role of wetland return water. Although no metabolic response was evident following the return of water from the wetlands to the Murrumbidgee – which was associated with increased nutrients and organic matter – this was likely due to the small volumes returned.

As emphasised earlier in this report, no major ‘improvements’ in primary production and ER rates as a result of environmental watering actions were detected due to the types of these watering actions delivered over the first 2 years of the LTIM project. It is strongly anticipated that increases in rates of primary production and ER will result when the added water also brings in higher concentrations of nutrients and organic carbon (Entrainment Model; see Section 1.3.2). It is suggested that the greatest benefit will occur when added water enables reconnection with backwaters and flood runners (and perhaps the floodplain itself). It is hoped and recommended that this contention be tested with real data associated with major wetting events in 2016–17 and beyond.

As Commonwealth environmental water was intended ‘to protect and restore the ecosystem functions of water-dependent ecosystems’, it is worth highlighting that although increased discharges frequently resulted in a small decline in primary production and ER rates (due to dilution), the effects appeared to be relatively temporary. Collecting data over years 3–5 (2016–19) will allow the disentangling of normal seasonal effects on metabolic rates (thus enabling future modelling of the ‘counterfactual’) and changes induced by Commonwealth environmental water. *For this reason, it is vital that watering actions not occur with the same magnitude and at exactly the same time each year*.

During preparation of revisions to this report and after completion of all Year 2 (2015–16) Selected Area data analysis and reports, a novel method for determining the benefits of smaller (in-channel) watering actions has been developed. This involves calculating the amount of organic carbon (the food resource at the base of the food web) created by photosynthesis – and consumed by ecosystem respiration – per kilometre of stream per day. This exciting development, a world first, will be explored in the Year 3 (2016–17) Basin-level evaluation. It only requires data that are already being collected – the daily stream metabolism data and the cross-sectional area of wetted stream at the gauging station closest to the dissolved oxygen logger.

In addition, from a water quality perspective, Commonwealth environmental water was intended ‘to ensure water quality is sufficient to achieve the above objectives for water-dependent ecosystems, and for Ramsar wetlands, sufficient to maintain ecological character’. This report only considered the stream data, not the wetlands. However, it was argued that Commonwealth environmental water had a beneficial effect in the Edward–Wakool by preventing the development of the low dissolved oxygen conditions found in a nearby site that did not receive this water.

References

Baldwin DS, Rees GN, Wilson JS, Colloff MJ, Whitworth KL, Pitman TL, Wallace TA (2013) Provisioning of bioavailable carbon between the wet and dry phases in a semi-arid floodplain. *Oecologia* **172(2)**, 539–550.

Baldwin DS, Wallace T (2009) Biogeochemistry. In: Overton IC, Colloff MJ, Doody TM, Henderson B, Cuddy SM (eds) *Ecological outcomes of flow regimes in the Murray–Darling Basin*. Report prepared for the National Water Commission by CSIRO Water for a Healthy Country Flagship. CSIRO, Canberra, pp 47–57.

Baldwin DS, Colloff MJ, Mitrovic SM, Bond NR, Wolfenden B (2016) Restoring dissolved organic carbon subsidies from floodplains to lowland river food webs: a role for environmental flows? *Marine and Freshwater Research* **67**, 1387–1399.Bernot MJ, Sobota DJ, Hall RO Jr, Mulholland PJ, Dodds WK, Webster JR Tank JL, Ashkenas LR, Cooper LW, Dahm CN, Gregory SV, Grimm NB, Hamilton SK, Johnson SL, McDowell WH, Meyer JL, Peterson B, Poole GC, Valett HM, Arango C, Beaulieu JJ, Burgin AJ, Crenshaw C, Helton AM, Johnson L, Merriam J, Niederlehner BR, O'Brien JM, Potter JD, Sheibley RW, Thomas SM, Wilson K (2010) Inter-regional comparison of land-use effects on stream metabolism. *Freshwater Biology* **55(9)**, 1874–1890.

Borchardt MA (1996) Nutrients. In: Stevenson RJ, Bothwell ML, Lowe RL (eds) *Algal ecology: freshwater benthic ecosystems.* Academic Press, San Diego, pp 184–227.

Boulton AJ, Brock MA (1999) *Australian freshwater ecology: processes and management* Gleneagles Publishing, Glen Osmond.

Bunn SE, Balcombe SR, Davies P, Fellows CS, McKenzie-Smith FJ (2006) Aquatic productivity and food webs of desert river ecosystems. In: Kingsford RT (ed) *Ecology of Desert Rivers.* Cambridge University Press, Cambridge, pp 76–99.

Dyer F, Broadhurst B, Tschierschke A, Thiem J, Thompson R, Driver P, Bowen S, Asmus M, Wassens S, Walcott A, Lenehan J, van der Weyer N (2016) Commonwealth Environmental Water Office Long Term Intervention Monitoring Project: Lower Lachlan river system Selected Area 2015–16 Monitoring and Evaluation synthesis report. Commonwealth of Australia, Canberra.

Ellis I, Meredith S (2004) *An independent review of the February 2004 Lower Darling River fish deaths: guidelines for future release effects on Lower Darling River fish populations.* A report to the New South Wales Department of Infrastructure Planning and Natural Resources. MDRFC Technical Report 7/2004. Murray–Darling Freshwater Research Centre, Wodonga, 46pp.

Fuß T, Behounek B, Ulseth AJ, Singer GA (2017) Land use controls stream ecosystem metabolism by shifting dissolved organic matter and nutrient regimes. *Freshwater Biology* **62(3)**, 582–599.

Gawne B, Roots J, Hale J, Stewardson M (2014) Commonwealth Environmental Water Office Long Term Intervention Monitoring Project: Basin Evaluation Plan. Report prepared for the Commonwealth Environmental Water Office by The Murray–Darling Freshwater Research Centre. MDFRC Publication 42/2014. MDFRC, Wodonga.

Gordon ND, McMahon TA, Finlayson BL, Gippel CJ, Nathan RJ (2004) *Stream hydrology – an introduction for ecologists*, 2nd edn. John Wiley and Sons, Chichester.

Grace M (2015) Long Term Intervention Monitoring Basin Matter — Stream Metabolism and Water Quality foundation report. Final Report prepared for the Commonwealth Environmental Water Office by The Murray–Darling Freshwater Research Centre. MDFRC Publication 69/2015. MDFRC, Wodonga, 9pp.

Grace M (2016) 2014–15 Basin-scale evaluation of Commonwealth environmental water — Stream Metabolism and Water Quality. Final report prepared for the Commonwealth Environmental Water Office by The Murray–Darling Freshwater Research Centre, MDFRC Publication 105/2016, October, 39pp.

Hall RO Jr, Tank JL, Baker MA, Rosi-Marshall EJ, Hotchkiss ER (2016) Metabolism, gas exchange, and carbon spiraling in rivers. *Ecosystems* **19**, 73–86.

Junk WB, Bayley PB, Sparks RE (1989) The flood pulse concept in river–floodplain systems. In: Dodge DP (ed) *Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences* **106**, 110–127.

McGinness HM, Arthur AD (2011) Carbon dynamics during flood events in a lowland river: the importance of anabranches. *Freshwater Biology* **56(8)**, 1593–1605.

Marcarelli AM, Baxter CV, Mineau MM, Hall RO Jr (2011) Quantity and quality: unifying food web and ecosystem perspectives on the role of resource subsidies in freshwaters. *Ecology* **92(6)**, 1215–1225.

Oliver RL, Hart BT, Olley J, Grace MR, Rees CM, Caitcheon CG (1999) *The Darling River: algal growth and the cycling and sources of nutrients.* Murray–Darling Basin Commission Report M386: CRC for Freshwater Ecology & CSIRO Land and Water, Canberra, 200pp.

Reynolds CS (1992) Algae. In: Calow P, Petts GE (eds) *The rivers handbook*, volume 1. Blackwell Scientific Publishers, Boston, pp 195–215.

Reynolds CS, Carling PA, Beven KJ (1991) Flow in river channels: new insights into hydraulic retention. Archiv für Hydrobiologie **121**, 171–179.

Reynolds CS, Descy J-P (1996) The production, biomass and structure of phytoplankton in large rivers. *Archiv für Hydrobiologia (Supplement)* **113**, 161–187.

Ryder DS, Watts RJ, Nye E, Burns A (2006) Can flow velocity regulate epixylic biofilm structure in a regulated floodplain river? *Marine and Freshwater Research* **57(1)**, 29–36.

Song C, Dodds WK, Trentman MT, Rüegg J, Ballantyne F (2016) Methods of approximation influence aquatic ecosystem metabolism estimates. *Limnology and Oceanography: Methods* **14(9)**, 557–569.

Southwell M, Frazier P, Hancock P, Martin B, Burch L, van der Veer N, Frost L, Ryder D, Tsoi WY, Butler G, Spence J, Bowen S, Humphries J (2016a) *Commonwealth Environmental Water Office Long Term Intervention Monitoring Project Gwydir river system Selected Area: annual evaluation synthesis and technical reports.* Commonwealth of Australia, Canberra.

Southwell M, Frazier P, Martin B, Burch L, van der Veer N, Cawley R, Frost L, Ryder D, Tsoi WY, Butler G (2016b) *Commonwealth Environmental Water Office Long Term Intervention Monitoring Project Junction of the Warrego and Darling rivers Selected Area: annual evaluation synthesis and technical reports.* Commonwealth of Australia, Canberra.

Southwell M, Thoms M (2011) Patterns of nutrient concentrations across multiple floodplain surfaces in a large dryland river system. *Geographical Research* **49(4)**, 431–443.

Thoms MC, Southwell M, McGuiness H (2005) Floodplain–river ecosystems: fragmentation and water resources development. *Geomorphology* **71(1–2)**, 126–138.

Tockner K, Pennetzdorfer D, Reiner N, Schiemer F, Ward JV (1999) Hydrological connectivity, and the exchange of organic matter and nutrients in a dynamic river–floodplain system (Danube, Austria). *Freshwater Biology* **41(3)**, 521–536.

Uehlinger U (2000) Resistance and resilience of ecosystem metabolism in a flood-prone river system. *Freshwater Biology* **45**, 319–332.

Wallace, T. W. and Cummings, C.R. (2016a). Influence of water level manipulation on biofilm composition in a highly regulated lowland river. Report prepared for the Department of Environment, Water and Natural Resources by the University of Adelaide and the Environment Protection Authority. 36pp.

Wallace, T. W. and Cummings, C.R. (2016b). Influence of water level manipulation on open water metabolism in a highly regulated lowland river. Report prepared for the Department of Environment, Water and Natural Resources by the University of Adelaide and the Environment Protection Authority. 36pp.Wallace and Cummings 2016a

Wallace TA, Furst D (2016). Open water metabolism and dissolved organic carbon in response to environmental watering in a lowland river–floodplain complex. *Marine and Freshwater Research* **67(9)**, 1346-1361.

Wassens S, Spencer J, Thiem J, Wolfenden B, Jenkins K, Hall A, , Ocock J, Kobayashi T, Thomas R, Bino G, Heath J, Lenon E (2016) Commonwealth Environmental Water Office Long Term Intervention Monitoring Project: Murrumbidgee river system Selected Area evaluation report 2014–16. Commonwealth of Australia, Canberra.

Watts R, McCasker N, Thiem J, Howitt J, Grace M, Kopf R, Healy S, Bond N. (2015) Commonwealth Environmental Water Office Long Term Intervention Monitoring Project: Edward-Wakool Selected Area Technical Report, 2014-15. Prepared for Commonwealth Environmental Water Office. Commonwealth of Australia: Canberra.

Watts RJ, McCasker N, Howitt JA, Thiem J, Grace M, Kopf RK, Healy S, Bond N (2016) Commonwealth Environmental Water Office Long Term Intervention Monitoring Project: draft Edward–Wakool Selected Area evaluation report, 2015–16. Institute for Land, Water and Society, Charles Sturt University, prepared for the Commonwealth Environmental Water Office. Commonwealth of Australia, Canberra.

Webb A, Baker B, Casanelia S, Grace M, King E, Koster W, Lansdown K, Lintern A, Lovell D, Morris K, Pettigrove V, Sharpe A, Townsend K, Vietz G (2017) Commonwealth Environmental Water Office Long Term Intervention Monitoring Project – Goulburn River Selected Area evaluation report 2015–16. Report prepared for the Commonwealth Environmental Water Office. Commonwealth of Australia: Canberra.

Ye Q, Giatas G, Aldridge K, Busch B, Gibbs M, Hipsey M, Lorenz Z, Mass R, Oliver R, Shiel R, Woodhead J, Zampatti B (2017) Long Term Intervention Monitoring for the ecological responses to Commonwealth environmental water delivered to the Lower Murray River Selected Area in 2015–16. A report prepared for the Commonwealth Environmental Water Office. South Australian Research and Development Institute, Aquatic Sciences, Adelaide.

Annex A. Other watering actions associated with water quality

Table A1 lists those watering actions that explicitly targeted water quality outcomes (as distinct from stream metabolism) or for which water quality was a target of monitoring. The three Barwon–Darling watering actions listed in Table 2 also had the water quality objective 'Water quality improvement including salinity and potential for algal blooms'. Similarly, three of the six Goulburn River watering actions in Table 2 also had the water quality objective 'Maintain water quality'.

Table A1. Watering actions explicitly targeting water quality outcomes (as distinct from stream metabolism) or for which water quality was the target of monitoring.

Location (CEWO Water Action Reference)	Dates	Flow component type	Commonwealth environmental water volume delivered (ML)	Expected ecological outcome	Monitored site(s)	Observed ecological outcomes	Influences
Broken Creek (lower) – Reach 3 (10041-01 2015–16)	18/08/15 – 30/11/15	Base flow	7183	Manage excessive azolla growth.	Rices Weir		
Broken Creek (lower) – Reach 3 (10041-01 2015–16)	01/10/15 – 16/05/16	Base flow	23 542	Maintain water quality, including dissolved oxygen (DO) levels >5 mg/L.	Rices Weir	Low oxygen event in early March 2016 (O_2 < 2mg/L)	High water temperature (30 °C), decomposition and respiration of blue-green algae
Broken Creek (lower) – Reach 3 (10041-01 2015–16)	28/09/15 – 30/11/15	Fresh	6188	Remove large azolla blooms.	Rices Weir		
Campaspe – Reach 4 (10003-02 2015–16)	26/08/15 – 05/09/15	Fresh	1700	Flush and mix pools for improved water quality.		Not monitored	Not monitored
Campaspe – Reach 4 (10003-02 2015–16)	27/10/15 – 04/11/15	Fresh flow	1559	Flush and mix pools for improved water quality. Mitigate threat of a summer toxic blackwater event.		Not monitored	Not monitored
Edward–Wakool (10038-05)	17/09/15 – 22/11/15	Base flow; fresh	2000	Maintain/improve water quality (especially dissolved oxygen, pH and salinity).	Tuppal Creek		

Location (CEWO Water Action Reference)	Dates	Flow component type	Commonwealth environmental water volume delivered (ML)	Expected ecological outcome	Monitored site(s)	Observed ecological outcomes	Influences
Gwydir (10043-03, 10043-05)	April–May 2016	Base flow	409	Mitigate declining water quality.	Carole Creek	No water quality issues reported	
Gwydir (10043-04, 10043-05)	April–May 2016	Base flow	2191	Maintain water quality.	Mehi River	No water quality issues reported	
Gwydir (10043-05)	April–May 2016	Base flow	3400	Mitigate declining water quality.	Gwydir River	No water quality issues reported	
Lachlan (10033-01, variation)	11/11/15 – 15/12/15	Fresh and/or regulated flow	9379	Improve water quality.	Lower Lachlan River Channel		
Loddon – Reach 4 (10001-02 2015–16)	24/08/15 – 07/09/15	Fresh	1477	Maintain hydrological connectivity and water quality.			
Lower Murray – SA (10031-03, 10047-01)	01/07/15 – 30/11/15	Base flow	556 000	Support the managed transport and export of salt and nutrients from the River Murray system.	South Australian River Murray and Coorong		
Lower Murray – SA (10031-03, 10047-01)	01/12/15 – 01/07/16	Base flow	242 000	- Reduce peak salinity in Coorong.	South Australian River Murray and Coorong	Salinity in north lagoon decreased	
Lower Murray – NSW, Vic and SA Murray – weir pool manipulation, Lock 15 raising *and* lowering (10031-06, 10031-09)	01/07/15 – 30/06/16	Fresh	5249	Support the managed transport and export of salt and nutrients from the River Murray system.			
Lower Murray – NSW, Vic and SA Murray – weir pool manipulation, Lock 7 raising *and* lowering (10031-06, 10031-09)	01/08/15 – 30/05/16	Fresh	2739	Support the managed transport and export of salt and nutrients from the River Murray system.			

Location (CEWO Water Action Reference)	Dates	Flow component type	Commonwealth environmental water volume delivered (ML)	Expected ecological outcome	Monitored site(s)	Observed ecological outcomes	Influences
Lower Murray – NSW, Vic and SA Murray – weir pool manipulation, Lock 5 raising (10031-06, 10031-09)	01/08/15 – 30/11/15	Fresh	4346	Support the managed transport and export of salt and nutrients from the River Murray system.			
Lower Murray – NSW, Vic and SA Murray – weir pool manipulation, Lock 2 raising (10031-06, 10031-09)	01/09/15 – 30/11/15	Fresh	738	Support the managed transport and export of salt and nutrients from the River Murray system.			
Mid-Murray – Gulpa Creek and Reed Beds Swamp (Millewa Forest) (10031-01, 10031-02)	22/06/15 – 24/07/15	Base flow and in-channel fresh	99,400	Support the managed transport and export of salt and nutrients from the River Murray system.			
Mid-Murray – Gunbower Creek (10030-01)	01/07/15 – 30/06/16	Base flow	13,606	Improve water quality and hydrological connectivity between Gunbower Forest and Gunbower Creek to support native fish, aquatic invertebrates and, nutrient and carbon movement.			
Mid-Murray – Carrs, Capitts and Bunberoo creek system (10048-01)	04/04/16 – 16/05/16	Fresh and wetland inundation	950	Improve water availability and quality in each wetland.			
Murrumbidgee (10035-04, -05, -11, -14)	17/10/15 – 09/02/16	Wetland inundation	18000	Improve water quality.	Nimmie-Caira		

Annex B. Summary statistics for all stream metabolism data stratified into the four seasons.

Data in the tables are summarised for each of the Selected Areas, i.e. Junction of the Warrego and Darling rivers, Gwydir river system, Lachlan river system, Murrumbidgee river system, Edward–Wakool river system, Goulburn River and Lower Murray River.

Table B1. Gross primary productivity (mg O_2/L/day).

Selected Area and season	No. sites	n	Mean	Standard deviation	Standard error	Min	Max	Median	25%	75%
Warrego–Darling – spring	2	8	1.79	0.81	0.28	0.85	2.92	1.64	1.12	2.52
Warrego–Darling – summer	2	4	3.97	1.05	0.53	2.76	5.22	3.94	3.36	4.55
Warrego–Darling – autumn										
Warrego–Darling – winter										
Gwydir – spring										
Gwydir – summer	2	3	1.84	0.07	0.04	1.77	1.89	1.86	1.82	1.88
Gwydir – autumn	2	8	6.68	1.91	0.67	2.73	8.50	7.16	6.25	7.94
Gwydir – winter										
Lachlan – spring	4	106	2.99	1.79	0.17	0.40	14.37	2.54	1.98	3.73
Lachlan – summer	4	215	2.60	0.98	0.07	0.87	5.96	2.31	1.83	3.30
Lachlan – autumn	4	117	1.93	1.05	0.10	0.51	7.49	1.75	1.32	2.30
Lachlan – winter	4	95	1.13	1.00	0.10	0.30	5.26	0.82	0.61	1.10
Murrumbidgee – spring	2	78	1.69	0.88	0.10	0.70	5.53	1.46	1.08	1.99
Murrumbidgee – summer	2	130	1.67	0.74	0.06	0.55	5.97	1.52	1.22	1.89
Murrumbidgee – autumn	1	28	1.20	0.42	0.08	0.81	2.46	1.06	0.91	1.30
Murrumbidgee – winter										

Selected Area and season	No. sites	n	Mean	Standard deviation	Standard error	Min	Max	Median	25%	75%
Edward–Wakool – spring	5	166	1.28	1.17	0.09	0.09	10.00	1.05	0.73	1.44
Edward–Wakool – summer	6	261	3.07	1.54	0.10	0.64	9.47	2.84	1.96	3.92
Edward–Wakool – autumn	6	128	5.46	2.53	0.22	2.49	13.58	4.45	3.96	6.07
Edward–Wakool – winter	6	58	1.21	0.58	0.08	0.33	3.97	1.18	0.89	1.36
Goulburn – spring	4	72	1.78	1.25	0.15	0.26	5.97	1.34	0.83	2.33
Goulburn – summer	4	65	3.31	1.88	0.23	1.26	12.33	2.88	2.03	4.13
Goulburn – autumn	3	82	1.41	0.79	0.09	0.56	5.87	1.10	0.93	1.73
Goulburn – winter	1	3	1.78	0.08	0.05	1.69	1.84	1.81	1.75	1.83
Lower Murray – spring	2	109	1.33	0.34	0.03	0.78	2.98	1.25	1.12	1.48
Lower Murray – summer	2	98	2.90	1.09	0.11	1.24	7.83	2.81	2.18	3.31
Lower Murray – autumn	2	2	4.80	1.82	1.29	3.52	6.09	4.80	4.16	5.45
Lower Murray – winter										

Note: n = number of sample days that met the acceptance criteria pooled over the number of sites in that Selected Area. No data were collected in autumn or winter in the Warrego–Darling ; in spring or winter in the Gwydir; and in winter in the Murrumbidgee and Lower Murray River.

Table B2. Ecosystem respiration (mg O_2/L/day).

Selected Area and season	No. sites	n	Mean	Standard deviation	Standard error	Min	Max	Median	25%	75%
Warrego–Darling – spring	2	8	1.66	0.72	0.25	0.63	2.57	1.76	1.10	2.12
Warrego–Darling – summer	2	4	3.87	0.54	0.27	3.41	4.64	3.71	3.60	3.97
Warrego–Darling – autumn										
Warrego–Darling – winter										
Gwydir – spring										
Gwydir – summer	2	3	4.71	0.92	0.53	3.65	5.28	5.20	4.42	5.24
Gwydir – autumn	2	8	7.46	2.37	0.84	3.57	10.95	7.25	6.79	8.18
Gwydir – winter										
Lachlan – spring	4	106	5.03	2.13	0.21	0.51	12.33	4.66	3.51	5.97
Lachlan – summer	4	215	5.04	2.02	0.14	1.50	13.13	4.21	3.61	6.46
Lachlan – autumn	4	117	4.62	2.22	0.21	1.40	17.20	4.22	3.45	5.51
Lachlan – winter	4	95	2.44	1.24	0.13	0.41	7.77	2.24	1.55	3.10
Murrumbidgee – spring	2	78	0.81	0.62	0.07	0.00	3.81	0.82	0.36	1.18
Murrumbidgee – summer	2	130	1.31	0.78	0.07	0.00	4.12	1.30	0.69	1.70
Murrumbidgee – autumn	1	28	1.78	1.07	0.20	0.77	5.89	1.56	1.05	2.17
Murrumbidgee – winter										

Selected Area and season	No. sites	n	Mean	Standard deviation	Standard error	Min	Max	Median	25%	75%
Edward–Wakool – spring	5	166	4.18	4.78	0.37	0.07	31.16	2.84	2.01	4.24
Edward–Wakool – summer	6	261	5.82	4.12	0.25	0.01	26.63	4.74	2.85	7.61
Edward–Wakool – autumn	6	128	3.63	2.02	0.18	0.04	11.75	3.42	2.46	4.63
Edward–Wakool – winter	6	58	1.75	1.15	0.15	0.02	5.03	1.45	1.03	2.40
Goulburn – spring	4	72	2.06	2.44	0.29	0.03	17.64	1.05	0.78	2.83
Goulburn – summer	4	65	4.39	2.18	0.27	1.49	9.46	3.63	2.49	6.19
Goulburn – autumn	3	82	1.84	0.97	0.11	0.23	4.28	1.68	1.09	2.54
Goulburn – winter	1	3	0.31	0.27	0.16	0.15	0.63	0.16	0.16	0.40
Lower Murray – spring	2	109	1.18	0.55	0.05	0.01	3.36	1.23	0.92	1.49
Lower Murray – summer	2	98	3.02	1.87	0.19	1.05	13.32	2.70	1.99	3.28
Lower Murray – autumn	2	2	7.37	4.64	3.28	4.09	10.65	7.37	5.73	9.01
Lower Murray – winter										

Note: n = number of sample days that met the acceptance criteria pooled over the number of sites in that Selected Area. No data were collected in autumn or winter in the Warrego–Darling; in spring or winter in the Gwydir; and in winter in the Murrumbidgee and Lower Murray River.

Annex C. Summary statistics for selected nutrient data collected during 2015–16

Data in the tables are summarised for each of the Selected Areas, i.e. Junction of the Warrego and Darling rivers, Gwydir river system, Lachlan river system, Murrumbidgee river system, Edward–Wakool river system, Goulburn River and Lower Murray River.

Table C1. Total nitrogen concentration (µg N/L).

Selected Area	No. sites	n	Mean	Standard deviation	Standard error	Min	Max	Median	25%	75%
Warrego–Darling	10	28	796	636	120	200	2800	500	400	925
Gwydir	15	54	981	1139	155	30	6680	730	535	1078
Lachlan	4	39	778	247	39	320	1470	680	600	935
Murrumbidgee	2	9	320	55	18	248	395	318	288	369
Edward–Wakool	7	54	762	669	91	290	3200	540	433	648
Goulburn	4	21	347	117	25	200	630	310	280	380
Lower Murray	2	28	796	636	120	200	2800	500	400	925

Table C2. Total phosphorus concentration (µg P/L).

Selected Area	No. sites	n	Mean	Standard deviation	Standard error	Min	Max	Median	25%	75%
Warrego–Darling	10	28	336	452	85	0	1700	100	0	600
Gwydir	15	54	139	94	13	30	430	130	70	180
Lachlan	4	39	72	49	8	25	337	60	51	78
Murrumbidgee	2	9	40	15	5	27	77.5	35	34	38
Edward–Wakool	7	54	64	31	4	30	220	55	50	70
Goulburn	4	21	34	12	3	20	60	30	30	40
Lower Murray	2	12	58	18	5	36	89	53	45	67

Table C3. Ammonia concentration (µg N/L).

Selected Area	No. sites	n	Mean	Standard deviation	Standard error	Min	Max	Median	25%	75%
Warrego–Darling	10	11	21.5	5.8	1.7	17.0	38.0	20.0	19.0	21.0
Gwydir	15	0	–	–	–	–	–	–	–	–
Lachlan	4	39	15.0	17.3	2.8	2.0	99.0	9.0	7.0	14.0
Murrumbidgee	2	9	3.5	1.8	0.6	1.1	5.0	5.0	1.9	5.0
Edward–Wakool	7	55	1.7	1.3	0.2	1.0	7.0	1.0	1.0	2.0
Goulburn	4	19	3.6	2.6	0.6	1.0	11.0	3.0	2.0	5.5
Lower Murray	2	12	4.9	3.4	1.0	3.0	15.0	3.0	3.0	6.0

Table C4. Nitrate concentration (µg N/L).

Selected Area	No. sites	n	Mean	Standard deviation	Standard error	Min	Max	Median	25%	75%
Warrego–Darling	10	54	173	199	27.0	0.0	592	98	19.6	210
Gwydir	15	32	68	148	26.2	2.0	599	4.5	3.0	24.3
Lachlan	4	9	11.9	25.2	8.4	0.8	79	3.0	2.5	3.3
Murrumbidgee	2	55	1.9	2.5	0.3	1.0	16.0	1.0	1.0	2.0
Edward–Wakool	7	12	69	83	24.0	2.0	270	35	14.0	92
Goulburn	4	12	2.5	3.2	0.9	1.0	11.0	1.0	1.0	1.5
Lower Murray	2	54	173	199	27.0	0.0	592	98	19.6	210

Table C5. Filterable reactive phosphorus concentration (µg P/L).

Selected Area	No. sites	n	Mean	Standard deviation	Standard error	Min	Max	Median	25%	75%
Warrego–Darling	10	28	162	238	45	15	823	57	34	115
Gwydir	15	54	52	37	5.1	0.0	195	45	26	68
Lachlan	4	39	14.2	4.1	0.7	5.0	24	15	11.5	16
Murrumbidgee	2	9	3.6	1.7	0.6	1.0	5.0	5.0	2.6	5.0
Edward–Wakool	7	55	3.0	0.9	0.1	2.0	6.0	3.0	2.0	3.5
Goulburn	4	21	4.1	5.8	1.3	1.0	27.0	3.0	2.0	3.0
Lower Murray	2	12	4.5	3.4	1.0	1.0	11.0	4.0	2.5	5.3

Table C6. Dissolved organic carbon concentration (mg C/L).

Selected Area	No. sites	n	Mean	Standard deviation	Standard error	Min	Max	Median	25%	75%
Warrego–Darling	10	28	12.9	5.1	1.0	8.4	29.8	10.6	9.5	13.9
Gwydir	15	54	13.6	6.7	0.9	4.5	36.0	11.1	9.2	17.8
Lachlan	4	39	9.8	1.0	0.2	7.0	12.0	10.0	9.0	10.0
Murrumbidgee	2	9	3.2	0.9	0.3	2.2	5.6	3.1	2.9	3.2
Edward–Wakool	7	61	4.8	1.6	0.2	2.9	11.0	4.6	3.7	5.6
Goulburn	4	21	4.0	1.3	0.3	2.5	6.9	3.8	3.0	5.1
Lower Murray	2	12	3.8	0.5	0.1	3.0	4.7	3.8	3.6	3.9