Science to support the management of riverine flows

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Executive Summary

Given the intense competition between the environment and other end-users for the Basin's freshwater resources, approval of the Basin Plan is a major milestone in Australia's water reform history. With runoff forecast to decrease within the Basin, competition for freshwater is likely to increase, and so there is a pressing need for the managers of environmental water to meet four 'operational objectives':

1. *Make effective decisions.* Decisions about how water is allocated at all jurisdictional (federal, state, regional), spatial and temporal scales needs to deliver outcomes concordant with Basin Plan objectives. An effective decision is one that results in outcomes concordant with explicit objectives.
2. *Maximise efficiency*. There are heavy constraints on the quantity of water available to achieve Basin Plan objectives, so we must maximise the efficiency of water allocations. We must deliver maximal environmental benefit per unit investment in environmental flows.
3. *Anticipate threats*. We are managing environmental water in a changing world (e.g. increased domestic demand in a drying climate). It follows that a wise strategy would be to optimise current delivery decisions while anticipating emerging threats to the effectiveness of those decisions and current water policy in the longer term.
4. *Provide evidence*. We are managing a highly contested resource, so we require scientifically-defensible evidence on two fronts: Evidence that flow decisions are actually delivering against Basin Plan objectives, and evidence that our decision-making processes align with best scientific practice, irrespective of ecological outcomes.

What roles must scientists fulfil to facilitate the meeting of these four operational objectives? We suggest that freshwater science must fulfil four major roles to support effective and efficient flow management. In what follows we define the four roles and argue why they must be fulfilled. To support our case, we use the Basin-Wide Environmental Watering Strategy (the Basin Strategy), the broader scientific literature, and our own recent experience with flow monitoring and evaluation programs. We then identify what we believe are the dominant barriers to the effective and efficient fulfilment of the four scientific roles. We then offer some solutions for removing those impediments.

Four scientific roles to facilitate flow management

Role 1: Monitoring and evaluation

Scientists must lead the design and implementation of monitoring programs, as well as the analysis and interpretation of monitoring data. Monitoring is essential for providing evidence of outcomes and making effective decisions.

Evidence

Monitoring and evaluation of managed flows is necessary if we are to provide evidence to stakeholders that environmental water is being managed effectively and efficiently. Given intensifying competition for freshwater, we are unlikely to demonstrate that current water allocations are required, let alone increase allocations, if we cannot provide strong evidence for their ecological value.

Effective decisions

Our ability to make effective decisions is dependent on our ability to predict the outcomes of the various decision-options available to us. Well-designed monitoring programs play a pivotal role in reducing uncertainty around decision outcomes. River ecosystems can respond to flows at fast (months) and slow (decades) temporal scales. Well-designed monitoring programs are essential to improving our understanding of these responses, particularly the slow responses. Further, the predictive models that play such a key role in flows management (see Role 2) have specific data requirements. Long-term monitoring programs are the primary means of satisfying those data requirements.

Role 2: Modelling for spatial and temporal projections

Predictive models improve our capacity to project flow responses through time and space. By 'project' we mean the process of predicting the state of river ecosystems and their services, with fully specified uncertainties, contingent on explicit scenarios for antecedent ecological state, water availability and climate. Predictive models play a particularly important role in facilitating Operational Objectives 1, 3 and 4; making effective decisions, anticipating threats and providing evidence.

Effective decisions

When faced with a decision, flow managers usually have numerous decision options. Which option is likely to yield the best ecological outcomes, given the antecedent ecological state of the system? The success of a decision may depend on the future climatic and flow conditions, so what are the relative advantages and disadvantages of each decision option, given the set of possible climatic futures over the coming years? We cannot answer these questions—hence make wise flow decisions—without predictive models. Predictive models enable us to simulate outcomes and evaluate risks associated with a suite of decision-options, thus facilitating identification of optimal decisions.

Anticipating threats

Effective flows policy and management hinges on our capacity to anticipate changes in water availability and other emerging threats. A Basin Plan objective is to improve the resilience of the Basin's flora and fauna to climate change and other possible threats. Meeting this objective requires anticipation of how a changing climate will affect flora and fauna, or how other drivers (e.g. high nutrient concentrations; salinity) will evolve to emerge as threats. We are managing water allocations in a changing environment, where the flow-response relations of today may change in the future. How well will the inundation rules of today apply in a warming and drying Basin? Answering this question requires improved predictive capacity.

Evidence

The Basin Strategy specifically mentions the challenge of obtaining robust scientific evidence about the contribution of environmental flows to ecological objectives—the problem of obtaining robust evidence from flow experiments is a special one, recognised by river scientists internationally. The Basin Strategy makes specific mention of this problem in acknowledgement of the need to draw conclusions concerning cause and effect from non-classical experimental designs; designs where replicates and controls are poor or do not exist. A solution to this problem is 'predictive inference', which involves comparing the *observed* ecological response with what we *predict* would have happened in the absence of the flow intervention. As the name suggests, this approach requires enhanced predictive capacity. Predictive inference is also required to meet certain reporting objectives of the Commonwealth Environmental Water Office's monitoring programs.

Role 3: Fundamental research

We define fundamental research as any research aimed at increasing our understanding of the basic relationships between riverine flows and ecological pattern and process. A key point of difference between monitoring and fundamental research projects is that the latter are not necessarily tied to a managed flow intervention. We contend that, in many cases, fundamental research may provide a more cost-effective pathway to effective decisions than monitoring.

Effective decisions

Fundamental research may most efficiently lead to identification of complementary actions. Flows have become such a prominent issue in river management that we often fall into the trap of thinking that flow manipulation is the single and best way to meet our ecological objectives. However, flows interact with many other environmental variables to shape ecological outcomes. Fundamental research to elucidate those interactions may lead to complementary actions that provide greater ecological returns per unit of environmental water invested. For example, fundamental research has shown that while flows may be crucial for mobilising and transporting nutrients, local habitat restoration plays a pivotal role in converting these biogeochemical outcomes into outcomes with more tangible value to stakeholders (e.g. more fish). The application is that joint management of local habitat and flows may yield synergistic benefits.

Fundamental research may be the best way to improve understanding about the ecological limitations of current flows policy. Current policy dictates (a) the amounts of water available for meeting objectives and (b) the constraints around how that water is delivered. Under the Basin Plan the Sustainable Diversion Limit (SDL) and operating constraints are being managed adaptively, and so will be reviewed periodically. Any such review needs to be informed by an improved scientific understanding of the system. How do we best improve our scientific understanding of ecological response to flow variability beyond the constraints of the current policy framework? To argue that monitoring is the answer would be a *non sequitur*, as monitoring primarily targets impacts of flows delivered under the current SDL and operating constraints. Fundamental research, by contrast, can reduce uncertainty about how current policy limits our capacity to meet Basin Plan objectives.

Role 4: Decision science

Decision science is an interdisciplinary field that develops scientific tools to integrate multiple forms of data (e.g. ecological; economic) to make transparent and replicable decisions about how resources should be allocated to effectively and efficiently meet management objectives. Applications of decision science offer more defensible environmental flow decisions and more efficient use of resources to support adaptive management of flows.

Evidence

The intersection of two problems creates the need for decision-making processes that align with international best-practice: (1) decisions will be scrutinised by economic, consumer and political stakeholders; (2) there is currently very high uncertainty about the outcomes we can expect from any particular flow allocation decision. This combination of having to make decisions in a high-stakes game, yet being uncertain about the outcomes of our decisions, necessitates the employment of scientific best-practice in our decision-making processes. The Basin Strategy acknowledges the need for ‘robust and transparent decisions’ in their annual water planning, but without mentioning how to achieve this. Decision science offers the solution.

Efficiency

Environmental water is a scarce and expensive commodity, so must be used to meet management objectives in the most efficient way. Likewise, funding to fulfil the four roles discussed herein is also a scarce resource, and so must be distributed to maximise returns per unit investment. Decision science offers applications to identify optimal resource allocation decisions. Such applications can, for example, optimise long-term and annual planning of water allocations to The Living Murray Icon Sites, and objectively identify how research funding should be most efficiently allocated to lead to more effective flow management decisions.

Barriers to implementation and some solutions

One overarching barrier—the need for a Basin-scale science investment strategy

Why do we need a Basin-scale investment strategy?

In the absence of an investment strategy developed in light of basin-scale management problems, scientific support of water management becomes extremely inefficient. Two reasons for this are as follows:

First, absence of a Basin-scale strategy results in *ad hoc* science investment patterns that do not cover the full spectrum of decisions that water managers must make. A Basin-scale strategy would prioritise science investments in a holistic fashion to inform the management decisions that need to be made at multiple spatial and temporal scales. It is currently commonplace within the Basin to observe ‘bottom-up’ patterns of science investment. Under this bottom-up approach, management questions at the local and regional spatial scale, and short temporal scales (i.e. monthly-annual) dominate investment strategies. In contrast, a top-down approach may be more likely to invest in ‘big picture’ management questions that target the basin-wide spatial scale and multi-year or decadal time frames. There needs to be a balance between top-down and bottom-up input to a basin-scale investment strategy

Second, absence of a Basin-scale strategy results in scientists and managers achieving a poor shared understanding of (a) why the four scientific roles are required to support flow management; (b) how they can complement each other to support the four operational objectives stated at the beginning of this Executive Summary.

How do we develop an investment strategy?

We suggest developing a science investment strategy according to the following three principles:

First, the strategy must be developed at the Basin-scale. A Basin-scale strategy is required to avoid *ad hoc* investment and have science adequately supporting flows management at the relevant spatial and temporal scales. The strategy should consider the specific management decisions that need to be made at the various spatial and temporal scales.

Second, the strategy must be developed by a consortium of scientists and managers across the relevant jurisdictional scales to ensure that science investments remain aligned with the specific needs and constraints of water managers.

Third, the strategy must recognise the need to build and maintain capacity within the four roles. The scientific skills required to successfully fulfil the four roles presented herein are in short supply. This is particularly true for modelling and decision science. We must not assume that the technical skills required to fulfil all roles can be accessed and then stored in an *ad hoc* fashion, so the strategy should be developed to build and nurture technical capacity for all four roles summarised above.

Introduction

Australia has just implemented one of its largest and most controversial ecological restoration projects in recent history. In 2012 a legislative instrument (Basin Plan 2012) came into effect to guide the management of freshwater flows within the river-floodplain ecosystem of the Murray-Darling Basin (MDB), which has experienced strong detrimental impacts of river regulation for decades (Box 1) (Kingsford 2000; Lake & Bond 2007; Walker & Thoms 1993). Given the intense competition between the environment and other end-users for the Basin's freshwater resources (Box 1), approval of the Basin Plan is a major milestone in Australia's water reform history. Under the Basin Plan, flows will be delivered to rivers and their floodplains with the objectives of protecting, restoring and improving the resilience of water-dependent habitats, ecosystem processes and biodiversity (MDBA 2014a). A quantity of water has been set aside to meet Basin Plan objectives as a result of setting a Sustainable Diversion Limit (SDL) for consumptive use.

The MDB is what some may refer to as a 'novel ecosystem' (Hobbs *et al.* 2009). It has been transformed from its natural state by humans, with the new socio-ecological system providing a suite of services to humans, while also providing habitat to a diverse assemblage of water-dependent flora and fauna (Colloff *et al.* 2016). The Basin Plan is not about restoring the MDB to a pre-regulation state, but to manage water to 'support productive industries, farmers and communities into the future, while leaving sufficient water in the Basin's river system to ensure a healthy environment' (MDBA 2014a). The flow management problem within the MDB is generally not one of delivering natural flow regimes (sensu Arthington *et al.* 2006; Poff *et al.* 2010), but to optimise flow management to achieve specific ecological objectives, within the heavy constraints of water availability and delivery (sensu Acreman *et al.* 2014). Those objectives centre on maintaining and/or restoring critical ecosystem processes (e.g. sufficient flow to flush salt from the lower segments) and ecological states that multiple stakeholders value (e.g. productive recreational fisheries).

Freshwater science played a pivotal role in setting the SDL and the development of the Basin Plan. Looking ahead, science must continue to fulfil roles that facilitate meeting of Basin Plan objectives and future adjustments to the SDL. However, the roles that freshwater scientists must fulfil are rapidly evolving, and are moving well beyond the provision of new fundamental knowledge (Poff *et al.* 2003). Indeed, given the transformative pressures humanity is placing on the planet, scientists have a social responsibility to re-examine their goals and focus (Lubchenco 1998). Now is a good time to critically evaluate the roles that scientists must fulfil, at this pivotal stage in Australian water reform.

Here we suggest that freshwater science must fulfil four major roles to support effective and efficient flow management: (1) scientifically-defensible monitoring and evaluation of managed and natural flows; (2) modelling to predict the ecological impacts of variability in flows and other ecological drivers in time and space; (3) fundamental research into flow ecology that complements well-designed monitoring projects; (4) supporting decision-making in a variety of ways, from provision of expert opinion through to assistance in identifying optimal decisions in the face of uncertainty.

The rest of this manuscript is divided into two parts: First, we argue why these four roles must be fulfilled. To support our case, we use the Basin-Wide Environmental Watering Strategy (BWS; MDBA 2014a)—the strategy that builds on Australia's Basin Plan to guide managers towards meeting Basin Plan objectives—the broader scientific literature, and our own recent experience with flow monitoring and evaluation programs.

Second, we identify what we believe are the dominant barriers to the effective and efficient fulfilment of the four scientific roles. We then offer some solutions for removing those impediments. We argue that the effectiveness and efficiency with which science can contribute to these goals would be greatly enhanced not thorough more funding per se, but through a carefully devised investment strategy that aims to address the right management problems at the right spatial scales. We hope that this document will encourage managers and scientists to reconsider their investment and research priorities, and strengthen their partnership to improve the management of riverine flows.

Box 1. The Murray-Darling Basin: Competition for Water

The Murray-Darling Basin (MDB) is Australia's largest river system, spanning 14% of Australia's surface area and five of its eight states/territories. Although it is ranked within the top 20 river basins of the world for its length and area, it discharges one of the world's smallest volumes of water for its size. Much of the MDB receives very little rainfall which, when coupled with low elevation and the slow-flowing nature of the rivers, results in approximately 94% of runoff being evaporated. In addition to the generally low discharge, the Basin experiences strong episodic droughts, certain of which may last a decade, compounding problems of water availability.

To secure water for domestic and agricultural uses, most of the Basin's rivers are now heavily regulated. The Basin is the focus of Australia's irrigated production. Consequently, humans have reduced discharge of the Basin by approximately 75% on average, and have greatly altered the annual hydrographs of its rivers (Maheshwari et al. 1995; McMahon and Finlayson 2003). Not surprisingly, these hydrological changes have resulted in strong, obvious detrimental impacts on the state of the Basin's river-floodplain ecosystem (Walker and Thoms 1993; Kingsford 2000). Despite the magnitude of the environmental problem, the Basin Plan is one of the most controversial pieces of legislation in Australia's recent history (http://theconversation.com/au/topics/murray-darling-351), because competition between the environment and other end-suers for the Basin's scarce water is so intense.

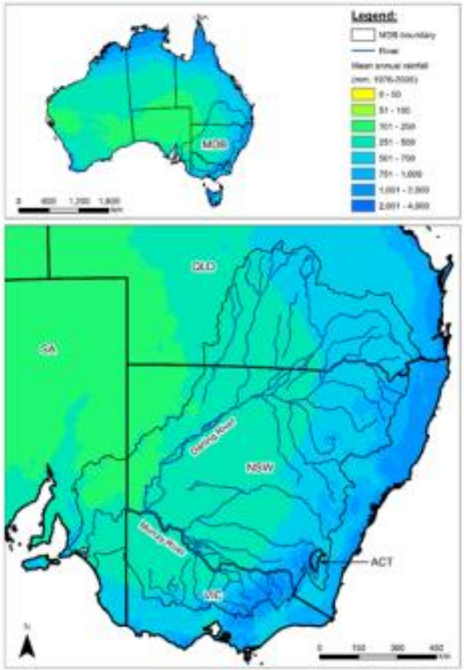


Table 1. Descriptions of the five stakeholder groups identified by Conroy and Peterson (2013). Stakeholders in riverine flow management are persons or organisations with a vested interest in the rationale for, and outcomes of, flow management decisions.

Consumers	Members of the public that use freshwater resources either consumptively or non-consumptively. The financial position of individuals in this group is not directly affected by flow management decisions. Examples include anglers, birdwatchers, hunters, boaters, campers and tourists to riverside communities affected by the aesthetics of river-floodplain ecosystems.
Non-government organisations (NGOs)	Organisations that advocate for the wise use of environmental water that are not part of any governmental organisation and are generally non-profit. Examples include International Union for the Conservation of Nature and Natural Resources (IUCN), the Murray-Darling Basin's Water Trust Alliance, and hunting and fishing lobby groups.
Government water management agencies	Regional, state and federal water management agencies responsible for managing riverine flows within their legally-mandated jurisdiction. In Australia, from federal down to regional, examples include Commonwealth Environmental Water Office, NSW Office of Environment and Heritage, and regional catchment management authorities.
Political	Elected representatives of regional, state and federal governments. Political stakeholders in flow management can have a strong impact on the activities of other stakeholder groups, particularly water management agencies.
Economic	Businesses and landholders whose financial position is affected by flow management decisions. Examples include power-generation companies, irrigators, floodplain landholders,

	regional councils, riverine tourism businesses, and businesses that supply goods and services to these groups.
Scientists	Individuals that have technical knowledge of, or interest in, the flow management decisions, but who are not directly affected by the decision in their technical capacity.

Role 1: Monitoring and evaluation

Monitoring projects that are well designed and implemented form a cornerstone of natural resource management (Conroy & Petersen 2013; Schindler & Hilborn 2015). The data obtained through monitoring are valuable for many reasons (Lindenmayer & Likens 2010; Lovett *et al.* 2007). In the context of flow management, monitoring is essential for two major reasons: 'reporting' and 'reducing uncertainty' (Figure 1).

Reporting

Monitoring and evaluation of managed flows is necessary if we are to provide evidence to consumer, political and economic stakeholders (Table 1) that the objectives underlying flow management are being met, and that environmental water is both necessary and being managed effectively (Bernhardt *et al.* 2005). Given the intensifying competition for freshwater (Colloff *et al.* 2016; Vorosmarty *et al.* 2000), ecologists and managers are unlikely to demonstrate that current water allocations to riverine ecosystems are required, let alone increase allocations, if we cannot provide strong evidence for their ecological value.

Reducing uncertainty

Monitoring and evaluation of flows is necessary to reduce uncertainty about how flow management affects ecological outcomes, as is the case with adaptive management more generally (Bayley 1995; Walters 1997). Uncertainty pervades any form of natural resource management and comes in different forms (Figure 1) (Regan *et al.* 2002). The more we lower uncertainty around flow management outcomes, the easier it is to manage the system and stakeholder expectations, and to achieve environmental outcomes as efficiently as possible (Table 1).

In reducing uncertainty, both parameter estimation and hypothesis testing are fundamental goals (Ellison 1996). When testing hypotheses our focus is primarily on reducing structural uncertainty, while reducing statistical uncertainty may be a higher priority if parameter estimation is our aim (Figure 1). As we will discuss later (Role 2: Modelling for spatial and temporal projections), quantitative models play a critical role in the adaptive management of riverine flows, and long-term monitoring projects provide the time series required to reduce uncertainty around parameters of those models (Clark *et al.* 2001; Shea 1998; Wolkovich *et al.* 2014). Parameter estimation aside, long-term monitoring is often necessary to reduce structural uncertainty about the impact of flows on certain ecological states (e.g. fish population size), which may exhibit delayed (> 5 year) responses to changes in flow regimes (Souchon *et al.* 2008). Within the context of the MDB, the Watering Strategy explicitly recognises that different ecological indicators will likely exhibit responses on very different timescales, and frames management objectives with this in mind (MDBA 2014a). Short-term monitoring projects (< 5 year) may be poorly suited to parameter estimation, but if designed well (see Table 3) they too can play a role in reducing structural uncertainty around ecological response to flows.

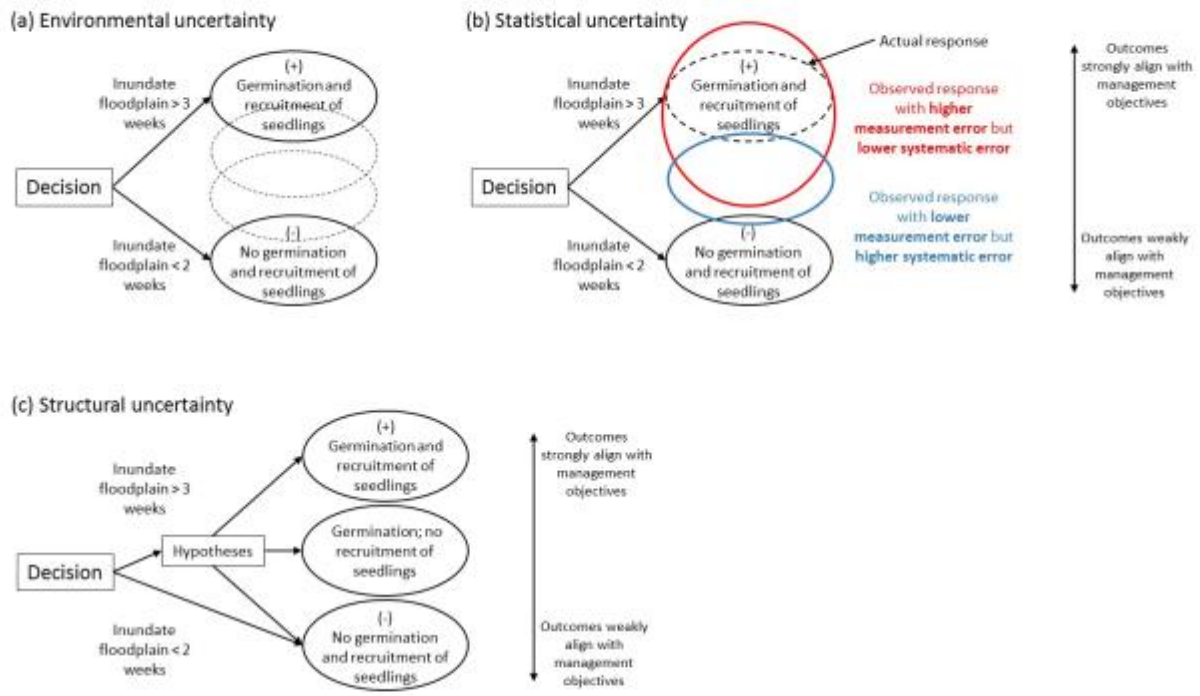


Figure 1. Types of uncertainty most relevant to flow management (adapted from Conroy and Peterson (2013) and Regan et al. (2002)). To illustrate the types of uncertainty we present a hypothetical example of the influence of single flow management decision (long or short floodplain inundation) on the germination and recruitment outcomes of a riparian tree species. (a) Environmental uncertainty refers to the influence of background environmental variables that are random in nature (e.g. climatic conditions), are beyond the control of the decision maker, but affect the outcome of a flow intervention. (b) Statistical uncertainty arises as a consequence of our inability to make perfect scientific measurements of ecological systems. Measurement error generates imprecision in our estimate. Systematic error occurs when our samples are biased. (c) Structural uncertainty refers to uncertainty in our understanding of the basic relationships among components within our model of flow-response (be that model conceptual or mathematical).

Role 2: Modelling for spatial and temporal projections

Quantitative predictive models of the dynamics of river ecosystems facilitate the effective adaptive management of river flows (Anderson *et al.* 2006; Shenton *et al.* 2012). By increasing our predictive capacity we improve our ability to project flow responses through time, which we hereafter refer to as forecasting, and scale flow-response dynamics spatially. Following Clark et al. (2001), we define ecological forecasting as the process of predicting the state of riverine ecosystems and their services, with fully specified uncertainties, contingent on explicit scenarios for antecedent ecological state, water availability and climate. By ‘state of riverine ecosystems’ we mean any physical (e.g. mean water velocity) or biological (e.g. a population) sub-system of the broader ecosystem. Spatial scaling involves using models of flow-response developed at narrow spatial extents and particular locations to predict flow-response dynamics at broader spatial extents and/or different locations (Rastetter *et al.* 2003).

Modelling facilitates (a) making more effective management decisions; (b) making causal inferences about the effects of environmental water; (c) identifying threats to the efficacy of flow management; (d) scaling flow-response dynamics to broader spatial extents throughout drainage basins.

More informed management decisions

When faced with a decision, flow managers usually have numerous decision options. Which option is likely to yield the best ecological outcomes, given the antecedent ecological state of the system? The success of a decision may depend on the future climatic and flow conditions, so what are the relative advantages and disadvantages of each decision option, given the set of possible climatic futures over the coming years? We cannot answer these questions—hence make wise flow decisions—without strong capacity for ecological forecasting (Polasky *et al.* 2011). Within the MDB, the Watering Strategy states that annual water prioritisation involves predicting the likely outcomes of water allocations, given antecedent conditions of the various catchments throughout the MDB (MDBA 2014a). This is a specific flow management problem that would be greatly strengthened by improved capacity for ecological forecasting.

Causal inferences about flow effects

Drawing robust, causal inferences about the impacts of flows on riverine ecosystems is particularly challenging. If we consider a flow intervention as an experimental treatment, then the treatment cannot be neatly replicated, nor do we have a control. Thus, the very well established analytical approaches associated with classical experimental design do not apply to flow interventions (Konrad *et al.* 2011; Olden *et al.* 2014; Webb *et al.* 2010).

Consider the management objective within the Watering Strategy of delivering water to ensure 'no loss or degradation' of key ecological indicators during dry years. This is an interesting analytical problem as the desired treatment effect is 'no change' in the ecological state of a single experimental unit (the river). To achieve this objective we need to know whether failure to deliver the flow would have resulted in a degraded ecological state of that single unit, usually in the absence of a suitable control. Such analytical problems are not unique to river ecology, as analysis of ecological effects in unreplicated, large-scale perturbations is a broader problem in adaptive management (Walters & Holling 1990; Westgate *et al.* 2013). Admirably, Australia's Murray-Darling Basin Authority specifically mentions this analysis problem in their Watering Strategy (MDBA 2014a) and evaluation framework (MDBA 2014b). The challenge is also recognised in the Australian Commonwealth's major investment in flow-response monitoring (Gawne *et al.* 2013).

One way to determine the effects of flow interventions is through various forms of 'predictive inference' (Gelman & Hill 2006; Ch. 9). Although this method of inference is technically challenging, it may overcome the problem of lacking a classical experimental design. The approach involves comparing the *observed* ecological response—and its associated confidence interval—with what we *predict* would have happened in the absence of the flow intervention (sometimes referred to as the 'counterfactual' or the 'potential outcome'; Gelman & Hill 2006). As the name suggests, predictive inference requires the capacity to forecast both hydrological and ecological dynamics at various temporal scales.

Capacity to anticipate emerging threats

Effective flows policy and management hinges on our capacity to anticipate changes in water availability and other emerging threats (Colloff *et al.* 2016). For example, a Basin Plan objective is to improve the resilience of the Basin's flora and fauna to climate change and other possible threats (MDBA 2014a). Meeting this objective requires that we can anticipate how a changing climate will affect flora and fauna, or how other drivers (e.g. high nutrient concentrations; salinity) will evolve to emerge as threats. We are managing water allocations in a non-stationary environment (a form of environmental uncertainty; Figure 1a), where the flow-response relations of today may change in the future (Bunn & Arthington 2002; Wolkovich *et al.* 2014 discusses the general case).

Consider floodplain vegetation communities: with increased frequency and magnitudes of heat waves and droughts forecast for the mid-latitudes (Perkins *et al.* 2012; Seneviratne *et al.* 2014; Sousa *et al.* 2011), we can expect more frequent physiological stress of floodplain vegetation (Capon *et al.* 2013; James *et al.* 2016). How will this affect the watering requirements of those communities? How well will the inundation rules of today apply in the warming and drying mid-latitudes? Answering such questions requires improved forecasting capacity.

Spatial scaling of flow outcomes

Resource management plans often mention the need to 'scale-up' effective management responses observed at particular locations and extents to other locations, where data may be scarce, and to broader spatial extents (Gregory *et al.* 2006; Urban 2005). Within Australia, for example, the Watering Strategy clearly states the need for a 'basin-wide' approach to water planning and management (MDBA 2014a). This basin-wide planning approach has extended to evaluation, such that the Commonwealth's major flow monitoring program has the objective of evaluating outcomes to flow interventions within unmonitored catchments (Gawne *et al.* 2013). Here again the solution is predictive inference; using quantitative models to predict what the likely outcomes of a management intervention would have been in an unmonitored location (Ferrier 2011). Accuracy of these predictions will vary substantially, depending on statistical uncertainty around model parameters, how dependent parameter values are on environmental context, information on the ecological state of the unmonitored location, and hydrological/hydraulic information, including data on the background and managed components of the hydrograph. As is the case for all ecological forecasting, the predictions should not be seen as definitive statements of what has happened as a result of the flow, but statements about the range of likely outcomes, given fully-specified assumptions and uncertainties (Clark *et al.* 2001).

Role 3: Fundamental research

We here define fundamental research as any empirical or theoretical research aimed at increasing our understanding of the basic relationships between riverine flows and ecological pattern and process. A key point of difference between monitoring and fundamental research projects is that the latter are not necessarily tied to a managed flow intervention. For example, empirical fundamental research may range from studying the relationships between natural flow variability and ecological responses (e.g. Mims & Olden 2012), through to controlled laboratory experiments aimed at elucidating cause-effect mechanisms in riverine food webs (e.g. Baldwin *et al.* 2014). Fundamental theoretical work can be similarly broad and may range from conceptual syntheses of flow ecology (e.g. Junk *et al.* 1989; Poff *et al.* 1997), through to exploring dynamic ecological responses to flows with mathematical models (e.g. Power *et al.* 1995). As argued by McDonald-Madden et al. (2010, 2011) we contend that, in many cases, reduction of structural uncertainty around the outcomes of flow decisions may be more effectively and efficiently reduced with fundamental research than with monitoring.

Fundamental research will lead to at least three desirable outcomes for flow managers, which we discuss briefly below.

Improved flow outcomes through synergistic river management

Flows have become such a prominent issue in river management that we often fall into the trap of thinking that flow manipulation is the single and best way to meet our ecological objectives. However, flows interact with many other environmental variables to shape ecological outcomes. Fundamental research to elucidate those interactions may lead to synergistic river management solutions that provide greater ecological returns per unit of environmental water invested.

As an example, consider the possible role of large woody debris in mediating nutrient outcomes from flows. Fundamental research has shown that overbank flooding plays an important role in mobilising and transporting dissolved nutrients between channel and floodplain habitats (Baldwin *et al.* 2013; Cook *et al.* 2015; Junk *et al.* 1989). Whether or not these dissolved nutrients are incorporated into the riverine food web may be determined by the densities of certain microbes in a river reach, which may in turn be affected by availability of hard substrates for microbial colonisation. Simple laboratory experiments have confirmed that the surface area of hard microbial substrates exhibits a strong, positive relationship with dissolved nutrient uptake (Baldwin *et al.* 2014). This fundamental research efficiently shows that while flows may be crucial for mobilising and transporting nutrients, habitat structure plays a pivotal role in converting these biogeochemical outcomes into outcomes with more tangible value to stakeholders (e.g. more fish). The application is that joint management of woody debris and flows may yield synergistic benefits.

Improved understanding about the ecological limitations of current flows policy

Consider the following scenario, germane to Australia's Basin Plan: Water policy dictates (a) the amounts of water, and (b) the domain of hydrological variability available to managers for meeting ecological objectives. Due to water diversions and delivery constraints (e.g. floodplain infrastructure), the domain of hydrological variation for managed flows is a subset of the broader domain of natural flow variability. The legislation that sets the amounts and constraints for delivery may be up for periodic review—as is the case for the SDL (MDBA 2014a)—and any such review needs to be informed by an improved scientific understanding of the system. How do we best improve our scientific understanding of ecological response to flow variability beyond the constraints of the current policy framework?

One may argue that the best way to improve our understanding in this situation is through monitoring. However, this would be a *non sequitur*, and would result in us primarily drawing inferences about the effects of the reduced domain of variability set by the current water policy. How can we provide scientific recommendations towards revising the current domain of variability if our ecological understanding is completely circumscribed by that domain? Within the Murray-Darling Basin, for example, meeting certain Basin Plan objectives may depend on the extent to which we can reconnect floodplain and channel habitats, but current legislation restricts most flows to the main channel (Bond *et al.* 2014; Stoffels *et al.* 2014). This, coupled with the fact we have a generally very poor understanding of the significance of river-floodplain connectivity to biota, implies that monitoring managed flows may be an ineffective way to improve our understanding of how delivery constraints affect our ability to meet management objectives.

In such situations, fundamental research is likely the most efficient way to reduce structural uncertainty (McDonald-Madden *et al.* 2010). Working with the above example, we need more fundamental research into the ecological consequences of river-floodplain connectivity scenarios. This research could take place in systems with minimal regulation of river-floodplain connectivity, or take novel experimental approaches towards better understanding how environmental conditions in floodplain and channel habitats (e.g. temperature) affect ecological processes. Inferences derived from such research could be scaled-up using models to forecast how relaxing river-floodplain connectivity constraints affect ecological dynamics at broader spatial scales.

Increased usability and generalisation of ecological knowledge

Water managers manage flows within multiple catchments at the extent of entire drainage basins (e.g. MDBA 2014a). Given the broad spatial extent of the management problem, we cannot expect to have detailed knowledge of context-specific responses to decisions in most river segments. It follows that managers require generalisations about ecological response to hydrographs (Poff *et al.* 2003). Review and synthesis of the peer-reviewed literature is an essential step towards converting large amounts of fragmented ecological information into a format that is more useable by managers. Good syntheses build the theoretical framework of flow ecology by identifying the common threads amongst individual studies; drawing out the general rules; refining conceptual models; and highlighting major knowledge gaps (Forscher 1963).

Role 4: Decision science

An ultimate test of freshwater science's utility to water management is how well it supports effective and efficient flow-allocation decisions. We have already discussed the importance of predictive capacity in supporting decisions, but there are several other ways that scientists can strengthen the decision-making processes of flows management. Indeed, over the last two decades we have seen the emergence of numerous scientific applications aimed entirely at how we can use information to make smarter decisions when managing our natural resources (Burgman 2005). For convenience, we refer collectively to these scientific applications as 'ecological decision science' ('decision science' hereafter).

Decision science operates at the interface between ecological science and natural resource management. It is a rapidly emerging, interdisciplinary field that develops scientific tools to integrate multiple forms of data (e.g. ecological; economic) to make transparent and replicable decisions about how resources should be allocated to effectively and efficiently meet management objectives. Within the context of flow management, applications within decision science offer at least two beneficial outcomes: (a) more defensible environmental flow decisions; (b) more efficient use of resources to support adaptive management of flows.

Defensible flow decisions

The intersection of two problems creates the need for decision-making processes that align with international best-practice: The first problem we face is the fact that decisions will be scrutinised by economic, consumer and political stakeholders (Table 1). This is an unavoidable consequence of managing an increasingly limited resource that is highly valued by stakeholders with apparently conflicting values (Naiman *et al.* 2002). Indeed, water managers within Australia have suggested to us that the decisions about water allocations are often more controversial than the actual outcomes (Conroy & Petersen 2013; Gregory *et al.* 2012). The level of scrutiny aimed at water managers will only increase as the human population grows, and as temperate climates become warmer and drier (Vorosmarty *et al.* 2000). The second problem is that there is currently very high uncertainty about the outcomes we can expect from any particular flow allocation decision.

This combination of having to make decisions in a high-stakes game, yet being uncertain about the outcomes of our decisions, necessitates the employment of scientific best-practice in our decision-making processes. Russo & Shoemaker (2001) summarise the need for a defensible decision-making process as a two-way table (Table 2).

Table 2. A two-way table explaining the need for scientifically-defensible decision-making processes when making decisions in the face of uncertainty. Adapted from Russo & Shoemaker (2001).

	Good decision process	Bad decision process
Desirable outcome	A "*deserved success.*"	"*Dumb luck*;" we cannot explain to stakeholders why a good outcome was achieved, and don't know what to expect next time.
Undesirable outcome	A "*bad break*", but we can defend the decision as the best one to make given all available information. Continue to reduce uncertainty around predictions.	"*Poetic justice;*" our decision process was not concordant with best-practice, so we deserve the criticisms stakeholders are aiming at us.

The Murray-Darling Basin Authority's Watering Strategy acknowledges the need for 'robust and transparent decisions' in their annual water planning, but without mentioning how they would achieve this (MDBA 2014a). Decision science offers frameworks for making objective, transparent and replicable decisions, despite what may appear to be unruly uncertainty. Towards that end, Conroy & Peterson (2013) broadly suggest three steps:

1. *Set explicit, quantifiable management objectives* in light of ecological knowledge, economic data and stakeholder values. Just because values are brought to bear on objectives does not mean the process used for setting objectives must itself be subjective.
2. *Model the relationships between explicit decision alternatives and objectives*. Using best available ecological and economic information, models are developed that describe the relations between the suite of alternative decisions available and management objectives. The models may explicitly incorporate operating and financial constraints associated with alternative decisions, as well as the trade-offs amongst decision-options.
3. *Modelling the outcomes, trade-offs and uncertainties associated with taking alternative decisions*. Quantitative models are used to predict the likely outcomes, uncertainties and trade-offs associated with alternative decisions. In light of this information a decision is made.

More efficient use of resources

'Efficiency' is a key word in the management of riverine flows. Environmental water is a scarce and expensive commodity, so must be used to meet management objectives in the most efficient way (Bunn & Arthington 2002). Likewise, funding to fulfil the four roles discussed herein is also a scarce resource, and so must be distributed to maximise returns per unit investment (McDonald-Madden *et al.* 2010). In both these cases we seek an optimal resource allocation. Decision science offers solutions to such optimisation problems, and we discuss two such applications here.

Federal water managers within Australia are responsible for prioritising water allocations to numerous floodplain reserves throughout the Murray-Darling Basin (MDBA 2014a) (Questions 3 and 6 in Figure 2). During wet years this may not be a particularly great challenge. By contrast, during dry years the magnitude of the challenge increases, as federal managers must decide which reserves will receive water and which will not. Any decision will involve trade-offs and may be contentious, as each reserve may be associated with passionate regional stakeholder groups that submit plausible arguments as to why their wetland should receive environmental water.

A solution to this problem is to use reserve-design algorithms that would find the optimal pattern of water allocation across reserves that maximises ecological returns per unit of water invested (Cabeza & Moilanen 2001; Linke *et al.* 2011; Possingham *et al.* 2000). In finding an optimal solution, these algorithms would take into account (a) the number (e.g. species number) and value (e.g. conservation status) of ecological assets within each reserve; (b) the likely responses of those assets (positive or negative) to inundation; and (c) the relative quantities of water (the costs) required to water each reserve.

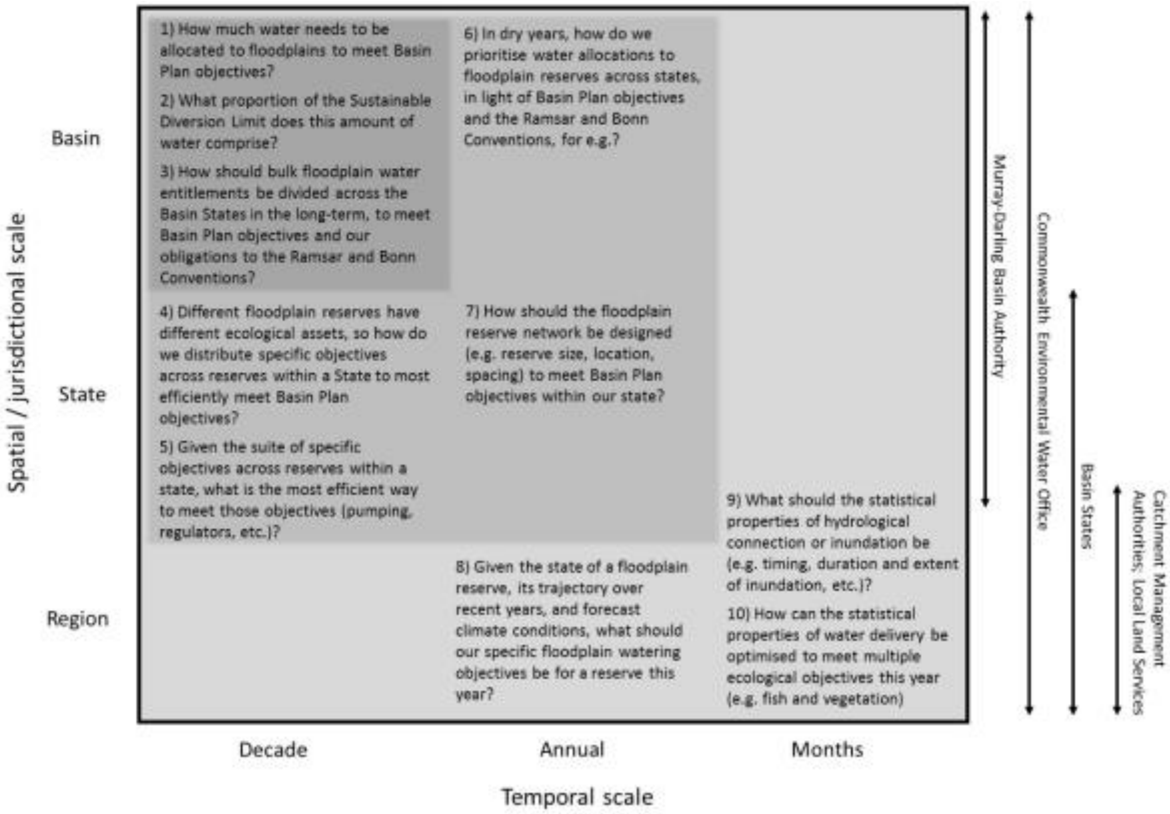


Figure 2. The decisions that water managers need to make vary depending on the spatial/jurisdictional and temporal scales of management. Here we present 10 questions concerning how water should be allocated to floodplains of the Murray-Darling Basin, Australia. On the right, the spatial scale of jurisdiction of four key management agencies are presented; there is only partial overlap in the types of decisions these agencies must make. The questions in this table are based on our interpretation of the Watering Plan (MDBA 2014) and our own experience in working with flow managers at different jurisdictional scales.

A second application of tools developed in decision science is to the problem of how to most efficiently invest in research to reduce uncertainty. Assume that we have numerous hypotheses about how uncertainty reduces our ability to achieve management objectives, but that monitoring and management require us to expend limited resources so that we can only reduce one of the many uncertainties: which uncertainty should we choose to reduce? Value of information analysis quantifies the value of reducing uncertainty in a decision-making process. The expected value of perfect information (EVPI) is the difference between the expected management outcomes when a decision is made using existing information and when the decision is made after collecting new information (Canessa *et al.* 2015; Yokota & Thompson 2004). In plain language, EVPI asks: "how much better would my management outcomes be if I could remove the uncertainty?" Value of information analysis can quantify the expected gains from a range of hypotheses relatively rapidly using existing information, enabling decision makers to invest scarce resources into promising hypotheses with more confidence about the expected returns. This is particularly useful when considering investment in resource-intensive, long-term adaptive management programs, where it is important to have confidence that the uncertainties targeted will make the largest difference to management outcomes. Box 2 presents a specific example.

Box 2: Using value of information to prioritise uncertainty reduction at Barmah Forest.

Value of information analysis has been applied to help prioritise intervention monitoring and management of Moira grass (*Pseudoraphis spinescens)* plains at Barmah Forest (Nicol and Chades, *in prep*.). Barmah Forest once supported the largest area of Moira grass plains in the Murray-Darling Basin, but the area of Moira grass plains has declined to the point that the ecosystem is now threatened with extinction (Colloff et al 2014). Although a basic model of the water regime for floodplain grassy wetlands is known, there remains uncertainty about how environmental watering impacts Moira grass growth at Barmah forest (Reid and Quinn 2004; Colloff et al 2014). Key uncertainties include the ideal duration, timing and depth of flooding required to promote Moira grass; the impacts of grazing on Moira grass; the ability of Moira grass to disperse and colonise over large distances, and the persistence and viability of the Moira grass seedbank.

Value of information analysis was used to quantify the expected benefits of carrying out 9 monitoring and management strategies to reduce the uncertainties in 8 hypotheses about the factors limiting Moira grass regeneration in Barmah forest. Experts estimated the relative likelihoods of each of the hypotheses based on their knowledge of the Barmah forest ecosystem. For each of the hypotheses, experts estimated the expected benefits of implementing each strategy relative to four measurable management outcomes (area of Moira grass restored, frequency of flowering years, percentage cover of Moira grass, and average depth of thatch) assuming that each of the hypotheses was true. The difference between managing after removing uncertainty and managing given existing uncertainty can be used to judge whether investing in resolving uncertainty is worthwhile. In Barmah forest, predictions suggested that removing uncertainty could increase the area of Moira grass, add extra flowering years, and increase average thatch depth. Percentage cover would not increase if uncertainty was resolved; there was negligible value of gaining new information for the purposes of increasing cover. These predictions can be used to help prioritise intervention monitoring at Barmah forest, as the expected benefits can be weighed against the expected costs of the proposed monitoring and management strategies.

Barriers to implementation and some solutions

Having presented the four roles that we believe scientists must fulfil to support management of riverine flows, we now discuss some major barriers to effective and efficient fulfilment of those roles.

One overarching barrier—the need for basin-scale science investment strategies

Before briefly discussing barriers specific to each role, we first argue that one of the greatest overarching impediments to successful fulfilment of the scientific roles is the absence of science-investment strategies at the scale of entire drainage basins. We contend that, in the absence of an investment strategy developed in light of basin-scale management problems, scientific support of water management becomes extremely inefficient. There are several reasons for this, and we touch on just two below.

First, absence of a basin-scale strategy results in *ad hoc* science investment patterns that do not cover the full spectrum of decisions that water managers must make. Figure 2 presents a subset of the decisions facing managers in Australia's Murray-Darling Basin, across the suite of spatial and temporal scales acknowledged in the Watering Strategy (MDBA 2014a). The decisions specifically concern the management of hydrological connectivity between rivers and floodplains. Funding for science is in short supply, so developing a science plan to answer the questions in Figure 2 requires a basin-scale, 'top-down' strategy. This basin-scale strategy would prioritise science investments in a holistic fashion, in light of the management decisions that need to be made at multiple spatial and temporal scales. It is currently commonplace, however, to observe 'bottom-up' patterns of science investment dominate investment strategy. Under this bottom-up approach management questions at the local and regional spatial scale, and short temporal scales (i.e. monthly-annual) dominate investment strategies (in contrast, a top-down approach may be more likely to invest in 'big picture' management questions that target the basin-wide spatial scale and multi-year or decadal time frames). There needs to be a balance between top-down and bottom-up input to a basin-scale investment strategy.

Second, absence of a basin-scale strategy results in scientists and managers achieving a poor shared understanding of (a) why the four scientific roles are required to support flow management; (b) how they can complement each other to meet scientific objectives around reducing uncertainty, reporting, and supporting decisions. Managers and scientists have all become very familiar with diagrams depicting adaptive management as a cycle of making a decision, implementing some management action, monitoring and evaluating the response, updating our knowledge, and repeating the process. This simplistic interpretation of adaptive management may have contributed to a perception that scientists have only a limited role to play in flows management. Within such graphical depictions, for example, monitoring and evaluation appears to be the only role for scientists, and the only means of reducing uncertainty. Arguably, many water management agencies now view the primary role of scientists as designing and executing monitoring projects. This is reflected in the distribution of funding within Australia, where almost all funding for science to support flows management gets channelled into monitoring, often producing very poor returns on investment (see 'Barriers within each role', below).

We suggest developing a science investment strategy according to the following three principles:

First, the strategy must be developed at the basin-scale. As previously discussed, a basin-scale strategy is required to avoid *ad hoc* investment and have science adequately supporting flows management at the relevant spatial and temporal scales. The strategy should consider the specific management decisions that need to be made at the various spatial and temporal scales.

Second, the strategy must be developed by a consortium of scientists and managers across the relevant jurisdictional scales to ensure that science investments remain aligned with the specific needs and constraints of water managers.

Third, the strategy must recognise the need to build and maintain capacity within the four roles. The scientific skills required to successfully fulfil the four roles presented herein are in short supply. This is particularly true for modelling and decision science (Gregory *et al.* 2006). We must not assume that the technical skills required to fulfil all roles can be accessed and then stored in an *ad hoc* fashion, so the strategy should be developed to build and nurture technical capacity for all four roles.

Barriers to monitoring and evaluation

Our experiences lead us to suggest that poor practice in design and implementation is the major barrier to effective flow monitoring and evaluation projects (Souchon *et al.* 2008). Poor practice extends well beyond riverine programs, with ecological monitoring programs often delivering low returns per unit investment (Lindenmayer & Likens 2010; Lovett *et al.* 2007; McDonald-Madden *et al.* 2010; Nichols & Williams 2006). Both long- and short-term monitoring projects have a place in reducing uncertainty. However, as described earlier (Role 1: Monitoring and evaluation), they have different uses. Monitoring projects should have clearly articulated goals that state the assumed conceptual model and whether they aim to resolve structural uncertainty (i.e. short term monitoring may be appropriate) or to improve parameter estimates (i.e. long term monitoring may be appropriate).

We offer six guidelines for effective monitoring and evaluation in Table 3. Examination of those guidelines reveals effective and efficient monitoring and evaluation of flows cannot occur without strong scientific involvement—from design, through to implementation, analysis and communication of outcomes—as well as strong partnerships between scientists and managers.

Table 3. Six guidelines for effective monitoring and evaluation of flows, based on a synthesis of the recommendations of Lovett et al. (2007), Nichols and Williams (2006), Walters (1997) and Lindenmayer and Likens (2009, 2010), as well as our own experience with design and implementation of such projects in the Murray-Darling Basin.

1. Set clear monitoring objectives that explicitly guide sampling design, in light of: • *Management objectives and decision options*. By designing a monitoring program around management objectives and decisions, we give ourselves the best chance of ensuring the monitoring project facilitates robust reporting of outcomes to stakeholder groups, and reducing uncertainty about ecological responses to the management decisions being made. • *Theoretical/conceptual frameworks*. Reference to the latest theory may be a means to at least three ends: (1) compelling research questions, hence improved advocacy from scientific stakeholders; (2) improved efficiency at the design phase of a monitoring project (e.g. why develop numerous conceptual models to guide specific questions/hypotheses if there are peer-reviewed, published frameworks that already fulfil the purpose?); (3) more efficient reduction in structural uncertainty, through ensuring research questions are novel and extend our understanding. • *Spatial and temporal scale of response*. Water managers and scientists must have a shared understanding of the likely spatial and temporal scales of response expected from each indicator. If managers and scientists share this understanding, they will then share expectations concerning, for example, the challenges of linking flow decisions and outcomes at large spatial scales, and the time required to report against certain management objectives associated with ‘slow’ ecological response variables. • *A clear plan for outputs and analysis*. Is the aim to output new knowledge within published papers and reports, or to estimate parameters of models that facilitate analysis and forecasting? (Arguably, a good monitoring project would do both.) The sampling/experimental design must be developed in light of the data requirements (including precision and accuracy) and assumptions of the models they are intended for. Consideration may need to be given to the problem of inference in unreplicated, perturbation studies.
2. Involve key stakeholders in the setting of objectives, at project inception. Prior to development of the monitoring and evaluation plan, stakeholders that can significantly influence the success of the plan must be involved. Failure to do so can greatly erode the quality and success of monitoring and evaluation.
3. Carefully consider the human and financial resources required to meet monitoring objectives. Set monitoring and evaluation objectives in light of financial constraints. Don’t spread financial resources too thinly by trying to monitor too much. Factor in the full cost of meeting all monitoring and evaluation objectives, including data management, frequent expert analysis of ecological dynamics, and communication of results to stakeholders; often projects allocate insufficient funds to the ‘evaluation’ half of monitoring and evaluation. Given the nature of monitoring objectives, long-term (>10 y) funding—hence very strong science-management partnerships—is usually required to meet objectives.
4. Include peer review. For quality assurance, the monitoring plan should be subject to expert review, before it is implemented.
5. Implement adaptive monitoring. Regularly check whether the data are suitable for their intended purpose, particularly early in the project’s development. Make adjustments to sampling methods if necessary, without compromising ability to meet core evaluation objectives of the project in the long-term. If, through hypothesis-testing, certain aspects of structural uncertainty are sufficiently reduced, then certain components of the monitoring project can be changed to tackle other aspects of structural uncertainty. Keep the monitoring interesting and relevant to scientific and management stakeholder groups.
6. Regularly analyse data and communicate results. Long periods of data collection without analysis and communication of results erodes the confidence of stakeholders in the project. Maintain data integrity and accessibility,

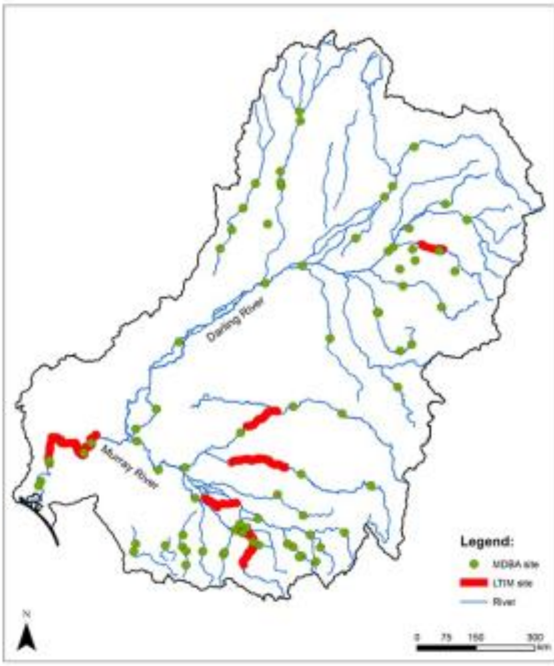
and annually analyse and present research findings to (a) increase the visibility and (b) demonstrate the utility of the monitoring project to stakeholders.

In addition to barriers to *efficacy*, a major barrier to *efficiency* is poor coordination of multiple monitoring projects across jurisdictional (e.g. international, federal, state, and regional agencies), spatial and temporal scales. Within Australia we see a proliferation of flow monitoring projects conducted over various spatial and temporal scales that, on their own, yield little in terms of scientifically-defensible reporting of flow outcomes and reduction of uncertainty. While they may add little value on their own, together they comprise enormous investment and, if strategically and scientifically coordinated, could yield far higher return on investment. If further monitoring projects are deemed necessary, they absolutely must be designed with a clear vision for how they complement existing monitoring and research activities. How will the data obtained with one monitoring project be combined with that of another, such that genuine synergies arise in robust reporting and reduced uncertainty? Lindenmayer and Likens (2010) suggested that integration of knowledge from different monitoring projects is one of the greatest challenges facing scientific monitoring and evaluation. A concrete example of complementarity in multi-scale fish monitoring projects is provided in Box 3.

Box 3. Complementary monitoring programs support basin-scale evaluation of flows

The Australian Commonwealth has recently implemented its Long-Term Intervention Monitoring (LTIM) program. The fish component of this program has the broad objective of evaluating short- (e.g. spawning) and long-term (population increase) response to managed and natural flows at multiple spatial scales, from river segments to the basin-scale. To meet this objective, targeted, intensive data collection was required to reduce statistical and structural uncertainty. Financial constraints meant LTIM had to trade-off spatial coverage of sites for data quality. LTIM fish monitoring now occurs at six long river segments of the Murray-Darling Basin (red segments, right). In turn, this increased the challenge of evaluating flow outcomes in catchments that were unmonitored.

The solution was to have the specific objective of estimating model parameters within the six LTIM sites, such that we may use predictive inference of fish outcomes in unmonitored catchments with good hydrology data (see 'Modelling for spatial and temporal projections'). However, doing so would be difficult without having data on the boundary conditions of the fish populations in those unmonitored catchments. For that we rely on a separate basin-scale monitoring program (MDB Fish Survey) that has the opposite approach of LTIM; broader coverage of sites (green dots, right) where data collection at each site is far less intense, and documents species present and their coarse relative abundances.



Barriers to modelling

As has long been recognised, arguably the greatest impediment to the parameterisation of models for effective ecological forecasting is the absence of appropriate data (Honrado *et al.* 2016; Shea 1998; Walters 1997; Wolkovich *et al.* 2014). Quality, long-term time series are essential for estimating model parameters. The required frequency and duration of measurements will depend on the ecological indicators being modelled, but for certain indicators (e.g. long-lived fish populations) annual censuses over 20 years or more may be required to reduce statistical uncertainty to desirable levels (Walters 1997). Long-term monitoring programs provide the data required to improve our capacity to forecast outcomes and anticipate change. Importantly, the presence of uncertainty should not stop model parameterisation and use in adaptive management while data is collected (Clark *et al.* 2001).

Barriers to fundamental research

Funding is often allocated to fundamental research by water managers following a crisis, with the research aimed at reducing uncertainty around what caused the crisis. Specific examples include floodplain acidification (Baldwin & Fraser 2009) and hypoxic blackwater flows (Whitworth *et al.* 2012) following extreme water diversion. A smarter approach to investment would be to use existing knowledge and models to anticipate possible threats, then prioritise fundamental research accordingly. This should be part of the basin-scale strategy such that we obtain knowledge to avoid crises, rather than achieving a *post-hoc* understanding of how they occurred.

Barriers to decision science

Obtaining the efficacy and efficiency benefits that come with employing decision science, requires cultural change in both science and management. Scientists need to shift their focus towards building stronger partnerships with managers such that the decision problems they face are better understood. This may take significant time away from other, more traditional performance indicators that scientists aim for, and so institutional change in reward systems may also be required.

Decision science is most effective when objectives are clearly expressed, quantitative and time-bound. Perhaps surprisingly, few agencies achieve this in their management plans. Part of the controversy (and arguably the success) of the Basin Plan is that it sets specific flow regimes and outlines relatively clear objectives, making it enforceable and allowing decision-makers to track success. However in many other ecological systems, there may be an aversion to committing to specific targets in case they are not achieved, despite the fact that all ecological systems are subject to many sources of uncertainty. This fear of 'failure' can undermine the ability of decision science to report on success and, more importantly, can obfuscate learnings because of imprecise goals. Management agencies that set clear priorities and embrace a culture of learning will stand to gain the most from decision science.

Different management agencies, at different jurisdictional scales, often have their own conventions when it comes to how science is brought to bear on flow decisions. Burgman (2005) notes that the approach to making decisions in the face of uncertainty should be determined by data, questions and analytical needs, not by professional convention. Accordingly, if we are to align decision-making processes with best-practice, then greater consistency of process across jurisdictions must be achieved, and those consistent processes have been provided by decision scientists (Conroy & Petersen 2013; Gregory *et al.* 2012).

Conclusion

The last two decades were a transformational period in riverine flow ecology and management (Arthington 2012). In writing this document we have taken a step back from our usual scientific tasks and asked: how does science need to operate if it is to best support riverine flow management? We have mapped out the four major roles that must be fulfilled, and identified some major impediments—and solutions—to progress. Given that the competition for riverine flows is increasing (Vorosmarty *et al.* 2000), the next two decades will place even greater demands on the skills of scientists and managers, and the strength of their collaborations. Scientists and managers must quickly strengthen partnerships at multiple scales to develop wise science investment strategies, so that we can effectively and efficiently maintain our socio-political license to operate, reduce uncertainty, and transform knowledge into smart flow decisions.

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