Environmental Flows Monitoring and Assessment Framework

Version 1.1

P. Cottingham
CRC for Freshwater Ecology, Victoria

G. Quinn
Monash University, Victoria
(Now at Deakin University, Victoria)

A. King
Department of Sustainability and Environment, Victoria

R. Norris
University of Canberra

B. Chessman
Department of Infrastructure, Planning and Natural Resources, NSW

C. Marshall
Department of Natural Resources and Mines, Qld

The Cooperative Research Centre for Freshwater Ecology is a national research centre specialising in river and wetland ecology. The CRC for Freshwater Ecology provides the ecological knowledge needed to help manage rivers in a sustainable way. The CRC was established in 1993 under the Australian Government's Cooperative Research Centre Programme and is a joint venture between:

ACTEW Corporation
CSIRO Land and Water
Department of Environment and Conservation, NSW
Department of Infrastructure, Planning and Natural Resources, NSW
Department of Natural Resources and Mines, Queensland
Department of Sustainability and Environment, Victoria
Department of Water, Land and Biodiversity Conservation, South Australia
Environment ACT
Environment Protection Authority, Victoria
Goulburn-Murray Water
Griffith University
La Trobe University
Lower Murray Urban and Rural Water Authority
Melbourne Water
Monash University
Murray-Darling Basin Commission
Sydney Catchment Authority
The University of Adelaide
University of Canberra

Please cite this report as:

Cottingham P., Quinn G., Norris R., King A., Chessman B. and Marshall C. (2005). *Environmental Flows Monitoring and Assessment Framework*. Technical report. CRC for Freshwater Ecology, Canberra.

ISBN 0-9751642-05

Cover photographs courtesy of Robert Ashdown (floodplain near Cooper Creek),
John Hawking (*Philopotamidae*) and Murray-Darling Freshwater Research Centre

Further copies are available from:
CRC for Freshwater Ecology
Tel: 02 6201 5168
Fax: 02 6201 5038
Email: pa@freshwater.canberra.edu.au
Web: http://freshwater.canberra.edu.au

Design and typesetting: TechType, Giralang ACT
Printing: Elect Printing, Fyshwick ACT

Table of Contents

Appendices

Boxes

Preface

The Cooperative Research Centre for Freshwater Ecology currently has research programs on:

1. flow-related ecological processes
2. restoration ecology
3. conservation ecology
4. water quality and ecological assessment.

These programs are anticipated to provide valuable new information on environmental watering requirements of river systems and on assessing the performance of environmental flow regimes, whether for the protection or the rehabilitation of river systems.

This report is intended to be a ‘live’ document, because it will be updated as new insights emerge on environmental flows and how to measure their performance.

Acknowledgement

Thank you to everyone who contributed to this report by attending workshops and commenting on drafts.

1. Monitoring and assessment of environmental flows

Environmental flow or streamflow management plans to meet environmental water requirements have been prepared for many regulated and unregulated streams across Australia. The emphasis of these plans has been to maintain or protect environmental or ecological values by ensuring sufficient water is available (e.g. by restrictions on diversions) for plant and animal communities or ecosystem functions to remain viable, or by returning water to flow-stressed streams as a rehabilitation measure (see Box 1, page 2). The implementation of the flow regimes recommended by these plans can represent a large investment in river protection and rehabilitation. Increasingly, stakeholders with an interest in water resource management will expect to see evidence of the environmental or ecological response of rivers to environmental flow regimes. Monitoring and assessment is therefore essential if we are to confirm and understand how environmental flows result in the predicted outcomes, and apply any lessons learnt to future management.

Environmental flows may focus on changes to the whole flow regime (e.g. changes to mean annual flow), on specific short-term events (e.g. targeted pulses) or both, or on the protection of components of the flow regime critical to the protection of ecological ‘assets’ — species, communities or ecological functions that have environmental values that are to be protected. As there are likely to be multiple drivers (i.e. factors other than modification to the flow regime) of river condition for most systems, other complementary management actions (e.g. provision of passage past barriers to migration, improved water quality, protection or reintroduction of physical habitat) may also be required if the anticipated ecological responses to environmental flows are to occur.

Monitoring and assessment is a major component of an adaptive management cycle (e.g. IEPEF 2002, Bosch et al. 2004), which includes steps such as the:

- establishment of management objectives
- review of resource condition
- formulation of management questions (hypotheses) to be tested
- implementation of management actions
- monitoring and assessment of collected information
- review of management objectives and whether they have been met, and revision of management objectives and actions in the light of new evidence.

The scope and goals of a monitoring and assessment program are best considered from the outset of an environmental flow project. This will help to ensure that the program is aligned with the ecological objectives of the environmental flow regime and can be included in management planning.

1.1. Key steps of the monitoring and assessment framework

This framework has been produced as a guide for water and catchment management agencies and authorities with responsibility for delivering and assessing the effectiveness of specific environmental flow regimes. The framework also serves as a checklist for scientists involved with designing and implementing monitoring programs. The framework focuses on assessments of particular environmental flow projects and can be applied to assess the ecological responses resulting from:

- releases of water from a storage such as a reservoir (regulated rivers),
- modified water extraction directly from a river (regulated and unregulated rivers),
- water allocation to specific sections of a system (e.g. allocation of water to icon sites in the Living Murray).

Box 1. Environmental flows and river management

The following definition has been adopted for this framework:

> *An environmental flow results from a management intervention that protects or modifies the flow regime of a river to achieve an ecological or environmental outcome.*

Such a definition can be applied equally to unregulated and regulated rivers.

In many instances, meeting a stream's environmental water requirements means the protection of existing components of the flow regime that are ecologically important. In unregulated streams, for example, this may be to ensure sufficient water remains in a stream so that critical habitat remains for biota during periods of low or zero flow, or to protect flow pulses that provide important biological cues. In such situations, limits may be applied to the volume or timing of water that can be diverted from a stream.

In regulated streams, environmental flows are usually designed to return some aspect of the volume, timing or frequency of flow components that may have been lost or modified by the presence of dams, weirs and associated infrastructure. Manipulating the flow regime to achieve an 'ecological or environmental outcome' means that environmental flows can be considered as a rehabilitation measure, guided by the science of restoration ecology (e.g. Lake 2001, Palmer et al. 1997, Bradshaw 1996). River rehabilitation implies the return of attributes such as community structure (e.g. fish or macroinvertebrate populations) or function of the original (e.g. production, respiration, nutrient cycling) but without a complete return to pre-disturbance condition (Figure 1). In many instances, factors such as widespread change to land-use or water management will mean that rehabilitation will not be possible. Environmental flows may then serve as a form of remediation where the stream moves to some state that represents a 'new' ecosystem.

A good conceptual understanding of how a river may recover from disturbance (in this case changes to the flow regime) is important to any monitoring and assessment framework. For example, there may be time lags before recovery becomes evident, the system may not respond as desired and progress to some alternative state, or may be unstable (Bradshaw 1996, Lake 2001). Monitoring and assessment programs have to account for such possibilities in order to answer questions such as 'What was done?' 'Did it work?' 'Why did it work or not work?' and 'Will it work in other situations?' (Michener 1997).

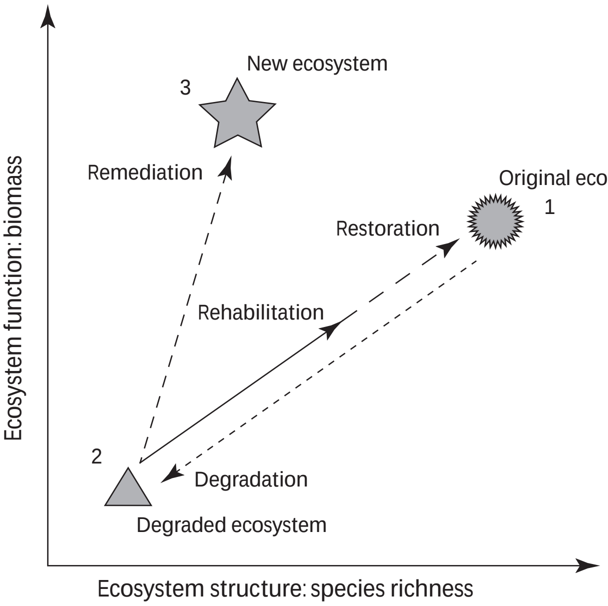


Figure 1. Potential ecosystem response to disturbance (from Bradshaw 1996). Note that rehabilitation targets will be less than full restoration of the original condition.

This framework:

- assumes that development of environmental flow recommendations has isolated the role of the flow regime in maintaining or improving river condition and considered other appropriate non-flow management actions;
- focuses predominantly on situations where (i) maintenance of flow or water levels is required as an ecosystem protection measure, and (ii) changes to the flow regime are required as a rehabilitation measure (although assessing the impact of further water resource development is not excluded);
- considers aspects of condition assessment, compliance monitoring and causal links (dose–response);
- considers the need to detect if there has been a response to the intervention (i.e. the direction of the response — e.g. increased or decreased abundance of biota) and the level of the effect (i.e. the strength of the response);
- recognises that stakeholder input will be required, particularly on agreeing on the size of the ecological or environmental response that will be the basis of an assessment program.

This monitoring and assessment framework is based on the following key steps:

1. Define the scope of the program and its objectives
2. Define the conceptual understanding of flow–ecology relationships and the questions (hypotheses) to be tested
3. Select variables to be monitored
4. Determine the study design, accounting for the specific activities and location
5. Optimise the study design and identify how data are to be analysed
6. Implement the study design
7. Assess whether the environmental flows have met the specific objectives and review the conceptual understanding and hypotheses.

The framework is consistent with approaches recommended by the *Australian Guidelines for Water Quality Monitoring and Reporting* (ANZECC & ARMCANZ 2000), and the steps recommended by Downes et al. (2002). The framework also responds to the recommendation of King et al. (2003), who argued that '*a consistent and rigorous approach to the design of monitoring would result in greater confidence about links between ecological response and flow change*.' The key steps of the framework are summarised in Figure 2 and explained in the following sections.

1.2. Define the scope of the monitoring and assessment program and its objectives

It is important to reflect on the objectives or outcomes that are the basis of the environmental flow recommendations for a river system and the objectives that are set for a monitoring and assessment program. Monitoring and assessment programs are most effective and informative when designed to answer clear and precise management and scientific questions.

This framework assumes that the relationship between flow regime and river condition has been examined in arriving at environmental flow recommendations and that the need to protect or modify the flow regime has been established (see Box 2). This step is thus one of revisiting or restating the existing objectives and of defining those objectives that will form the basis of the monitoring and assessment program.

Often, an environmental flow regime for a river is presented as a package of recommendations related to various flow components, such as low flows, bank-full flows, flow pulses, overbank flows and rates of rise and fall (e.g. DNRE 2002). Each recommendation should be related to an environmental or ecological objective or outcome.

Box 2. Environmental flow objectives

Most environmental flow studies make clear statements on the timing, duration and magnitude of flow events predicted to achieve some desired outcome or condition (see Table 1). Environmental flow objectives that describe specific elements are preferred to broader statements of outcome such as '… improved river health', which can be difficult to define.

A challenge is then to move from stated objectives to the quantifiable targets that are the basis of a monitoring and assessment program. Developing quantifiable targets requires consideration of appropriate variables to measure, and of the amount of evidence (effect size) needed to convince stakeholders that the environmental flows had the desired outcome. These issues will be considered in greater detail later in the framework.

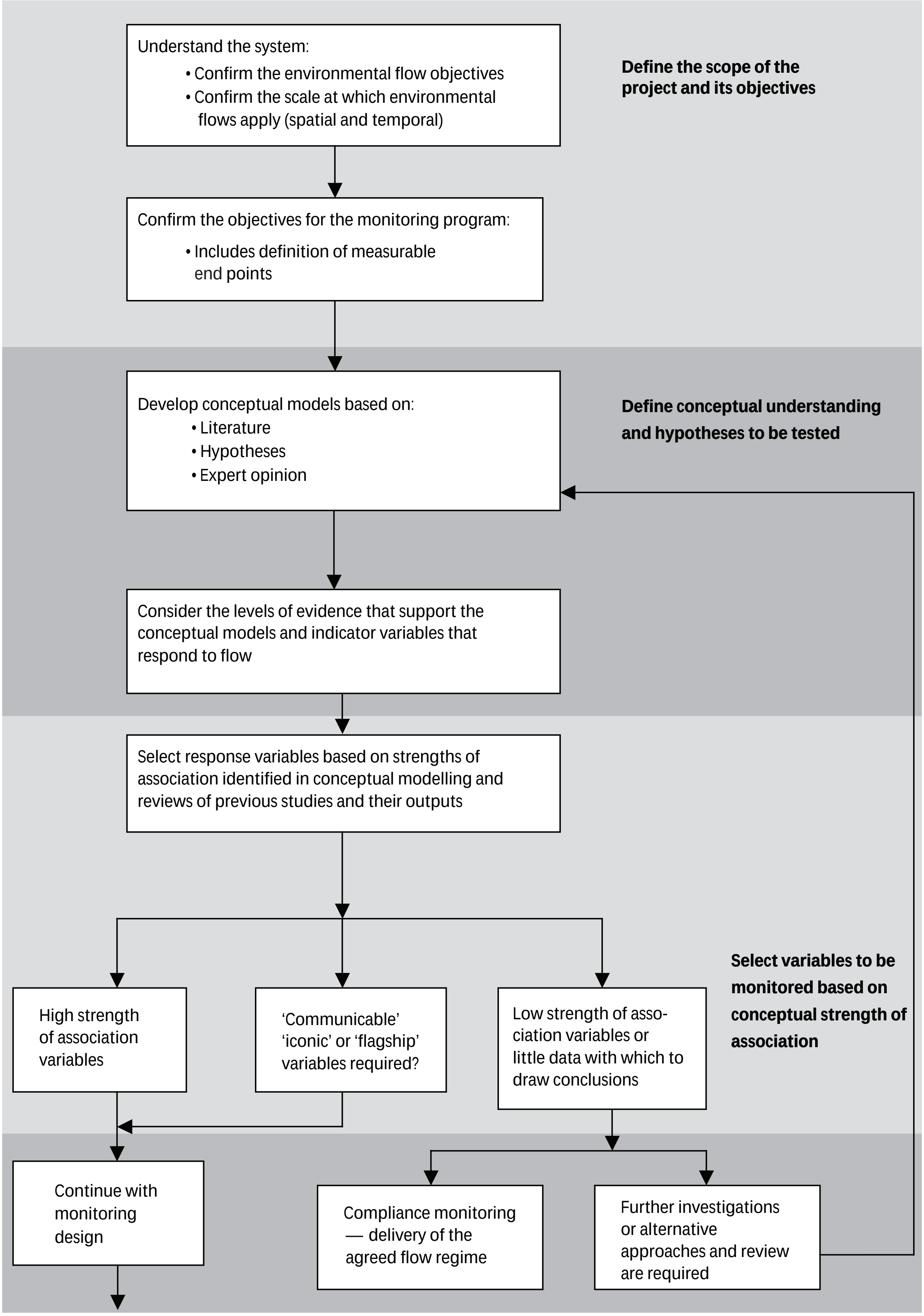
Heron et al. (2002) proposed that environmental flow objectives should contain five distinct elements, which provide a useful checklist when integrating monitoring and assessment within an adaptive management cycle:

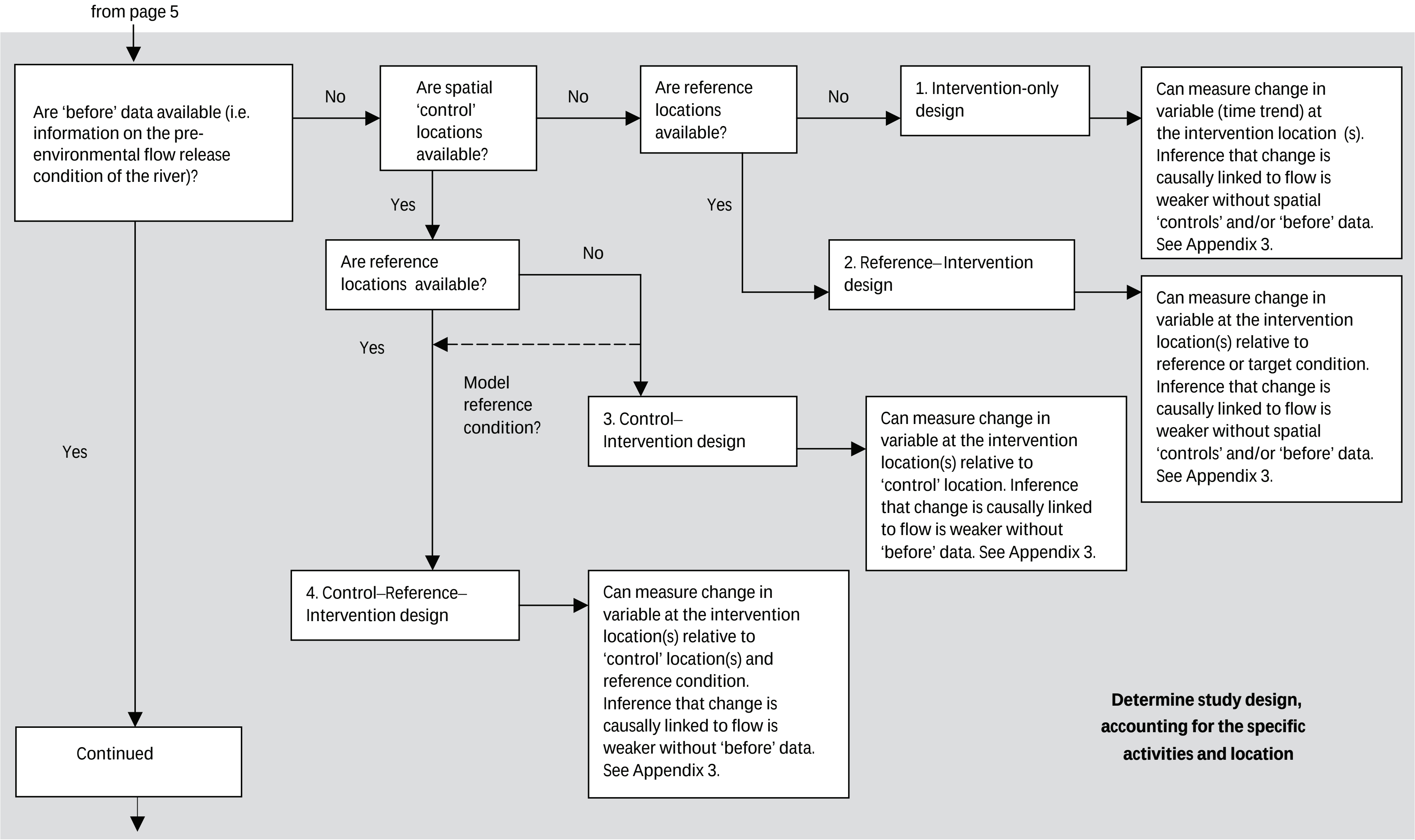
1. the component of the environment that is addressed (e.g. individual species, communities, process)
2. the 'event' that needs to be protected (e.g. fish spawning, fish migration, community diversity)
3. the target. This is essentially the purpose or aim of the objective. It may be a value that the event should reach, or how far it may deviate from natural, or some target compared to the current condition .
4. the 'Success Criteria', detailing what conditions need to be achieved to ensure that the objective is met. The success criteria always relate directly to the 'event'.
5. the 'Measure of Success', or the variable that needs to be measured, and what value it must attain. Often, the Success Criteria cannot be easily measured directly, so the Measure may be some other factor that can be used as a surrogate.

Table 1. Example objectives and environmental flow recommendations for the Wimmera River, Reach 2 (Huddleston-McKenzie River); Compliance point = Faux Bridge, Gauge no. 415240 (SKM 2002)

	Flow			Objective/Rationale
Season	Magnitude	Frequency	Duration	
Summer	0 ML/d	Annually	17–30 days	Natural stress to promote macroinvertebrate biodiversity
	Minimum flow 6 ML/d	Annually	Dec–May	Maintain quality and quantity of habitat for native fish, macroinvertebrates and aquatic vegetation
	>16 ML/d	3 annually	7–15 days	Enhance recruitment of short-finned eels and river blackfish
Spring (Jul–Nov)	>164 ML/d	2–3 annually	Minimum 14 days	Maintain riparian vegetation and habitat for native bird species
	Minimum flow 60 ML/d	Annually	July–Nov	Inundate snags and other elements that provide habitat for native fish, macroinvertebrates and aquatic vegetation, and maintain longitudinal connectivity
Annual	6,000 ML/d	Annual	Minimum 2 days	Provide high flows to cue and enhance recruitment of golden perch, Murray cod and Macquarie perch, maintain riparian vegetation and habitat for native bird species and facilitate channel-forming processes.

Figure 2. Generic environmental flow monitoring framework — summary outline. Note that variables to be measured will be those hypothesised to respond to flow change.





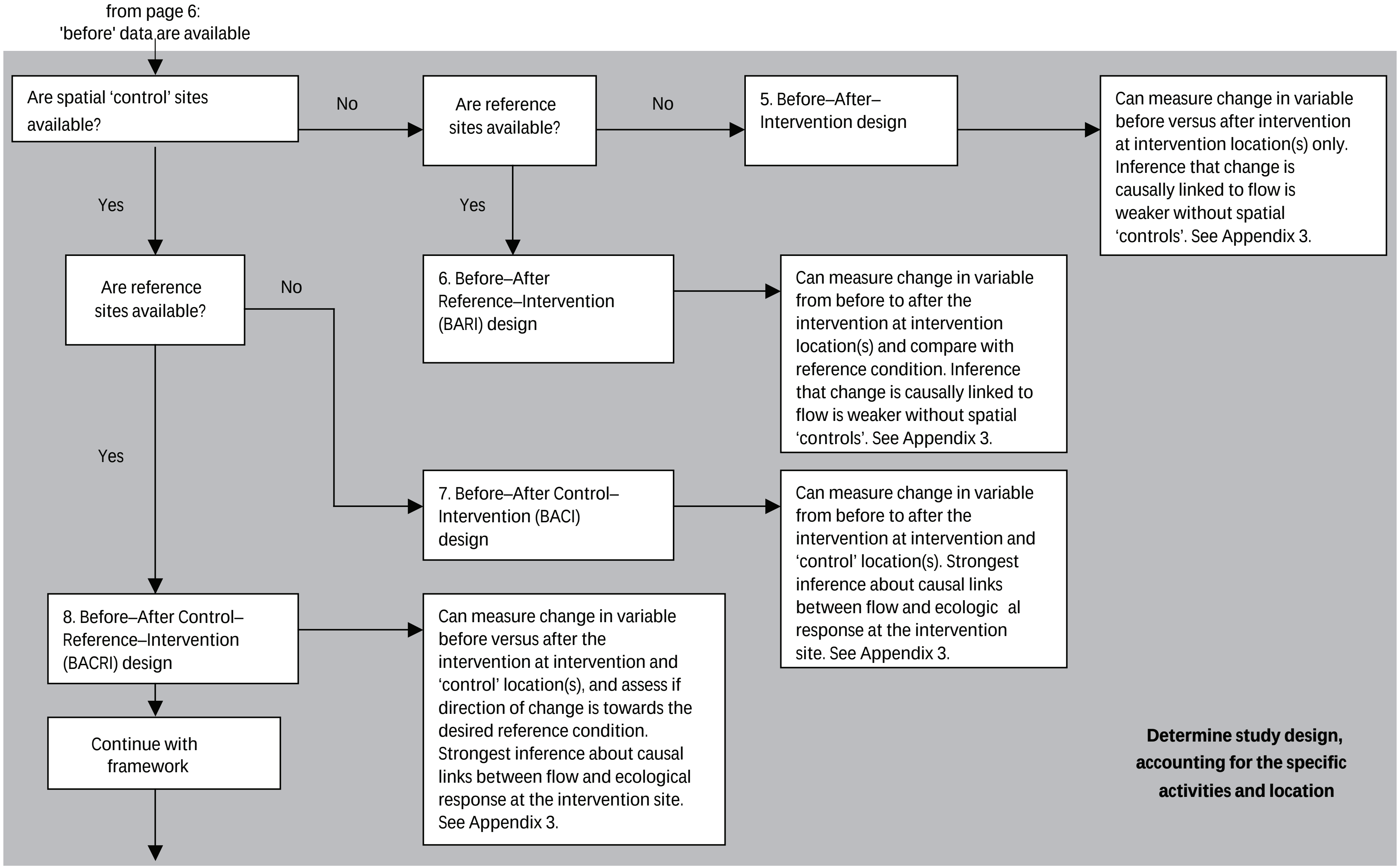
Can measure change in variable (time trend) at the intervention location (s). Inference that change is causally linked to flow is weaker without spatial 'controls' and/or 'before' data. See Appendix 3.

Can measure change in variable at the intervention location(s) relative to reference or target condition. Inference that change is causally linked to flow is weaker without spatial 'controls' and/or 'before' data. See Appendix 3.

Can measure change in variable at the intervention location(s) relative to 'control' location. Inference that change is causally linked to flow is weaker without 'before' data. See Appendix 3.

Can measure change in variable at the intervention location(s) relative to 'control' location(s) and reference condition. Inference that change is causally linked to flow is weaker without 'before' data. See Appendix 3.

Determine study design, accounting for the specific activities and location



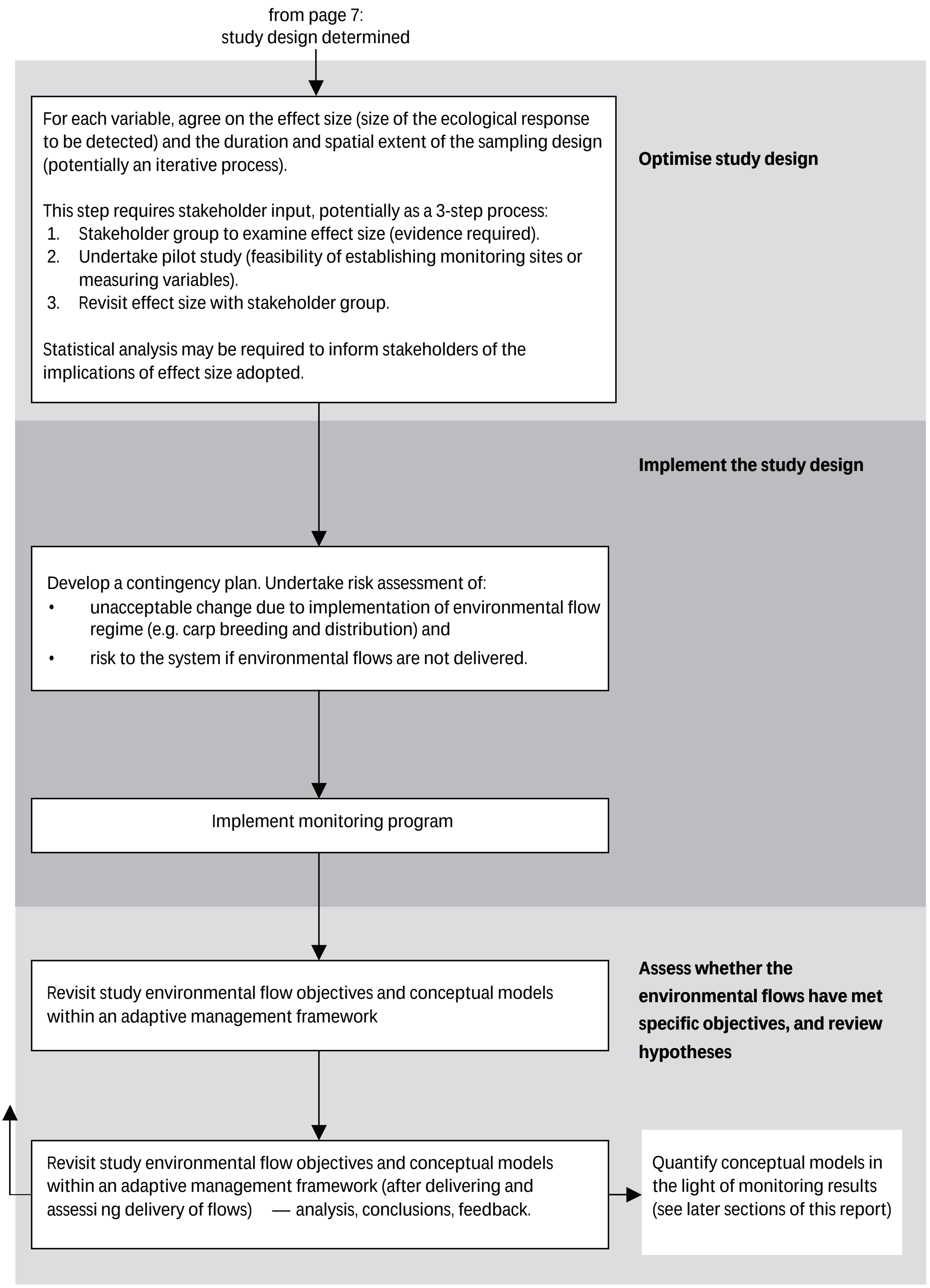
Can measure change in variable before versus after intervention at intervention location(s) only. Inference that change is causally linked to flow is weaker without spatial ‘controls’. See Appendix 3.

Can measure change in variable from before to after the intervention at intervention location(s) and compare with reference condition. Inference that change is causally linked to flow is weaker without spatial ‘controls’. See Appendix 3.

Can measure change in variable from before to after the intervention at intervention and ‘control’ location(s). Strongest inference about causal links between flow and ecological response at the intervention site. See Appendix 3.

Can measure change in variable before versus after the intervention at intervention and ‘control’ location(s), and assess if direction of change is towards the desired reference condition. Strongest inference about causal links between flow and ecological response at the intervention site. See Appendix 3.

Determine study design, accounting for the specific activities and location



from page 7:
study design determined

For each variable, agree on the effect size (size of the ecological response to be detected) and the duration and spatial extent of the sampling design (potentially an iterative process).

This step requires stakeholder input, potentially as a 3-step process:

1. Stakeholder group to examine effect size (evidence required).
2. Undertake pilot study (feasibility of establishing monitoring sites or measuring variables).
3. Revisit effect size with stakeholder group.

Statistical analysis may be required to inform stakeholders of the implications of effect size adopted.

Optimise study design

Implement the study design

Develop a contingency plan. Undertake risk assessment of:

- unacceptable change due to implementation of environmental flow regime (e.g. carp breeding and distribution) and
- risk to the system if environmental flows are not delivered.

Implement monitoring program

Revisit study environmental flow objectives and conceptual models within an adaptive management framework

Assess whether the environmental flows have met specific objectives, and review hypotheses

Revisit study environmental flow objectives and conceptual models within an adaptive management framework (after delivering and assessing delivery of flows) — analysis, conclusions, feedback.

Quantify conceptual models in the light of monitoring results (see later sections of this report)

These can include geomorphology and water quality attributes if linked conceptually to the interaction of organisms with their environment. The temporal and spatial scale at which the objective or outcome will apply is likely to vary, depending on the nature of the flow component and the biota or ecological processes that are predicted to respond. A package of environmental flow recommendations may represent a large change to the management of a river system, and the water that may be available for consumptive or agricultural purposes. Some recommendations may be implemented quickly (e.g. those that pose little risk to the security of urban or agricultural supply), while other recommendations may not be delivered for some time (e.g. while environmental water rights are secured, or if environmental flow releases pose a high risk to infrastructure), if at all. Confirming which environmental flow recommendations are to be delivered and their spatial and temporal bounds is an important consideration, as it influences the scope and realism of the monitoring program objectives.

1.3. Define the conceptual understanding of flow–ecology relationships and the questions (hypotheses) to be tested

Conceptual models are useful tools for explicitly defining interactions in a river system, in this case the relationship between the flow regime and potential ecological responses. The models can be used to:

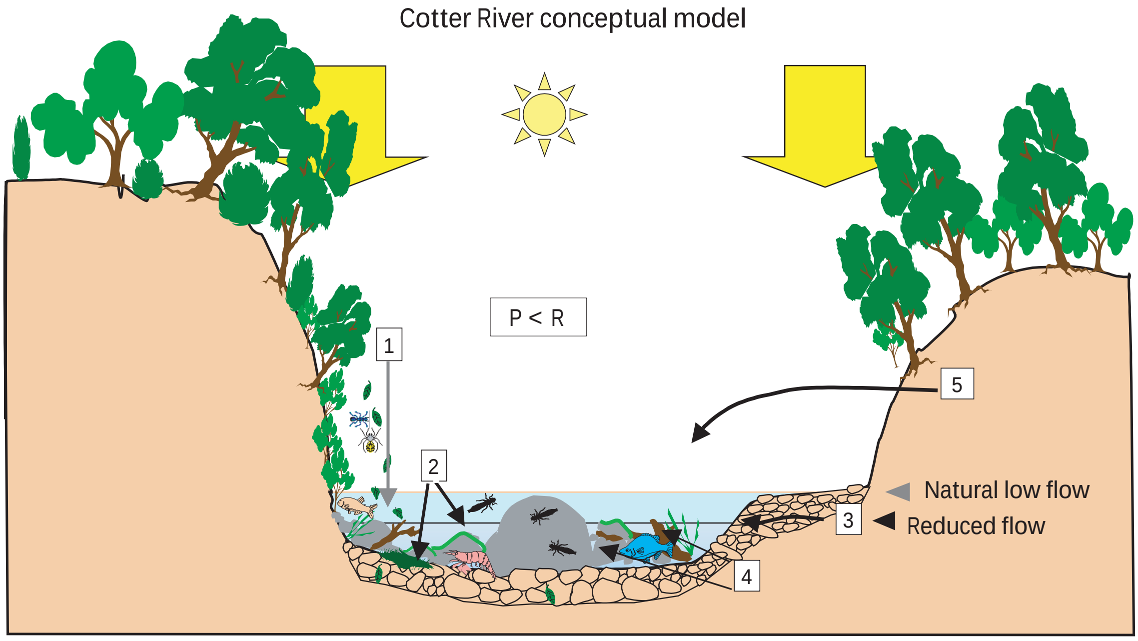
- highlight the relationships between biota and the physical and chemical environment,
- show how a river might respond to disturbances or events such as altered flow regimes,
- provide the basis for hypotheses that can be tested in a monitoring and assessment program.

Ideally, the relevant conceptual models that were the basis for setting environmental flow objectives will also provide the basis from which to design a monitoring and assessment program.

Conceptual models are best developed from a broad knowledge base of the study region including biological, chemical, hydrological, geological and geomorphological attributes. This can include knowledge extrapolated from similar systems, the scientific literature, general hypotheses and models relevant to that type of river system, such as the Flood Pulse Concept (Junk et al. 1989), and considerations from experienced scientists and managers, such as those appointed to ‘scientific panels’ (Cottingham et al. 2002). The different components and links in a model are likely to have varying levels of uncertainty. However, a review of environmental flow monitoring programs (King et al. 2003) found that the underlying assumptions and uncertainty associated with conceptual models are rarely stated explicitly. The level of uncertainty and the temporal scale of predicted ecological responses to changes in the flow regime are important considerations for a monitoring and assessment program.

Figure 3 is an example of a conceptual model that can be used to develop hypotheses to be tested by a monitoring and assessment project. For example, the model suggests that decreased low flows and a reduced frequency of flushing have led to an increased retention of nutrients and fine sediment, resulting in conditions favourable for the growth of filamentous algae and biofilm that is unpalatable for macroinvertebrates, increased armouring of the stream bed and a reduction in habitat availability and quality for macroinvertebrates and small fish. A set of environmental flow hypotheses might then be that:

> *a flow pulse (e.g. equivalent to bankfull discharge) with a duration of 3–4 days will*
>
> - *mobilise and flush fine sediments from the bed substrate,*



1. Riparian vegetation encroaches into the channel and reduces channel capacity. 2. Unpalatable filamentous algae accumulate. 3. Reduced flow results in armouring, reduced flushing of detritus, nutrients, fine sediment. 4. Habitat space for macroinvertebrates and fish in the substratum is reduced because of armouring and infilling with fine sediments. Also, some parts of the bottom may be exposed. 5. Sediment and organic matter may enter the channel directly from adjacent valley slopes and may not be flushed by low flows in the main channel.

Figure 3. Ecological responses expected when flow is reduced in the Cotter River, Australian Capital Territory (R. Norris, CRCFE, pers. comm.).

- *scour filamentous algae and biofilm from the bed,*
- *increase habitat diversity and availability and, ultimately, increase macroinvertebrate and fish diversity and abundance.*

Such hypotheses are an important basis for the selection of variables to be measured as part of the monitoring and assessment program, in this case suggesting that flow, sediment grain size, filamentous algae and biofilm cover, macroinvertebrate and fish communities should all be measured.

1.4. Select the variables to be monitored

The selection of appropriate variables is a very important component of monitoring and assessment program design. Factors to consider when selecting variables include:

- the specific environmental flow objectives and hypotheses to be explored by the monitoring and assessment program,
- the degree of confidence that changes in a variable imply that there are causal links between flow changes and environmental or ecological response,
- information that may be required to assess and manage risks to the system (e.g. if the system does not receive the required environmental flows, or if the environmental flows result in some undesirable outcome),
- information to assist communication and foster community engagement (e.g. icon species).

There is an enormous amount of literature on potential variables of a wide range of different stressors in river systems (Downes et al. 2002). Watts et al. (2001) used an extensive range of criteria to select which variables would be used when studying environmental flows in the Murrumbidgee River, including:

- responsive to changes in flow at spatial and temporal scales relevant to river management,
- responsive within the timeframe of the project,
- have scientific justification,
- represent important structural and/or functional component of the riverine ecosystem,
- easily measured and quantitative,
- responses easy to interpret,
- can determine and measure directions of change,
- respond differently to background variability,
- cost-effectiveness,
- relevant to policy and management needs,
- cover a range of habitats and trophic levels, several measures of biodiversity, a range of organisational levels and a range of spatial and temporal scales.

King et al. (2003) examined the variables used in existing environmental flow monitoring programs in Australia. They found that only some of these variables have as yet been causally linked to changes in flow regime and respond in a predictable manner (Table 2). New variables, with direct and predictable responses to flows, will no doubt emerge in time and monitoring programs should be flexible so that new variables can be incorporated as our understanding of relationships between flow change and ecological responses improves.

This framework does not include instruction on how to measure selected variables and manage the data collected. Guidance on these and other related issues can be obtained from resources such as the *Australian Guidelines for Water Quality Monitoring and Reporting* (ANZECC & ARMCANZ 2000) and *Recommended Methods for Monitoring Floodplains and Wetlands* (Baldwin et al. 2004). These references contain detailed descriptions of water quality and biological measures, including information on the spatial scale at which to monitor. Importantly, a quality assurance/quality control (QA/QC) program is recommended as an essential step in collecting high quality and reliable data.

1.5. Determine the study design

This framework assumes that we are interested in establishing causal links between environmental flows and ecological responses in a specific river system. The term ‘location’ is used to represent a section of river that is the target of environmental flow recommendations. A ‘location’ may be a whole stream, a reach or a localised pool–riffle sequence or wetland. The spatial scale of a ‘location’ will be determined by the environmental flow objectives. The term ‘intervention’ is used to describe the environmental flow regime.

Australian rivers are often highly variable in nature, in terms of both hydrology and ecological response (Puckridge et al. 1998). Separating changes in ecological condition due to environmental flows from other natural or human induced variability requires an understanding of conditions both before and after environmental flows are delivered. Conditions at the location where an environmental flow regime is implemented (preferably assessed both before and after the intervention) can then be compared with conditions at locations that represent ‘control’ and/or ‘reference’ conditions (Downes et al. 2002). ‘Control’ locations are as similar to the intervention location as possible, except that there is no intervention (environmental flow) there. For example, if an environmental flow were to be released from a large dam on a regulated

Table 2. Environmental variables* with established causal links with changes to the flow regime (adapted from King et al. 2003)

Ecosystem components	Response variables	Where used	Comments
River productivity	Benthic production/respiration, water column production, bacterial activity	Mitta Mitta	Short-term responses to specific flow events as predicted
Biofilm	Total/algal/organic biomass, productivity	Murrumbidgee, NSW IMEF†, Mitta Mitta	Consistently responded as predicted to flow events in the Murrumbidgee and Mitta Mitta
	Composition	Mitta Mitta	Structural and functional responses of biofilm were evident immediately following peak flows
Macroalgae	Filamentous algae abundance	Mersey, Snowy	Preliminary results suggest good response to flow events in Mersey study
Macro-invertebrates	Community structure and abundance	Snowy, Mitta Mitta, Mersey	Several attributes measured in cobble habitats responded rapidly to variable flow releases in Mitta Mitta study. Preliminary results suggest good response to flow events in Mersey study.
	Number of families, SIGNAL scores	Mitta Mitta	Responded rapidly to variable flow release
	Community structure, relative abundance and species occurrence on snags	Campaspe	Preliminary results suggest good response to flow stress
	Mayfly larvae (abundance, species richness and diversity)	Murrumbidgee	Responded predictably to flow events in upper reaches
	Abundance and composition of shrimp fauna	Campaspe	Preliminary results suggest good response to flow stress
	Community structure and abundance of wetland macroinvertebrates	NSW IMEF†, Barmah-Millewa wetlands	Some evidence that shows good responses to flow events at Barmah-Millewa wetlands
Vegetation	Riverbank understorey vegetation (species composition, distribution, abundance, survival, growth, reproduction)	Murrumbidgee	Survival and total biomass responded predictably to flow events in lower reaches
	Wetland vegetation	NSW IMEF†, Barmah-Millewa	Successful for Barmah-Millewa project
Fish	Larval fish (occurrence, relative abundance, community composition)	Campaspe	Preliminary results suggest good response to flow stress
	Recruitment	Snowy, Mersey	Preliminary results suggest potentially good response to flow stress for the Mersey
Waterbirds	Abundance, diversity and breeding occurrence in wetlands	Barmah-Millewa wetlands	Easily communicated and can assess effect of watering quickly
Frogs	Abundance, diversity and breeding occurrence in wetlands	Barmah-Millewa wetlands	Easily communicated and can assess effect of watering quickly

*It is assumed that hydrological variables such as mean daily flow will be automatically included.
†IMEF = Integrated monitoring of environmental flows

river then a ‘control’ would be a similar river where flow is regulated via a dam, but without an environmental flow release. ‘Control’ locations are always more useful if they are in rivers separate from the rivers having intervention, although occasionally upstream versus downstream comparisons might be applicable, such as upstream versus downstream of a storage from which flows are released.

Reference locations are those that are, as nearly as possible, in the condition of an environment undisturbed by human activity. Having both ‘control’ and reference locations allows us to determine if an environmental flow causes an ecological response, and if the condition at the intervention location changes towards a desired future state. Reference conditions help to describe what a river system might be in the absence of disturbance (e.g. flow regulation or diversion) and so provide useful comparison with which to gauge recovery at the intervention location. It is important to distinguish between ‘natural’ and ‘target’ reference condition (see Box 1). Returning a modified river system to a ‘natural’ or pre-disturbance state is usually unachievable. A ‘natural’ reference condition provides a useful basis against which river condition can be compared, but it should not be confused with the ‘target’ condition/s upon which the environmental flow objectives have been set and will be assessed. Reference locations, like ‘controls’, may not be readily available. However, it may be possible to model reference condition based on a desired future condition or conditions where the influences of flow regulation or water diversion have been removed. For example, environmental flow studies often model the pre-disturbance flow regime by removing the influence of impoundments and water extraction.

In addition to spatial ‘controls’ (i.e. ‘control’ locations), temporal ‘controls’ also increase our confidence that an observed response is due to the environmental flow regime. Temporal ‘controls’ simply mean measuring the selected variables at the intervention site before the environmental flow regime commences. Collecting information before and after an intervention, at both ‘control’ and intervention locations, allows us to use BACI (Before–After Control–Intervention) designs that can be very powerful for inferring causality between a management action and an ecological response (Downes et al. 2002). Designs 7 and 8 in Figure 2 are BACI designs and provide the strongest inference about causal links between ecological responses and flow modifications, assuming that variables being measured have a strong conceptual basis. These more ‘experimental’ designs are based on the BACI designs for monitoring the effects of spatially-explicit human activities in the environment (traditional impact assessment) (Downes et al. 2002).

It is often the case that ‘before’ data, and/or ‘control’ and reference locations are not available, meaning that traditional BACI designs cannot be implemented. This is particularly likely for large regulated rivers, where comparable rivers without environmental flows do not exist. For example, what river might be an appropriate ‘control’ for environmental flows on the River Murray? In addition, funding and personnel constraints will almost always mean there is a limit to what can be monitored, at what spatial scale and for how long (Michener 1997). BACI designs including ‘before’ sampling plus ‘control’ (and even reference) rivers can be expensive, and will usually only be used in high priority cases, rather than generally applied across a broad scale to assess responses to environmental flows. This creates the dilemma of making tradeoffs in designing monitoring programs. Is it better to sample a limited number of variables at a few locations for a long period of time, or to sample a larger number of variables over a shorter period of time? Is it better to sample a limited number of variables at a large number of locations? The use of environmental flows as a river protection and rehabilitation tool is a relatively new pursuit and only a small number of environmental flow monitoring and assessment programs have been established in Australia (King et al. 2003). It is recommended that an emphasis be placed, where possible, on measuring fewer high-quality variables within a scientifically sound study design. It is likely that this investment will be more informative to river management and restoration ecology than trying to measure a large number of potentially less informative variables.

In situations where ‘controls’ are not available, then monitoring designs are restricted to simply assessing the responses to environmental flows at intervention locations. Two types of designs might be used. If before-intervention data are available, because the environmental flow regime had a clear starting date, then ‘before’ versus ‘after’ contrasts are possible (designs 5 and 6 in Figure 2). If ‘before’ data are not possible, then monitoring can only assess responses at intervention locations through time (design 1 in Figure 2). There may also be situations where ‘before’ data are not possible but ‘control’ (or reference) rivers are available, so intervention versus ‘control’ (or reference) contrasts through time are possible (designs 2–4 in Figure 2). Advice from experienced statisticians will be helpful when considering the inferences that may be drawn from the study designs available and how best to proceed with data analysis (see later sections).

Clearly, designs that focus on assessing physical, hydrological and ecological responses to changed flow regimes in rivers without ‘before’ data or ‘control’ rivers (i.e. only at intervention locations) will be commonly used. This might be because ‘control’ rivers or ‘before’ data are not available (e.g. Wimmera and Glenelg Rivers; Sharpe and Quinn 2004). It may also be because the goal of monitoring is to provide an assessment of environmental flow regimes more regionally and BACI-type designs are not feasible economically for so many rivers. Queensland and New South Wales have encountered both problems when trying to adopt BACI designs for monitoring environmental flows and have responded by evaluating predictions, based on an understanding of how rivers respond hydrologically or ecologically to modified flows (including environmental flows). Both jurisdictions monitor numerous intervention locations to measure whether the predicted environmental or ecological outcomes hold true. The approach used by Queensland is termed ecological performance monitoring and focuses on measuring hydrological and hydraulic conditions required (or critical) for identified ecological assets. NSW has modelled conditions that would exist without the environmental water allocation and also the natural condition, so that three scenarios can be tested: ‘environmental flows’, ‘full development’ and ‘natural’. This enables a BACI-type experiment, albeit with modelled, rather than physical, ‘controls’ and benchmark conditions. The NSW method is an integrated approach to monitoring environmental flows, measuring both physical and ecological responses. These two programs are summarised in Box 3.

Designs without spatial and/or temporal ‘controls’ make it harder to determine whether the observed ecological or environmental responses are caused by environmental flows, i.e. it is more difficult to rule out alternative explanations. Location-specific BACI-type designs allow us to test predictions about ecological responses to environmental flow responses more formally, and provide greater confidence when inferring a causal link between responses and environmental flows. Understanding causal links between observed responses and environmental flows is critical for future predictions and adaptive management. Where environmental flows can be treated as a management experiment, and before-intervention data and/or spatial ‘control’ rivers are available, the BACI designs outlined in this framework should be adopted. Experience to date in Australia suggests that opportunities to apply BACI designs will be relatively rare. Where possible, we should take advantage of such opportunities, as they will provide the strongest inference that an environmental flow causes the predicted environmental or ecological response and will also complement studies where evaluation of predictions at intervention locations is the only option available (a ‘levels of evidence’ approach, see Appendix 1).

The ‘study design’ section in Figure 2 provides a decision tree to help identify the design/s that may be applied at a particular location, taking into account the availability of ‘before’ data, ‘control’ and reference locations. The inferences that may be drawn from the various study designs are discussed in more detail in Appendix 3.

1.6. Optimise study design

Arriving at the optimal study design will often be an iterative process. It is not unusual for aspects of the preferred study design to be confounded with each other — for example, due to logistical constraints such as difficult study site access, or due to unforeseen factors such as localised disturbance (e.g. localised pollution).

A critical step in the optimisation process is getting agreement on the evidence that will convince stakeholders that the environmental flows delivered the predicted response. This requires consideration of effect size, which is the size of the ecological response that is to be detected by the monitoring and assessment program. Effect size is, therefore, closely linked to specific targets that should be the measure of the set environmental flow objectives. For example, if an environmental flow objective is to protect or reinstate native fish populations, then measurable targets might include the species of interest, targets of abundance (e.g. 50% increase over 3 years), frequency of successful recruitment (e.g. 2 out of 5 years) and spatial extent (range) over which recruitment is expected. Recent reviews (e.g. Lloyd et al. 2003) have highlighted the non-linear nature of many ecological responses to changes in the flow regime; in some instances large ecological responses have resulted from relatively small changes to the flow regime, while in other cases relatively large changes to the flow regime were required before an ecological response was detected. The potential for such hysteresis effects should be considered when evaluating a suitable effect size.

The smaller the effect size to be detected, the greater the sampling intensity and therefore resources required. As most monitoring and assessment programs are likely to have limited resources, the challenge will be to minimise the effect size with the given resources. Any trade-off between sampling intensity for a given effect size and budgets will be determined, at least in part, statistically (Downes et al. 2002). Statistical advice should be considered for informing stakeholders about the implications of trade-offs between the desired effect size and study design.

A pilot study is very valuable as it helps to define the spatial and temporal variation that exists within the study system. The information collected during a pilot study may be used to refine the study design if appropriate locations are not available, or if it is not possible to measure the desired variables, or if variability means it is unlikely that the desired effect size can be detected.

Ideally, optimisation of the study design requires stakeholder input, potentially as a 3-step process:

1. Get stakeholders to examine the effect size required (evidence required from the monitoring program).

Box 3. Assessing predicted responses to environmental flows: the Queensland and New South Wales approaches

Managers sometimes require a regional-scale (even statewide) assessment of ecological responses of rivers to environmental flows. This might involve assessing a range of river types with quite different environmental flow objectives, 'control' rivers will not always be available, and the environmental flow regime may be initiated gradually, precluding simple before–after intervention comparisons. Even if 'before' data and/or 'control' rivers were available, it would be too expensive to implement full BACI designs at so many rivers to provide a regional assessment. One option for monitoring in such circumstances is to focus on assessing outcomes predicted by hypothesised flow–ecology relationships only at intervention locations (i.e. rivers receiving environmental flows). The predicted outcomes might be hydrological (with implied ecological consequences) or a mixture of physical and biological responses. This approach has been adopted for regional-scale monitoring of environmental flows in Queensland and New South Wales.

In Queensland, each water resource plan (WRP) outlines a number of 'ecological outcomes' relevant to that catchment. To assess the performance of a water resource plan with respect to meeting its environmental or ecological outcomes, the monitoring program will aim to isolate the effects of flow from all other effects, in achieving these outcomes. River flow is only one of the many stressors that need to be managed effectively to ensure that environmental or ecological outcomes are met, but the scope of a WRP is to manage only flow. For this reason, assessment of a WRP is not based on information about ecological condition, because it is recognised that condition cannot be directly and unequivocally attributed to management of water. Managing river flow alone cannot guarantee ecological outcomes, but provision of appropriate river flow is one important management action contributing towards achieving environmental and ecological outcomes.

Monitoring to assess plan performance will be based on highly valued components of the natural environment ('ecological assets') that reflect the ecological outcomes of that WRP. An ecological asset may be a species, group of species, biological function, particular ecosystem or place of value for which the provision of water (flow) is directly critical. The term critical means that certain aspects of the way water is provided are necessary to maintain the biological integrity of the asset. The intention is not to manage river flow to benefit one asset in particular (i.e. not fish farming). Rather, the process involves identifying valued components of the ecosystem that have a critical link to different attributes of the natural flow regime and then determining if flow management has the potential to impact upon these attributes.

The scope of the ecological performance monitoring is therefore to measure whether water management is providing flow related conditions (such as velocity, depth, connectivity to required habitat, appropriate timing and duration etc.) that are critical for the identified ecological assets. Critical ecological responses of assets to flow conditions may include: breeding/spawning of particular species of aquatic plants and animals, completion of life stages/recruitment of particular species of plants and animals, or movement of particular species. By examining the direct link between aspects of ecology and their water-related critical needs, it is expected that the effect of water management can be isolated and assessed.

(continued next page)

Box 3 (continued)

In taking this approach, monitoring responsibilities will be two-fold. First, it is necessary to measure physical (hydraulic) variables such as water depth, water velocity, area of inundation and timing of inundation, which are uniquely influenced by managing water and are critically linked to the biological water requirements of identified assets. This will form the basis of the assessment criteria. Second, targeted research programs will be designed to improve our understanding and better quantify the critical water requirements for the asset of interest.

Ecological performance will be assessed by examining how the hydraulic variables were provided in space and time under current management arrangements, compared with assessment criteria for providing sustainable water requirements of variables of ecological assets. Assessment criteria will state the conditions for an acceptable risk to the sustainable future of an ecological asset. It is acknowledged that the 'best available' information about some ecological assets and related variables is limited and this adaptive management approach will allow new information from the targeted programs to be incorporated into the assessment process, as it becomes available.

New South Wales has also adopted a predictive approach to assessing responses to environmental flows in regulated rivers across the state. They had considered BACI-type designs for specific rivers but recognised that control and/or reference rivers were almost never available. As the environmental flows were being implemented gradually, before versus after contrasts were also difficult. They developed the Integrated Monitoring of Environmental Flows (IMEF) program for six rivers that are regulated by large storages. IMEF is based around 16 generic and valley-specific hypotheses of how these river systems should respond to environmental flows. These hypotheses include aspects of water quality (especially algal blooms), providing or improving habitat, maintaining or improving the condition of estuaries and wetlands, temperature changes, wetting/drying cycles, riparian vegetation and channel geomorphology. These hypotheses were prioritised for each river valley. The monitoring program was designed to evaluate these predictions using appropriate field sampling methods.

The IMEF program is important because the hypotheses being evaluated arose from NSW river flow objectives and their subsequent environmental flow rules. The hypotheses represent predictive relationships between changes to river flows and ecological responses that can be tested not only by the type of sampling regime used with IMEF but also by case-specific monitoring designs as described with this framework.

2. Undertake a pilot study to establish the feasibility of establishing monitoring sites and evaluate the variability and suitability of the variables to be measured.
3. Revisit the effect size with stakeholders, considering the variables to be included and the benefit–cost tradeoffs of sampling with spatial limits, temporal limits or limited frequency.

If there is no opportunity to undertake a pilot study due to time or resource constraints, then the initial stages of the monitoring project can be used as a 'pilot', recognising that the project will require review and possibly further refinement after 1–2 years.

The *Australian Guidelines for Water Quality Monitoring and Reporting* (ANZECC & ARMCANZ 2000) provide a useful checklist from which to assess the final monitoring study design:

1. Has the study type been made explicit and agreed upon?

2. Have the spatial boundaries of the study been defined?
3. Has the scale of the study been agreed to?
4. Has the duration of the study been defined?
5. Have the potential sources of variability been identified?
6. Are there sufficient sampling stations to accommodate variability?
7. Are the sites accessible and safe?
8. Can sites be accurately identified?
9. Has spatial variation in sites been considered, and have options to minimise this variation been considered?
10. On what basis is the frequency of sampling proposed?
11. Have decisions been made about the smallest differences or changes that need to be detected?
12. Is replication adequate to obtain the desired level of precision in the data?
13. Have the measurement parameters been chosen?
    (a) Are they relevant?
    (b) Do they have explanatory power?
    (c) Can they be used to detect changes and trends?
    (d) Can they be measured in a reliable, reproducible and cost-effective way?
    (e) Are the parameters appropriate for the time and spatial scales of the study?
14. Has the cost-effectiveness of the study design been examined?
15. Have the data requirements been summarised?

1.7. Implement the study design

Implementing the adopted study design should be relatively straightforward, particularly if a pilot study has been undertaken to help avoid or resolve potential problems (e.g. location of suitable monitoring sites; assessing the suitability of potential variables). Some additional planning will help ensure that high quality data and information are collected as part of the study, and help provide flexibility to adapt the program in the light of new information or changed circumstances.

A QA/QC program is a wise investment that will help to minimise the sampling errors and detect and correct problems that may arise in a sampling program. The *Australian Guidelines for Water Quality Monitoring and Reporting* (ANZECC & ARMCANZ 2000) outline quality assurance (QA/QC) considerations for field sampling, laboratory testing and data handling that serve as a useful guide for those designing environmental flow monitoring programs.

The delivery of a package of environmental flow recommendations can represent a significant change to the management regime of a river. Circumstances, such as prolonged drought or changed management priorities, can mean that intended environmental flow releases are not delivered. It is recommended that a contingency plan be prepared that outlines steps that would be taken in response to changed circumstances. Such a plan should consider the implication of, and response to such issues as:

- the risk to the river system if environmental flows are not delivered;
- the rationale of the study design and potential statistical analyses, and if these are likely to be compromised;
- the risk of an unacceptable change due to implementation of an environmental flow regime (e.g. carp breeding and increased dispersal of introduced species; blackwater events).

1.8. Have the environmental flows met their specific objectives?

River rehabilitation or protection experiments, such as the delivery of environmental flows, should be reviewed within an adaptive management framework. It is important that the findings are disseminated quickly and efficiently to stakeholders, so that managers can use the new information in their decision-making. As the assessment of large-scale rehabilitation projects is a relatively new pursuit in Australia, it is recommended that the results of such experiments be externally reviewed and made widely available. This may be facilitated in the future via repositories such as State agency websites and databases such as the Victorian Data Warehouse.

Once the environmental flows have been delivered and relevant data have been collected and analysed, it is time to revisit the environmental flow objectives, conceptual models and hypotheses that form the basis of the monitoring and assessment program. This ‘learning’ step helps to strengthen or modify hypotheses, and guide the refinement of the monitoring program in the light of an improved understanding of flow–ecology relationships. It is also essential information for managers, who will often have to compare the potential benefits from managing flow and from other management actions (e.g. protection or reinstatement of physical habitat), and set priorities accordingly.

Assessment of monitoring results can also inform or assist the development and application of models that help explain broad-scale processes, such as the interaction of flow and other factors driving river condition or ecological processes. Modelling approaches such as Bayesian networks and artificial neural networks are becoming more widely used in natural resource management (e.g. Lek and Guegan 1999, Borsuk et al. 2001), particularly in terms of scenario testing and developing a predictive capability that can help set priorities for action. Having monitoring and assessment results readily available will make it easier to develop and adopt such tools in the future.

2. Other issues

2.1. Levels of evidence and causal inference

A Multiple Lines and Levels of Evidence (MLLE) approach (Figure 4) is described in Appendix 1. MLLE can contribute to monitoring programs that are designed to detect ecological responses to management interventions (see also Beyers 1998, Downes et al. 2002). There is increasing recognition that strong 'experimental' designs (e.g. BACI) will often not be possible for many monitoring programs and that other supporting evidence will be needed to strengthen the inference of causal links between the intervention (e.g. environmental flows) and the response. Downes et al. (2002) proposed that a 'levels of evidence' approach could be used to provide further support for conclusions that an observed ecological response in a monitoring program was due to the intervention being monitored. This general concept of using a range of different types of evidence when drawing conclusions has broad acceptance in the scientific community. However, a consistent way of combining the different forms of evidence in a formal, quantitative, way has not yet been devised.

Norris et al. (2004) proposed MLLE as a way of formalising and refining the conceptual understanding of ecological responses to interventions such as environmental flows. This application of MLLE is partly based on a system for ranking different forms of evidence and hence weighting their contributions to an overall conclusion about causal links. While only in the early stages of development, the MLLE approach should be considered as a potential tool that can help us reach conclusions about causal relationships and appropriate response variables in situations in which:

- additional information can add to improved conceptual understanding at the location of interest and help direct the collection of new data,
- natural variability makes it difficult to reach a conclusion about a causal relationship,
- monitoring designs incorporating 'before' data and/or 'control' locations,

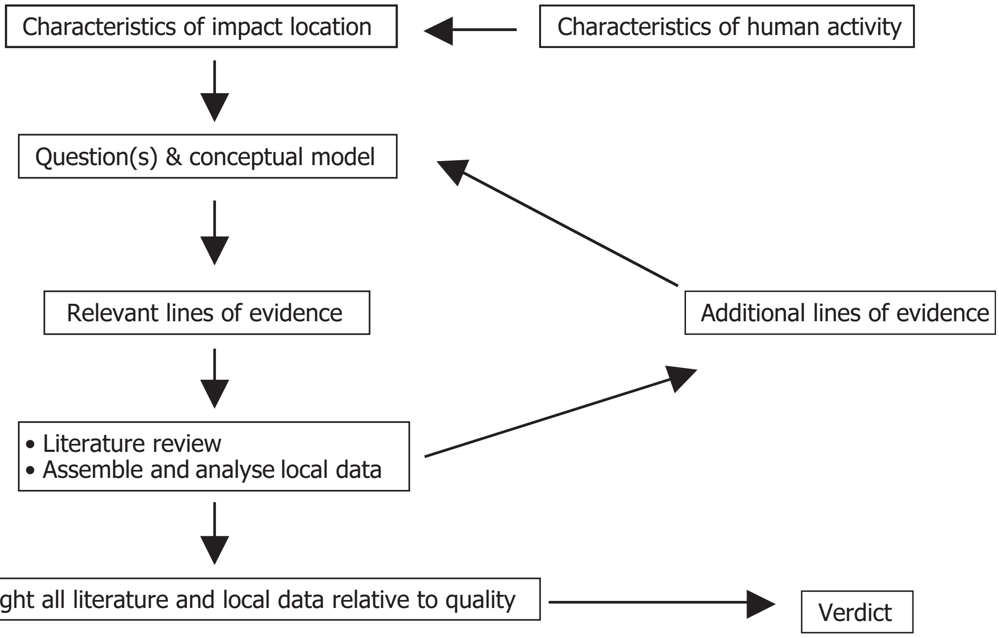


Figure 4. Steps in the MLLE process (after Downes et al. 2002; restated in Norris et al. 2004)

which provide good ‘experimental’ evidence for causality, are not possible.

MLLE is currently being trialled to examine relationships between ecological attributes and flow regime in the Cotter River in the Australian Capital Territory (Norris et al. 2004). Whether or not the proposed weighting system is broadly applicable to combining different forms of evidence in monitoring programs will be evaluated as the project unfolds.

2.2. Analysis of monitoring data

There are two broad types of statistical analysis that would be applicable to the monitoring data collected from the various designs in Figure 2.

First, linear models relating the variable of interest to either spatial (intervention versus ‘control’) or temporal (‘before’ versus ‘after’, or trends through time) comparisons are appropriate for single response variables (e.g. species richness, ecological health, abundance of key taxa). The linear models are sometimes known as regression or ANOVA models, although more flexible versions include generalised linear models and generalised additive models (Quinn and Keough 2002). A range of methods is available for assessing the fit of various models to the monitoring data. While traditional frequentist methods that produce confidence intervals and *P*-values for rejecting null hypotheses can be useful, there is increasing application of Bayesian methods that assess model parameters more directly.

Second, multivariate methods are valuable to find patterns when many variables are considered together (e.g. abundances of many taxa). These analyses are often summarised graphically (ordination plots or cluster diagrams), but complex hypotheses about multivariate responses can also be tested (Quinn and Keough 2002).

The critical issue is that the analysis must be formally linked to the monitoring design and the specific hypotheses of interest. If the monitoring is well designed, the statistical analysis, whether traditional or Bayesian, will be robust and interpretable. The involvement of advisors with statistical expertise is essential in the design and analysis of the monitoring.

2.3. Priorities for monitoring

The range of designs in Figure 2 suggests that criteria for prioritising which to use in individual situations is required. Clearly, applying full BACI (or BAC(Reference)I) designs for all environmental flow monitoring will not be economically viable. These designs should only be used in those situations where ‘before’ data and/or valid ‘control’ rivers are available, and the expected outcomes from the monitoring will have broad conceptual value (i.e. contribute to our understanding of flow–ecology relationships) and be applicable to other river systems. In other cases, especially when an assessment of responses to environmental flows at a regional (even state-wide) scale is required, predictions can be evaluated by monitoring only at intervention sites. The combination of focused BACI experiments with assessments of responses at other intervention sites, where ‘before’ data or spatial ‘controls’ are unavailable, should provide the best mix of causal understanding and spatial generality to inform river managers.

There may be some situations where there is little justification for investing in any monitoring. In particular, if the planned change to flow regime is very small and before-intervention data and/or spatial ‘control’ locations are not available, it will be difficult to design a cost-effective monitoring program that has a reasonable chance of detecting responses to flow change. Pilot data on spatial and temporal variability of chosen variables will be very valuable for deciding whether or not to monitor, as well as for designing the most effective monitoring program if monitoring goes ahead.

3. Further reading

ANZECC and ARMCANZ (2000). *Australian Guidelines for Water Quality Monitoring and Reporting*. Australian & New Zealand Environment and Conservation Council and the Agriculture and Resource Management Council of Australia & New Zealand. http://www.deh.gov.au/water/quality/nwqms/pubs/mg-contents.pdf

Baldwin D., Nielsen D., Bowen T. and Williams J. (2004). Recommended Methods for Monitoring Floodplains and Wetlands. Murray-Darling Freshwater Research Centre report to the Murray-Darling Basin Commission.

Beyers D. (1998). Causal inference in environmental impact studies. *Journal of the North American Benthological Society* 17(3), pp. 367–373.

Borsuk M., Higdon D., Stow C. and Reckhow K. (2001). A Bayesian hierarchical model to predict benthic oxygen demand from organic matter loading in estuaries and coastal zones. *Ecological Modelling,* 143, pp. 165–181. http://www.iemss.org/iemss2002/proceedings/pdf/volume%20due/11_borsuk.pdf

Bosch O., Ross H., Witt B. and Smith C. (2004). Adaptive management: outcomes of the OzAM 2003 workshop, Brisbane. University of Queensland and the Murray-Darling Basin Commission.

Bradshaw A. (1996). Underlying principles of restoration. *Canadian Journal of Aquatic Science* 51(1), pp. 3–9.

Cottingham P., Thoms M. and Quinn G. (2002). Scientific panels and their use in environmental flow assessment in Australia. *Australian Journal of Water Resources* 5(1), pp. 103–112.

DNRE (2002). A method for determining environmental water requirements in Victoria. Catchment and Water Division, Department of Natural Resources and Environment, Melbourne, Victoria.

Downes B., Barmuta L., Fairweather P., Faith D., Keough M., Lake P.S., Mapstone B. and Quinn G. (2002). *Monitoring Ecological Impacts: Concepts and Practice in Flowing Waters*. Cambridge University Press, UK.

Heron S., Doeg T. and Sovitslis A. (2002). 'Maribyrnong River Flow Restoration Plan: Management Options for Ameliorating Flow Stress.' Report for the Port Phillip Catchment and Land Protection Board and the Department of Natural Resources and Environment, Melbourne.

IEPEF (2002). 'An Adaptive Management Approach to the Implementation of Environmental Flows in the Hawkesbury-Nepean River.' Report of the Independent Expert Panel on Environmental Flows for the Hawkesbury Nepean, Shoalhaven and Woronora catchments. http://www.dlwc.nsw.gov.au/care/water/sydneys_future/pdfs/adaptive_mngmnt_approach_enviroflows.pdf

Junk W., Bayley P. and Sparks R. (1989). The flood pulse concept in river-floodplain systems. *Canadian Special Publication of Fisheries and Aquatic Sciences* 106, pp. 110–127.

King A., Brooks J., Quinn G., Sharpe A. and McKay S. (2003). 'Monitoring Programs for Environmental Flows in Australia — A Literature Review.' Department of Sustainability & Environment, Sinclair Knight Merz and the CRC Freshwater Ecology. http://www.dpi.vic.gov.au/dse/nrenari.nsf/

Lake P.S. (2001). On the maturing of restoration: linking ecological research and restoration. *Ecological Management & Restoration* 2(2), pp. 110–115.

Lek S. and Guegan J. (1999). Artificial neural networks as a tool in ecological modelling, an introduction. *Ecological Modelling* 120, pp. 65–73. http://www.clas.ufl.edu/users/mbinford/geo5159/GEO5159/Lek1999.pdf

Lloyd N., Quinn G., Thoms M., Arthington A., Gawne B., Humphries P. and Walker K. (2003). *Does Flow Modification Cause Geomorphological and Ecological Response in Rivers? A Literature Review from an Australian Perspective*. Technical report 1/2004, CRC for Freshwater Ecology, Canberra. http://freshwater. canberra.edu.au> Publications> Technical reports > 2003.

Michener W. (1997). Quantitatively evaluating restoration experiments: research design, statistical analysis, and data management considerations. *Restoration Ecology* 5(4), pp. 324–337.

Norris R., Liston P., Mugodo J., Nicols S., Quinn G., Cottingham P., Metzeling L., Perriss S., Robinson D., Tiller D. and Wilson G. (2004). Multiple lines and levels of evidence for detecting ecological responses to management interventions. Proceedings of the Fourth Australian Stream Management Conference, Launceston (to appear).

Palmer M., Ambrose R. and Poff N.L. (1997). Ecological theory and community restoration ecology. *Restoration Ecology* 5(4), pp. 291–300.

Puckridge J., Sheldon F., Walker K. and Boulton A. (1998). Flow variability and the ecology of large rivers. *Marine and Freshwater Research* 49, pp. 55–72.

Quinn G.P. & Keough M.J. (2002). *Experimental Design and Data Analysis for Biologists*. Cambridge University Press.

Sharpe A.K. & Quinn G.P. (2004). *Monitoring Environmental Flows in the Wimmera and Glenelg Rivers*. Sinclair Knight Merz and CRC for Freshwater Ecology, Melbourne.

SKM (2002). Stressed rivers project environmental flow study: Wimmera River. Sinclair Knight Merz, Melbourne.

SKM (2003). Wimmera bulk entitlement environmental investigation. Sinclair Knight Merz, Melbourne.

Watts R., Ryder D., Chisholm L. and Lowe B. (2001). Assessment of environmental flows for the Murrumbidgee River: Developing biological indicators for assessing river flow management. Final report to the NSW Department of Land and Water Conservation. Johnson Centre, Charles Sturt University, Wagga Wagga, Australia.

Appendix 1. Overview of the Multiple Lines and Levels of Evidence (MLLE) approach

MLLE is proposed as a logical way of organising evidence to make a causal inference (e.g. Beyers 1998, Downes et al. 2002). A MLLE framework can help researchers and managers reach conclusions about causal relationships in situations where:

- additional information can add to improved conceptual understanding at the location of interest and help direct the collection of new data,
- natural variability makes it difficult to reach a conclusion about a causal relationship,
- monitoring designs incorporating 'before' data and/or 'control' locations, which provide good 'experimental' evidence for causality, are not possible.

A line of evidence is:

- a type of evidence; for example, an ecosystem attribute that is investigated in relation to a stressor or intervention (e.g. fish abundance, macroinvertebrate species richness, macrophyte biomass).

A level of evidence is:

- the value of one of a number of criteria used to determine the case for inferring (i.e. strength of evidence) that a given human activity causes a given ecological change (Table 3).

Norris et al. (2004) adapted the steps recommended by Downes et al. (2002) when considering ecological responses to changes in the flow regime of the Cotter River, ACT (Figure 4). The steps outlined (i.e. characterising the activity at the intervention location; exploring the conceptual understanding of the system in order to predict responses to the intervention (e.g. environmental flow); and confirming the lines of evidence (variables) to consider) are all consistent with aspects of this framework for monitoring and assessing environmental flows.

Downes et al. (2002) presented their 'levels of evidence' approach as a method for ascribing causal links when their recommended BACI designs could not be applied and causal inference from a monitoring program was weak. Using other levels of evidence was proposed to strengthen conclusions that a response was caused by an intervention, such as an environmental flow regime. However, Downes et al. (2002) highlighted that we do not yet have a method for combining these levels of evidence in a robust way to draw conclusions about strength of inference.

In their use of MLLE to examine flow–ecology relationships in the Cotter River, Norris et al. (2004) trialled a formal procedure for weighting the quality of scientific papers based on aspects such as the type of study design, the number of

Table 3. Examples of causal criteria to be applied when evaluating levels of evidence (Norris et al. 2004)

Causal criterion	Description
Biological plausibility	Biological mechanism that could explain the relationship
Biological response	Evidence of the biological response following the stressor
Dose–response relationship with the stressor	Evidence of a dose–response relationship between the stressor and the biological response
Consistency of association	Expected biological response always occurs in the presence of the stressor

‘control’ or reference sites and the number of impact (intervention) sites. The results supported the inference that changes to macroinvertebrate community structure can be causally linked to changes in the flow regime in rivers comparable to the Cotter. This would suggest that macroinvertebrate communities should be included when assessing predictions about ecological responses to changes in the flow regime of the Cotter River. While Norris et al. (2004) found that causal inferences about the response of other river attributes (e.g. fish and vegetation communities) to changes in the flow regime were weaker than for macroinvertebrates, this does not mean that these attributes were unimportant or could be ignored. If such results were used as the sole basis for selecting variables to monitor, then this would mean that we only accepted evidence for well-studied attributes regardless of whether they were the most effective means for drawing causal inferences.

The trial of MLLE by Norris et al. (2004) focused on selection of variables to be monitored, but this will be governed in large part by the conceptual understanding of the system. So for variables where direct evidence is not strong, a well-designed and powerful scientific design will be required to establish causal links between the intervention and the environmental or ecological response (in this case changes to the flow regime and ecological responses).

MLLE can potentially be used in distinct ways when developing a monitoring and assessment program:

- reviewing the existing literature for evidence of a *general* proposition (e.g. that change from natural flow regime reduces macroinvertebrate species richness in upland streams);
- using evidence for such a general proposition in *design of a local monitoring program* to test a *specific* proposition (e.g. that change from the natural flow regime has reduced macroinvertebrate species richness);
- interpreting the data from a local monitoring program to assess the evidence for the *specific* proposition.

The use of MLLE to support environmental or ecological assessment is an area of ongoing research and has the potential to be a valuable tool in the future. New insights on its application will be considered in future reviews of this framework.

Appendix 2. Wimmera-Glenelg environmental flows monitoring program

More details on the Wimmera-Glenelg environmental flows monitoring program can be obtained from Sharpe and Quinn (2004). The key steps involved are summarised in the following sections. Note that the monitoring and assessment program was developed without specific information about the package of environmental flows to be delivered. Thus the program was designed to be flexible enough to accommodate more specific objectives in the future.

A2.1. Define the scope of the project and its environmental objectives

Six broad environmental objectives had previously been identified for both the Wimmera (SKM 2002) and the Glenelg rivers and formed the basis for environmental flow recommendations. The objectives were based on maintaining or reinstating components of the flow regime that: (i) contribute to channel-forming processes, (ii) maintain or improve habitat conditions for biota such as fish, and (iii) control nuisance growth of algae and aquatic plants. For example, the broad objectives set for the Wimmera River catchment were to:

1. Provide an environmental flow regime throughout the year that includes:
    - periods of no flow comparable in frequency and duration to those that would have occurred during pre-water resource development conditions;
    - minimum environmental flows during low flow periods; and
    - flows of a sufficient magnitude to maintain water quality and facilitate geomorphological processes.
2. Maintain, and where possible restore, longitudinal connectivity by:
    - providing minimum environmental flows during low flow periods;
    - ensuring farm dam development in the upper catchment does not impact upon flow magnitude and variability in downstream reaches; and
    - improving the frequency, duration and magnitude of floods in the terminal lakes.
3. Maintain, and where possible improve, stream habitat condition by providing environmental flows that can facilitate channel-forming processes.
4. Manage flows for 24 threatened, flow dependent, flora species.
5. Maintain self-sustaining populations of endemic native fish including river blackfish, southern pygmy perch and mountain galaxias.
6. Manage flows to minimise algal blooms and the development of *Azolla* mats.

Management objectives set for various flow-dependent assets (e.g. threatened fish species, riparian vegetation communities) and links with components of the flow regime were reviewed (e.g. Table 4).

A2.2. Define the conceptual understanding of flow–ecology relationships and the questions (hypotheses) to be tested

Flow recommendations for specific reaches of the Wimmera (SMK 2003) and Glenelg rivers were reviewed (e.g. Table 5). Information on the timing, duration and magnitude of flow events and the biological or geomorphic outcomes expected are based on the conceptual understanding (model) of the river system. The conceptual understanding of the flow-dependency of ecological assets and their response to changes in the flow regime were described on a reach-by-reach basis. This conceptual

Table 4. Example environmental management objectives for the Wimmera River catchment (from SKM 2002)

Environmental objective	Target feature	Relevant flow component
Maintain self-sustaining populations of river blackfish and short-finned eel	• Habitat for subsistence • Recruitment/breeding	• Seasonal low flows throughout the year • Spring/summer freshes
Restore self-sustaining populations of Murray cod, golden perch and Macquarie perch	• Habitat for subsistence • Recruitment/breeding • Movement	• Seasonal low flows throughout the year • Winter/Spring freshes • Winter/Spring high flows

Table 5. Example objectives and environmental flow recommendations for the Wimmera River, Reach 2 (Huddleston-McKenzie River); Compliance point = Faux Bridge, Gauge no. 415240 (SKM 2003)

Flow				Objective/Rationale
Season	Magnitude	Frequency	Duration	
Summer	0 ML/d	Annually	17–30 days	Natural stress to promote macroinvertebrate biodiversity
	Minimum flow 6 ML/d	Annually	Dec–May	Maintain quality and quantity of habitat for native fish, macroinvertebrates and aquatic vegetation
	>16 ML/d	3 annually	7–15 days	Enhance recruitment of short-finned eels and river blackfish
Spring (Jul–Nov)	>164 ML/d	2–3 annually	Minimum 14 days	Maintain riparian vegetation and habitat for native bird species
	Minimum flow 60 ML/d	Annually	July–Nov	Inundate snags and other elements that provide habitat for native fish, macroinvertebrates and aquatic vegetation, and maintain longitudinal connectivity
Annual	6,000 ML/d	Annual	Minimum 2 days	Provide high flows to cue and enhance recruitment of golden perch, Murray cod and Macquarie perch, maintain riparian vegetation and habitat for native bird species and facilitate channel-forming processes.

understanding also underpins the monitoring and assessment program.

A2.3. Select the variables to be monitored

The following criteria were used to select variables to be measured as part of the monitoring program:

- Links to the environmental flow objectives.
- There is an established causal link between the variable and the stressor or rehabilitation activity.
- The variables include those of high socio-economic or ecological importance.
- The variables are efficient (i.e. cost-effective) to sample.
- The availability of baseline data to complement 'before–after' comparisons.

Information from previous studies and historical data can provide valuable information on the condition of flow-dependent assets under different flow regimes. Information on water quality, hydrology, biological and physical conditions was reviewed, and knowledge gaps were identified. Because much of the available data and information had been collected for purposes other than detecting ecological responses to environmental flows, it was not surprising that data suitable for assessing baseline conditions or to predict ecological responses to changes in the flow regime were limited.

Tables that summarised the variables, appropriate methods and spatial and temporal attributes of the monitoring program were provided (e.g. Table 6), as were location-based monitoring schedules (e.g. Table 7).

A2.4. Determine the study design

Two broad strategies for monitoring the effects of a changed flow regime were initially considered. The first was a comparison between conditions at the intervention locations and ‘reference’ condition (e.g. least disturbed) that is used for river health assessment. The second strategy was to use the traditional BACI designs often adopted for detecting ecosystem response to human disturbance (impact assessment). There were difficulties in applying both strategies in the Wimmera and Glenelg catchments. Reference condition monitoring does not easily identify causal links between changes in river health and the flow regime. The difficulty in assigning a starting point for the environmental flow regime and how water would be allocated spatially made it difficult to define the ‘before’ and ‘control’ elements of a BACI design. The monitoring approach eventually recommended was based on detecting trends at key locations over time and comparing the direction and magnitude of these changes with the environmental objectives set for each system. Specific contrasts between reaches (e.g. upstream versus downstream comparisons) could be used to infer causal links between flow changes and observed ecological responses. While not true ‘control’ versus impact comparisons, they can contribute to a levels-of-evidence approach to linking changes to the flow regime and ecological response.

Potential study locations were identified on the basis of the sites used to develop reach-specific environmental flow recommendations, representativeness of the proposed location with respect to the reach, and sites established as part of pre-existing programs that complement the data to be collected by the environmental flows monitoring program.

Table 6. Example of recommended response variables to be recorded at each location in the Wimmera and Glenelg rivers (from Sharpe and Quinn 2004)

Variable	Methods	Spatial design	Temporal design
Water quality Key: pH, DO, EC, temp Second tier: TN and TP	Appropriate portable meter, collect water samples for laboratory analysis for any nutrient analyses. Nutrients probably not required for pools and VWQMN data will probably suffice for this.	Water quality will need to be collected in pools at each site. All Wimmera reaches except Burnt Creek and all Glenelg reaches except Chetwynd-Wannon have active VWQMN stations. These stations should be used and additional in-situ measures should be taken at other sites.	Water is sampled monthly at VWQMN sites. These data should be used. Key parameters should also be measured monthly at additional sites during summer when water quality is likely to be a problem.
Fish	Backpack electrofishing by a qualified person. Fyke nets set out overnight, ensuring end out of water so don’t drown mammals or diving birds. Bait traps set overnight near snags or emergent vegetation.	Three replicate pools at each site.	Sampling in summer only, focusing on pools at each site.

Table 7. Example of recommended monitoring sites for reaches in the Upper Wimmera catchment

Recommended monitoring sites	Variable	Monitoring frequency
Key site: Glynwylln VWQMN site 415206 Will need to establish cross-sections at this site	Water Quality: Measure DO, EC, pH, Temp at the surface and depth in pools	Monthly Additional event monitoring to assess changes after freshes
	Hydrology: Measure discharge and water levels Visually assess flow and habitat inundation	During flow events Only needs to be done once for each flow type, not repeated each year
	Geomorphology: Measure pool dimensions, sediment deposition, distribution of debris (photopoints and/or direct measurement)	Short-term responses measured before and after specific flow events. Only needs to be done once for each flow event.
	Geomorphology: Measure channel cross-sections and longitudinal sections, vegetation extent and vegetation composition	Every 3–5 years but should always be done in summer to accurately measure vegetation.
	Macroinvertebrates: Standard EPA rapid bioassessment techniques	Autumn and Spring every 3–5 years.
	Fish: Various sampling techniques	Early summer every 3–5 years, but will need to be done more frequently if trying to detect responses to specific flow releases such as spring freshes.

A2.5. Identify potential statistical analyses

As this monitoring and assessment program was developed without specific details on the package of environmental flows to be delivered, four broad analytical approaches were outlined:

1. Detection of temporal trends in key response variables at selected locations. Analyses include time-series and linear model methods, where the response variable is modelled against time.
2. Specific temporal contrasts between sets of years or between before and after a particular flow event. Such temporal contrasts can be analysed using ANOVA designs.
3. Comparison of reaches (spatial contrasts), which if incorporating ‘before’ and ‘after’ comparisons may also be analysed using ANOVA designs.
4. Multivariate comparison of assemblages of organisms such as macro-invertebrates or fish. Ordination methods (e.g. multidimensional scaling using dissimilarity indices such as Bray–Curtis) with specific spatial (between reach) and temporal (between years or before and after events) contrasts using ANOSIM (analysis of similarity) or NPMANOVA (non-parametric multivariate analysis of variance).

Statistical advice should be sought on the assumptions and applicability of the above approaches so the most appropriate methods are selected.

A2.6. Implementation and assessment of objectives

The Wimmera-Glenelg environmental flow monitoring and assessment program is currently being implemented and results are not yet to hand.

Appendix 3. Potential study designs

The study designs identified in Figure 2 have the following characteristics:

(1) *Intervention-only design*. In circumstances where an environmental flow regime has already been implemented (no before-intervention data are possible) and there are no spatial 'controls' or reference systems for comparison, monitoring is constrained to measuring changes in chosen variables in the intervention river. These responses can be evaluated against specific predictions based on the conceptual model. Causal links between temporal change in ecological response and flow are difficult to determine because the change might have occurred without the environmental flow. This design is very common, especially for larger rivers (no 'controls') and when regional-scale (state-wide) assessment is required (see Box 3).

(2) *Reference–Intervention design*. A modification of (1) above, where there are no before-intervention data but the same variable(s) are measured through time in a reference system, i.e. one that is much less flow-modified and represents the desired direction of change for the intervention system. This design provides slightly better evidence for causal link between temporal change in response and flow, because natural changes through time can be measured at reference sites. It is also possible to assess whether the trend of change at the intervention location is towards the reference condition.

(3) *Control–Intervention design*. Like (2) above except that comparison is with a 'control' system, i.e. a river system similarly flow-modified to the intervention system but without environmental flows. This design provides stronger inference about causality because comparison with the spatial 'control' reduces the likelihood of flow effects being statistically confounded with natural change.

(4) *Control–Reference–Intervention design*. Combination of (2) and (3) above. Statistical analyses test for divergence in temporal trends between the intervention and the 'control', and for convergence in temporal trends between the intervention and the reference location. This design provides causal strength similar to (3), with the added advantage of assessing whether the trends are in the desired direction — towards reference condition.

(5) *Before–After–Intervention design*. Standard 'intervention analysis' design comparing before versus after intervention. 'Before' data act as a baseline or temporal 'control', a measure of whether temporal trends occur naturally (although obviously at a different time to 'after' intervention data). Evidence for causal links is limited by lack of spatial 'controls', so it is unclear whether or not the change after intervention would have occurred independently of environmental flows. This design is also difficult to use if an environmental flow regime is implemented gradually, because then before–after comparisons are hard to define.

(6) *Before–After Reference–Intervention (BARI) design*. As for (5) but with a spatial component; namely, a reference system that provides some measure of whether natural change coincides with intervention. This design allows assessment of whether the trend of a response is towards the reference condition. The test of interest is whether any before–after difference at the intervention location is the same as at the reference location. The causal inference associated with this design is limited because the reference system and the intervention system are in

different conditions prior to the intervention. This makes it difficult to rule out a response to some other factor at the intervention location coinciding with the start of the environmental flow.

(7) *Before–After Control–Intervention (BACI) design*. As for (6), but using a spatial 'control' system instead of a reference system. This design provides a strong inference about causality because comparison with spatial and temporal 'controls' reduces the likelihood of confounding flow effects with natural spatial and temporal change, i.e. any change in the river after intervention is more likely to be due to environmental flows.

(8) *Before–After Control–Reference–Intervention (BACRI) design*. A combination of (6) and (7) that provides strong evidence for causal links between flow change and response and also measures whether the change is in the desired direction — towards reference condition.

Note: Designs involving control–intervention contrasts are improved by having multiple 'control' streams (e.g. MBACI designs; see Downes et al. 2002) to reduce the likelihood that the change observed in the intervention stream might have happened anyway.