# Victorian Environmental Flows Monitoring and Assessment Program

## Stage 1: Statewide Framework

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# 1 INTRODUCTION

The Victorian River Health Strategy recognises the flow regime as an integral part of healthy river ecosystems (DNRE 2002a). Flow regimes are to be managed by:

- imposing environmental flow conditions on Bulk Entitlements (BEs) for urban and rural water authorities;
- providing Bulk Entitlements for the environment in flow-stressed river systems, and the recovery of water for Environmental Water Reserves;
- specifying environmental flow regimes to be provided in Streamflow Management Plans (SFMPs) for priority unregulated rivers; and
- establishing clear management rules for other unregulated rivers that will protect the environment.

The Victorian Government is to establish Environmental Water Reserves that define a legally recognised share of water to be set aside to maintain the environmental values of Victoria's river systems (DSE 2004). The Environmental Water Reserves will be managed via an adaptive management cycle, whereby threats to environmental values will be identified, and management actions implemented and then evaluated and refined. For example, water will be delivered as environmental flows to achieve specific ecosystem outcomes in a number of Victoria's large regulated rivers. The performance of the environmental flows will be evaluated against their specific objectives and results from monitoring and assessment used in future decisions on water resource management and allocation.

Monitoring the effects of environmental flows will provide an opportunity to investigate the ecosystem responses to changes in the flow regime and provide new information that can support future decision-making within an adaptive management cycle. The provision of environmental flows represents a considerable investment in river protection and rehabilitation, especially given the competing demands for consumptive uses of water. Future decisions about the provision of environmental flows will rely on evidence that demonstrates the benefits or otherwise of these water allocations.

The large-scale delivery of environmental flows is a relatively new form of river rehabilitation. While there are recent examples of performance monitoring of environmental releases for individual river systems, both in Australia and internationally (e.g. King et al. 2003, Patten et al. 2000), the establishment of a large-scale (Statewide) evaluation program has only been attempted in New South Wales (Chessman and Jones 2001).

## 1.1 Statewide program objectives and outcomes

The intention of the Victorian government is to:

- *Evaluate ecosystem responses to environmental flows in six to eight regulated rivers that are to receive enhancements (to various degrees) to their flow regime.*

To achieve this, the Department of Sustainability and Environment (DSE) requires:

1. a consistent, scientifically defensible, framework for monitoring environmental flows in pre-defined regulated rivers across Victoria.
2. detailed, hypothesis based, monitoring plans for each specific river where the delivery

of environmental flows is expected or underway.

3. sufficient flexibility in the monitoring framework and plans so that they can be adapted in light of changing conditions and information generated by the on-going data analyses.
4. on-going scientific support to review the data and critically analyse the monitoring programs as implemented by the Catchment Management Authorities (CMAs). A full-scale data analysis and a review of progress against the program objectives for each monitoring program are anticipated every three years.

The individual rivers (and associated environmental flow study) to be included in the Statewide program are the:

- Broken River (Cottingham et al. 2001),
- Goulburn River (Cottingham et al. 2003),
- Campaspe River (Marchant et al. 1997),
- Loddon River (LREFSP 2002),
- Thomson River (Earth Tech Engineering 2003),
- Macalister River (SKM 2003a),
- Wimmera River (SKM 2002),
- Glenelg River (SKM 2003b).

The Statewide program is to be delivered in three main stages:

1. development of an overarching Victorian (Statewide) framework for monitoring ecosystem response to environmental flow releases,
2. development of targeted monitoring and assessment plans for individual river systems, and
3. data analysis and interpretation, and program review after three years.

This report describes Stage 1 of the program.

### *1.1.1 Process used to develop a Victorian framework*

The project team undertook the following tasks when developing the Statewide monitoring and assessment program:

- clarified how information from the monitoring and assessment program will be used in the future;
- confirmed the volumes of water available for environmental flow purposes in each river system;
- summarised the flow objectives possible with the water available;
- showed how conceptual models can be used to underpin the flow-related objectives, develop hypotheses to be tested in a monitoring and evaluation program, and identify variables to be monitored;
- provided guidance on how to express hypotheses so that they are based on conceptual links between environmental flows and ecosystem response, and are related to measurable outcomes;
- considered which flow objectives should be included in the Statewide framework and plans for individual river systems (based on factors such as the degree to which the environmetnal flow regime has already been modified, conceptual models of flow-ecology relationships, relative size of the proposed flow change, ability to detect the predicted responses, stakeholder expectations);

- provided criteria for selecting the variables to be monitored, and guidance on how to reduce uncertainty associated with data collected as part of monitoring programs;
- provided guidance on the expertise required for data collection and handling;
- considered study designs that may be applied to the various river systems, and how best to establish control and reference conditions against which ecological outcomes can be measured;
- considered the need for standardised sampling methods and protocols;
- considered the need for pilot studies or sensitivity analyses that will assist decisions on the data and information to be collected and sampling intensity;
- identified standards to be applied for the effective collection, interpretation and storage of data;
- considered a mechanism for ensuring that appropriate experimental design and data analysis methods are adopted consistently throughout the State.

A CRCFE framework for developing environmental flow monitoring and assessment projects (Cottingham et al. 2005) was used to provide the basis of the Victorian program. This was supplemented by advice provided at a workshop (held on the 9th June 2005) attended by DSE staff and scientists with experience in environmental flow and monitoring programs. Comments from other scientists on the proposed monitoring program have also been incorporated into this document.

# 2 ENVIRONMENTAL FLOW STUDIES AND A SUMMARY OF WATER AVAILABLE FOR ENVIRONMENTAL PURPOSES

## 2.1 The Victorian FLOWS method

Environmental flow recommendations for most of the rivers in the Statewide program were developed by application of the Victorian FLOWS methodology (DNRE 2002b). The exception were the recommendations developed for the Campaspe River, which were developed by a scientific panel based on their experience of the river (Marchant et al. 1997). This work predated the FLOWS method and DSE intends to re-examine the environmental water requirements of the Campaspe using the FLOWS method to ensure consistency across the State. The FLOWS method was developed in Victoria to assess the environmental flow requirements of rivers and streams when setting streamflow management plans or bulk entitlements. FLOWS is based on the natural flow paradigm, which suggests that different parts of the flow regime have different ecological functions (Poff et al. 1996, Richter et al. 1997), and examines the ecosystem implications of changes to components of the flow regime in order to arrive at recommendations (Figure 1).

The following generic components of a flow regime are likely to be ecologically important:

- *Cease to flow* – periods where no flow is recorded in the river channel, which can lead to partial or complete drying of the riverbed. During these periods, the river can contract to a series of pools that act as a refuge habitats for in-stream biota.
- *Low (base) flows* – the low flow that generally provides a continuous flow through the channel. The flow may be limited to a narrow area of the channel in the upper reaches of a stream, but will provide flow connectivity between habitats within the channel.
- *Freshes and pulses* – are small and short duration flow events that exceed the baseflow of the previous few days (e.g. following summer rainfall events). These are important to refresh water quality in pools after periods of low flow or cease to flow and to move silt from productive substrates. Scientific Panels often use a working definition of freshes as flow pulses greater than 1 standard deviation of the preceding average base flow.
- *High Flows* (in-channel) – persistent increase in baseflow that occurs with the onset of the wet season. These are flows that cover the bed and some low in-channel benches. They allow full connection between all habitats with the river channel and are important for fish passage during migration.
- *Bankfull flows* – flows that fill the channel, but do not spill onto the floodplain. They have mainly geomorphologic functions, such as maintaining the channel shape and form, and preventing in-filling of pools. The impact of river regulation practices, such as storing water over the high flow season, is mainly to reduce the frequency of these flows. They also have ecological functions, connecting habitats associated with more elvated in-channel benches, backwaters, anabranches, etc. High flows and bankful flows may also provide stimuli for migration and spawning.
- *Overbank flows* – these exceed the bankfull flow and spill out of the channel onto the floodplain. These are ecologically important for sustaining habitat structure and diversity of wetland waterbodies, and for bringing food (either carbon dissolved from the floodplain floor, or in the form of leaves and twigs) to the stream channel. The rising limb of an overbank flow represents the 'commence to flow' for floodplain

features such as wetlands. On the receding limb, the bankfull level represents a 'cease to flow' for floodplain features.

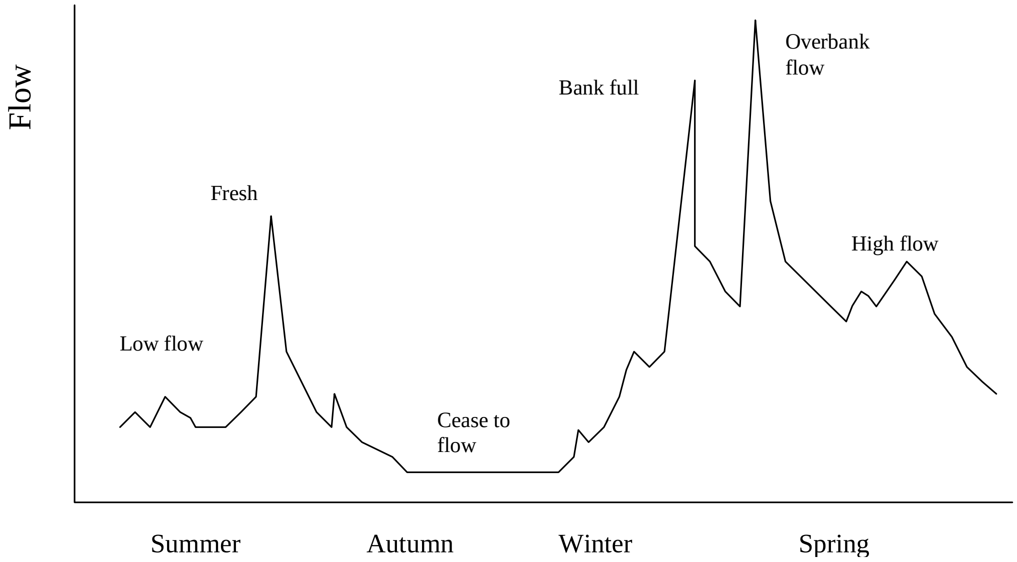


**Figure 1: Time series showing different components of a natural flow regime in southern winter-rainfall dominated systems.**

The FLOWS methodology is undertaken as a 2-stage process (Figure 2) that (i) considers current ecosystem conditions, how conditions have been affected by current management of the flow regime, and identifies flow-related ecosystem objectives as the basis of environmental flow recommendations; and (ii) develops environmental flow recommendations to meet the stated flow-related objectives, and identifies other management activities that will complement the recommended changes to the flow regime (e.g. physical habitat works, water quality improvements and so on). While the FLOWS method provides a framework to arrive at environmental flow recommendations, the rationale for the recommendations is left to those applying the method, usually a technical or scientific panel. The panel reviews how ecosystem condition may have responded to natural disturbance and human activities and the extent to which management of the flow regime has impacted on current river condition. Flow-related ecosystem objectives (e.g. desired future state) are developed in consultation with stakeholders, and the panel then recommends changes to the size, frequency and timing of ecologically important flow components in order to achieve the stated objectives. The panel may choose to apply additional tools (e.g. hydraulic models) in arriving at its recommendations. For example, the FLOWS method applied to the Broken, Loddon, Goulburn and Thomson studies was supplemented by the application the Flow Events Method (FEM) developed by the CRC for Catchment Hydrology (Stewardson 2001). FEM is a framework that facilitates the analyses of key flow events by comparing the current flow regime to natural.

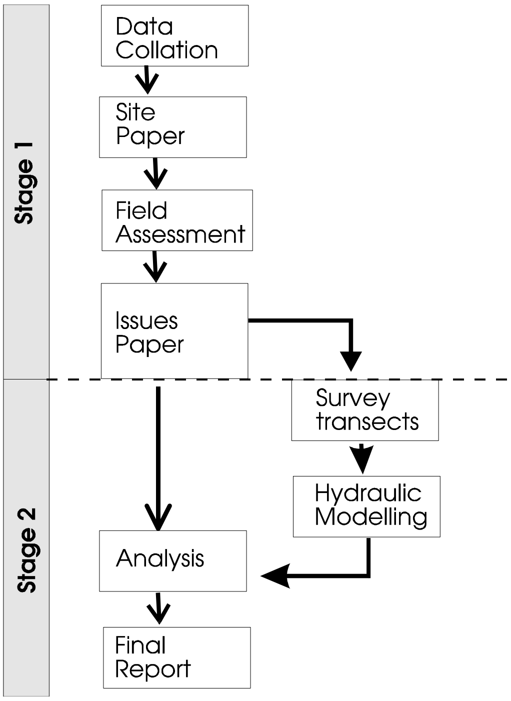


**Figure 2: Outline of the FLOWS method (from DNRE 2002b).**

## 2.2 Water available for environmental purposes

The volumes of water available for environmental purposes in each river system are still being estimated and secured by DSE and other stakeholders. The flow components recommended for each river system are summarised in Table 1. Indicative volumes available to individual river systems are summarised in Table 2.

Final volumes, and how they will be distributed, will be finalised and implemented via environmental operating strategies that will be prepared over the next 12-18 months. It is important to note that government commitments to providing extra environmental allocations for the Snowy River and to the significant ecological assets identified in the Living Murray initiative will mean changed flow management for the Murray River. Water diverted to the Snowy River that would normally be released to the Murray River will now be supplied by releases from the Broken and Goulburn Rivers (P. Lay, DSE, pers. comm.).

### Table 1: Summary of flow components recommended for each river system.

| Flow Component | Broken | Goulburn | Campaspe | Loddon | Thomson | Macalister | Wimmera | Glenelg |
|---|---|---|---|---|---|---|---|---|
| Cease to flow† | | | | | | | ✓ | |
| Low flow: | | | | | | | | |
| summer-autumn | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| winter-spring | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Freshes and pulses: | | | | | | | | |
| summer-autumn | | | ** | ✓ | ✓ | ✓ | ✓ | ✓ |
| winter-spring | | | | ✓ | ✓ | ✓ | | ✓ |
| Bankfull discharge | | * | ** | ✓ | ✓ | ✓ | ✓ | |
| Overbank flow (floodplain inundation) | | ✓ | | ✓ | ✓ | ✓ | | |
| Rate of rise and fall | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

† Most studies made cease to flow provisions by attaching the condition '… or natural' to low flow recommendations (e.g. 10 ML/d or natural). * Included in floodplain inundation flow. ** Runoff from summer rainfall events in the upper catchment is to be passed along the entire length of the river.

### Table 2: Indicative volumes of water available for environmental purposes over the next 5-10 years (from the Victorian Government White Paper *Securing Our Water Future Together – Our Water Our Future*, 2004).

| System | Indicative volume of additional water for environmental purposes | Potential flow components to be delivered |
|---|---|---|
| Broken | 44 GL anticipated from decommisioning Lake Mokoan | Low flows, spring freshes* |
| Goulburn/Loddon | 95 GL consisting of 78 GL anticipated from sales water conversion and 17 GL of high reliabilty entitlement from water savings (channel reconfiguration) | All components |
| Campaspe | 7 GL anticipated from sales water conversion | Spring freshes |
| Thomson | 18 GL consisting of 10 GL as a bulk entitlement for the environment and an anticipated 8 GL from system savings | All components except overbank flows |
| Macalister | 7 GL consisting of anticipated 5 GL from improved distribution infrastructure and 2 GL from water efficiency savings | All components except overbank flows |
| Wimmera-Glenelg | Up to 83 GL | All components |

* Decommissioning of Lake Mokoan is likely to result in an increased frequency of spring freshes along the Broken River. While there was no specific recommendation to increase the frequency of such freshes (Cottingham et al. 2001), such an outcome was considered worthy of further consideration.

# 3 MONITORING & ASSESSMENT PROGRAM DESIGN

A framework developed specifically for the evaluation of ecosystem responses to environmental flows (Cottingham et al. 2005) encompassed the following key steps:

1. define the scope of the project 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 study design and identify how data are to be analysed, accounting for the specific activities and location, and the necessary QA/QC protocols required,
5. optimise study design,
6. implement the study design,
7. analyse data to assess whether the environmental flows have met specific objectives (or are progressing in the right direction) and review conceptual understanding and hypotheses,
8. revise environmental flow objectives, monitor and analyse for ecological outcomes (i.e. complete an adaptive management loop).

While designed for evaluating outcomes in individual river systems, this framework can also be adapted to cover multiple rivers in a Statewide program. An additional consideration was the release of water to meet downstream irrigation demands and provide water for environmental purposes in downstream areas (for example sites identified in the Living Murray Initiative), in addition to providing environmental flows in the source rivers. For example, water from the Broken and Goulburn Rivers will be released to supplement irrigation supply in the Murray River, given that water from the Snowy Scheme is to be diverted to meet the needs of the Snowy River. This means that for some rivers, it will be necessary to detect ecosystem response to a new ‘flow regime’ that includes releases for agriculture and domestic supply as well as for the environment.

Implementing a Statewide program (Figure 3) will allow the Victorian government to evaluate environmental flow performance at a hierarchy of scales (large to small) relevant to water management:

- State jurisdictional level,
- river basin or regional level (i.e. in the context of the Murray River and the Murray Darling Basin),
- individual river systems,
- individual reaches along a river.

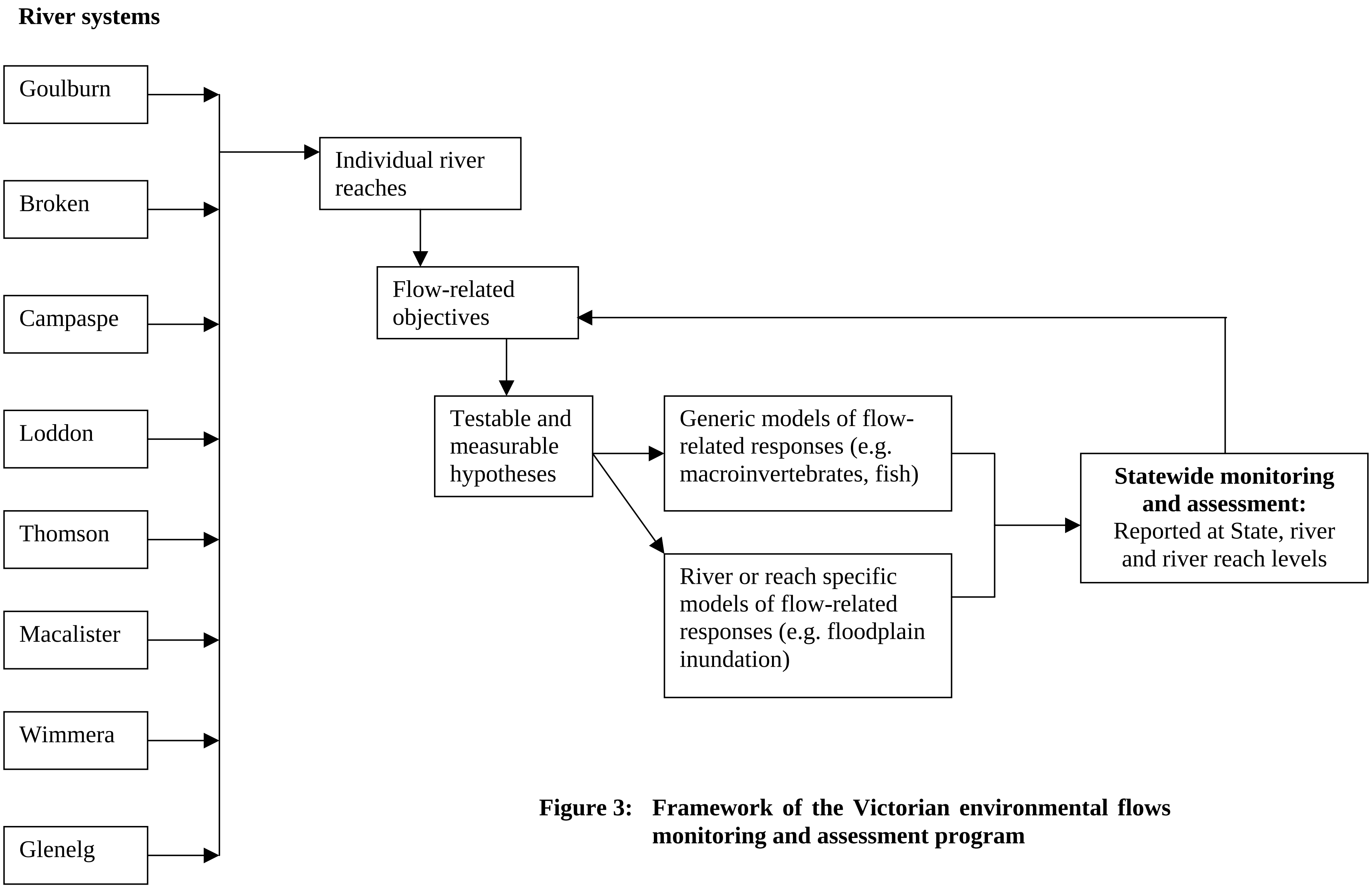


**Figure 3: Framework of the Victorian environmental flows monitoring and assessment program**

Ideally, the design of a monitoring and assessment program would occur in conjunction with the development of water management strategies and the establishment of operating rules for environmental flow releases along the study rivers. Factors such as climatic conditions and water demand could then be considered in terms of the risk they pose to the delivery of the recommended environmental flow regimes. The monitoring and assessment program would then be in a position to consider the likelihood of such scenarios where the environmental flows were not delivered and the consequences for the river ecosystem (i.e. within a risk assessment framework, e.g. Hart et al. 2005). However, as the development of operating strategies and rules for each of the river systems is expected to happen over the next 12-18 months, the development of this monitoring and assessment program was based on advice from DSE about likely (plausible) environmental flow regimes (Figure 4). Accordingly, it is hoped that the development and implementation of the monitoring and assessment program will inform the process of establishing operating rules for water management in the future. The stochastic nature of factors such as climatic conditions and water demand means that in reality the flow releases from dams will have a probabilistic element (i.e. flow releases will vary, depending on current and antecedent conditions and variable demand). As this variability has yet to be analysed, it will not be possible to fully account for stochastic properties of flow in the design of monitoring and assessment program at this stage (see also Chapter 3.5).

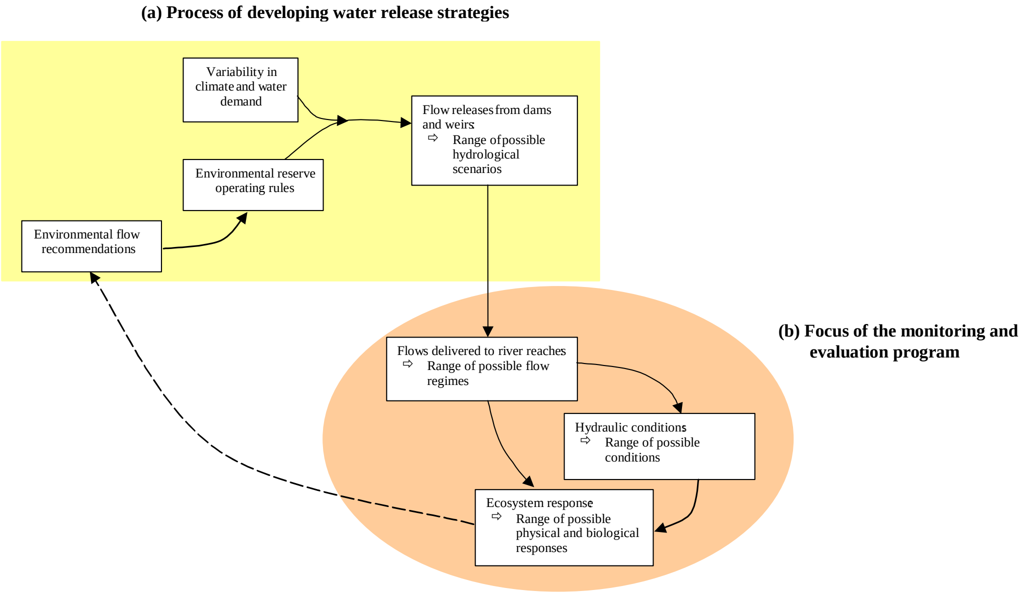


**Figure 4: Separate processes for (a) identifying environmental water requirements and water release strategies and (b) developing a monitoring and assessment program. Ideally, the process of developing the monitoring and assessment program would occur in conjunction with the establishment of the operating rules for environmental flow releases. Water release strategies are to be developed by DSE as a separate exercise to the establishment of the Statewide monitoring and assessment program.**

## 3.1 Summary of environmental flow recommendations

The flow components most likely to be delivered for each river system are listed in Table 3. It is important to note that the volumes of water available and operating rules for release are still being formulated by DSE. The flow components listed in Table 3 are considered ‘plausible’ based on the advice of DSE (i.e. not all of the flow components identified in Tables 1 and 2 will be delivered over the next 5-10 years). It is anticipated that there will be sufficient water available to deliver most of the recommended smaller flow components (low flows, freshes) in each system. The delivery of larger flow components such as overbank (floodplain) flows recommended for sections of the Loddon, Thomson and Macalister Rivers are unlikely. The Goulburn River is the only system for which there is sufficient water to inundate floodplain areas, as recommended.

**Recommendation for Stage 2:**
It is important that the volume of water available to each river system and the timing of its release are confirmed as individual monitoring and evaluation plans are developed. This will be essential for confirming the environmental flow objectives and releases to be included in the monitoring and evaluation program. Parameters to be monitored may differ between rivers, depending on what changes have already been made to the flow regime and what flow objectives are likely to be met.

**Table 3: Summary of potential flow components and relevant ecosystem attributes for each river system (see individual reports for more details).**

| System | Additional flow components likely to be delivered | Ecosystem attributes identified by scientific panels as potentially responding to a new flow regime created by the addition of the flow components |
|---|---|---|
| Broken | • low flows,<br>• rate of rise and fall | • native fish communities,<br>o slackwater (low velocity) habitat for larva and juvenile fish,<br>• macroinvertebrate communities,<br>o low flow wetted area<br>• in-channel aquatic macrophytes<br>o shallow water (<0.3 m) habitat for macrophytes |
| Goulburn | • low flows,<br>• bankfull flows*,<br>• floodplain/wetland flows (overbank flows),<br>• rate of rise and fall | • floodplain/wetland macrophytes, inverterbates and wetland specialist fish,<br>• riparian plant communities<br>• river geomorphology and sediment scour<br>o proportion or river affected by armouring<br>• native fish communities (in-channel),<br>o deep-water (> 2 m) refuge habitat for native fish, |
| Campaspe | • low flows,<br>• spring pulses,<br>• rate of rise and fall | • native fish communities,<br>o pool habitat<br>o slackwater (low velocity) habitat for larva and juvenile fish,<br>o fish passage (depth > 0.3 m)<br>o migration triggers<br>• macroinvertebrate communities,<br>o low flow wetted area<br>o salinity<br>• in-channel macrophytes<br>o salinity<br>• riparian plant communities |
| Loddon** | • low flows,<br>• spring freshes,<br>• bankfull flow,<br>• rate of rise and fall | • native fish communities,<br>o area water depth > 0.4 m<br>o inundation of snags<br>o migration triggers<br>• macroinvertebrate communities,<br>o low flow wetted area (> 0.1 m depth)<br>o cease to flow periods |

| System | Additional flow components likely to be delivered | Ecosystem attributes identified by scientific panels as potentially responding to a new flow regime created by the addition of the flow components |
|---|---|---|
| | | • in-channel macrophytes<br>• riparian plant communities<br>• entrainment of organic litter (carbon)<br>• river geomorphology and sediment scour |
| Thomson | • low flows,<br>• spring and summer freshes and pulses,<br>• bankfull flows<br>• rate of rise and fall | • native fish communities,<br>o area water depth > 0.4 m<br>o low flow inundation of snags<br>o migration triggers (including larval and juvenile fish migrations)<br>o fish passage<br>• Alien fish control<br>o cease to flow periods<br>• macroinvertebrate communities,<br>o low flow wetted area (> 0.1 m depth)<br>o pool area (> 0.5 m depth)<br>• in-channel macrophytes<br>• riparian plant communities<br>• entrainment of organic litter (carbon)<br>• river geomorphology and sediment scour<br>• water quality improvement (pools) |
| Macalister | • low flows,<br>• spring and summer freshes and pulses,<br>• bankfull flows<br>• rate of rise and fall | • native fish communities,<br>o area water depth > 0.4 m<br>o low flow inundation of snags<br>o migration triggers (including larval and juvenile fish migrations)<br>o fish passage<br>• macroinvertebrate communities,<br>o low flow wetted area (> 0.1 m depth)<br>o pool area (> 0.5 m depth)<br>• in-channel macrophytes<br>• riparian plant communities<br>• entrainment of organic litter (carbon)<br>• river geomorphology and sediment scour<br>• water quality improvement (pools) |
| Wimmera | All components (see section 2.1) | • native fish communities,<br>• macroinvertebrate communities,<br>• in-channel macrophytes<br>• riparian plant communities<br>• floodplain/wetland plants<br>• terminal lakes ecosystems<br>• entrainment of organic litter (carbon)<br>• river geomorphology and sediment scour<br>• water quality improvement (pools) |
| Glenelg | All components (see section 2.1) | • native fish communities,<br>• macroinvertebrate communities,<br>• in-channel macrophytes<br>• riparian plant communities<br>• estuary ecosystems<br>• entrainment of organic litter (carbon)<br>• river geomorphology and sediment scour<br>• water quality improvement (pools) |

* accounted for with the delivery of floodplain/wetland flows

** recommended floodplain inundation to achieve river redgum regeneration unlikely to be delivered.

## 3.2 Conceptual underpinning of objectives and hypothesis development

Conceptual diagrams and models are useful for exploring and defining interactions and relationships in a river system, for example to:

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

The term ‘hypotheses’ in this report refers to a number of ‘predictions’ or ‘questions’ that are to be tested as part of the monitoring and assessment program and not simply testing of the null hypothesis, which is usually an hypothesis of no difference or no relationship (Quinn and Keough 2002).

Environmental flow recommendations for each of the rivers in this study were developed using the FLOWS methodology after considering the timing, duration and magnitude of the flow regime components required to achieve specific environmental objectives or outcomes. The recommendations were all based on a conceptual understanding of flow-ecosystem relationships and how they might have been affected by past changes to the flow regime and their probable response to reinstatement of more natural flows. For example, the ecosystem responses expected with lower than natural base flows and, in response, the release of environmental flows are presented conceptually in Figure 5. Decreased low flows and a reduced frequency of flushing are considered to have increased the retention of nutrients and fine sediment, resulting in conditions favourable for the growth of filamentous algae and biofilms that are unpalatable for macroinvertebrates. Armouring of the streambed has also increased, resulting in 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,
    - ⇨ scour filamentous algae and biofilm from the bed,
    - ⇨ increase habitat diversity and availability and, ultimately, increase macroinvertebrate and fish diversity and abundance.

Such hypotheses help to identify the ecosystem variables that should 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 community structure and diversity should all be measured.

The environmental flow monitoring and evaluation program designed for the Thomson River (WGCMA 2004) provides a useful demonstration of using a conceptual understanding of flow-ecology relationships to generate hypotheses to be tested and to identify variables to measure. While the outcomes identified in Table 4 are useful for communicating a vision of a desired future state, they are only a starting point for the design of a monitoring and evaluation program. For example, the objective of securing ‘self sustaining populations of native fish’ provides no guidance on the attributes that should be measured and evaluated. This statement would be defined as an *assessment endpoint* in a traditional ecological risk assessment (Suter 1993), being a statement of the environmental values to be protected (see also Hart et al. 2005). Attainment of this goal is assessed by the use of one or more *measurement endpoints*. These are measurable ecosystem targets or outcomes, believed to be causally linked to the assessment endpoints (Suter 1993). An indication of the mechanism(s) by which flow releases achieve the intended outcomes, and the criteria by which success may be measured and judged, are also required (Chessman and Jones 2001, Heron et al. 2002).

The WGCMA (2004) plan defined 'a self-sustaining population of a native fish species' as one where a number of different age classes can be found, where juvenile fish are recruited into the population and where a proportion of those juvenile fish survive to following years. They then used this definition and available biological information for the relevant species to identify the population structure and attributes expected of a self-sustaining population (Figure 6), and the variables to measure in order to assess if the native fish objectives had been met:

- community composition (species present);
- abundance of each species (numbers present);
- health of the fish present (fitness, based on length:weight ratios); and
- population structure of each species (indicators of breeding and recruitment).

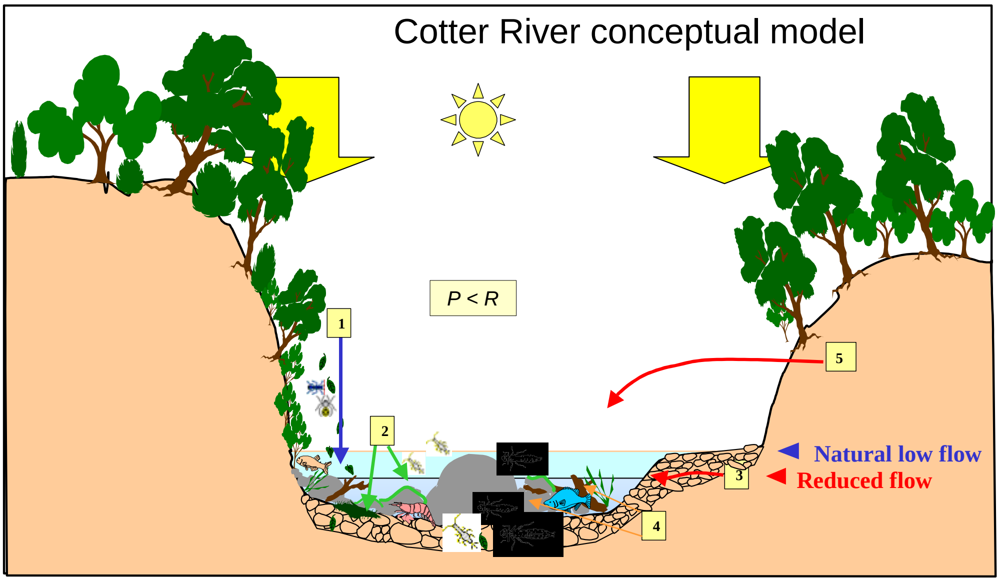
The population structure identified in Figure 6 was also used to predict the structure in the Thomson River expected to occur with successful recruitment over a number of years, after the proposed environmental flow regime has been implemented (Figure 7).

The WGCMA (2004) seeks to monitor the outcomes described in Table 4 in 2 ways:

1. replicated fish surveys at fixed sites through time examining: community composition, species abundance, health of fish (fitness) and population structure;
2. an assessment of spawning of migratory fish (Australian grayling).

The fish surveys will provide a broad assessment of fish populations in the study catchments in response to alterations in the overall flow regime through time (years), compared with a reference river. Using this approach alone, it may not be possible to distinguish between the effects of flows and other confounding changes in the catchment (eg. riparian restoration) or how specific flow events have caused a particular ecological response. Explicitly examining a predicted ecological response to a particular critical flow can strengthen the association and levels of evidence causally linking flows to ecological changes. The monitoring program also includes monitoring of the downstream migration of Australian grayling larvae to assess spawning success in relation to increased low flows and high flow freshes during autumn and winter. Fish larvae have been used as indicators of spawning success in several environmental flow assessment programs, notably the Campaspe Flow Manipulation Project (e.g. Humphries et al. 2002, 1999).

**Recommendation for Stage 2:**
A review of the relevant hypotheses for each river system, ensuring that they include attributes that are measurable, and are linked to environmental flow objectives for the system. Hypotheses should consider both short- (e.g. event based, months, 1-2 years) and long-term ecosystem responses (3 years and beyond).



1 Riparian vegetation encroaches into the channel and reduces channel capacity. 2 Unpalatable filamentous algae accumulates. 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 with low flows in the main channel.

**Figure 5: Proposed ecological responses to changes in the flow regime of the Cotter River, Australian Capital Territory (adapted from Healthy Waterways 2002, Smith and Storey 2001, R. Norris, University of Canberra, pers. comm.).**

**Table 4: Desired outcomes for native fish in reaches of the Thomson River (from WGCMA 2004)**

| Reach | Thomson River Measurable Outcome |
|---|---|
| 2 | Presence of self-sustaining populations of native non-migratory fish species (River blackfish, Mountain galaxias and Southern pygmy perch) |
| 3 | Presence of self-sustaining populations of native non-migratory and migratory fish species (River blackfish, Mountain galaxias, Southern pygmy perch, Short finned eel, Long finned eel, Common galaxias, Australian grayling, Australian smelt and Tupong) |
| 4a | Presence of self-sustaining populations of native non-migratory and migratory fish species (River blackfish, Southern pygmy perch, Flatheaded gudgeon, Short finned eel, Long finned eel, Common galaxias, Estuary perch, Australian grayling, Australian smelt and Tupong) |
| 4b | Presence of self-sustaining populations of native non-migratory and migratory fish species (River blackfish, Southern pygmy perch, Flatheaded gudgeon, Short finned eel, Long finned eel, Common galaxias, Australian grayling, Australian smelt and Tupong) |
| 5 | Presence of self-sustaining populations of native non-migratory and migratory fish species (River blackfish, Southern pygmy perch, Flatheaded gudgeon, Short finned eel, Long finned eel, Common galaxias, Estuary perch, Australian grayling, Australian smelt and Tupong) |
| 6 | Presence of self-sustaining populations of native non-migratory and migratory fish species (River blackfish, Southern pygmy perch, Flatheaded gudgeon, Short finned eel, Long finned eel, Common galaxias, Estuary perch, Australian grayling, Australian smelt and Tupong) |

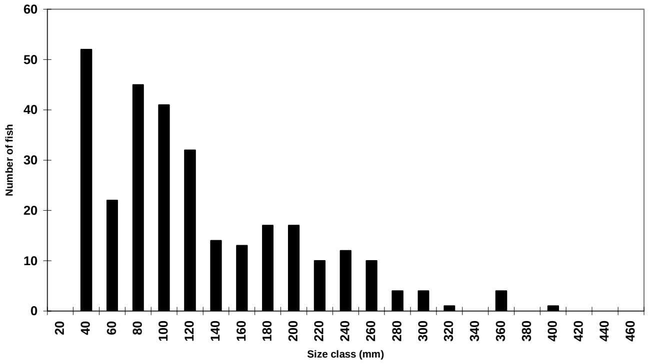
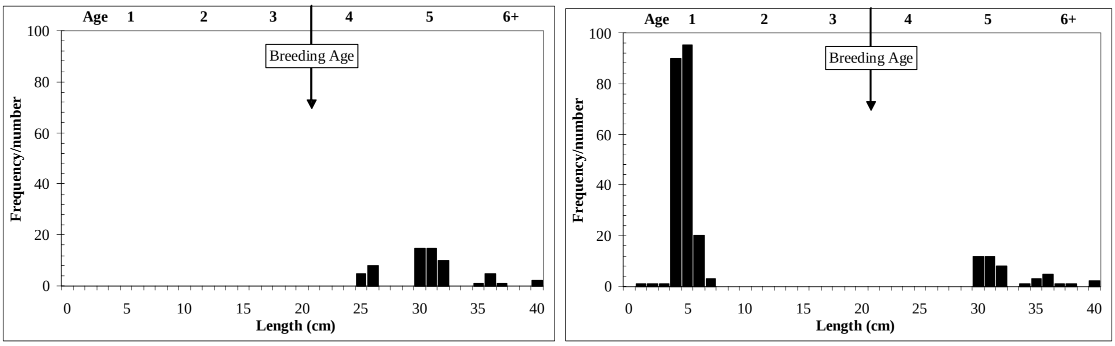
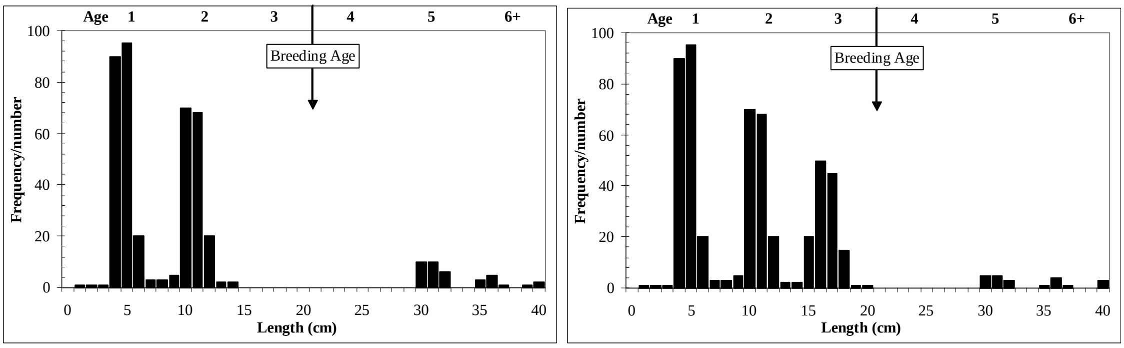


**Figure 6:** **Blackfish community structure in Armstrong Creek, based on repeated and extensive sampling (from Koehn *et al*. 1994; cited in EWG, 2000 as reference condition for blackfish).**



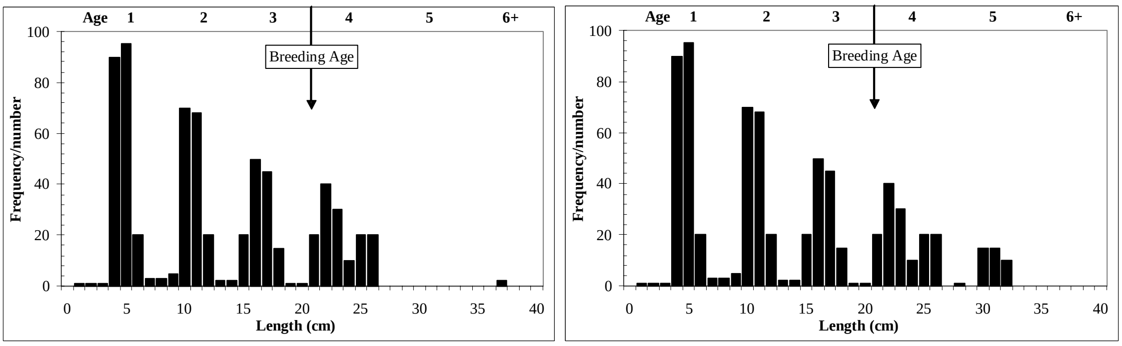
Year 0 – poor condition, only large fish

Year 1 – recruitment of juveniles



Year 2 – recruitment and survival

Year 3 – recruitment, survival and growth



Year 4 – survival and growth to breeding age

Year 5 – recruitment from fish from Year 1

**Figure 7:** **Hypothetical change in fish population structure from poor condition with only large fish present, to a reference condition fish community with all age classes present (from WGCMA 2004).**

### *3.2.1 Summary of predicted ecosystem response to environmental flow releases in Victoria*

A number of flow-related ecosystem objectives/predictions are common to the rivers included in this program (Table 5). It should also be noted that altering long-established, regulated flow regimes can pose a risk, for example by providing conditions favourable for undesirable species such as carp, or increased rates of bank slumping and erosion. Such possible adverse outcomes should be considered as part of the planning process when setting desirable environmental flows for individual rivers.

Less common (river or river reach specific) attributes include:

- floodplain-wetland inundation (regeneration of floodplain vegetation, provision of wetlands habitat for fish, carbon and nutrient cycling, riverine production) recommended for the Goulburn river;
- increased low flows to maintain habitat connectivity and fish passage in the Thomson and Macalister Rivers.

Chessman and Jones (2001) used the following criteria to set priorities for the hypotheses that were adopted as part of the NSW IMEF program, which are also relevant to this program:

- the likelihood that a measurable response of the type described by the hypothesis will occur, given the magnitude of environmental flows in relation to other flow variation;
- the practicality of testing the hypothesis using techniques that can be implemented in a routine monitoring program at a large spatial scale;
- the feasibility of developing an effective sampling and statistical design to test the hypothesis, bearing in mind likely confounding factors;
- the length of river to which the hypothesis might apply (giving lower priority to hypotheses with only localised applicability); and
- the lack of existing studies already producing information relevant to the hypothesis (giving higher priority to those attributes with known high quality information already being collected – eg. Campaspe flow project variables).

The ecosystem responses expected with the delivery of the environmental flow recommendations identified in section 3.1 are likely to occur over a range of spatial and temporal scales. The responses also include a mixture of hydraulic, physical and biological outcomes. For example, macroinvertebrates may respond within weeks or months to flow events that scour biofilm to promote more palatable regrowth, or that flush fine sediment from riffle habitat. Other responses, such as successful breeding and recruitment of native fish, may only occur over much longer timeframes (e.g. 5 years or more). **It is important to remember that successful rehabilitation in individual river systems may require decades.** The Statewide program should include evaluation of both long- and short-term hypotheses. Evaluation of short-term hypotheses will be important for demonstrating to stakeholders that manipulating flow regimes can be a successful form of river rehabilitation, and can be used to confirm or improve our understanding of hydraulic and/or physical habitat and/or biological relationships with the hydrology of individual rivers. This information can also be used to explore and reduce uncertainty (Appendix 2) in flow-ecosystem response models that may be used to support environmental flow decisions in the future. Being able to demonstrate short-term ecosystem responses will help to keep stakeholders committed to long-term monitoring and assessment that matches the long-term nature of ecological responses embedded in many environmental flow objectives.

**Recommendation for Stage 2:**
The generic conceptual models outlined in this report should be refined and confirmed in consultation with the Scientific Panels who developed the flow recommendations for each river system. The criteria proposed by Chessman and Jones (2001) should be applied to the consolidated list of predictions (i.e. for all rivers) when deciding on the hypotheses that will underpin the Statewide assessment of environmental flows. This is likely to be an iterative process as the monitoring plans for individual rivers are developed. Conceptual models for adverse outcomes (e.g. spread of pest species) should also be considered.

**Table 5: Common flow-related predictions**

| River attribute | Generic predictions | Relevant river system |
|---|---|---|
| **Common flow-related objectives** | | |
| River geomorphology (channel maintenance). | • High flows, bank full flows and overbank flows will mobilise sediment, provide scour and provide lateral connection with features such as flood runners and floodplain features that will contribute to natural geomorphic processes. | Goulburn, Loddon, Thomson, Macalister, Wimmera, Glenelg |
| Native fish populations | • Low flows will maintain or increase the availability of low velocity (slack water) areas, provide habitat for juvenile and larval fish, and promote recruitment.<br>• Increased low flows will maintain or increase the deep-water habitat available for large bodied fish.<br>• Flow pulses will provide biological cues for breeding and migration. | All rivers |
| Macroinvertebrates | • Low flows will maintain or increase low flow wetted area and pool area and provide additional or improved habitat for macro invertebrates. | Broken, Campaspe, Loddon, Thomson, Macalister, Wimmera, Glenelg |
| Riparian vegetation | • Bankfull flows will promote regeneration of riparian species and favour flood dependant and tolerant riparian species over terrestrial species. | Goulburn, Campaspe, Loddon, Thomson, Macalister, Wimmera, Glenelg |
| In-channel (aquatic macrophytes) | • Low flows will provide shallow water and low-velocity habitat suitable for growth of aquatic macrophytes. | Broken, Campaspe, Loddon, Thomson, Macalister, Wimmera, Glenelg |
| Water quality | • Freshes and pulses will reduce salinity and disrupt stratification in pools that can decrease water quality (e.g. DO). | Campaspe, Wimmera, Glenelg |
| Organic matter entrainment | • High flows, pulses and bankfull flows will return carbon (such as leaf litter) to the river and contribute to aquatic production and respiration. | Goulburn, Campaspe, Loddon, Thomson, Macalister, Wimmera, Glenelg |
| **Common ecosystem risks** | | |
| Invasive species | • Flow pulses, bankfull flows and overbank flows may favour the breeding of invasive species such as carp | All rivers |
| Bank instability | • Adjusting current unnatural rates of rise and fall in water level can result in increased bank slumping and erosion | All rivers |
| Black water events | • Inundation of floodplain areas with high organic matter loading can result in black-water events of low dissolved oxygen and release of toxicants that can kill aquatic organisms. | Goulburn River |

## 3.3 Selecting variables to monitor

The selection of appropriate variables should be guided by:

- 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 and/or adjust the environmental flows (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. response of icon species).

Watts et al. (2001) identified a number of factors that might be considered when selecting variables to monitor, including:

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

For example, the WGCMA (2004) adopted measures of macroinvertebrate and fish community structure, noting attributes that were related to specific flow-related objectives, had a sound conceptual underpinning, and for which there were established sampling and analysis protocols (State Environment Protection Policy objectives in the case of macroinvertebrates).

**Recommendations for Stage 2:**
Individual monitoring and assessment plans should state clearly the rationale for adopting particular variables.

## 3.4 Study design considerations

The Victorian Government is seeking to measure improvements in ecosystem condition in response to changed management activities and river improvement works, which include river protection and rehabilitation measures such as implementing environmental flow regimes, amongst many other actions. Being able to demonstrate causal links between implementing environmental flow regimes and ecosystem responses will be an important feature of evidence-based decisions on water management in Victoria in the future. Firstly, however, we must be able to detect the changes in ecosystem condition. Freshwater systems in Victoria are monitored via a number of programs, such as the Victorian water quality monitoring network (VWQMN), the Sustainable Rivers Audit (for fish), the Index of Stream Condition (ISC) program, the EPA fixed sites network, and other regional and local programs. These networks and programs predominantly assess the condition (and trends) of freshwaters to help set broad-scale management priorities, and were not established to assess the response of ecosystems to specific disturbances (such as flow regulation) or interventions (impact assessment). As such, they have different objectives, cover different spatial scales and answer different questions to those required of environmental flow studies. Detecting ecosystem responses to interventions such as environmental flows requires the testing of specific hypotheses and this form of river rehabilitation should be considered as a management experiment conducted within an adaptive management cycle (e.g. Arthington and Pusey 2003, Lake 2001, Poff et al. 2003).

Before-after-control-impact (BACI) designs are commonly applied when trying to separate changes in ecological condition due to a management action from other natural or human-induced variability, and they can be very powerful for inferring causality between a management action and ecological response. Conditions at the intervention location (in this case where an environmental flow regime is implemented) can then be compared with conditions at locations that represent 'control' and/or 'reference' conditions (Downes et al. 2002), both before and after the intervention. 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 (i.e. towards the predicted ecosystem state). For example, the use of both control and reference locations in studies of regulated in rivers of the ACT made it possible to separate the impact of flow regulation from that of the fires that affected the area in 2003 (Chester and Norris 2005 (*in press*), Peat et al. *submitted*). Deposition of sediment following the fires affected benthic communities. Streams without flow regulation recovered quickly but regulated streams did not. Subsequent environmental flow releases in the regulated Cotter River saw a recovery of benthic communities (compared with nearby regulated river sections that did not receive environmental flows) towards that of the reference locations.

For interventions such as environmental flow releases, control locations should be as similar to the intervention location as possible, except that there is no intervention (environmental flow) affecting the control location. For example, if an environmental flow were to be released from a large dam on a regulated river then a control would be located on 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 located in rivers independent of the rivers having intervention (to avoid potential autocorrelation effects), although occasionally upstream versus downstream comparisons might be the only comparison possible, 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. Reference conditions help to describe what a river system might be like in the absence of disturbance (e.g. flow regulation or diversion) and so provide a useful comparison with which to gauge recovery at the intervention location. However, it is important to distinguish between ‘natural’ and ‘target’ reference condition. Returning a modified river system to a ‘natural’ or pre-disturbance state (i.e. restoration in the strict sense) is usually unachievable. While a ‘natural’ reference condition provides a useful theoretical basis (benchmark or standard) against which river condition can be compared, it should not be confused with the ‘target’ condition/s upon which the environmental flow objectives have been set and will be assessed. The target condition usually represents an improved state that may or may not represent elements of natural conditions (Arthington and Pusey 2003).

Studies that include sampling before and after the intervention at the intervention, control and reference locations (i.e. providing temporal and spatial replication) are very powerful for inferring causality between the intervention and ecosystem responses. However, they are very difficult to apply to large regulated river systems such as those involved in this study. In many instances, suitable control and reference locations will not be available, although 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. As environmental flow regimes are often implented over time, defining what represents 'before' conditions can be very difficult and there may only be limited opportunity for sampling prior to the first stages of environmental flow releases.

Cottingham et al. (2005) identifed a number of study designs that might be applied, depending on the availability of before data, and control and reference locations (Table 6). The inferences that can be drawn from each study design are discussed in Appendix 3.

**Table 6: Potential study designs**

| Design | Before data | After data | Control sites | Reference sites | Design and Analysis |
|---|---|---|---|---|---|
| 1 | N | Y | N | N | Intervention only |
| 2 | N | Y | N | Y | Reference-Intervention |
| 3 | N | Y | Y | N | Control-Intervention |
| 4 | N | Y | Y | Y | Control-Reference-Intervention |
| 5 | Y | Y | N | N | Before-After-Intervention |
| 6 | Y | Y | N | Y | Before-After-Reference-Intervention |
| 7 | Y | Y | Y | N | Before-After-Control-Intervention |
| 8 | Y | Y | Y | Y | Before-After-Control-Reference-Intervention |

It is likely that opportunities to apply BACI and MBACI designs in the systems being studied will be rare. For example, when establishing a monitoring program for the Thomson River, the WGCMA (2004) found that a lack of control locations and limited opportunity for collecting before-data precluded the adoption of a BACI design. The best option available was to evaluate whether or not predictions associated with the relevant environmental flow objectives were realised (termed objective/prediction assessment). For some reaches and objectives, reference (comparison) locations provided points of comparison. Thus the study design included elements of reference-intervention and before-after-reference-intervention designs.

Where environmental flows can be treated as a management experiment, and before-intervention data and/or spatial control rivers are available, BACI designs should be adopted as they allow us to test predictions about ecological responses to environmental flows more formally, and provide greater confidence when inferring a causal link between responses and environmental flows. At the State level, BACI designs, for individual rivers or across multiple rivers, can complement studies where evaluation of predictions at intervention locations is the only option available (e.g. provide a 'levels of evidence' approach (Downes et al. 2002) for testing predictions based on ecosystem models). In some circumstances it may be possible to do reach-by-reach comparisons that provide small-scale spatial controls. It will be important in such circumstances to try and rule out any obviously confounding factors.

Additional short-term ecosystem studies should also be considered to support the monitoring program and provide information to assist with environmental flow recommendations in the future. For example, the spawning and migration of Australian grayling is being investigated in the Thomson River (WGCMA 2004). The study will provide valuable information on the degree to which spawning and migration of this species is reliant on changes to the flow regime or other factors. Targeted studies of this nature can provide valuable information to assist the design or management of environmental flow regimes across the State.

### *3.4.1 Application to the Statewide program*

The Statewide program (Figure 3) will test predictions of flow-ecology response (models) developed in the environmental flow projects that have been undertaken for each of the rivers. Additional response models will also be considered to address potentially undesirable outcomes of delivering environmental flows, for example the possible response of exotic flora and fauna to a new flow regime, or effects on bank stability and other outcomes.

The performance of new environmental flow regimes will be assessed by testing whether ecological conditions along the relevant river reaches respond as predicted by the response models. It will be important to describe the starting condition (i.e. pre-intervention) for each river system and so enable before-after comparisons and allow estimation of prior distributions of model variables or measurement endpoints for use in statistical analyses. A review of what data exist for each river system will be important (e.g. to describe *before* and *control* or *reference* conditions). Some additional investigations (e.g. field work) may be required if there is no available information that describes how flow regulation has affected a river system or current conditions.

In many cases the flow-ecology response models will be applicable to a number, if not all of the rivers monitored in this project. Where possible, rivers and reaches will be treated as spatial replicates for testing the flow-ecology response models (although there are some cases where response-models are river specific). In many cases, it should be possible to consider the State as a unit, within which particular environmental flow ‘treatments’ are replicated, or at least provided at different levels, in the manner of a regression (e.g. delivery of low flows or freshes in individual river systems), and examine the concordance of responses. Spatial replication helps to rule out confounding factors and provide more generalities that allow the transferability of results for use in future decision making (i.e. providing greater certainty that the results were due to environmental flow releases). Through the incorporation of co-variates into statistical models, it should be possible to draw stronger inferences about the effects of various flow modifications on the individual river systems being studied.

## 3.5 Study optimisation

Most monitoring and assessment programs have limited resources. This means that elements that might be included in the ‘best-available’ study design (e.g. the response variables included, sampling intensity) have to be balanced against cost and the availability of the staff to collect, manage and analyse data. A critical step in this process is getting agreement on a ‘significant’ effect size (i.e. the magnitude of the ecosystem response required to convince stakeholders the system has changed enough due to an intervention). Effect size is closely linked to the specific targets that should be the measure of the set environmental flow objectives. The smaller the effect size that must be detected, the greater the sampling intensity and therefore resources required for the program. Statistical advice should be sought to inform stakeholders about the implications of trade-offs between the desired effect size and study design.

Cottingham et al. (2005) suggested that setting the effect size is best undertaken as a 3-step process:

1. get stakeholders to examine effect size required (evidence required from the monitoring program).
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 effect size with stakeholders, considering the variables to be included and the benefit–cost tradeoffs of sampling within spatial limits, temporal limits or limits in frequency.

However, all three steps are rarely implemented due to timing constraints (e.g. environmental flows are about to be released, which often precludes activities such as pilot studies[1]).

Recommendation for Stage 2:
Discussion of effect size and statistical power will be necessary when finalising the study design and agreeing on the monitoring effort (sampling intensity) required for each river system. Specialist statistical advice should be sought so that the implications of decisions on effect size and interpretation of results can be considered.

Once the desired effect size is clarified, the design of the monitoring program can be adjusted to maximise our ability to successfully detect the predicted responses, within the constraints of a given monitoring budget and timeframe. As flow release rules are still being formulated by DSE, this optimisation step will be based on a ‘plausible’ flow regime[2] expected during the various stages of implementing the environmental water reserve. For example, the first stage may be the current flow regime prior to implementation. The second stage may be after an initial round of water recovery schemes has been completed, and a proportion of the environmental water becomes available. The final stage may be on delivery of the full environmental water reserve. These ‘plausible’ flow regimes will initially be based on modelled flow regimes (e.g. using 20 years of modelled daily flows) that include assumed

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[1] Environmental flow releases have commenced or are imminent in some systems included in the Statewide program (e.g. Wimmera River, Thomson River) and this precludes the use of pilot studies. In such circumstances, the first year of the monitoring and assessment program should be considered as a pilot study, followed by a review of factors such as the variables to be monitored, sampling locations and intensity, effect size and implications for statistical analysis.

[2] The actual flow regime will depend on resolution of environmental flow operating rules for the rivers and both climate and water demand over the monitoring period. It is important to note that developing and finalising operating rules for environmental flow releases is to be undertaken as a separate project by DSE. Presumably the final selection of operating rules will consider the stochastic nature of river flow, water demand and climatic factors to maximise the likelihood of meeting environmental flow targets. Response models developed in stage 2 of this monitoring project could inform development of operating plans for delivering the environmental water reserve.

environmental flow operating rules (at the dams and diversion weirs) and historic climate sequences (with modelled water demands).

Ultimately, the monitoring program will be designed to inform analyses and adjust the ecology-response models to minimise the predicted variation in responses caused by factors other than the environmental flow (i.e. minimise the “noise”). This will increase the chance of detecting the predicted ecological responses to the environmental flow. The optimisation stage also provides an opportunity to examine the effect of additional monitoring on improved estimation of variables included in the flow-ecology response models. For example, additional monitoring effort may be required in early years to help quantify model variables with sufficient precision. Monitoring in subsequent years can then be reduced to a program primarily centred on assessing whether targets have been achieved or not (*sensu* Gerber et al., 2005). In this way it is possible to objectively consider trade-offs of sampling effort, survey techniques and monitoring costs. In some cases, this analysis will indicate that the chance of detecting an environmental response is small, suggesting that monitoring focus on other responses. In addition, the discipline of examining flow-ecology model uncertainties may reveal assumptions made in environmental flow studies that require more careful thought.

## 3.6 Data collection and management

The collection of high quality data will be critical to the success of the Statewide program. Consistency and repeatability of the sampling protocol is essential if trends both within and between river systems are to be detected. Cost-effective programs will also make use of data collected as part of existing programs (e.g. VWQMN, SRA, ISC, SEPP), so that sampling and analysis costs can be defrayed across programs, and existing information can be used directly where possible (e.g. as ‘before-data’ or to inform the selection of appropriate variables to monitor). Standard sampling and analysis protocols should also be utilised wherever possible.

Resources such as the *Australian Guidelines for Water Quality Monitoring and Reporting* (ANZECC & ARMCANZ 2000), *Recommended Methods for Monitoring Floodplains and Wetlands* (Baldwin et al. 2005), and *Rapid Bioassessment Methodology for Rivers and Streams* (EPA 2003) are recommended as starting points for identifying the appropriate data collection methods. Consistent sampling methods should be applied wherever possible so that collected data are comparable between and within rivers. For example, the rapid bioassessment methodology developed for Victoria (EPA 2003) and standardised electrofishing techniques (Baldwin et al. 2005, NSW Fisheries 1997) can be applied to all river systems.

A quality assurance/quality control (QA/QC) plan is recommended as an essential step in collecting high quality and reliable data (ANZECC & ARMCANZ 2000, Baldwin et al. 2005, US EPA, 1996). Such a plan should be based around four elements:

- project management,
- measurement/data acquisition,
- assessment and oversight, and
- data validation and usability.

The QA/QC plan should identify important standards that are to be maintained for the life of the monitoring program, for example the minimum training standards and qualifications of staff who collect field and laboratory data (e.g. Baldwin et al. 2005), and the format required for the management and reporting of data, including database structures. DSE has also requested that any major analysis of the results or review of program performance be peer reviewed. This is a wise investment to ensure that any results and interpretation are of a high standard.

It is also recommended that data collected by the Statewide program be stored in a central repository, such as the Victorian Data Warehouse (or similar entity) that is used to manage data collected by water quality and ISC programs.

**Recommendation for Stage 2:**
Monitoring and assessment plans for individual rivers should adopt recognised sampling protocols and methods so that data are comparable. A Statewide QA/QC protocol should be prepared so that collected data are of a consistently high quality. The QA/QC protocol should include a review of the sampling and analysis methods adopted by the relevant CMAs to ensure consistency across the State. This will ensure that the collected data will be comparable.

## 3.7 Data analyses

The application of linear models and use of multivariate methods serve as two broad types of statistical analysis that can be applied to the monitoring data collected by the overall program (Cottingham et al. 2005). Linear models that relate the response 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). These linear models are sometimes known as regression or ANOVA models, although more flexible versions include generalised linear and generalised linear mixed models (GLM and GLMM) and generalised additive models (GAM) (Quinn and Keough 2002). A range of methods is available for assessing the fit of various models to the monitoring data. GLM’s also have the added advantage of very few assumptions and can handle unbalanced designs and missing data points.

Multivariate methods are valuable for finding patterns when many variables are considered together (e.g. abundances of many taxa). Many of these analyses present the multidimensional data in a simplified graphic form (e.g. ordination plots or cluster diagrams) to aid interpretation, but complex hypotheses about multivariate responses can also be tested using techniques such as the multivariate analysis of variance (MANOVA; Quinn and Keough 2002). Unfortunately, these types of analyses only perform properly with appropriately structured data sets. The assumptions required go well beyond the types of restrictions for univariate linear analyses (e.g. ANOVA), although more recent developments allow robust assessment of hypotheses in a multivariate context (e.g. PERMANOVA; Anderson 2005).

DSE has specified that Bayesian models (Appendix 1) are to be considered for the analysis of the collected monitoring data. The key advantage with Bayesian analyses is flexibility, as it is possible to fit models of varying complexity using many different distributions for variable values. Effects such as spatial and temporal autocorrelation can be readily built into models, as can site specific covariates (e.g. flow-related habitat features such as the availability of pools or riffles). Hypotheses can still be tested, but are not limited to falsifying the null hypothesis, as is the case for the more commonly applied frequentist statistics. For example, if we are interested in demonstrating a 20% increase in fish population density over time, we can directly calculate the probability, given our data, that this has been achieved. An important advantage of using Bayesian models is that alternative models of causality can be retained and revised in light of new data (for example to explore whether ecological response is related to environmental flow releases or other factors). The Bayesian framework is also more suited to the continual analysis of data on a regular basis, rather than waiting until a specified period has been covered before a valid analysis can be performed (as is often required under a frequentist framework).

The response models will be expressed mathematically to unambiguously define the response predicted for any given environmental flow regime. Data re-sampling methods (e.g. Monte-Carlo simulation and including Bayesian Markov-chain Monte-Carlo methods) can be used to characterise uncertainty in model responses and model inferences. These uncertainties can be a consequence of:

- our limited ability to characterise natural variability in environmental parameters (e.g. variability in the depth of pools or fish density along a river reach),
- uncertainty in our estimates of fixed model parameters[3] (e.g. Manning's roughness coefficient or a coefficient of flow in a model of algal cell growth rate),
- uncertainty in the structure (relationships) of the model.

In most cases the most plausible flow-ecology model structure will be adopted, based on literature review and expert advice.

By considering uncertainties within our model we produce stochastic predictions. Appendix I and II discuss the development of stochastic predictions of biological and physical responses respectively. Bayesian models explicitly provide stochastic predictions of ecosystem responses by generating statistical distributions of parameter estimates, rather than the single Maximum Likelihood estimate more common in frequentist methods. In principle, these stochastic models will estimate the variation expected in each response variable if our model is sufficiently correct. In some cases, it will be possible to then test the 'correctness' of the model by assessing whether or not the model could have plausibly produced the experimental data. Such a test provides for greater confidence in the continued use of the model and evaluating the performance of the environmental flow regime. Furthermore, the Bayesian models can be used to optimise the monitoring design and improve our ability to distinguish the effect of environmental flows from other sources of environmental variation in our response variables.

**Recommendation for Stage 2:**
It will be important to clearly define how data are to be analysed as part of the detailed monitoring design in stage 2. This applies both to analysis of environmental flow responses along individual rivers, reaches and at the State level. This should include discussion of the assumptions, flexibility or limitations associated with potential types of statistical analyses.

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[3] It is acknowledged that factors we may treat as fixed entities usually exhibit some variability in a natural setting, either predictably (e.g. Manning's roughness coefficient for a given river stretch decreases with water depth) or unpredictably (other factors such as nutrient and light levels interact in a complex way to affect the value of a flow coefficient, and algal cell growth, over time). Models are employed as useful abstractions of nature, and treating variables as fixed is justified in order to make the modelling exercise more tractable.

# 4 STAGE 2 CONSIDERATIONS

Monitoring and assessment plans exist or are being finalised for some of the river systems being considered in this project. Where plans already exist, they will be compared with the Statewide framework and recommendations made, if necessary, to ensure that all plans have a consistent basis. Stage 2 of the project will therefore require:

- a review of existing monitoring plans for the Thomson and Macalister systems,
- a review of existing monitoring plans for the Wimmera and Glenelg systems,
- development of individual monitoring and evaluation plans for the Goulburn and Broken systems,
- development of individual monitoring and evaluation plans for the Campaspe and Loddon systems, and
- consolidation of the Statewide monitoring and evaluation program.

Prior to commencing each plan, the project team will liaise with DSE and the relevant CMAs to agree on the scope of work, to scope existing studies that may be relevant and specific tasks required for each river system, consistent with the direction provided in this report. This will ensure that the requirements for each plan are clear and that there are sufficient resources available to complete each plan.

In finalising plans for individual rivers and the Statewide program, it will be necessary to:

- confirm the rationale for the environmental flow regime recommended for each river system.
- confirm the volume of water available to each river system and the timing of its release as individual monitoring and evaluation plans are developed. This will be essential for confirming the environmental flow objectives and releases to be included in the monitoring and evaluation program.
- reviewing the relevant hypotheses, ensuring they include attributes that are measurable, will be a key activity when developing monitoring and assessment plans for each river system.
- confirm and refine the generic conceptual models for riverine attributes in consultation with the Scientific Panels who developed the flow recommendations for each river system.
- state clearly the rationale for selecting variables to monitor.
- describe the starting conditions from which environmental flows will be evaluated as part of before-after comparisons and allow estimation of prior distributions of model parameters or measurement endpoints for use in statistical analyses.
- confirm the sampling protocols and methods to be used for data collection.
- prepare a QA/QC plan to ensure that collected data are of a consistently high quality.
- confirm how data are to be analysed and implications for data collection and statistical analysis.
- identify a process for feedback to stakeholders and for overseeing the Statewide program.

## 4.1 Reporting of results and future program review

Reporting of results will be a critical part of the Statewide program.

At the end of the first year of monitoring, a progress report will be prepared by an expert assessment panel convened by DSE to:

- summarise the key findings to date,
- discuss the implications of the results in terms of ecological outcomes and future monitoring and assessment requirements,
- present consolidated conceptual models and models of physical attributes that have been used for uncertainty analysis, and
- discuss any implications for future monitoring, assessment and management decision-making.

While data analysis and reporting will be the responsibility of the expert assessment panel, the implementation of the monitoring and assessment plans for each river system will be the responsibility of the relevant CMAs. It is recommended that a forum be organised so that the Statewide framework can be presented to the CMAs and other stakeholders, and issues related to implementation of a monitoring plan for each river discussed.

At the end of Year 3, the expert assessment panel will undertake a more formal review of the ecosystem responses to environmental flow releases, where applicable (in some instances the requisite environmental flows may not have been released and the project may still be in the 'before-data' collection stage). The requirements for subsequent reviews will be articulated at this stage.

### *4.1.1 Intellectual property issues*

It is the intention of DSE to have the results prepared by the expert assessment panel and then peer reviewed and published in the international scientific literature. This will require that data and information collected as part of the program are forwarded by the relevant CMAs in a consistent and timely manner. It will also require that the assessment panel and associates be given priority access to the collected data for publication in high profile scientific journals. This may require intellectual property and reporting agreements to be discussed further between DSE, the CMAs and the expert assessment panel so that other publications arising from the program do not affect publication of the overall results in the scientific literature. The need for such agreements should be considered as monitoring and assessment plans are developed for the individual rivers.

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# 6 APPENDIX 1: SHORT DISCUSSION OF BAYESIAN STATISTICAL ANALYSIS

Frequentist statistical methods assume that a measurement or experiment can be done many, many times, and that outcomes have "long-term probabilities" from which the observed value is a representative. While such methods produce confidence intervals and *P*-values that can can be useful for testing null hypotheses, there is increasing application of Bayesian methods that assess model parameters more directly (e.g. Wyatt 2003, Gelman 1995). The frequentist approach to parameter estimation, usually based on maximum likelihood techniques, assumes that parameter values are fixed, but unknown, quantities. The data are used to estimate the parameters. The conclusions must be couched within the mindset that any experiment could be repeated infinitely often, and the results compiled. Thus the classic 95% confidence interval (CI) is not, as is usually assumed, an interval that has a 95% probability of containing the unknown parameter value. Because the parameter value is fixed, it is either in the interval or is not. Rather, if we were to re-sample the population and calculate 95% CIs an infinite number of times, 95% of the calculated intervals would contain the unknown value. This type of logical interpretation is difficult for most people to grasp. Similarly difficult, but for different reasons, is the interpretation of frequentist test *p*-values. For a t-test comparing the means of two populations, a *P*-value of 0.04 does not mean there is a 1 – 0.04 (96%) probability that the two means are different. Rather, *given* that the two means are in fact equal, there is a 4% chance over a long-run of repeated samples that we would obtain these sample data.

Bayesian analyses treat all data points and parameters as realizations of random variables (Gelman 1995). Thus, probabilistic interpretations – those that most people give incorrectly to frequentist analyses – are appropriate. Interestingly, the Bayesian *credible interval* – the analogue of the CI – will be equal to the CI for the same data if we assume no prior knowledge and the same distributions of the variables. However, a credible interval is to be interpreted probabilistically because the parameter is considered to be a random variable rather than a fixed unknown quantity. Thus there is a 95% probability that the random variable will take a value that lies within this interval.

Bayesian analyses also allow us to use prior information about parameter values to strengthen inference. Thus, if we believe *a priori* that a parameter value lies within a certain range, this can be used to tighten the estimate of the parameter value following the collection of sample data. The use of a prior estimate is mandatory within the Bayesian framework, and this has caused controversy in the past. However, because parameters are treated as random variables within the Bayesian framework, we may view parameter estimates as levels of belief concerning a given value. Viewed from this standpoint, there is very little problem with the idea of using data to update one's prior belief about a parameter value/hypothesis. Moreover, if we truly believe that we know nothing about a parameter value, we can use so-called non-informative priors, and allow the data to speak solely for themselves. In any case, for most analyses, the effect of a prior on the analysis will be small once more than a few data points have been collected; Bayesian inference always is dominated by data, even when there are relatively small amounts of information. From the point of view of the monitoring of the effects of environmental flow releases, a prior distribution for a parameter value may be the results of the previous year's data, which is then updated by the data from the current year. Importantly, such an analysis will result in identical results to that which considers the data from the two years simultaneously (with a non-informative prior). This is why the Bayesian framework is ideally suited to the sequential analysis of data through time as more information is collected.

A Bayesian analysis proceeds through the use of Bayes' rule. The rule is:

$$P(\text{model}|\text{data}) = \frac{P(\text{model})P(\text{data}|\text{model})}{P(\text{data})}$$

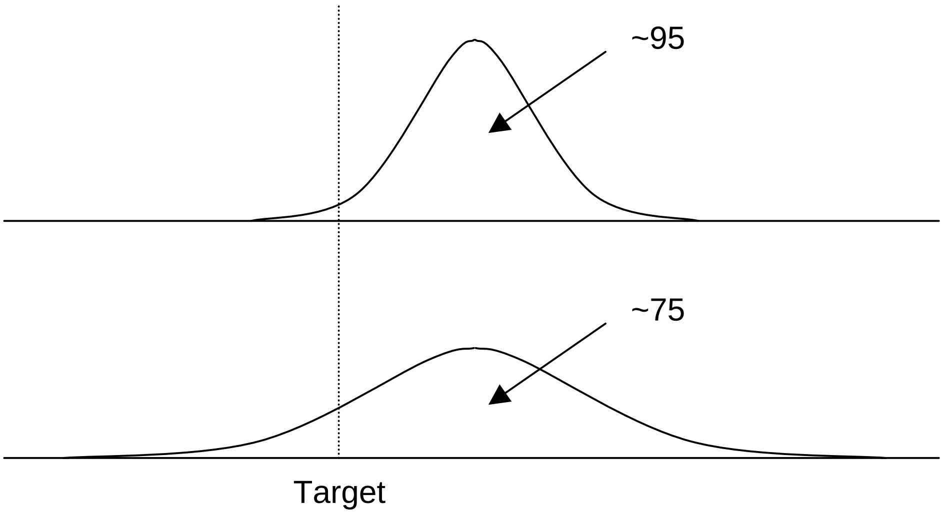
where *P* represents a probability distribution, 'data' are the data collected to be analysed, and 'model' is the parameter to be estimated. The model may be as simple as a point-wise estimate for a single parameter, or may be multiple probability distributions for several parameters that are related to each other in a quantitative model. *P*(model) is the prior probability for the model – our prior belief (and we can now see why it is mandatory to include this in the analysis). *P*(data|model) is known as the likelihood function, and is the statistical distribution that we assume for the data.. *P*(model|data) is known as the Posterior estimate, and is the probability distribution for the model parameters *given* the data ("|" represents a conditional distribution or X given Y). *P*(data) is the marginal distribution, and is simply needed to normalize the numerator back to a total probability of 1.

In practice, computer packages for performing Bayesian analyses such as WinBUGS require a specification of the prior distribution, and a statement of the form of the likelihood function (e.g. normal, gamma) in order to calculate the posterior.

The key advantage with Bayesian analyses is flexibility. We can fit models of arbitrary complexity using many different distributions for parameter values. Effects such as spatial and temporal autocorrelation can be readily built into models, as can site specific covariates (see below). Hypotheses can still be tested, but we are not limited to falsifying the null hypothesis as outlined above. For example, if we are interested in demonstrating a 20% increase in fish population density over time, we can directly calculate the probability, given our data, that this has been achieved.

For the monitoring of effects of environmental flows, issues of statistical power are of great importance. For many monitored parameters, targets will be set (e.g. the 20% increase mentioned above). Such issues can be addressed using Bayesian analyses by running prior simulations to work out probabilities of achieving effect sizes of interest.

In a frequentist analysis, the sample size required to statistically detect a given effect size relies on the falsification level for the null hypothesis (commonly 0.05), the effect size (e.g. 20% increase), and the expected variance of the data (so prior knowledge is used!). Similarly, in a Bayesian framework, we require estimates of the variance (we would probably use the same estimate as for the prior variance) and desired effect size. We will also need an estimate of the posterior mean (required because we are not simply testing a null hypothesis), and a necessary degree of belief in the posterior. For example, the target may state, "a 20% increase in native fish numbers demonstrated with 90% probability". The key to higher confidence in the posterior estimate is the variance of the posterior estimate. With a smaller variance, the posterior probability distribution will range over a smaller range of parameter values, and we will have greater confidence in testing whether a target has been met. In the figure below, the two distributions have the same mean, but the lower distribution has greater variance. If we are seeking to answer to the question, "is the parameter greater than the target value?" then we are approximately 95% confident of answering in the affirmative for the first distribution, but only 75% confident for the second distribution.



The variance of the posterior estimate is a function of sample size and the prior variance. As an example, for a normally distributed posterior, the posterior *precision* (the inverse of the variance) is calculated as

$$\frac{1}{\sigma^2} = \frac{1}{\sigma^2_0} + \frac{n}{\sigma^2_d}$$

where $\sigma^2$ is a variance and the subscripts 0 and $d$ represent prior and data variances respectively. It is easy to see that the greater the sample size, the higher the posterior precision and thus the lower the posterior variance. This leads to greater statistical confidence. If we set the expected data variance equal to the prior variance, we will be able to use inverse cumulative probability distributions to determine the sample size required to determine whether a target has been exceeded with a stated confidence for any given posterior mean.

Data analysis and assessment of predictions of flow-ecosystem relationships have to be flexible so that it is possible to evaluate environmental flow performance at a hierarchy of scales: the State, rivers (catchments) and river reaches. In addition to the frequentist statistical methods, Bayesian models are likely to be a very suitable method for this approach. With this technique, knowledge about how unique components of each experimental unit (State, river, reach) are likely to affect flow related outcomes, can be built into models to improve the precision of estimates at any given experimental unit. Within the hierarchy, the different experimental units also “borrow strength” from one another – that is, if we expect two rivers to behave similarly, then the data from one river can be used to augment and strengthen the inference from the other river, and vice-versa. This is consistent with the levels of evidence approach suggested by Downes et al. (2002).

### Example application of a Bayesian model of fish density

As a hypothetical example, suppose that we have a model of available fish habitat along a reach of river. This model may have been built up from a simple rule concerning minimum depth of pools required for adult fish, which is then ‘matched’ against data from a hydraulic model of the river reach that will provide an estimate of available habitat for any given flow scenario. The sampling (e.g. electrofishing designed in consultation with fish experts) focuses on areas of suitable habitat and data on the numbers of fish captured are converted to site-specific estimates of density using either standard or more advanced methods (Wyatt 2003).

Our sampled data will cover a subset of the available habitat. We are interested in obtaining an estimate of population density at each of the sampled sites, but also at the non-sampled sites. With estimates for all sites, a reach-scale estimate of density or population can be obtained. It is likely that local-scale population density will be affected by local-scale factors. For instance, we might expect that the number of fish to be found in one pool would be a function of the number of pools within a nearby range. Thus higher local densities of pools could be expected to lead to higher densities of fish per pool. Similarly, we might expect that cold water releases would result in lower fish densities. If the effect of cold water diminishes along the length of the reach, we would expect to see higher densities, on average, at the less affected end of the reach.

These effects, and potentially many others, can be built into a Bayesian hierarchical model of fish densities for the reach. The variable of interest that we are trying to estimate is the mean density of fish for any pool. If we take a simple approach and assume linear effects of both pool density and cold water, the mean density would be modelled as:

$$\mu = \alpha + \beta\,.\ \text{pool density} + \gamma\,.\ \text{temperature}$$

where $\alpha$,$\beta$, and $\gamma$ are parameters to be estimated. Each of these so-called ‘hyper-parameters’ would have to have a specified prior probability distribution. These can either be made non-informative (typically zero mean and large variance), to reflect a lack of knowledge about the system, or they can be informed by best-available knowledge. The strength of the prior knowledge can also vary. If we have good survey data from another system that gives a mean and standard deviation for the pool density effect, this could be used as a highly informative prior distribution. Conversely, if we are confident that the effect of increased temperature will be negative, but do not know the magnitude of it, we could specify the prior density as one that cannot take negative values, but can take a wide range of positive values.

The Bayesian model then estimates the density of fish at the sites, treating the different sites as *exchangeable* units. Exchangeability implies that we consider that the different $\mu$ values have been drawn from a larger population. Thus two samples of $\mu$ values should not differ by an amount more than can be reasonably expected given the variance in the probability distribution for the hyper-parameters. For this example, the concept of exchangeability must be extended a little. We have already stated that we expect $\mu$ to differ dependent on the local pool density and temperature at the site. However, *conditional* on these variables, we still expect $\mu$ values to be drawn from the same population.

A hierarchical model will consider the data from all sites simultaneously and estimate values for $\alpha$, $\beta$ and $\gamma$, together with their uncertainties. The estimate for $\mu$ at any site is a function of $\alpha$, $\beta$ and $\gamma$. The consequence of this is that the data from other sites will affect the estimate of $\mu$ at any one site. Sites with more data will have a greater influence than sites with fewer data. The model ‘borrows strength’ from other sites to inform the estimate at each site. This is appropriate because we believe that the population density at any site will be affected by the same variables as at any other site. The other consequence of this behaviour is that we can model the density of fish for sites in the reach at which we have *no* data, as long as we can provide information on pool density and temperature. Using such estimates, we can make a reach-level estimate of population density that is much more informed than a simple average of the sampled-site density estimates that we started with.

Two further aspects should be mentioned. First, if there truly is no effect of temperature, and our expectation was in error, the results will not be unduly affected. For this scenario, following implementation of the Bayesian model, the estimated value for $\gamma$ from the data and prior information would be close to zero, but with high uncertainty. With such a finding, it might be advisable to run the model again without this covariate, or to consider a different model structure. Second, it is advisable for any Bayesian model to conduct posterior predictive checks. Simply put: given the parameter values estimated, and their uncertainty, are the data we collected consistent with the model structure. This is done by drawing ‘false data’ from the posterior predictive distribution, and determining whether they are consistent with actual data. Discrepancies may point to a problem with the model structure (perhaps it’s an exponential relationship between density and pools, not linear).

The example above serves to illustrate the utility of Bayesian hierarchical models for analysing data of the types that will be collected as part of environmental flows monitoring. Simpler or more complex models can be built as desired (e.g. to account for spatial autocorrelation along the river reach). Once such models have been built and tested on monitoring data, they can be used to make estimates about expected effects under different flow scenarios. For instance, if environmental flows will lead to more habitable pools in a reach, we would reasonably expect the population of adult fish to increase, although this would take some time due to their slow growth. Moreover, these estimates will be delivered with their associated uncertainty, allowing levels of confidence in predictions of what might happen. For instance, we might be 90% confident that we will see an increase in mean density of 20%, and at the same time be 50% confident that the increase will actually be 40%. As long as we have confidence in the structure of the models created, they can be used for target setting in this way.

Bayesian hierarchical models are discussed in detail in Gelman et al. (1995). An example of a hierarchical model used for modelling fish data similar to this hypothetical example can be found in Wyatt (2003).

# 7 APPENDIX 2: MODELLING UNCERTAINTY

The monitoring program can be used to explore the components of the river response that are uncertain and where the range of uncertainty is sufficiently large to influence environmental flow management decisions. We might consider the following “system” for environmental flow management (Figure 8). The top box is what we can control… the release valves and diversions along the river. The bottom box is what we are trying to achieve through environmental flow management. Each arrow is a linkage that is modelled during the environmental flow study.

The first link (indicated by an arrow in the system diagram below) is usually modelled using a water resource allocation model (e.g. REALM). The second link is modelled using a flow routing procedure (sometimes REALM is used for this too). The third link is modelled using a hydraulic model for a sample reach of the river. The final link is normally modelled conceptually during the environmental flow study rather than explicitly using a mathematical model. Some relation (e.g. linear) between the hydraulic variables and biological response will need to be assumed (and possibly tested).

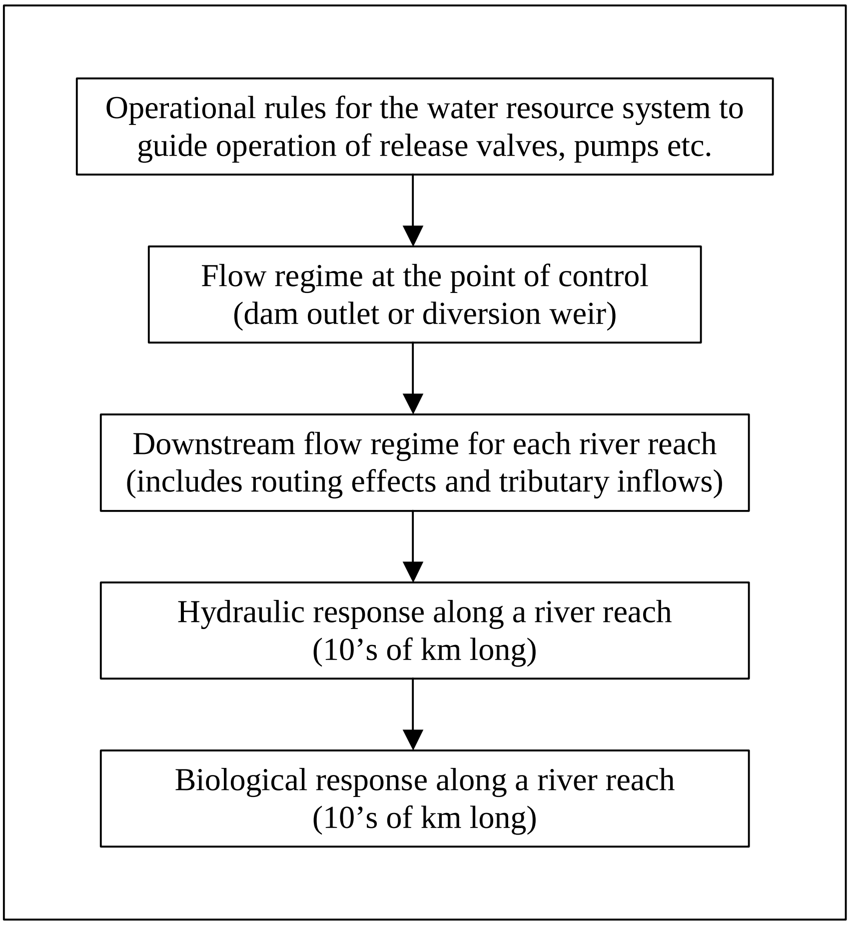


**Figure 8: System diagram representing responses to environmental flow management.**

Models used to represent each link in this system are uncertain. We often ignore this uncertainty during the environmental water allocation process. However, when it comes to monitoring, we need to examine this uncertainty carefully. Indeed it is this uncertainty we are trying to reduce through the monitoring program. If there was no uncertainty we would not need to monitor responses, our models would be sufficient.

It is often assumed that the physical parts of the system (flow modelling and hydraulic response) are well known and uncertainties are insignificant in the face of biological uncertainties. Our experience is that this is often wrong. Uncertainties associated with the physical modelling can be large and it will be difficult to interpret the results of a biological monitoring program if we do not also address the uncertainty in the physical responses through a carefully designed physical-response monitoring program.

Although uncertainties are large, we often have a good understanding of the form of these responses (i.e. model structure):

- hydraulic habitat variability along a reach using a representative sample reach,
- assuming the climate over the monitoring period is similar to the historical climate sequence (e.g. we are not entering a 5 year drought), or
- selection of model parameters such as Manning’s roughness parameter in the hydraulic model or parameters for the flow routing model.

A long history of hydraulics and hydrologic research gives us a reliable set of models for representing physical responses to flow management decisions. The uncertainty is associated with representing environmental variability by sampling and selecting input parameters for models. These uncertainties can be quantified as part of the monitoring program design to inform the selection of hydraulic surveys and the need for additional streamflow gauges. They will also identify the surveys required to estimate model parameters.

Note that the system we have drawn above does not include driving variables of rainfall and water demand. These will have a big effect on flow regimes and hence biological response. These driving variables are also quite uncertain and are to be examined by DSE as operating rules are developed for the rivers included in this study (i.e. separately to this project). To appreciate the importance of these drivers, one need only consider the failure of the Experimental Environmental Flow Study for the Campaspe River to deliver an environmental flow release because of an unexpected drought sequence during the monitoring period.

The following steps outline a procedure for including uncertainty issues in monitoring program design:

- identify response models (conceptual)
- evaluate capacity to represent models mathematically
- identify potential sources of uncertainty in response models
    - o natural variability
    - o measurement error
    - o model error
        - ⇨ model structure
        - ⇨ model parameters
- decide on:
    - o –input variables (dam operating rules or hydrograph)
    - o –output variables (habitat variables or biological response)

- Monte-Carlo or other procedure to identify influence of different errors on response
- design monitoring program to:
    - –address key sources of uncertainty in response models, and
    - –inform the state and response of the system.

A hypothetical environmental flow release from Thomson Dam is used to illustrate how the physical components of the monitoring program will be informed by a systematic analysis of model uncertainties. Consider an environmental flow release from Thomson Dam to maintain minimum pool depths during dry periods as refuge areas for large-bodied fish. It is possible to model streamflow along each reach of the river using a routing model and gauged streamflow data. We can then sample and model hydraulic conditions along the reach to establish the distribution of pool depths at our biological survey sites for a range of low flows. A Monte-Carlo analysis based on error models of input parameters can then be used to estimate our uncertainty in the change in pool depths with the release of the environmental flow. Error in our input parameters for the Monte-Carlo analysis will be modified to represent the benefits of additional data collection (e.g. new streamflow gauges, long length of river surveys, surveys undertaken at a greater number of locations). The optimum survey design will be that which returns sufficient confidence in the hydraulic response for the least cost and it is possible to experiment numerically with alternate survey designs to find an optimum.

# 8 APPENDIX 3: POTENTIAL STUDY DESIGNS

The study designs identified in Table 6 have the following characteristics:

1. **Intervention-only design**. In circumstances where an environmental flow regime has already been implemented (no before-intervention data are available) 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 models, which in turn are based on best-available scientific information and previous studies. Causal links between temporal change in ecological response and flow are difficult to determine because the change might have occurred independently of the environmental flow. This design is very common, especially for larger rivers (no 'controls') and when regional-scale (state-wide) assessment is required.

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 understanding causal links between temporal change in response and flow, because natural changes through time can be measured at reference locations. It is also possible to assess whether the trend of change at the intervention location is towards the reference condition or not.

3. **Control–Intervention design.** Like (2) above except that comparison is with the '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 simultaneous comparison with the spatial 'control' reduces the likelihood of flow effects being confounded with effects of 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.

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 changes in the intervention system. This design allows assessment of whether the trend in a response is towards the reference condition or not. The test of interest is whether any before–after difference at the intervention

location is the same as any such change 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.

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 'control' 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. Designs involving control-intervention contrasts are improved by having multiple control streams (e.g. MBACI designs), which strengthens evidence against the argument that the change observed in the intervention stream might have happened regardless of the intervention (environmental flow).