Comparative Evaluation of Environmental Flow Assessment Techniques: Best Practice Framework

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The research project 'Comparative Evaluation of Environmental Flow Assessment Techniques' has produced the following four reports.

Arthington, A.H., Pusey, B.J., Brizga, S.O., McCosker, R.O., Bunn, S.E. and Growns, I.O. (1998) *Comparative Evaluation of Environmental Flow Assessment Techniques: R&D Requirements.* LWRRDC Occasional Paper 24/98. ISBN 0 642 26743 X.

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List of abbreviations

ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
DNR	Department of Natural Resources, Queensland
LWRRDC	Land and Water Resources Research and Development Corporation

1. Introduction

This report is one of four arising from the project 'Comparative Evaluation of Environmental Flow Assessment Techniques' ' funded by Environment Australia, the Land and Water Resources Research and Development Corporation (LWRRDC) and the National Landcare Program. An introduction to the project is provided in the first report, *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods* (Arthington & Zalucki 1998a).

The objectives of the project are as follows.

1. Review currently used and available techniques for assessing flow requirements, so that water managers have the key information and recommendations on which techniques are suitable for which suite of environmental values, their limitations, advantages and cost-effectiveness.
2. Propose a 'best practice' framework for the application of techniques to environmental flow assessment.
3. Provide research and development priorities for the refinement, development and integration of the techniques to facilitate their use in water allocation and water reform.

Reports arising from the project are:

- *Comparative Evaluation of Environmental Flow Assessment Techniques: R&D Requirements* (Arthington, Pusey, Brizga, McCosker, Bunn & Growns 1998a).
- *Comparative Evaluation of Environmental Flow Assessment Techniques: Best Practice Framework* (Arthington, Brizga & Kennard, this report).
- *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Holistic Methodologies* (Arthington 1998a).
- *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods* (Arthington & Zalucki 1998a).

This report is concerned with a best practice framework for environmental flow assessments in Australia. It attempts to rationalise the different approaches and holistic methodologies developed and/or applied in Australia and to suggest the most appropriate contexts for their use.

A three-tiered system of environmental flow assessments is suggested, to accommodate relatively rapid reconnaissance studies at catchment scale, holistic studies for determination of ecosystem flow requirements at the catchment or sub-catchment scale, and detailed investigation of special issues at all scales. This hierarchy includes a temporal dimension to ensure that sufficient time is allowed for the application of each methodology at appropriate spatial scales. Of particular relevance is the level of background knowledge of the catchment and river system in question, and the time required to fill essential knowledge gaps before the assessment can proceed or be completed. A time frame is suggested for each tier of the assessment hierarchy, with the proviso that it should be adjusted as the need arises in particular circumstances.

The three-tiered system of environmental flow assessment is nested within a single overarching best practice framework applicable to regulated and unregulated river systems. The framework, adapted from Brizga (1998), presents a structured and systematic methodology for environmental flow assessment incorporating consideration of factors other than flow which may influence river condition and the effectiveness of flow allocations and flow management. It also includes a process for addressing human use and water infrastructure constraints in a realistic fashion.

Environmental flow methodologies applied in Australia are all dependent to some degree on professional judgements made on the basis of the best scientific information available and experience. Scientific panels give this advice to the best of their ability, often within very short time frames. All holistic methodologies recognise the constraints imposed by inadequate scientific data (especially long-term data) and the weakness of environmental flow recommendations based on professional judgement. To overcome this they recommend a process of monitoring and further research with a feedback loop to ensure that the flow management strategy is revised and adjusted as new information becomes available. This process of generating and testing hypotheses is essential to strengthen the particular flow assessment, and to add to our broader understanding of river ecology and processes driven by the flow regime. Without it, environmental flow strategies will continue to be based on surrogate measures of biological requirements and ecological processes.

Monitoring and appraisal of the outcomes and benefits of environmental flows, and a phase of special investigations and/or research, are important features of the proposed best practice framework.

2. Context of environmental flow assessments

To fulfil the objectives of the Council of Australian Government's water reform process and uphold the National Principles for the Provision of Water for Ecosystems (ARMCANZ & ANZECC 1996), environmental flows must be assessed and provided in many different contexts. The two fundamental contexts are regulated and unregulated river systems.

Regulated systems are those where natural flows are managed by major structural interventions, that is, inter-basin transfers, major dams, large weirs, distribution channels and associated water management infrastructure. In unregulated systems, the flow regime may be variously modified from the natural state by changes in land use, farm dams, levee systems, minor and major water diversions, harvesting of within-channel floods and floodplain flows, wetland modifications (infilling, drainage, diversion) and groundwater pumping. These incremental developments of a catchment and its water resources can have a substantial effect on the natural flow regime.

In regulated and unregulated river systems, environmental flow assessments may vary greatly in scale, from relatively simple flow restoration projects in a single reach of a regulated river to whole-of-catchment water resource planning in large basins with a mixture of regulated and unregulated tributaries. Different methods are likely to be appropriate at these different spatial scales (Tharme 1996; Dunbar et al. 1998).

The third contextual issue is the level of development and commitment of existing water resources to consumptive use, and the scope for improving existing system management or greatly expanding the development of water resources in the catchment. Existing uses and infrastructure arrangements place a constraint on the provision, and sometimes the effectiveness, of environmental flows and these constraints must be taken into consideration in a realistic fashion as part of the assessment process.

Other significant variables are the size of the river basin and the nature of the flow regime, which may vary from intermittent to perennial, and from seasonally predictable to highly unpredictable in nature. Flow regimes may differ considerably in the sub-catchments of very large river basins (eg. the Burdekin; see Pusey & Arthington 1996). The extent and role of groundwater systems is another variable that is generally given only limited consideration in environmental flow assessments.

The assessment of environmental flows originated in freshwater systems, whereas holistic assessments of the riverine ecosystem must consider the influence of river flows on downstream tidal systems (estuaries, coastal wetlands, coastal embayments, near-shore waters, offshore islands, and so on). To establish these linkages and build them into environmental flow assessments requires a different and largely new set of methods.

Environmental flow studies have been criticised by scientists participating in the studies and by the broader community for focusing on flow-related issues and management strategies to the virtual exclusion of other factors which influence the condition of river systems. These other factors include vegetation clearing, agricultural development, forestry, roads, present and historical mining, river and floodplain management, and urban development. Assessments of the impacts of regulation carried out as part of environmental flow studies need to determine the significance of flow regulation relative to other factors in terms of producing observed disturbances, as not all observed changes and disturbances are flow-related and the effects of some changes may cancel out or compensate for flow-related impacts. A focus on flow-related issues stems partly from the definition of the scope of environmental flows studies within their terms of reference, as well as the narrow focus on flow which is inherent in the majority of existing environmental flow methodologies (Brizga 1998). Some methodologies incorporate a process for considering other influences on river condition (eg. the Flow Restoration Methodology, Arthington 1998b) but there is no framework suitable for integrating the full range of anthropogenic disturbances into environmental flow assessments.

Frameworks for assessing environmental flows must have a number of properties to address all of these circumstances at the most relevant spatial and temporal scales. Holistic methodologies reviewed in LWRRDC Occasional Paper Number 26/98, *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Holistic Methodologies* (Arthington 1998a), are a significant improvement on traditional single-issue methods because they aim to consider the needs of the entire riverine ecosystem. However, no existing methodology is entirely suited to all circumstances of environmental flow assessment and management in Australia, and most methodologies do not give adequate consideration to management issues that are not related to river flows. Each methodology has its strengths and original elements, and these need to be evaluated and incorporated into a best practice framework for river flow management.

The next section of this report aims to rationalise the different approaches and holistic methodologies used in Australia and to suggest the most appropriate contexts for their use.

3. Types of environmental flow methodology

Holistic methodologies for assessing environmental flows may take one of two fundamentally different approaches, or may combine both approaches (Brizga 1998):

- a 'bottom-up' approach, where the environmental flow regime is built up by flows requested for specific purposes from a starting point of zero flows;
- a 'top-down' approach, where the environmental flow regime is developed by determining the maximum acceptable departure from natural flow conditions.

Bottom-up approaches are commonly used in Australia but new top-down processes are emerging from recent studies. The most useful elements of these two approaches, and how they could be integrated, are discussed below.

3.1 Bottom-up approaches

Most of the holistic methodologies used in Australia are basically variations on the theme of building a flow regime from the bottom up, starting with low flows and adding freshes and floods to cover the full range of natural flows. These methodologies include:

- Holistic Approach;
- Building Block Methodology;
- Expert/Scientific Panel Assessment Method;
- Habitat Analysis Method; and
- Flow Restoration Methodology.

The type of flow regime developed on the basis of bottom-up methodologies depends on the knowledge base of the participants in the process and the availability of reliable data about the river system or others of a similar nature. The scientific basis of these methodologies varies, from visual inspections by a scientific panel to more systematic analysis of the river system involving a detailed assessment of the flow requirements of as many ecosystem 'components' as possible. Most methodologies involve a multidisciplinary approach, which starts with consideration of the flows required to maintain geomorphological processes and channel structure, and then considers the habitat, reproductive and dispersal requirements of aquatic plants, riparian vegetation, aquatic invertebrates and fish. The needs of 'water-dependent wildlife' (frogs, reptiles, the platypus, mammals and birds) are increasingly being considered, as are the flows that influence certain aspects of water quality. Flows are also being recommended to maintain various ecological processes (eg. nutrient and energy exchanges between the river channel and its floodplain, and the ecological linkages between rivers, estuaries and coastal waters).

All bottom-up methodologies are vulnerable to the charge that there is a limited quantitative basis to estimating the 'blocks' of flow which make up the overall flow recommendation. Flows that provide habitat for aquatic biota may be quantified using a 'wetted perimeter', transect or habitat modelling approach (eg. the In-stream Flow Incremental Methodology), with various additions to these flows to ensure biological processes such as fish migration and reproduction, plant recruitment, and so on. Although attention has been given to identifying flushing flows for various geomorphological and ecological purposes, there are very few quantitative methods to define the relationship between various sizes and characteristics of freshes and floods and the geomorphological and ecological processes they sustain (eg. channel structure, habitat heterogeneity, nutrient and energy exchanges with the floodplain, movements of biota, estuarine processes). For example, Brizga (1998) concluded that quantification of flows for geomorphological purposes is limited by a lack of methods to quantify both flow and sediment-driven processes.

Bottom-up holistic approaches depend upon historical flow data for the catchment, preferably daily flow data, to provide a sound understanding of the 'natural' flow regime and the extent to which it has been modified. The development of a hydrological model with a daily time step, representing the entire catchment and capable of simulating extended historical flow sequences, is becoming an essential part of environmental flow assessments. However, there is concern as to the accuracy of these models at very low and very high flows, specifically, that they do not account for the effects of changes in land use and other catchment modifications on the flow regime. Another concern is that the time lengths of flow and rainfall records used to simulate historical flow sequences may not be long enough to capture cyclic and episodic flow patterns and events, El Niño phenomena or the effects of climate change. In this context, the closure of many stream-gauging stations in Queensland and other areas of Australia was unfortunate.

Bottom-up construction of modified flow regimes is likely to form the basis of most Australian environmental flow assessments into the foreseeable future for the following reasons.

1. Understanding of flow-ecology relationships is improving rapidly, so the approach is becoming more acceptable to scientists, water managers and the community.
2. Water managers have generally accepted that some features of the 'natural' flow regime are more important than others and must be maintained in modified flow regimes to protect aquatic habitat and biota, geomorphological and ecological processes and ecosystem 'values'.
3. A bottom-up approach has become entrenched within all holistic frameworks in use in Australia.
4. A bottom-up approach can be applied in regulated and unregulated rivers, at all spatial scales and in all development contexts.
5. The alternative top-down approach is new, challenging to quantify and needs further development and testing.

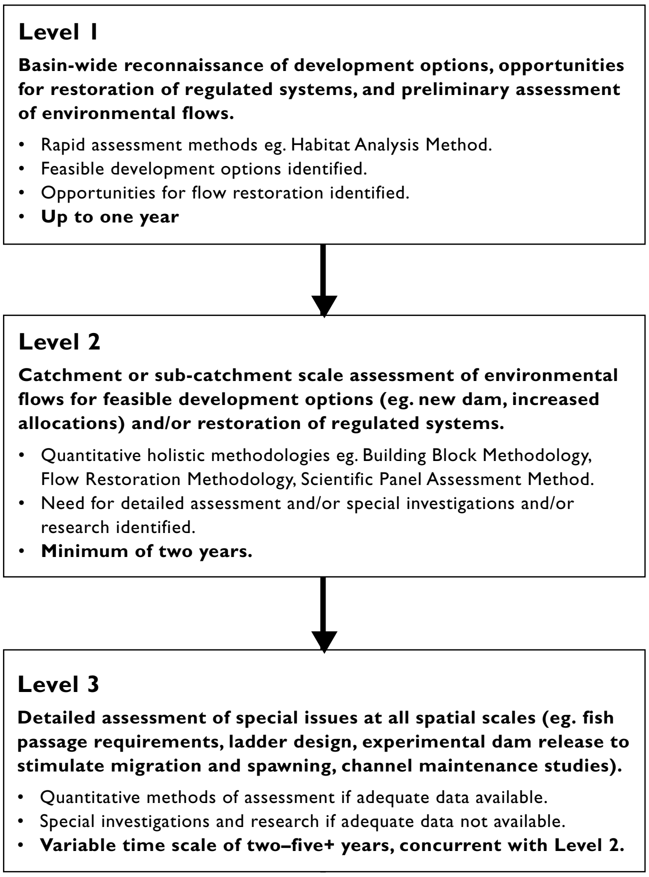
3.2 Best practice for bottom-up assessments

Tharme (1996) and Dunbar et al. (1998) suggested a three-tiered hierarchy to accommodate the circumstances, objectives and spatial scales of environmental flow assessments. A three-tiered hierarchy is recommended here as the best practice framework for application of bottom-up approaches. It is summarised in Figure 1 and elaborated below.

Environmental flow assessments must also be developed within an appropriate temporal framework, one that recognises the time required to apply each methodology at the appropriate spatial scales. Of particular relevance in Australia is the level of background knowledge of the catchment and river system in question, and the time required to fill essential knowledge gaps before the assessment can proceed or be completed. Although some environmental flow assessments may need to be conducted rapidly to match very short planning horizons (and political agendas), new water resource projects take time to plan, consider and test alternatives for the location and design of infrastructure. Flow restoration projects involving extensive and costly modifications to water infrastructure tend not to proceed very rapidly.

There is, therefore, a lengthy period for the conduct of most environmental flow assessments, and time can be spent on more detailed assessments, experimental investigation of special issues and original research. Dams are not built using professional judgement based on the best scientific information available. They are built according to detailed specifications based on decades of scientific research plus assessments of the unique features of each construction site, and they are built to withstand and outlast the vagaries of climate and river discharge. Environmental flow regimes should be 'built' in the same fashion, based on old and new scientific understanding plus assessments of the unique

Figure 1: *Hierarchy for environmental flow assessments*



Level 1

Basin-wide reconnaissance of development options, opportunities for restoration of regulated systems, and preliminary assessment of environmental flows.

- Rapid assessment methods eg. Habitat Analysis Method.
- Feasible development options identified.
- Opportunities for flow restoration identified.
- **Up to one year**

Level 2

Catchment or sub-catchment scale assessment of environmental flows for feasible development options (eg. new dam, increased allocations) and/or restoration of regulated systems.

- Quantitative holistic methodologies eg. Building Block Methodology, Flow Restoration Methodology, Scientific Panel Assessment Method.
- Need for detailed assessment and/or special investigations and/or research identified.
- **Minimum of two years.**

Level 3

Detailed assessment of special issues at all spatial scales (eg. fish passage requirements, ladder design, experimental dam release to stimulate migration and spawning, channel maintenance studies).

- Quantitative methods of assessment if adequate data available.
- Special investigations and research if adequate data not available.
- **Variable time scale of two–five+ years, concurrent with Level 2.**

features of each river system and with a capacity to predict outcomes under different climatic and discharge conditions.

3.2.1 Basin-wide assessments

This level of assessment involves basin-wide reconnaissance of environmental flow requirements in the context of assessing possible development options, dam sites, opportunities for allocation of unregulated flows, and so on. At this whole-of-catchment scale of assessment, a relatively rapid method is required to assess the environmental implications of many alternative development scenarios. Simple hydrological methods, such as the Montana Method, flow-duration curve analysis (see Pusey 1998) or 'bulk water estimates' (Tharme 1996), have been used at the reconnaissance level of flow assessments.

The Queensland Water Allocation and Management Planning Initiative has developed a rapid method to estimate the flows required to maintain all types of habitat, using habitat as a 'surrogate' for assessing the flow requirements of the various biological and other components of the riverine system. This is termed the Habitat Analysis Method (Walter et al. 1994; Burgess & Vanderbyl 1996).

The Habitat Analysis Method is a bottom-up approach which identifies aquatic habitats in a catchment or tributary, and then uses key flow statistics to describe the flows that will maintain those habitats, plus a few biological 'trigger' flows and some larger flows to maintain geomorphological and ecological processes (eg. nutrient and energy exchanges with the floodplain). The key flow statistics include measures of water quantity and temporal aspects of desirable flows (eg. for floodplain flows, the key flow statistic is the frequency of flooding, with the size of the flood [discharge] determined from floodplain elevations). The Habitat Analysis Method is relatively rapid, as it usually does not involve original field work in the catchment (although some critics would argue that a reconnaissance field trip is essential to appreciate the habitat characteristics of different geomorphological zones). The Habitat Analysis Method is suitable for determining desirable environmental flows at many different points in a catchment, rather than at a few critical sites within representative reaches (Burgess & Vanderbyl 1996).

The Habitat Analysis Method for constructing a modified flow regime has developed considerably since its first formulation (Walter et al. 1994) but could be strengthened in several ways. The whole process could be refined and standardised so that each study assembles a certain set of background information and records and presents it to the Technical Advisory Panel in an agreed format. The flow bands, which essentially determine the wetting up of different habitats (eg. within-channel, riparian, wetland and floodplain), could be refined. More flow 'events' could be added (eg. to ensure fish passage, to stimulate fish migration and spawning, to maintain larval fish habitats, to flush sediments, and maintain other ecological processes – see the Logan River trial of the Building Block Methodology and the Brisbane River trial of the Flow Restoration Methodology). The number and types of key flow statistics describing these processes could be increased. Various statistics have been explored in the Fitzroy Water Allocation and Management Planning project (DNRQ 1998b). Two Australian flow characterisation projects are exploring alternative flow statistics to develop a broad protocol for describing flow regimes in ecologically meaningful terms. Some rationalisation of approaches and flow statistics is warranted.

The Habitat Analysis Method and use of key flow statistics is considered to be superior to simple hydrological methods, such as the Montana Method and flow-duration curve analysis (see Pusey 1998), traditionally used at the reconnaissance level of flow assessments. However, the Habitat Analysis Method is not sufficient for environmental flow assessments at the next level in the hierarchy, which requires a more detailed, holistic assessment of environmental flow requirements.

Basin-wide reconnaissance of environmental flow requirements require *a minimum of one year* in a large catchment, but this can vary depending upon such factors as the time required to construct a hydrological model of the catchment and the level of background information available.

3.2.2 Holistic catchment or sub-catchment assessments

This level of assessment would follow on from a basin-wide reconnaissance of possible development options. It might apply to selected sub-catchments where more detailed environmental flow specifications are required before dams and other water infrastructure can be designed, or where there is a need to improve existing water management practices by restoring some elements of the flow regime or modifying the infrastructure. These circumstances require a far greater level of detail in the application of bottom-up approaches. The spatial scale of most of the assessment may involve a few sub-catchments, but the implications of flow scenarios would need to be considered in terms of water management in the whole catchment, including downstream estuarine and coastal systems.

The Holistic/Building Block Methodology and the Flow Restoration Methodology are appropriate models for use at this level of flow assessment (see Tharme 1996). These methodologies have the potential to assess the needs of all ecosystem components. The Building Block Methodology is used mainly to construct modified flow regimes in rivers proposed for future development, whereas the Flow Restoration Methodology is designed to implement environmental flows in rivers with a history of flow regulation. At this scale of assessment, the methods used to assess the flow requirements of the whole system (channel structure, invertebrates, fish, aquatic and riparian vegetation) should be as quantitative as possible. Quantitative methods should be selected on the basis of their suitability for addressing the key issues in the catchment, and the available information base for the river system. Professional judgements must be made in selecting appropriate methods from the array reviewed in this study (Arthington & Zalucki 1998a) and other literature. If suitable quantitative methods are not available, environmental flow recommendations must be based on professional judgement using the best scientific information for the catchment or similar catchments.

The Building Block Methodology is the most structured and well-documented methodology available for constructing a flow regime from the bottom up, and well worth further exploration in Australia. It continues to develop and improve in South African applications, and the Logan River trial in Queensland has added new quantitative methods for assessing the flow requirements of invertebrates, aquatic macrophytes and freshwater and estuarine fish (see Arthington & Long 1997; Arthington & Lloyd 1998). A Building Block Methodology manual will shortly be available in South Africa.

The Holistic Approach remains a loose set of methods for bottom-up construction of a flow regime. It has been applied in various ways in Australia (eg. Davies et al. 1996; Growns & Growns 1997), and forms the basis of most holistic frameworks (eg. Scientific Panel Assessment Method; Flow Restoration Methodology). These applications continue to improve the basic bottom-up approach and its suitability in both regulated and unregulated rivers.

The Flow Restoration Methodology is based on the Holistic Approach, with various features adapted from the Building Block Methodology to address the problem of restoring flows in regulated river systems. It is technically more rigorous than the Scientific Panel Assessment Method (Thoms et al. 1996), although the latter does include a second tier of investigation and research to be conducted at a later stage, as does the Flow Restoration Methodology. New South Wales appears to be using a similar bottom-up approach and various rules for assessing and managing environmental flows in regulated and unregulated river systems. A Rapid Assessment Methodology is being developed in Victoria for use in streams which are not regulated by major impoundments; this appears to be taking a simple bottom-up approach but documentation has not been reviewed here.

The best elements of all of these bottom-up approaches could be developed into a standard Australian methodology to parallel the Building Block Methodology for use at the intermediate level of environmental flow assessments. Such a methodology would sit comfortably within the framework of the Water Allocation and Management Planning catchment-wide assessment process, and provide the rigour needed to address detailed flow requirements in existing regulated systems as well as in areas destined for future regulation.

The sub-catchment level of environmental flow assessments requires *a minimum of two years* to conduct, depending upon the level of quantitative information available. If basic life-history phenomena are not known for key species of fish and riparian and aquatic plants, then field surveys over at least 18 months will be required to establish the timing of reproduction and recruitment processes.

At this second level of assessment, some aspects of environmental flow recommendations will be based on limited data and professional judgement, and will amount to hypotheses about flow-geomorphology and flow-ecology relationships. These issues should be referred to the third level of the assessment hierarchy for further investigation and research.

3.2.3 Detailed assessments at all spatial scales

The third level of environmental flow assessment would be nested within the second, and applied where quantitative assessments are essential and there are limited data available on important issues and processes. For example, a flow restoration project may involve substantial modifications to water infrastructure, such as outlet pipes or a sediment bypass facility, and considerable expense. Detailed assessment of environmental flow requirements would be important to ensure that the best approach is taken to infrastructure design and water management strategies. The spatial scale of detailed assessments may vary from site to reach level (eg. requirements of an endangered fish species), but may also involve consideration of processes operating over sub-catchment and catchment scales (eg. floodplain processes).

Tharme (1996) suggested that this level of assessment might use the Building Block Methodology to address the needs of the whole ecosystem, but a method such as Physical Habitat Simulation (PHABSIM) could be applied to assess the requirement of a protected fish species, for example. However, Tharme (1996) noted that PHABSIM outputs are limited to losses and gains of physical habitat with changes in discharge, and do not address movement, reproductive requirements and other processes affecting the survival and recruitment of individual fish species, let alone the needs of fish assemblages and aquatic invertebrate communities (see also Pusey & Arthington 1991; Pusey 1998).

In many catchments, it will not be possible to assess the environmental flow requirements of significant aquatic species or communities, or complex interactions between flow, sediment and processes affecting channel and bank structure and so on, without conducting short-term experimental release studies or other special investigations, or longer term research on key processes. The opportunity for focused investigations and research should be built into this third tier of the environmental flow assessment hierarchy. Most holistic methodologies recognise this and recommend further investigations and special research projects in the catchment.

The time frames of detailed quantitative flow assessments, special investigations and research will vary but, as a guide, it is suggested that the assessment of special issues should run concurrently with the second tier holistic assessments and may extend anywhere from *two–five+ years.* The timing of each project would be related to the timetable of water infrastructure design and construction, with each investigation producing its outcomes at the appropriate time to guide planning and design.

4. Top-down approaches

4.1 System targets

Bottom-up methodologies are all vulnerable to lack of data and limited understanding of processes and may therefore leave out some critical component of the flow regime (Bunn 1998). As the knowledge base increases, more detail and refinement can be seen in environmental flow recommendations. It has been noted that the more that is known about a river system, the closer the recommended environmental flow regime is likely to come to the natural regime (Bunn 1998). Whilst this may be an admirable outcome from a scientific perspective, it leaves water managers with little scope for consumptive water use. This dilemma has been put in terms of the question: How much water does a river need? (Richter et al. 1997), to which a scientist might reply: What sort of river do we want?

A significant difficulty with all bottom-up approaches is to define the overall objective of the environmental flow regime. Targets such as 'desired future state', 'maintenance of current environmental values' and 'maintain maximum environmental benefits' are not easy to translate into quantitative end-points for the river, or condition indices, or other measures of ecosystem function. There are also the issues of who should decide on the objectives for a particular river system and how different perspectives should be reconciled.

A process is needed whereby different environmental flow scenarios can be related to different ecological end-points for the river. One suggestion from the Logan River trial of the Building Block Methodology was that the desired future state could be refined into a series of much more specific objectives for each ecosystem 'component'. For example, flows to maintain the species diversity of the fish fauna, and to achieve normal migrations, reproductive processes and productivity, would be reasonable objectives for a fish ecologist to address in a river destined for further water resource development, or in a regulated river where restoration of the modified flow regime is the objective of the study. These broad objectives could be refined down to a series of clearly identified targets for the assessment of environmental flows (eg. habitat for all life history stages, fish passage in critical reaches, access to spawning and larval habitat on the floodplain).

Even if the knowledge base does not permit such detailed objectives to be assessed comprehensively, working through them and relating them back to elements of the flow regime is regarded as essential to introduce greater rigour into flow assessments.

The Building Block Methodology produces one flow regime for river maintenance and one for drought conditions. After the workshop, alternative desired future states and flow regimes are evaluated (see King & Louw 1998). A focus on meeting specific objectives would facilitate the assessment of these different scenarios and the probable outcomes for the river if some components of the recommended environmental flow regime cannot be provided. Clear objectives are also required to establish relevant components in the monitoring program and to assess how well it achieves the desired future state for the river.

An alternative to post-workshop evaluation of different flow scenarios for achieving different future states is to construct several different scenarios during the workshop, each addressing a different river state (Arthington & Lloyd 1998). Apart from the effort required to construct more than one flow regime from the bottom up (at least one day per river site), there still remains the enormous uncertainty as to the ecological outcomes of each flow regime for the river system.

Predicting what might happen when a river system receives reduced quantities of flow might be amenable to some type of habitat modelling exercise (eg. use of PHABSIM or a model relating stage heights to degree of wetland inundation). However, predicting ecological outcomes when quantitative plus temporal features of flow regimes vary from natural is far more difficult. All holistic methodologies aim to mimic the temporal characteristics of the natural flow regime, expressed as timing, frequency, flood peak, flood duration, and rate of rise and fall of flood levels. There would be few instances where the effect of altering even a few of these attributes can be predicted for a single species, let alone all biological components of a river system. Some other process for assessing the ecological implications of modified flow regimes is needed.

4.2 Evaluating outcomes of modified flow regimes

The ecological implications of modified flow regimes cannot be predicted from the bottom up by predicting outcomes for each ecosystem component and then integrating those predictions to produce a series of alternative outcomes for a river system. Such a capacity is highly desirable, and to develop it should be one of the main targets of environmental flow research.

The alternative to predicting from the bottom up is a 'top-down' approach whereby the environmental flow regime is developed by determining the maximum acceptable departure from natural flow conditions (Brizga 1998). In Australia, two frameworks have added a top-down process for assessing the ecological implications of alternative modified flow regimes. These are:

- Habitat Analysis Method and benchmarking; and
- Flow Restoration Methodology

The Environmental Flows Decision Support System (Young et al. 1995) aims to develop a series of simple models to demonstrate the possible outcomes of various flow modifications, but this is not yet available as a fully documented process.

4.2.1 Habitat Analysis Method and benchmarking

The benchmarking process developed during the Fitzroy Water Allocation and Management Planning project (DNR 1998a, 1998b) determines environmental flows from the bottom up and then assesses the maximum acceptable departure of the flow regime from natural conditions. The environmental flow requirements of the riverine ecosystem are built up from lowest to highest desirable flows, each flow addressing an important geomorphological or ecological requirement. The total environmental regime is theoretically close to the natural one if the construction process is comprehensive and includes all relevant ecosystem components and ecological processes. Key flow statistics or hydrological indicators are used to describe the geomorphological and ecological conditions desired in the river system. At present the focus is on flows to maintain habitats, biological triggers and ecological processes (DNR 1998b).

Flow management rules are constructed to maintain critical flow thresholds and to mimic such features as the natural timing, frequency and duration associated with each flow threshold. Simulations are then run to capture different scenarios of water resource development plus the relevant environmental flow requirements. The resulting flow regimes are analysed to produce a series of key descriptive statistics, each statistic describing the quantitative or temporal dimensions of the critical flow thresholds, such as the frequency of riparian or floodplain inundation. Each key statistic is then compared with the value for the natural, unregulated flow regime, and the percentage change from the natural flow regime is calculated. Limits on the acceptable deviation from the natural flow regime are identified by comparison with other river systems which have been degraded through specific types of flow regulation. For example, a relatively small change in the frequency of floodplain inundation may equate to a very degraded floodplain ecosystem. This process of comparison with degraded river systems has been termed 'benchmarking' (DNR 1998b; Vanderbyl 1998).

By taking an overall view of about 12 statistics describing key features of the flow regime, the benchmarking process can be used to rate each water management scenario in terms of its potential impact on the river ecosystem. At its present stage of development, benchmarking can be used to rank a flow scenario as likely to have relatively little impact, or likely to produce a degraded or seriously degraded river system.

4.2.2 Flow Restoration Methodology

The Habitat Analysis Method and benchmarking were developed for rapid assessment of options for future water resource development at the scale of whole catchments, some of them very large (eg. the Fitzroy system). The benchmarking process assesses how a river might respond when a flow regime is progressively altered from the natural state. The Flow Restoration Methodology is applied in the opposite circumstance (that is, regulated river systems) where the question is how a river might respond when a flow regime becomes progressively more like the natural state (Arthington 1998b; Arthington & Zalucki 1998b).

The Flow Restoration Methodology uses original field and desktop studies to determine the effects of past and present flow regulation on the river ecosystem, and develops flow scenarios from the bottom up, each scenario gradually reinstating the flows that have been modified by regulation and deemed necessary to restore ecological functions. The resultant flow regimes are then described using key hydrological statistics. These statistics are compared with those for the unregulated flow regime to assess the effect on the river of not reinstating various flow characteristics. This methodology uses historic photographs and maps, ecological data from adjacent catchments, and predictive models to provide the benchmarks for the unregulated condition, and to assess the effects of existing flow regulation. It does not presently include a process for benchmarking the effects of flow restoration, other than by consideration of the degree of change in each hydrological statistic if desirable flows are not reinstated.

The ecological outcomes of not reinstating desirable flows can be assessed quantitatively, for example, by predicting habitat availability at different discharges or by predicting species composition using a RIVPACS type of approach. Kennard et al. (1998) developed a RIVPACS-type model to predict fish species composition from data on fish-habitat relationships in catchments adjacent to the Brisbane River. The model was used to predict the species expected in the habitats available at selected sites in the Brisbane River, and outcomes interpreted in terms of the possible effect of Wivenhoe Dam and flow regulation. Such a model could be used in the alternative circumstance, that is, to predict the species expected on the basis of habitat changes as natural flows are progressively restored, although such an application has not been attempted to date.

Flow restoration projects could adopt the Water Allocation and Management Planning benchmarking procedure to rank the outcomes of not restoring critical flows. This would require that nearby catchments with similar flow regimes have been regulated in similar ways to the river being studied and to various degrees, so that a sliding scale of ecological responses to flow regulation is available. Relevant ecological data would need to be available or collected in suitable formats. Unfortunately, regulated catchments in south-eastern Queensland are not suitable as benchmarks for the different types and degrees of regulation occurring in the Brisbane River system, where the Flow Restoration Methodology was developed.

4.2.3 Environmental Flows Decision Support System

The intention of the Environmental Flows Decision Support System project (Young et al. 1995) is to develop a series of simple models which will assist users to identify how changes in a river's flow regime will affect various ecological indices of river condition (Young et al. 1995). Models will be developed to show the effects of hydrological change on such features as fish populations, riparian vegetation and algal blooms. This approach assumes sufficient knowledge and understanding to predict the effects of flow regimes on ecological indices of river condition. An ecology-flows handbook will underpin the development of the predictive models. The approach is commendable but is entirely dependent upon adequate data and understanding to develop the predictive models. Benchmarking against degraded catchments was developed because it is generally not possible to model and predict ecological outcomes of different levels of flow regulation or flow restoration in regulated rivers.

4.3 Best practice for top-down assessments

There are significant parallels between the top-down procedures now employed in the Queensland Water Allocation and Management Planning benchmarking system and the Flow Restoration Methodology. The best elements of these procedures could be developed into a single methodology using an agreed set of key flow statistics and an agreed process for benchmarking in degraded catchments.

A definite limitation of the benchmarking process is that suitable reference systems may not be available to assess the ecological effects of extent of change in key flow statistics. It may be especially difficult to find regulated systems with similar types of flow regime where both quantitative and temporal characteristics have been modified in the same ways or to the same degree as anticipated in the catchments proposed for development or flow restoration. For example, where are the benchmarks for rivers like the Cooper, which is largely unregulated? Where are there examples of floodplains that have been inundated every second or third or fourth year instead of every year, or exposed to some mix of partial inundation and reduced frequency of inundation? How valid is it to compare between river systems if their flow regimes differ from that of the study catchment?

Benchmarking against levels of degradation in other catchments with regulated flow regimes appears to be the strongest top-down approach in use in Australia. It is new, and requires critical evaluation in a series of catchments, as well as in terms of fundamental ecological issues and the best techniques for assessing degradation. These research needs are discussed in LWRRDC Occasional Paper Number 27/98, *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods* (Arthington & Zalucki 1998a).

4.4 Combined bottom-up – top-down approach

The most rigorous approach to holistic environmental flow assessment may be a combined bottom-up – top-down approach, where an environmental flow regime is initially developed using a bottom-up approach, and is then evaluated by cross-checking against a top-down assessment incorporating a benchmarking process to assess the ecological implications of various water management and environmental flow scenarios.

A combined approach could be applied to all three levels of the assessment hierarchy defined above, that is, to reconnaissance and basin level assessments, holistic catchment and sub-catchment assessments and detailed assessments at all spatial scales.

A bottom-up – top-down approach could be incorporated into any of the holistic methodologies used in Australia by adopting (and improving) the benchmarking methods developed in Queensland. Alternatively, a combined bottom-up – top-down approach could be developed into a single standard methodology and prescriptive manual for Australian environmental flow assessments.

The advantage of a uniform approach is that there will be repeated case studies amenable to comparison of outcomes in many different catchments and types of flow environment around Australia. Regional principles for river flow management might be expected to emerge, and any such principles would strengthen the basin-wide assessments based on less rigorous methods.

The utility of the Environmental Flows Decision Support System as a set approach to environmental flow assessment in the Murray-Darling Basin, and possibly in Australia generally, is still open to question. How the system might best be utilised is discussed in the final section of this report.

5. Best practice framework for holistic environmental flow assessments

Previous sections of this report have attempted to rationalise the different approaches and holistic methodologies developed and/or applied in Australia and to suggest the most appropriate contexts for their use. A three-tiered system of environmental flow assessment has been suggested, with the effort and time spent increasing as the spatial scale of assessments decreases, and more focused and quantitative assessments are necessary.

At all levels of this hierarchy, it is suggested that the most rigorous approach to environmental flow assessment should involve a combined bottom-up – top-down approach.

This section of the report presents and describes a single overarching best practice framework for environmental flow assessment, within which the three-tiered system and the combined bottom-up – top-down approach could be nested. The proposed new framework is outlined in Figure 2 (adapted from Brizga 1998).

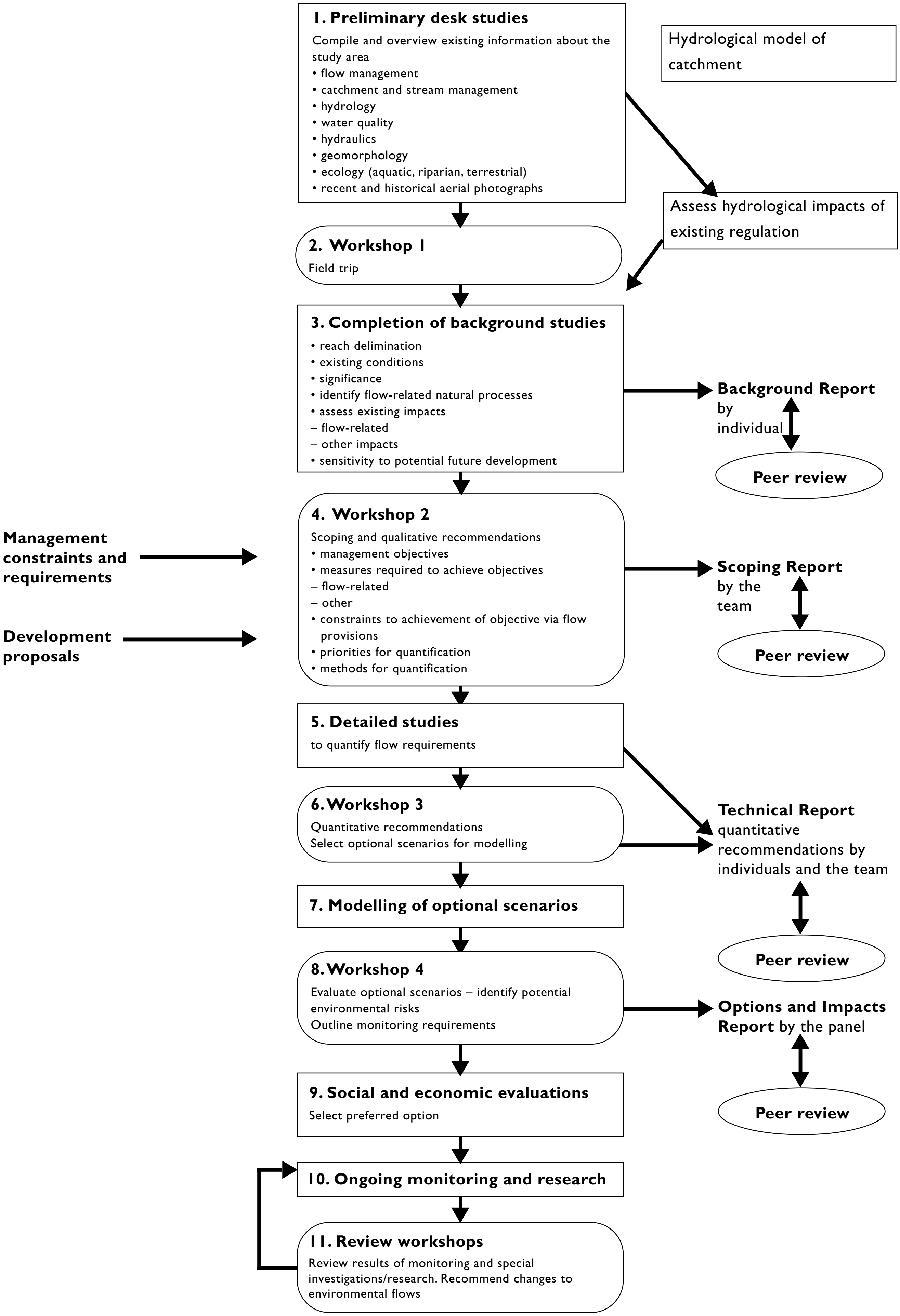
This framework builds on procedures followed in the Building Block Methodology, Water Allocation and Management Planning projects and the Flow Restoration Methodology. It includes a process for considering factors other than flow which may influence river condition and the effectiveness of flow management, as well as a process for addressing human use constraints and their impact on the provision of environmental flows in a realistic fashion. A monitoring and further investigations/research phase is built into the framework, with a feedback loop to permit adjustment of environmental flow allocations if the desired objectives are not being achieved, or better information has become available from special investigations and research.

Key features of this framework include:

- applicability to unregulated and regulated systems;
- a multidisciplinary approach;
- a scoping stage after the completion of background studies and before the commencement of detailed quantitative assessments, so that constraints and trade-offs can be considered before significant efforts are put into quantifying flows which may not be deliverable, or may not provide significant environmental benefit because of other constraints;
- an opportunity to develop a clear focus before detailed quantitative investigations are carried out;
- provision for the acknowledgment of all significant factors, including those which are not flow-related;
- provision to consider the full range of flows, insofar as they affect significant geomorphological and ecological attributes in at least a qualitative manner;
- human use constraints are openly considered and are incorporated into environmental flow objectives as qualifying statements;
- a staged reporting schedule is defined;
- peer review should be incorporated into the process – a review after the completion of each report would allow feedback to be obtained in time to assist in deciding whether further work is necessary to consolidate/complete the tasks to that point, as well as determining directions for the next stage;
- the process provides an ongoing interface with stakeholders through the staged reporting process, and by seeking stakeholder inputs at the scoping workshop; and
- the process includes a monitoring phase and a final workshop where results of initial monitoring and the implications of the results are discussed and possible changes in flow rules are outlined.

The framework set out in Figure 2 (see page 15) has 11 main stages, including 5 multidisciplinary workshops. Square boxes indicate work carried out individually by team members while rounded boxes indicate workshops involving all members of the environmental team. Disciplines which should be included in the environmental team include hydrology, hydraulics, geomorphology, water quality and ecology (aquatic, riparian and terrestrial vegetation, aquatic invertebrates, freshwater and estuarine fish, other water-dependent vertebrates). Close interaction between the disciplines is considered to be necessary because of interdependencies between physical and ecological

Figure 2: *Best practice framework for assessing environmental flows in river systems (adapted from Brizga 1998)*



processes. Workshops are seen as an efficient means of fostering such interaction. There may need to be some individual follow-up work and consultation among team members after the workshops to finalise outcomes at each stage.

The steps and activities envisaged in the framework are as follows.

1. **Preliminary desk studies**. The first step in the process is the compilation and overview of existing relevant information about the study area. This is done by individual team members assigned particular tasks. A hydrological model of the catchment with a daily time step and environmental flow node should be available at this stage of the project. The model is used to describe the natural and existing flow regime and to assess the hydrological impacts of past and existing flow regulation.

2. **Workshop 1**. This is essentially a field inspection of the stream(s) in question, carried out together by the whole study team. It is a familiarisation exercise, which also underpins identification of geomorphological river zones and selection of river reaches for further study.

3. **Completion of background studies**. Completion of the geomorphological and ecological background studies is carried out on the basis of the compilation of existing information, the group field inspections (Workshop 1) and the results of the assessment of hydrological impacts of existing regulation. At this stage, relatively homogenous river zones and reaches are identified that encompass the full range of geomorphological, hydraulic and hydrological variation in the catchment or sub-catchment. Then, for each reach, assessments are undertaken by each team member of existing conditions, significant features, flow-related natural processes, impacts of existing flow regulation and other human activities, and likely sensitivity of the stream to potential future flow-related development. Methodologies for assessment (eg. expert opinion versus detailed studies) will depend on whether the study is a rapid basin-wide assessment or a more detailed assessment of particular development options, and the level of resources available to the project. A background report is prepared by the full team.

4. **Workshop 2**. This is held after the completion of the background studies and circulation of the background report prepared by the team members. Several tasks are undertaken at this workshop:

Task 1. The first task in the workshop is to develop a vision of desired future geomorphological and ecological conditions for the river system and for particular reaches. The vision should take into account inputs from stakeholders, give realistic consideration to human use constraints, and specify what those constraints are. For example, "to provide specified geomorphological and ecological benefits, without exacerbating bank erosion on adjacent properties, and without modification of outlet works of existing dams or reducing security of supply from those dams by more than 5%" (Brizga 1998). The geomorphological and ecological objectives which need to be met to achieve the vision should be outlined in detail, so as to assist in identifying optional management strategies.

Task 2. The purpose of this task is to identify management measures which could be used to achieve the specified environmental objectives. Flow-related measures (eg. minimum flow, flushing flow) and other measures not related to flow regime (eg. revegetation, structural works, catchment management measures) should be identified. The relative appropriateness of flow management and other measures should be considered. For example, point-source pollutants can be diluted by flow, but this problem can often be more satisfactorily addressed by off-stream treatment works. Also, a dilution flow could be regarded as a consumptive use of water rather than an environmental flow. Critical dependencies should be determined, for example, the need to establish indigenous vegetation communities along cleared streams before an environmental flow provision can be expected to provide significant benefits in terms of riparian vegetation. Specific issues should be formally referred to other river management programs if they exist, or to the relevant management agencies for action.

Task 3. Once the relevant issues have been scoped and agreed on in qualitative terms, decisions can then be made about the level of quantification that is required. These decisions should be related to the objective of the assessment (catchment-wide assessment, catchment or sub-catchment level assessment or detailed assessment at any spatial scale).

Priorities for quantification and suitable methods should be determined, taking into account cost, time, knowledge about the processes in question, data availability, and the feasibility of implementation of a specific recommendation. As the geomorphological and other methods reviews have shown (Brizga 1998; McCosker 1998; Pusey 1998), techniques are available to quantify only a limited number of the factors which may be relevant in environmental flow studies, and suitable data may only be available for a subset of these.

A decision also needs to be made as to whether the environmental flow will be determined using a bottom-up or top-down approach, or both, as well the specific techniques to be used (eg. 'rule of thumb', hydraulic assessments, trial release).

An example of the feasibility of implementation is provided by considering a reach controlled by a large un-gated dam, in which instance there may be no point in making detailed calculations of a flushing flow unless there is a possibility of retrofitting of the structure to make it capable of passing a significant flood pulse. Under these circumstances it would probably suffice for the study team to flag that it is an issue and maybe give a ballpark estimate of the required flow.

5. Detailed studies. This step consists of detailed field and desktop studies to quantify flow requirements, using the procedures agreed at Workshop 2. Work would be carried out individually or collaboratively, as appropriate. The recommendations of the various disciplinary experts are then combined and integrated in Workshop 3, and the quantitative flow and any other recommendations (eg. need for further investigation of particular issues and longer term research) are written up in a technical report.

6. Workshop 3. A set of optional flow management strategies is outlined, with indications of their ecological and water resource management implications, so as to provide a basis for the social and economic evaluations. Optional management scenarios for hydrological modelling and ecological assessment (via a benchmarking process) are selected at this workshop.

7. Modelling of optional scenarios. The modelling of alternative environmental flow scenarios would be carried out after Workshop 3, and the results presented and evaluated by the environmental team in Workshop 4.

8. Workshop 4. This workshop evaluates the optional scenarios, and identifies potential environmental risks associated with alternative scenarios, based on a benchmarking process. Monitoring requirements would also be specified at this stage. Following Workshop 4, an Options and Impacts Report is prepared, which will form the basis of social and economic evaluations. The other three reports shown in Figure 2 (Background Report, Scoping Report and Technical Report) can be appended to the Options and Impacts Report to provide a complete record of the process.

9. Social and economic evaluations. The next step is an evaluation of the social and economic implications of the optional management scenarios. The bulk of this evaluation is undertaken by relevant analysts, but there should be interaction with the study team to receive their input into the final consideration of environmental flow options, once the social and economic implications are understood. This phase also involves consideration of alternative ways to deliver environmental flows or improve environmental conditions (eg. alternative infrastructure arrangements, adjustments to channel morphology to accommodate the modified flow regime, creation of habitat refuges or installation of a fish ladder).

10. Ongoing monitoring/research. Outcomes of monitoring and any ongoing research on special issues are evaluated at regular intervals (one–two years) and further adjustments are made to flow management, as necessary. Monitoring and research should be undertaken by key members of the original study team to ensure continuity and standardise monitoring methods.

11. Review workshops. Regular workshops are held to evaluate the outcomes of routine monitoring and discuss the results in relation to the benefits expected from environmental flow allocations. These workshops consider the need for adjustments to the environmental flow allocations and recommend any necessary changes. The timing of the first workshop is related to the expected time of delivery of the first monitoring results (one–two years). At this time, the results of special investigations should also be available for input into the revised environmental flow regime.

6. Socio-economic evaluation of flow scenarios

The best practice framework includes an evaluation of the social and economic implications of alternative flow management scenarios. This review has not thus far considered how such evaluations might be conducted, as to do so extends the project beyond its intended scope. However, a few comments can be made on available approaches which may merit further development.

Scott et al. (1998) developed a suite of models and assessment techniques for evaluating the implications of environmental flows for other water users in a catchment. The aim of this LWRRDC project was to develop a combination of simulation and stochastic dynamic programming techniques to derive the best water management decisions through time for ecological purposes while at the same time attempting to maximise net revenue from irrigated cropping systems in a highly variable environment (Arthington et al. 1998b; Dudley et al. 1998; Scott 1998; Scott et al. 1998). This study modelled alternative scenarios for sharing reservoir capacity, natural in-flows to the storage, and tributary flows for maximum benefit to the environment and to water users (irrigators). The ecological objective was to maximise some measure of 'environmental effectiveness', where environmental effectiveness was defined as the degree of achievement of a particular target flow regime (either the natural flow regime or a modified flow regime produced using the Holistic Approach).

Arthington et al. (1998a) and Scott et al. (1998) proposed a methodology for expressing the target flow regime as a statistical 'objective function' in the modelling process (based on the matrix of flows used in Colwell's (1974) analysis of flow regimes), and then developed indices of environmental effectiveness for use in trade-off curves. Initially, median daily flow was used as the measure of environmental effectiveness. This project successfully identified a sharp kink or critical point on a trade-off curve at which there would be a rapid decline in environmental benefits gained for a relatively small increase in mean annual net revenue from irrigated agriculture. At the critical point on the trade-off curve, a large proportion of tributary flows and a small share (20%) of reservoir capacity were allocated to the environment. Environmental benefits were high at this point, because the natural tributary flows would achieve a good flow quantity as well as desirable levels of flow variability, whereas the reservoir capacity share would top up the tributary flows to approximate the target level for environmental protection.

Various statistical measures of flow characteristics were explored to help explain why this particular allocation of reservoir in-flows, reservoir capacity and tributary flows would be more effective than other scenarios (Scott et al. 1998). The final part of the study suggested additional statistical indices of important flow characteristics to be used as measures of environmental effectiveness (eg. achievement of certain percentile flows, minimum flows for specific purposes) and began the development of a multivariate index of environmental effectiveness incorporating all of the desirable characteristics of a target environmental flow regime.

The Flow Restoration Methodology applied in the Brisbane River environmental flows study (Arthington 1998b; Arthington & Zalucki 1998b) incorporated a simple process for evaluating the effects of alternative environmental flow scenarios on other water users. The Brisbane River daily flow model was used to simulate a range of environmental flow scenarios over an historical time frame of 100 years. The effects of various environmental flow scenarios on the historical no-failure yield of the system were then modelled (Ruffini et al. 1998). This analysis was used to identify the flow scenarios of most benefit to the environment and least impact on system yield, as well as flow scenarios which could only be achieved under new infrastructure arrangements. A threshold situation was identified where the historical no-failure yield decreased rapidly, corresponding to the environmental flow scenario most closely approximating natural baseflows in the system.

The main conclusion drawn from the modelling of historical no-failure yields under different environmental flow scenarios was that partial restoration of the natural low flow characteristics of the Brisbane River downstream from Wivenhoe Dam could be achieved by releasing all in-flows >500 MLd^{-1}. However, this would reduce system yield in the future by 60%. Reinstatement of these very low flows would be impossible while releases from Wivenhoe Dam down to Mt Crosby for urban water supply are maintained at their present level. Lowered flows, while desirable for geomorphological and ecological purposes, would be even more difficult to achieve in the future.

Modelling and evaluating alternative environmental flow scenarios as part of the overall study facilitated consideration of several different infrastructure arrangements to deliver the recommended environmental flows. The main infrastructure alternatives were changes in water delivery mechanisms, that is, using pipes or artificial channels as a conduit for water rather than the river channel, and the conjunctive use of several alternative water sources to provide urban water supplies.

Although the analysis of social and economic implications of alternative flow scenarios should be undertaken as a separate activity in an environmental flow study, there should be interaction with the environmental study team to receive their input into final consideration of environmental flow options once the social and economic implications are understood. Ecologists and geomorphologists can make a significant contribution by suggesting alternative ways to deliver environmental flows (eg. alternative infrastructure arrangements) or strategies for improving environmental conditions by other mechanisms (eg. adjustments of channel morphology to accommodate the modified flow regime, creation of habitat refuges or installation of a fish ladder).

7. Relationship of best practice framework to the Environmental Flows Decision Support System

The best practice framework for environmental flow assessment outlined above is a staged process involving a multidisciplinary environmental team. Workshops figure prominently in the process as they are considered to offer the best process for developing a vision for the study, for integrating the various disciplinary inputs and achieving consensus on desirable environmental flows. At various stages in the process, desktop, field and modelling studies are required, their scope depending upon the objective of the study, that is, basin-wide rapid assessment of options, holistic assessment of environmental flows at sub-catchment scale, or detailed studies of special issues in river reaches.

As a generic framework for assessing environmental flows, the Environmental Flows Decision Support System (Young et al. 1995) may not be sufficiently flexible to address all of the issues covered in the best practice framework. Environmental Flows Decision Support System may serve as a tool within this best practice framework but would not appear to be capable of duplicating it. Although it is drawing upon holistic methodologies and other developments around Australia and overseas, the Environmental Flows Decision Support System may at best provide a sophisticated platform for assembling information about a catchment (eg. maps, flow and hydraulic data for geomorphological zones and river reaches, assessments of river condition) within a geographic information systems platform.

The Environmental Flows Decision Support System is designed to give guidance on possible outcomes in response to changes in flow regimes and to do this must incorporate flow-ecology models specific to a catchment or a series of catchments. It is understood that the decision support system is not designed to integrate the outputs from a range of flow-ecology models to produce one or several modified flow regimes. This process takes place within some broader framework, with the particular methodologies and processes to be employed left to the users to decide.

One of the possible outcomes of the decision support system, in its early formulations, is a relatively simplistic overview of alternative environmental flow scenarios for any river system, simply because of the practical difficulties of getting all the relevant information into the flow-ecology models, and the lack of a broader process for the construction of modified flow regimes. This would be rather unfortunate since relatively sophisticated methodologies for assessing environmental flows are already available in Australia. Coupling the Environmental Flows Decision Support System with, or incorporating, the best elements of the systematic and structured holistic methodologies now in use in Australia would greatly strengthen this support system.

8. Conclusions and recommendations

To fulfil the objectives of the Council of Australian Government's water-reform process and uphold the National Principles for the Provision of Water for Ecosystems (ARMCANZ & ANZECC 1996), environmental flows must be assessed and provided in both regulated and unregulated river systems of different sizes, levels of development and options for further development, human uses and constraints, and desired environmental outcomes.

No existing holistic methodology is entirely suited to all circumstances of environmental flow assessment and management in Australia, and most methodologies do not give adequate consideration to management issues that are not related to river flows. Each methodology has its strengths and original elements, and these need to be evaluated and incorporated into a best practice framework for river flow management.

Holistic methodologies for assessment of environmental flows may take one of two fundamentally different approaches, or may combine both approaches:

- a bottom-up approach, where the environmental flow regime is built up by flows requested for specific purposes from a starting point of zero flows;
- a top-down approach, where the environmental flow regime is developed by determining the maximum acceptable departure from natural flow conditions.

The construction of modified flow regimes using a bottom-up process of the Holistic/Building Block type is likely to form the basis of most Australian environmental flow assessments into the foreseeable future for several reasons.

1. Understanding of flow-ecology relationships is improving rapidly, so the approach is becoming more acceptable to scientists, water managers and the community.
2. Water managers have generally accepted the idea that some features of the natural flow regime are more important than others and must be maintained to protect aquatic habitat, biological ecosystem components and ecosystem values.
3. A bottom-up approach has become entrenched within all holistic frameworks in use in Australia.
4. A bottom-up approach can be applied in regulated and unregulated rivers, at all spatial scales and in all development contexts.
5. The alternative top-down approach is new, has received little exposure, is challenging to quantify and needs further development.

All bottom-up methodologies are vulnerable to the charge that there is a limited quantitative basis to estimating the blocks of flow which make up the overall flow recommendation. Considerable research is required to redress this (see Arthington & Zalucki 1998a).

Bottom-up holistic approaches depend upon historical flow data for the catchment and hydrological models with a daily time step. The successful use of the natural historical flow regime as the basis for constructing modified flow regimes from the bottom up will be limited by the accuracy and precision of hydrological models and their capacity to simulate extended historical flow sequences.

A significant difficulty with all bottom-up approaches is to define the overall objective of environmental flow regime. Targets such as 'desired future state', 'maintenance of current environmental values' and 'maintain maximum environmental benefits' are not easy to translate into quantitative end-points for the river, or condition indices, or other measures of ecosystem function.

The ecological implications of modified flow regimes cannot be predicted from the bottom up by predicting outcomes for each ecosystem component and then integrating those predictions to produce a series of alternative outcomes for a river system.

The alternative to prediction from the bottom up is a top-down approach, whereby the environmental flow regime is developed by determining the maximum acceptable departure from natural flow conditions. In Australia, two frameworks have added a top-down process for assessing the ecological implications of alternative modified flow regimes. These are:

- Habitat Analysis Method and benchmarking; and
- Flow Restoration Methodology.

The most rigorous approach to holistic environmental flow assessment is considered to be a combined bottom-up – top-down approach, where an environmental flow regime is initially developed using a bottom-up approach, and is then evaluated by cross-checking against a top-down assessment incorporating a benchmarking process to assess the ecological implications of various water management and environmental flow scenarios.

A bottom-up – top-down approach could be incorporated into any of the holistic methodologies used in Australia by adopting (and improving) the benchmarking methods developed in Queensland. Alternatively, a combined bottom-up – top-down approach could be developed into a single standard methodology and prescriptive manual for Australian flow assessments.

The advantage of a uniform approach is that there will be repeated case studies amenable to comparison of outcomes in many different catchments and types of flow environment around Australia. Regional principles for river flow management might be expected to emerge, and any such principles would strengthen the basin-wide assessments based on less rigorous methods.

Development of a standard methodology and manual would be a large task and may not be worth the effort unless there is agreement that Australian water agencies should adopt a consistent and structured methodology. The present fragmented and highly variable response of water management agencies to the Council of Australian Government's reform agenda and the National Principles for the Provision of Water for Ecosystems suggests that it may be very difficult to achieve any consensus on a consistent and structured methodology.

Existing methodologies are hybrids of one another, constantly changing and adapting within individual case studies, and improving with each test case. The whole enterprise may be too fluid to redirect and control to a useful degree. However, an infusion of new funding could be directed to specific types of improvement in existing environmental flow methodologies and State/Territory strategic approaches to river flow management and river management in the broader context of integrated catchment management.

This study has described a single overarching best practice framework for environmental flow assessment, within which a three-tiered hierarchy of environmental flow assessment and the combined bottom-up – top-down approach could be nested. This framework adds a new dimension by offering a process for consideration of factors other than flow which may influence river condition and the effectiveness of flow management, and a process for addressing human use constraints and their impact on the provision of environmental flows in a realistic fashion.

Environmental flow assessments must be developed with an appropriate temporal framework, one that recognises the time required to apply each methodology and technical assessment at an appropriate spatial scale. A time frame is suggested for each tier of the assessment hierarchy, with the proviso that time allocated should be adjusted as the need arises in particular circumstances. The recommendations of this report are:

- catchment-wide assessments: a minimum of one year;
- holistic catchment or sub-catchment assessments: a minimum of two years;
- detailed assessments at all spatial scales: two–five+ years.

The best practice framework described above should be applied in a variety of situations around Australia and then evaluated before any attempt is made to consolidate it into a set procedure.

As a generic framework for assessing environmental flows, the Environmental Flows Decision Support System may not be sufficiently flexible to address all of the issues covered in the best practice framework. The decision support system may serve as a tool within this best practice framework but would not appear to be capable of duplicating it. Coupling the Environmental Flows Decision Support System with, or incorporating, the best elements of the systematic and structured holistic methodologies now in use in Australia would greatly strengthen this decision support system.

Appendix

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