Comparative Evaluation of Environmental Flow Assessment Techniques: R&D Requirements

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A.H. Arthington

B.J. Pusey

S.O. Brizga

R.O. McCosker

S.E. Bunn

I.O. Growns

Land & Water Resources
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GPO Box 2182
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Telephone: (02) 6257 3379
Facsimile: (02) 6257 3420
Email: public@lwrrdc.gov.au
WebSite: www.lwrrdc.gov.au

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Authors (see page 22 for contact details):

Australian Water Technologies	Dr Ivor O. Growns
Brizga and Associates Pty Ltd	Dr Sandra O. Brizga
Centre for Catchment and In-Stream Research, Griffith University	Professor Angela H. Arthington Associate Professor Stuart E. Bunn Dr Bradley J. Pusey
LANDMAX	Robert O. McCosker

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List of abbreviations

CRCFE	Cooperative Research Centre for Freshwater Ecology
DPI	Department of Primary Industries
IFIM	In-stream Flow Incremental Methodology
LWRRDC	Land and Water Resources Research and Development Corporation

1. Introduction

Angela H. Arthington

This report is the final 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 LWRRDC Occasional Paper Number 27/98 *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, this report).
- *Comparative Evaluation of Environmental Flow Assessment Techniques: Best Practice Framework* (Arthington, Brizga & Kennard 1998).
- *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Holistic Methodologies* (Arthington 1998).
- *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods* (Arthington & Zalucki 1998a).

This report is concerned with R&D requirements and priorities to ensure the refinement, development and integration of methods and frameworks to facilitate their use in water allocation and water reform. It presents two main strands of R&D.

1. R&D required to improve individual methods of environmental flow assessment, based on the recommendations of the reviews contained in LWRRDC Occasional Paper Number 27/98, *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods* (Arthington & Zalucki 1998a).
2. R&D required to improve existing holistic methodologies and the proposed best practice framework for environmental flow assessment.

2. R&D on methods addressing geomorphological issues

Sandra O. Brizga

2.1 Limitations of existing methods

The following summary of methods addressing the development of flow requirements for geomorphological purposes is taken from Brizga (1998).

In Australia, geomorphological contributions in relation to the identification of flow requirements for channel morphology have largely been reported in the 'grey' literature rather than in peer-reviewed publications such as international scientific journals. This may reflect an implicit attitude to this type of work as an 'application' of knowledge and methods derived from other research (eg. impacts of regulation) rather than a research field in its own right. This may at least be partly due to geomorphology's origins as a science of description and explanation, and discomfort and a lack of protocols within the discipline regarding involvement in management intervention (Brizga 1998).

Much of the geomorphological literature concerned with relationships between flow and channel morphology focuses on the identification of a single representative 'dominant' or 'channel forming' flow which can be used as an input to equations derived from regime-based engineering approaches. This contrasts with the requirement of environmental flow studies for an understanding of the geomorphological significance of the full range of flows.

Geomorphological explanations of links between flows and channel morphology have been focused primarily on the medium to high flow end of the spectrum, on the assumption that flows only affect channel morphology through erosion and sediment transport, and that it is the high flows which have the greatest potential to erode and transport most of the sediment. However, low flows can be argued to have geomorphological significance through their effects on vegetation growth. Vegetation affects channel morphology by altering flow hydraulics and surface resistance to erosion, and thus can influence processes of erosion and deposition by altering the effectiveness of larger flows.

It is widely agreed in the geomorphological literature that river flows have significance for estuarine and coastal systems, and that upstream regulation can lead to considerable impacts in these areas. However, there are no established methodologies for determining environmental flow requirements for geomorphological purposes in estuarine and coastal systems.

A weakness in many environmental flow studies is in the area of hydraulics. Hydraulics provides a critical link between hydrology and geomorphological processes such as sediment transport. However, the majority of environmental flow teams have not included an hydraulics expert. Hydraulic information made available in environmental flow studies is generally limited to single points along the river, and the data provided may be unreliable, resulting in uncertainty in the flows specified for geomorphological purposes (eg. flushing flows and entrainment flows).

Considerable benefits could be gained through closer integration of hydraulic expertise into environmental flow studies. The use of suitable hydraulic models would provide hydraulic information that is reach-based rather than applying only at individual points along the river. Better hydraulic inputs would allow more detailed and definite conclusions to be drawn about geomorphological processes.

No environmental flow regime which makes provisions for geomorphological purposes has yet been implemented in Australia (Brizga 1998). Haworth (1996) pointed out that the flow regime proposed by the Snowy River Expert Panel is "quite unlike anything that has existed before, and therefore the geomorphic response may not resemble the pre-impoundment conditions". Thus the current status of environmental flow recommendations in this field is the generation of hypotheses which are yet to be tested. There is a need to actually implement and monitor an environmental flow regime designed to address geomorphological considerations, to ensure that it actually fulfils the desired purpose. Wherever possible (eg. where there is existing infrastructure), trial releases should be used to test proposed environmental flow regimes.

Carrying out a trial of an environmental flow regime before making a binding commitment is not feasible in all circumstances (eg. where high flow recommendations are used to constrain the extent of development in a catchment, or the nature of new infrastructure such as the size of gates in a new dam or weir). Therefore it would be desirable to carry out rigorously monitored trials on a range of representative rivers throughout Australia as a scientific study, and to use the results of the trials to evaluate and refine methodologies.

An important consideration in the design of monitoring and evaluation programs is the long lag times involved in geomorphological adjustments, which may take decades to centuries or even longer. This also has implications for the specification of time frames for monitoring and for management adaptation in response to monitoring outcomes.

Dams and weirs do not only affect the flow regimes of rivers, they also affect sediment delivery processes, because they at least partially obstruct the downstream flow of sediment. There would appear to be little point in providing an environmental flow capable of delivering sediment to an estuary or coastline if the required sediment is being trapped in a dam or weir further upstream.

Sediment delivery has often been ignored or inadequately addressed in Australian environmental flow studies, as it generally falls outside the brief for such studies. There are at least two reasons why it needs to be addressed: (1) the long-term implications of reduced sediment delivery to estuaries and coasts; and (2) clearwater erosion is rare downstream of Australian dams because floodflows generally only occur as infrequent spills. If flows capable of scouring the bed are released on a regular basis (eg. to satisfy environmental flow requirements for flushing or maintenance flows), there is potential for clearwater erosion problems to develop if there is no ongoing supply of sediment for the river to scour.

Overseas, some attempts are now being made to bypass sediments around dams and weirs (eg. by injection of bedload immediately below weirs). The suitability of such approaches to Australian river systems needs to be assessed.

The role of factors other than flow regulation needs to be taken into account in environmental flow studies. There are few catchments in Australia where the sole human impact is flow regulation. Generally, flow regulation is one of many factors which may have affected a river system. Other factors include clearing, agricultural development, forestry, roads, present and historical mining, river and floodplain management, and urban development. Thus 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. For example, Brizga and Craigie (1997) found that on the Yarra River, although there had been a downward shift in the flood frequency distribution as a result of water resource development for Melbourne's water supply, implying reduction in stream power, in situations where the river is confined by levee banks, the reduction in stream power has been compensated by increases in stream power resulting from the confinement of flow by levee banks.

Assessments which have been narrowly focused on flow-related issues have been the subject of criticism. For example, Haworth (1996) argued that Erskine (1996) paid insufficient attention to the effects of sediment and nutrient inputs from agricultural parts of the catchment, particularly the Monaro Tablelands, in his assessment of the impact of the Snowy Mountains Scheme on the Snowy River. In some instances, a narrow focus on flow has been encouraged in the briefs written for environmental flow studies; for example, the Technical Advisory Panels involved in the Queensland Water Allocation and Management Planning projects have until recently been strongly urged to restrict their deliberations to flow-related issues.

Environmental flows are one of a broad suite of management tools that can be used to maintain and enhance riverine ecosystems. The extent of benefit provided by an environmental flow may depend on other measures. For example, in the case of the Barron River, it was argued that there was little point in specifically providing sufficient flow to deliver sediment to the coast at a rate equal to or greater than the rate at which sediment was being removed by coastal processes, unless measures were also taken to make that sediment available downstream of Barron Gorge Weir (Brizga 1997).

2.2 R&D priorities: Geomorphological issues

The following R&D priorities addressing the development of flow requirements for geomorphological purposes are taken from Brizga (1998).

1. Development of a checklist of geomorphological issues and potential impacts to be considered in environmental flow studies would help ensure a systematic approach to environmental flow assessments.
2. R&D is required to clarify the relationship of the full range of flows to channel morphology and geomorphological processes, including low and medium flows which have hitherto been largely ignored in the geomorphological literature.
3. There is a need to determine whether environmental flows recommended for geomorphological purposes actually achieve their objectives.
4. The potential for monitoring to contribute to adaptive management varies. In situations where a new dam or weir is constructed on the basis of an environmental flow provision, it is too late to make major changes which would require infrastructure alterations. Therefore it is necessary for environmental flow trials to be carried out in a range of streams as a research exercise, and the results documented in detail and disseminated.
5. There is a need to develop a framework and methods for environmental flow assessment for estuarine and coastal requirements; at present little has been done in this area.
6. Studies are required to determine the feasibility of sediment bypassing dams and weirs, and to develop guidelines in relation to this matter. Field experiments would probably be required.
7. The integration of hydraulics, including hydraulic modelling techniques, into environmental flow studies needs to be developed.

3. R&D on methods for wetland and riparian vegetation

Robert O. McCosker

3.1 Wetland vegetation

3.1.1 Limitations of existing methods

The following summary of methods addressing the development of flow requirements for wetland and riparian vegetation is taken from McCosker (1998).

Methods used for assessing flooding requirements of terminal wetland vegetation are primarily concerned with determining quantities of water required to inundate a given area. Both the water budget and satellite imagery approaches have been found to provide reasonably accurate estimates in this regard. However, other factors, including timing, duration and frequency of flooding, are important parameters that should be considered for the maintenance of wetland plant communities. The normal procedure for estimating wetland flooding requirements has been to initially determine the volume of water required by application of either of the above methods. Timing, duration and frequency have then been estimated by a combination of analysis of historical streamflow records and assessment of the flooding requirements of certain elements of the wetland biota, most commonly waterbirds.

There is general agreement amongst wetland plant ecologists that the suite of plant species present in a wetland exist in response to the particular water regime that has historically prevailed in that wetland. Because there is limited published information about the water regime requirements of specific plant species, the common approach has been to recommend restoration of a flooding regime that mimics the natural regime. Unfortunately, no methodology has been formulated for assessing environmental flow requirements of wetland vegetation that considers all aspects of a water regime.

The techniques described in this review that have been used to assess water requirements of terminal wetlands have not been developed to the extent that they could be considered formally as methodologies. They are techniques that researchers have trialled in a quest to more confidently predict the quantity of water required to inundate specific wetlands. Because of unsatisfied demand for water by the irrigation industry in valleys that contain significant wetlands, the focus has been to determine bulk water requirements of wetlands. Water managers have been required to allocate water for wetlands without eroding the security of entitlement of extractive water users. Consequently, the primary focus has been on water quantity, with less emphasis on timing, duration and frequency. Further research is required to develop these techniques into methodologies that include consideration of other critical aspects of water regimes.

Methods for assessing the water regime of floodplain wetlands rely heavily on the availability of reliable long-term hydrological data (including rainfall, evaporation and streamflow) from locations in reasonably close proximity to the wetlands under examination. River height levels at which wetlands fill can be determined by local knowledge, ground survey, or analysis of remotely sensed images. The advantage of utilising local knowledge is the low cost, however, the reliability of such information may be questionable. Conducting ground surveys and acquiring a set of satellite images can both be quite expensive. However, there is a greater degree of confidence in the accuracy of information gained through these avenues. The advantage of this essentially desktop methodology for studying the water regime of floodplain wetlands is that it is cost-effective and utilises existing data that are available for most Australian rivers.

3.1.2 R&D priorities for flow requirements of wetland vegetation

1. Techniques for assessing terminal wetland water requirements need to be further refined to include consideration of water quantity and the timing, duration and frequency of flooding.
2. Existing information on the water regime requirements (eg. depth, duration, timing and frequency) of common riverine and wetland plant species should be collated. Further research will be required to fill important information gaps.
3. Building on 2 above, develop a list of indicator plant species of healthy and degraded rivers and wetlands for different climatic zones in Australia, and document the water regime tolerances of these species.

4. Techniques for assessing the interaction between surface water and groundwater in wetlands need to be developed.
5. A prescriptive manual that outlines a step-by-step procedure for assessing the water regime requirements of riverine and wetland plant communities would be a valuable addition to all environmental flow methodologies.

3.2 Riparian vegetation

3.2.1 Limitations of existing methods

The methods described in McCosker (1998) that have been used to determine flow requirements of riparian vegetation along Australian rivers have received limited application and few of the applications have been reported in the literature. Consideration of riparian vegetation has been a recent addition to environmental flow assessment methodologies. As yet, there is no prescriptive procedure for assessing the water regime requirements of riparian vegetation.

Because of the limited understanding of the water regime requirements of riparian vegetation, the application of all available methodologies draws heavily on the assessment of past and present flow regimes and the extent to which a modified regime may have affected the vegetation (McCosker 1998). Recommendations for environmental flows for riparian vegetation are normally made under the assumption that a modified flow regime that mimics the natural regime will be best for the vegetation.

The Expert Panel (Swales & Harris 1995) and Habitat Analysis (Walter et al. 1994) methods rely principally on prior knowledge by the riparian vegetation expert about the riparian vegetation communities and the dynamic relationship between the vegetation and hydrology of the river being studied. There is no formal process in either of these techniques for the expert to follow and no quantitative studies are undertaken. Predictions about how the riparian vegetation communities may respond to changes in flow regime are based on opinion. The lack of formal procedure raises questions about the capacity of the methods to be accurately replicated by different practitioners in the same river, and/or the same practitioner in different rivers.

The Expert Panel and Habitat Analysis methods are relatively cost-effective and can be conducted over a short time frame. The multidisciplinary nature of the panel allows a broad ecosystem perspective of the river to be presented. These methods are useful rapid assessment techniques for providing a 'snapshot' of the condition of the riparian vegetation of a river at a particular point in time. However, as they do not rely on quantitative analysis, there may be risks in using them as the basis for making long-term decisions about the flow requirements of riparian vegetation.

The Building Block Methodology (King & Louw 1998) and Flow Restoration Methodology (Arthington & Zalucki 1998b) require much more detailed knowledge of the riparian vegetation community at each representative site as a basis for making recommendations. By conducting a detailed botanical survey at representative sites and recording the location of species within the channel, the practitioner is forced to consider the relationship between plant species and streamflow. Analysis of hydrological data for the site assists the practitioner to develop an understanding of key elements of the flow regime that should be restored or preserved. Important elements of the flow regime include quantity, timing, rate of rise and fall, duration, peak flows, and return periods (McCosker 1998).

An ability to make accurate predictions about the potential impact of a modified flow regime on riparian vegetation may require a more detailed understanding of vegetation and hydrological links than the relationship between vegetation and streamflow. It has been found that alluvial groundwater can play a significant role in supplying water to riparian vegetation, particularly in semi-arid environments (Mitsch & Gosselink 1986; Kondolf et al. 1987; Harris 1988) . Research in Australia has found that river red gums (*Eucalyptus camaldulensis*) can draw a substantial proportion of their water requirements from shallow alluvial aquifers (Bacon et al. 1993; Thorburn et al. 1994). Australian applications of methods to determine flow requirements of riparian vegetation have largely ignored the role that groundwater may play in supplying water to plants in the riparian zone.

The riparian vegetation along many Australian rivers has been severely altered by clearing, grazing and exotic plant invasion. In many instances the present vegetation bears little resemblance to that which existed before white settlement. This raises questions about the desired future state of vegetation on rivers where riparian vegetation has been substantially altered by anthropogenic factors. Should management aim to preserve the status quo, or attempt to restore the original vegetation structure and floristics? The restoration of an apparently favourable flow regime for riparian vegetation may be ineffective if factors such as intensive grazing and weed invasion are at play (see McCosker 1998). The application of techniques currently available for assessing environmental flow requirements of riparian vegetation may be placing a disproportionate expectation on river flows to restore and maintain the vegetation. A greater understanding is required of the interaction between fluvial and terrestrial factors in the shaping of riparian plant communities.

A knowledge of the flooding requirements and tolerances and the role that floods play in the life cycles of individual plant species is required to enable confident predictions about the long-term response of vegetation to modified flow regimes. For example, identification of plant species as *flood-dependent* or *flood-tolerant* may enable more accurate predictions to be made about the potential effect of altering a flow regime. Flood-dependent species are likely to be more sensitive to changes in flow regime than flood-tolerant species, which may thrive in a regulated stream. This is evident in the Brisbane River below Wivenhoe Dam, where the flood-tolerant weeping bottlebrush (*Callistemon viminalis*) has extensively colonised shorelines at the regulated flow level. The apparently more flood-dependent river oak (*Casuarina cunninghamiana*) appears to have received less opportunities for recruitment following river regulation. The result of river regulation in this instance is a trend towards a monoculture of weeping bottlebrush (McCosker 1998).

There is little published information about the water regime requirements of plant species that commonly occur in the riparian zones of Australian rivers. The exception is river red gums. A body of research has been directed toward defining the flooding requirements and tolerances of this species (eg. Gomes & Kozlowski 1980; Bren & Gibbs 1986; Chesterfield 1986; Dexter et al. 1986; Bren 1987; 1988; 1992; Brewsher et al. 1991; Bacon et al. 1993; Mensforth et al. 1994; Thorburn et al. 1994; Bacon 1996).

Published research on water uptake by black box (*Eucalyptus largiflorens*) includes papers by Jolley and Walker (1996) and Slavich et al. (in press). Craig et al. (1991) made recommendations about the flooding requirements of lignum (*Muehlenbeckia florulenta*) from an examination of the effects of edaphic and flood-related factors on its distribution and abundance on the Murray River floodplain in South Australia.

Raine and Gardiner (1995) provide a valuable addition to the scant pool of literature on the life history and habitat preferences of Australian riparian plant species. Their report draws on the results of a research project designed to promote the use of native vegetation in rehabilitating and managing riparian land. Although the project was based on the coastal rivers of northern New South Wales, much of the information is applicable to other regions. The report discusses at length the role of native plants in river and riparian management. It describes the growth habit, any special requirements for growth, preferred location within the riparian zone, and requirements for recruitment of many riparian plant species.

Further knowledge about the hydrological requirements of Australian riparian plant species is needed to enable more accurate predictions regarding in-stream flow requirements of riparian vegetation. In particular, we need to place more attention on the interaction between surface streamflow and groundwater and the extent to which vegetation draws water from each. This aspect of riparian plant ecology has received little attention in the application of environmental flow assessment methods in Australia.

3.2.2 R&D priorities for flow requirements of riparian vegetation

1. All existing information about the water regime requirements and flooding tolerances of plants that occur in riparian zones in different regions of Australia needs to be collated into a single publication.
2. Greater knowledge is required of the most suitable timing, frequency, duration and recession rates of floods for recruitment and maintenance of riparian vegetation.
3. A research effort needs to be directed toward assessing the role of groundwater in maintaining riparian plant communities.
4. Improved knowledge is required of the potential effectiveness of implementing environmental flows to rivers where the original riparian vegetation has been substantially altered by clearing, grazing and exotic plant invasion.
5. A prescriptive manual that outlines a step-by-step procedure for assessing the water regime requirements of riparian plant communities would be a valuable addition to all methodologies.

4. R&D on methods for freshwater fish

Bradley J. Pusey

4.1 Limitations of existing methods

Pusey (1998) has highlighted some of the deficiencies associated with the methods used in Australia to define the environmental flow requirements of freshwater fish. Recommendations for future research are made in light of these deficiencies, and personal research experience in the fields of environmental flow management and fish ecology.

Environmental flow management is, in a real sense, a predictive exercise. The critical question being addressed is one of 'how much water can be harvested from a river without ecological damage?' Thus water resource managers are using a knowledge base which has been forced to move from the purely descriptive into a premature predictive phase. The various methods available for assessing environmental flow needs must themselves be assessed in light of this problem, in addition to considerations related to time and cost-effectiveness (Pusey 1998).

The Montana Method (Tennant 1976) and flow duration curve analysis (Stalnaker & Arnette 1976) are obviously rapid mechanisms by which environmental flows may be defined, and have the added advantage of not requiring extensive field observations. However, as has been previously stated (Richardson 1986; Arthington & Pusey 1993), their application is constrained by profound uncertainty as to the applicability of North American criteria to Australian circumstances. No studies have ever been undertaken to compare habitat 'quality' at different percentile flows, nor to determine how long ecosystems can be maintained at set levels of flow (eg. 20th percentile flow) without detriment. Thus the use of these rapid hydrological methods cannot be strongly defended. That is not to say, however, that flow duration curve analysis has no role in the assessment process; it is necessarily a critical inclusion needed to establish the nature of the flow regime and boundary conditions.

Transect analysis and habitat modelling (ie. PHABSIM or RHYHABSIM) provide more sophisticated mechanisms to establish flow guidelines and are focused much more strongly on the relationship between flow and habitat. Consequently, they are more likely to be more relevant to the protection of fish species. However, both methods are labour-intensive and time consuming. Notwithstanding the criticisms detailed in Pusey (1998) concerning the hydraulic basis of the modelling procedure, their quantitative nature ensures that decisions based upon these methods are more easily defended, provided the information upon which habitat criteria are based is rigorously collected and analysed. Further reliance on these methods does require strong validation of the relationship between habitat structure, habitat use and fish assemblage composition, a significant knowledge gap for most areas of Australia.

Expert panel and holistic methodologies vary greatly in the time and expense required to conduct them. Significant advantages of these techniques are that they recognise that the information base is deficient in some areas, that environmental flow decisions must consider a range of taxa other than just fish, and that important ecological processes must also be included.

The Expert Panel Assessment Method (Swales & Harris 1995) may have further utility in the initial phase of an environmental flow process, particularly in establishing areas of particular ecological concern. However, it suffers from a lack of defensibility due to the subjective manner in which different flows are assessed, and a lack of transparency in the manner by which assessments are incorporated into recommendations for a modified flow regime. The Scientific Panel Assessment Method (Thoms et al. 1996) is a significant improvement due to its more holistic outlook and the fact that the decision-making process is better detailed and, to an extent, based on the collection of quantitative data. An advantage of this method is the consideration of habitat in an extended spatial hierarchy, such that habitat incorporates such off-stream features as floodplains rather than habitat in a few supposedly representative critical reaches.

Holistic methodologies such as the Building Block Methodology (King & Louw 1998), the Holistic Approach (Arthington et al. 1992a) and the Flow Restoration Methodology (Arthington & Zalucki 1998b) seek to be more inclusive and, to differing degrees, are founded on the development of a strong quantitative basis with relevance to the river in question, and on information on other rivers in the region. They are, therefore, more regionally oriented. The workshop component of each is explicit, as are the mechanisms by which final flow recommendations are achieved by the participants. A significant advantage of these approaches is that they allow for the incorporation of a range of methods to address particular issues but, importantly, are not constrained to accept the recommendations offered by any one method without an assessment of its advantages or disadvantages compared with a range of other methods and for other components of the riverine ecosystem. The ability to include other ecosystem components or processes such as the transfer of carbon is an advantage and increases the defensibility of holistic approaches.

Tunbridge (1997) believed that there was only one correct method for assessing an environmental flow which presents a very low level of risk to the biota. That method required "... the collection of data which identifies species present, river hydraulics and structure, water quality, behaviour and biology of the biota and identification of habitats" followed by "... examination of the flow regime, identification of critical areas of habitat, river or environment that need to be protected and the identification of factors that act adversely on habitat useability or directly on biota". Only then can the necessary conditions required to protect biota be established. Obviously, additional areas of investigation such as community metabolism could, and should, be added.

Tunbridge (1997) recognised that this protocol represented a full environmental study and that it was an expensive one in terms of time and money. It was important to recognise, however, that deviation from this protocol represented a significant increase in risk to the biota (Tunbridge 1997).

In conclusion, all of the methodologies or approaches discussed above and in Pusey (1998) have deficiencies to a greater or lesser extent. Methods that are cost-effective and time-effective may ultimately be found to be environmentally expensive, because of a questionable theoretical underpinning with respect to their relevance to Australian conditions. Cost-effectiveness needs to be assessed with respect to the long term rather than the short term.

4.2 R&D priorities for flow requirements of fish

4.2.1 R&D on ecological issues

There are seven distinct areas in which insufficient knowledge hampers ability to manage environmental flows in a sustainable manner as they relate to freshwater fish. These areas are as follows.

1. An understanding of the habitat requirements of many species of fish.
2. An understanding of basic life history and its relationship to hydrology for many fish species.
3. An understanding of patterns of fish movement and their relationship to hydrology.
4. An understanding and appreciation of the links between freshwater and estuarine systems.
5. An understanding of the processes that govern inter-specific interactions between freshwater fish and understanding of links between landscape, hydrology and community metabolism.
6. The absence of clear guidelines available to water managers on the day-to-day management of in-stream flows and ability to include flow variability in such a process.
7. An almost complete absence of validation of the sustainability of prescribed environmental flow allocations.

It can be seen from this list that nearly all these problems are of an ecological nature, specifically, an incomplete ecological understanding. Four of these seven points are addressed briefly below in relation to the R&D required to improve assessment of the flow requirements of freshwater fish. A full account can be found in Pusey (1998). Item 4 above is addressed in Section 5 of this report.

4.2.2 Habitat requirements of fish

All of the in-stream flow methodologies described in Pusey (1998) deal in one way or another with the relationship between flow, habitat and fish, yet there is still a great degree of uncertainty about the habitat requirements of many of Australia's freshwater fishes. This is particularly so for northern Australia but is also a characteristic of south-eastern Australia. A synthesis of the ecology of Australia's freshwater fishes is lacking, although regional variations on this theme have been produced, for example, Koehn and O'Connor (1990).

Harris and Gehrke (1997) collected data concerning fish distributions and habitat structure (flow, depth, width, substrate, vegetation, cover, and so on) and this information will be of considerable benefit when fully analysed and made available.

Current research undertaken by the Centre for Catchment and In-Stream Research at Griffith University, is focused on defining the macro-habitat and micro-habitat requirements of about 60 species of Queensland freshwater fishes. Whilst this may appear to be comprehensive, the data are limited in spatial extent, being collected mostly from seven rivers across a range of three distinct hydrologies, and limited to fishes occurring in small to medium-sized streams (ie. those efficiently sampled by back-pack electrofishing). Data for abut 55 species need to be collated into a reference manual.

The In-stream Flow Incremental Methodology (primarily the habitat modelling component, PHABSIM), despite its many potential drawbacks, has been used in Australia and will probably increase in usage.

For the In-stream Flow Incremental Methodology to be useful, the following issues require further research.

1. Complete and publish regional summaries of the habitat requirements of individual fish species.
2. Determine the relationship between discharge variability and habitat fidelity or plasticity. Experimental examination of changes in habitat use under conditions of differing discharge variability will be required.
3. Develop methods to include the availability of additional critical habitat elements such as woody debris or macrophyte beds in the modelling process using PHABSIM.
4. Establish whether there is any congruence between a reach's modelled suitability and the actual biomass or density of fish over a range of river and hydrological types.
5. Explore use of the In-stream Flow Incremental Methodology modelling package to generate habitat duration curves for individual species at a site. Such applications seem intuitively more useful given that there is little empirical evidence to suggest a linear relationship between habitat suitability and fish density or biomass as implied by the In-stream Flow Incremental Methodology.
6. Develop methods that allow for the consideration of multi-species assemblages rather than for individual species (see Arthington et al. 1992b for one approach). The risk assessment approach used by Davies and Humphries (1995) warrants further development.
7. In-stream Flow Methodology and multiple transect methods are focused very narrowly on a restricted range of habitat types (generally riffles because they appear to be the most affected by changes in flow volume). A focus on riffle areas may be more appropriate in some areas of Australia and types of flow regime (predictable versus unpredictable) than others. Information is needed to allow an assessment of the range of habitat types requiring attention in different river systems.
8. A national examination of regional variation in discharge patterns and variability is needed to identify the characteristics of different river systems and to provide a guide to the essential flow and habitat conditions which must remain relatively unchanged in any modified discharge scenario.

4.2.3 Fish life history and relationship to hydrology

The definition of critical habitat and flow requirements is virtually impossible without detailed life history information. The freshwater fish fauna of many parts of Australia, particularly northern Australia, is essentially unstudied. Life history studies appear limited to those south-eastern species of economic importance or to those species that can be found close to major population centres. Few studies have addressed the interaction between hydrology and life history. No published studies exist that compare how life histories vary within species or assemblages in regions of differing flow variability, although such work is under way in some parts of the country (eg. Victoria and Queensland).

The investigation of larval fish biology of freshwater fishes is still in its infancy in Australia. It would seem that the appropriate management of flows and habitat for spawning and for larval fishes is a necessary prerequisite for the management of overall stocks, yet this aspect remains little studied.

Further examination of the environmental cues that stimulate spawning is also warranted. Research is needed to distinguish the degree to which floods stimulate spawning and the degree to which floods enhance recruitment through the provision of greater areas of habitat, thereby increasing survivorship. Harris and Gerhke (1997) have highlighted the need for a better understanding of the interaction between streamflow and recruitment in order to facilitate better management of fish stocks.

This information is required in a range of different river types and flow regimes.

The R&D priorities are as follows.

1. Complete and publish regional summaries of fish life histories.
2. Determine the environmental cues that stimulate fish spawning using a range of methods (eg. field work, experimental release studies).
3. Determine larval habitat requirements in a range of different river types and flow regimes.
4. Determine how fish life histories vary within individual fish species or fish assemblages in regions of differing flow variability.
5. Collate existing data on fish population dynamics in a range of different river types and flow regimes and assess their utility for developing models predicting fish abundance and recruitment. Identify information gaps and establish R&D projects to develop recruitment models for key species occurring in focus catchments with different types of flow regime around Australia.

4.2.4 Patterns of fish movement and relationship to hydrology

Migration has traditionally been an area of concern in large rivers of south-eastern Australia and has been an important factor in the environmental flow decisions of many of the studies reviewed by Pusey (1998). However, much of this research is limited in taxonomic extent and, even for such apparently important species as golden perch, the dynamics of this process are still not fully understood (Mallen-Cooper 1996).

Research directed at assessing the efficiency of fishways or the ability of fish to negotiate low-level weirs has yielded valuable information on patterns of movement. The compilation and synthesis of these data should be encouraged in order to provide better access to water managers. Moreover, empirical studies of the swimming abilities of adult and juvenile fishes are needed (Harris & Mallen-Cooper 1994). Without such data, assertions that the passage requirements of one species of particular economic value are sufficient to accommodate most others species (eg. Hogan et al. 1997) or all life history stages remain unvalidated.

Migration, for whatever purpose, is an important process in rivers of northern Australia but, with the exception of studies by Bishop et al. (1995), studies related to this area have been limited to assessments of the efficiency of fishways (eg. Kowarsky & Ross 1981; Russell 1991; Hogan et al. 1997; Stuart 1997). These studies have, however, revealed important insights into the degree of movement exhibited by freshwater fishes of northern Queensland. The report of Stuart (1997) on the efficiency of a vertical slot fishway on the Fitzroy River is particularly noteworthy, revealing that different species migrate under different flow conditions. Stuart recommended that fishway design must be able to accommodate low flow conditions. The Queensland Department of Primary Industries has commenced an investigation of fish passage in regulated rivers of the state and these data will provide very considerable assistance to water managers when the program is completed.

The R&D priorities are as follows.

1. Develop regional summaries of the movement and migration requirements of individual fish species in rivers with different channel morphology and flow regimes. Identify information gaps and establish R&D projects to define movement and migration requirements of key species occurring in focus catchments with different types of flow regime around Australia.
2. Develop a protocol for assessing fish passage requirements as part of environmental flow studies.
3. Review and develop methods for restoration/ construction of critical reaches required to achieve fish passage in regulated rivers.
4. Develop fishway designs to achieve successful fish passage under the full range of flows likely to be recommended in environmental flow regimes.

4.2.5 Inter-specific interactions between freshwater fishes and understanding of links between landscape, hydrology and community metabolism

There has been (and probably will continue to be) considerable debate about the role of biotic factors in the regulation of freshwater fish communities, and few Australian studies have examined fish trophic ecology from a community ecology perspective. The extent of species interactions is of considerable importance in assessing the potential impacts of river regulation. For example, most regulation results in an increase in the constancy and predictability of downstream flows. If the trophic structure of a fish assemblage occurring in a river has evolved under conditions of flow variability and is presumably characterised by trophic generalism, what are the expected outcomes of an increase in flow predictability with respect to species richness and assemblage structure? This question has not been addressed in depth in any of the world literature, although it has been alluded to previously (Grossman et al. 1990; Arthington et al. 1992). Experimental evaluation of this problem will prove useful in predicting the impacts of flow regulation on fish assemblages.

Identification and quantification of the links between fish trophic structure and sources of production, particularly with respect to the importance of off-stream sources such as floodplains and their associated water bodies, will prove a useful aid in defining environmental flow strategies, especially with respect to the need for and characteristics of large flushing flows. For example, if it can be shown that the major role of floodplain inundation with respect to riverine food webs is the transport of terrestrial carbon to the riverine environment and that this occurs rapidly, then the appropriate strategy may be one of a single short flood flow. If, however, such transfer occurs slowly or is mediated by the passage of organisms from the river to the floodplain and back again, then the appropriate strategy may be one of either multiple or more prolonged single flood events. The incorporation of flows large enough to result in floodplain inundation is likely to be the most expensive and contentious issue in many environmental flow studies. Therefore it is critical that the need for such flows be unequivocally demonstrated and quantified.

The analysis of spatial and temporal patterns of community metabolism has only recently been applied to an environmental flow study, but is likely to achieve greater significance in the future. For example, such lines of investigation in rivers in south-western Australia and the Border Rivers region of south-western Queensland have revealed surprising links between in-stream primary production and higher level food webs (S.E. Bunn, pers. comm.). These links are potentially sensitive to changes in flow to the extent that a failure to consider them in any modified flow regime would probably result in significant and widespread impacts post-regulation.

The R&D priorities for flow-driven floodplain processes are as follows.

Flow-driven floodplain processes should be addressed in a series of focus catchments selected through a consultative process involving Environment Australia, water management agencies and relevant research groups. Research in a series of focus catchments must be carefully planned to ensure integration of a series of linked and interacting processes (eg. effects of flood flows on physical habitat structure, the responses of vegetation, invertebrates and fishes, and consequences in terms of key ecosystem processes).

This research should be conducted in unregulated and minimally disturbed catchments selected to serve as reference areas for comparison with systems that are regulated in various ways and to various degrees. A research strategy in relation to regulated rivers is outlined in Section 7.3.

5. Influence of river flows on coastal fisheries

Stuart E. Bunn

5.1 Limitations of existing methods

It is apparent from the review by Bunn et al. (1998) that very little quantitative information is available on the relationships between river flows and coastal fisheries, and that this constrains our ability to predict the consequences of flow regulation for coastal ecosystems. Additional research is required to develop predictive models from existing catch and flow data that:

- identify which attributes of the flow regime appear to be important (this is likely to be species-specific and region-specific, though generality should be sought); and
- can quantify likely changes to fish stocks (and associated economic implications) if the flow regime is altered.

At the same time, research is needed to establish the causal mechanisms that underlie observed relationships between flow and catches in order to improve the knowledge base upon which coastal fisheries are managed.

5.2 R&D priorities: River flows and coastal fisheries

5.2.1 Development of predictive models

Very little quantitative information on the relationships between flow and fisheries is available and much of this (eg. from recent flow management studies on the Logan and Fitzroy Rivers in Queensland) should at best be considered as preliminary. Further studies are required to build on these studies and to extend them to other river systems.

A broader geographical coverage of estuarine and coastal systems is needed and should include:

- temperate south-western Australia, comparing estuaries permanently open to the sea with those that are periodically or frequently closed;
- temperate south-eastern Australia;
- subtropics (building on work in Moreton Bay);
- wet tropics;
- wet-dry tropics (eg. building on work in the Fitzroy and Gulf of Carpentaria, as well as north-western Australia).

This will capture not only the full range of climatic conditions, flow regimes and habitat types, but also a broad range of target species.

Additional issues arise in estuaries or embayments with multiple rivers, where the potential impacts of flow regulation in one river may be offset by maintenance of natural flows in the other(s). However, it is possible that one river may have a disproportional influence on catches in the embayment, even if it does not dominate the total run-off. For example, flows from the Logan River in south-east Queensland explain more variation in total fish catches in Moreton Bay (Loneragan & Bunn, in press) than do flows from the Brisbane River (Bunn & Loneragan 1998). There may be several reasons for this, including a more concentrated fishing effort in the southern bay or greater presence of juvenile habitats.

The search for time-lagged effects, which may be indicative of enhanced recruitment or survivorship of juveniles through increased productivity, should be given a high priority. These effects are likely to represent real changes in fish/crustacean population size rather than flow-induced variations in catchability. The potential additive (or multiplicative) effects of these factors must also be resolved.

No attempts have been made in the above studies to link anomalies in size (age)-frequency data on long-lived species to particular flow events that can be associated with the cohort (age-class) in question. This could provide additional evidence of flow-driven changes in population dynamics and identify the range of flow events that lead to enhanced (or failed) recruitment.

Little emphasis has been placed on the indirect effects of river regulation on coastal fisheries through changes in coastal geomorphology resulting from changes in flow regime and the delivery of sediment. The long-term consequences on the distribution of fish habitats (eg. mangroves and seagrass beds) and physical and chemical conditions (eg. in estuaries that periodically are closed) should be addressed.

In the case of species that make extensive use of fresh or brackish water habitats as part of their life cycle (eg. barramundi), the impact of flow diversions (including levee bank construction) on habitat availability should be quantified.

5.2.2 Research on causal mechanisms

The presence of time-lagged effects in the relationship between flow and catches of certain long-lived species (eg. barramundi) indicates actual variation in population size, rather than a simple change in catchability (resulting from increased movement or concentration of individuals in particular areas, for example). To understand the implications of flow regulation and effectively manage stocks of these species, it will be important to understand the causal mechanism(s) that underlie this flow-driven response.

For example, if recruitment success is linked to availability of juvenile habitat (eg. floodplain wetlands), is it a consequence of the area of inundation, the duration or perhaps enhanced production of food sources stimulated by catchment-derived nutrients? Alternatively, is enhanced recruitment the result of greater access of adults to spawning sites?

What evidence is there of a transfer of energy from primary production (stimulated by high flow and catchment nutrients) into secondary production in coastal systems? Simple relationships between algal production and flow could be examined in the same way as for fisheries data (as above). Transfer of increased primary production into coastal food webs is likely only if catchment nutrients stimulate production of palatable forms of benthic or pelagic algae. Under what conditions (eg. flow, nutrient load and turbidity) does this occur? Alternatively, are there particular conditions under which production is shifted into unconsumable plant biomass?

The degree to which increases in catchability associated with river flow equate to increases in stock abundance is unclear. Indeed, it may be that during times of high flow, fish stocks are susceptible to over-harvesting as a result of high catchability, and ecological sustainability may be threatened at such times.

Further research in this area will provide better information upon which to base principles of coastal fisheries management. It is conceivable that the strategies of fisheries managers may need to change from year to year in response to patterns and magnitudes of riverine flow, ensuring that fish stocks are not over-exploited during times of vulnerability induced by variations in riverine flow.

6. R&D on methods for invertebrates

Ivor Growns

The research issues and needs identified by Growns (1998) are summarised in Table 1 (page 16). A small proportion of the information necessary to develop environmental flow methods for invertebrates is being addressed by current research. Some of the research is required to further develop some specific methods, such as the In-stream Flow Incremental Methodology. However, the majority of the research that is required is more general in nature. This is because there is currently a lack of information on the specific flow requirements of the vast majority of invertebrates. Information on the flow requirements of invertebrates would enhance the ability of most flow allocation methods to provide flows for invertebrate species. Some flow requirements of invertebrate species are obvious, such as the current speed necessary to maximise the feeding potential of filter feeding animals. However, it is likely that many flow requirements may be more subtle. For example, the abundance of a population of a species or invertebrate community structure may be influenced by flows that occurred previously in the river.

Table 1: *Summary of research needs identified for the development of environmental flow allocation methods for invertebrates*

Research need	Current project				
	CRCFE Campaspe Project	LWRRDC – Critical flow events	LWRRDC – Hydrological disturbance	LWRRDC – Application of IFM	DPI (Hobart) Habitat-based method
Further develop approaches that consider the flow requirements of whole ecosystems, not just parts of them.					
Conduct appropriately designed long-term (greater than five years) monitoring of rivers once environmental flow allocations have been implemented, which will require a commitment by government and industry for adequate funding.	✓				
Test a range of methods that assess environmental flows by conducting the preliminary assessments, implementing the recommended flows from the assessment and then measuring the response of target species, processes or indicators.					
Establish the relationship between habitat diversity/abundance and faunal diversity and abundance across impacted and reference streams throughout Australia.					✓
Develop multiple species weighted usable area curves for use in the IFIM.					
Test ability of SI curves to be transferred between rivers.				✓	
Define in which types of rivers flushing flows may be relevant.					
Investigate water flow requirements at different life history stages for invertebrates.					
Determine the ability of current small-scale field-based water velocity metres to measure flows relative to the scale that invertebrates may respond to.					
Define the importance of invertebrate drift in ecological processes and population dynamics of invertebrate populations.					

Note: Research in progress 1998 marked with ✓

7. R&D priorities to improve holistic methodologies

Angela H. Arthington

7.1 Limitations of existing methodologies

Holistic methodologies for assessment of environmental flows may take one of two fundamentally different approaches, or may combine both approaches (Arthington 1998; 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.

The review of holistic methodologies currently applied in Australia concluded that construction of modified flow regimes using a bottom-up process of the Holistic/Building Block type seems likely to form the basis of most Australian environmental flow assessments into the foreseeable future (Arthington 1998).

There are several reasons for this. Perhaps the most important is that water managers have generally accepted the idea that some features of the 'natural' flow regime are more important than others and must be maintained as environmental flows to protect aquatic habitat, biological ecosystem 'components' and ecosystem 'values'. These important flows are being defined from the bottom up as low, medium and high flows of various magnitudes and temporal attributes (frequency of occurrence, timing, rate of rise and fall of flood hydrographs, and predictability). All holistic methodologies in use in Australia aim to construct (or to restore) modified flow regimes using a bottom-up process (see Arthington 1998).

Construction of an environmental flow regime in a bottom-up, step-wise fashion requires a sound understanding of the flow requirements of ecosystem 'components' and this understanding is limited in many Australian catchments. Bottom-up holistic approaches also depend upon historical flow data for the catchment and accurate hydrological models with a daily time step. The successful use of the 'natural' historical flow regime as the basis for constructing modified flow regimes will be limited by the accuracy and precision of hydrological models and their capacity to simulate extended historical flow sequences. Furthermore, flow regimes must be analysed in a consistent manner to describe flow-ecology relationships, yet there is no uniformity of approach throughout Australia. A further significant impediment is the lack of a suitable, user-friendly computer package for the analysis of flow data in ecologically meaningful ways. There are various programs in use within various research groups and agencies, and limited opportunities to share expertise.

Environmental flow strategies need to be transformed into day-to-day operating rules for water managers, and mechanisms are needed by which flow variability can be factored into water release strategies to an appropriate degree. The establishment of a process that directly links operating rules with forecasted weather patterns may be useful in this regard. In order to be useful, however, the establishment of flow conditions within individual rivers must be shown to be correlated with such indices as the Southern Oscillation Index.

A phase of monitoring and adjustment of initial environmental flow strategies is a key feature of all holistic methodologies. However, there is no set methodology and spatial/temporal framework for assessing the beneficial outcomes of environmental flows, and for follow-up adjustments. Interim recommendations made in good faith by expert panels tend to become final recommendations by default. A practical process is required to ensure that the outcomes of monitoring are used to achieve adjustments and fine tuning of interim environmental flow regimes.

7.2 R&D priorities to improve 'bottom-up' holistic methodologies

To improve the construction of modified flow regimes from the bottom up using holistic methodologies requires R&D to improve fundamental understanding of flow-driven geomorphological and ecological processes, and R&D to improve various steps in the holistic process itself. The following priorities are suggested.

1. Considerable R&D is required to improve fundamental understanding of the geomorphological and ecological processes driven by flow regimes in a range of river types throughout Australia, using focus catchments and multidisciplinary research teams to ensure adequate coverage and integration of key issues. R&D priorities relating to geomorphology, channel morphology, sediment processes, wetland and riparian vegetation and fish, and flow-driven ecological processes have been identified above.

2. Research is needed on other issues of importance that tend to be neglected in environmental flow assessments for want of adequate understanding and suitable assessment methods:

   - water and flow requirements of water-dependent vertebrates other than fish;
   - flow and water quality relationships;
   - surface and groundwater relationships;
   - the water requirements of all waterbodies in a catchment.

3. Information on the water and flow requirements of water-dependent vertebrates other than fish (frogs, reptiles, waterbirds) should be collated into a series of regional documents relevant to river types and flow regimes. Knowledge gaps should be identified and R&D commissioned to fill key gaps. Existing reviews of information on platypus (Scott & Grant 1997; Zalucki & Arthington 1998) should be combined with advice on methods for gathering essential data to support new environmental flow assessments.

4. R&D is required to support the inclusion of flow-driven water quality processes into environmental flow assessments. An assessment of existing methods and water quality models should be commissioned, and a process developed to integrate water quality assessment and management into the proposed best practice framework for management of river flows. Some water quality problems may need to be addressed through catchment management, point-source remediation, and so on.

5. Methodologies are required to ensure that surface-groundwater relationships and the water requirements of all waterbodies in a catchment are adequately assessed and incorporated into water management strategies. These issues may require a fundamentally different approach to conventional environmental flow assessment, such as the development of a water budget for the catchment, and independent but linked consideration of flowing and standing waterbody requirements.

6. Research is needed to assess the sensitivity of hydrological simulation models to various factors and processes (eg. how do rainfall run-off models respond to variability in soil infiltration rates; what are the effects of vegetation clearing, afforestation and different forms of land use on flow regimes in different climatic zones; do off-stream storages have a significant effect on flow regimes; are the levels of accuracy of simulation models across the full range of flows acceptable given their uses in environmental flow assessments?).

7. Australia needs a robust Windows-based computer package for flow data analysis incorporating a wide range of flow statistics and graphical formats for display of flow characteristics. Work already in progress in Australia (eg. Cooperative Research Centre for Freshwater Ecology, Cooperative Research Centre for Catchment Hydrology, Centre for Catchment and In-Stream Research) should be reviewed to define the most suitable statistical methods, flow indices and graphical formats. The capacity of the Environmental Flows Decision Support System (Young et al. 1995) to provide this analytical and graphical package should also be reviewed. A new project may need to be commissioned to develop a stand-alone Windows-based computer package accessible to research groups, agencies, community groups, and so on.

8. The mechanisms and processes now in use to transform environmental flow strategies into operational rules for water managers (eg. the use of environmental flow nodes within the Integrated Quantity Quality modelling framework) should be reviewed, and an acceptable set of processes developed that directly links operating rules with forecasted weather patterns (eg. Southern Oscillation Index).

9. A small workshop is needed to develop a protocol for monitoring the outcomes and benefits of flow releases from dams, and of the whole environmental flow regime at suitable spatial and temporal scales. Monitoring should be linked to the key

geomorphological and ecological processes to be maintained by the environmental flow regime, and measured using robust, responsive indicators (eg. habitat structure, biological diversity, recruitment processes, P/R ratios).

10. Mechanisms for including a process of adaptive environmental management into flow management procedures need to be investigated and implemented in Australia.

7.3 R&D priorities to improve a 'top-down' process of benchmarking against modified flow regimes

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 (see *Comparative Evaluation of Environmental Flow Assessment Techniques: Best Practice Framework*, Arthington et al. 1998).

Benchmarking against levels of degradation in other catchments with similar types and levels of flow regulation appears to be the strongest top-down approach in use in Australia. The Environmental Flows Decision Support System (Young et al. 1995) appears to be developing a somewhat similar general approach by developing models of flow regulation impacts. However, its focus on the Murray-Darling system and the limited number and scope, and possibly the relative simplicity, of the flow-ecology models, may limit its utility as a tool for use throughout Australia. Certainly, flow-ecology models must be developed for different climatic zones, regional river types and flow regimes, and for a range of key species and issues. Benchmarking against levels of degradation in other catchments is a new approach, and requires critical evaluation in terms of fundamental ecological issues, the best techniques for assessing river degradation, the selection of key flow statistics to describe and quantify levels of flow regulation, and the development of models to predict responses to different types and levels of flow regulation.

A focused Australia-wide R&D strategy is required to address these topics in a coordinated manner.

The recommended steps in the R&D strategy are as follows.

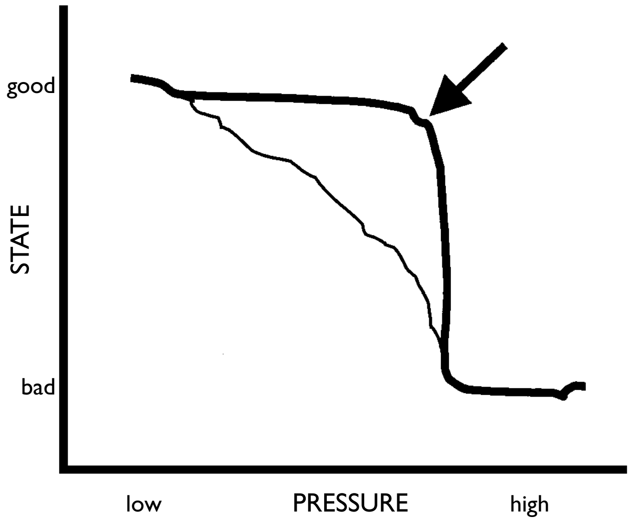
1. Undertake a national examination of regional variation in river discharge patterns and variability in order to identify river systems with similar flow characteristics and flow regimes. Then analyse the extent to which these flow regime types have been modified in both unregulated (but modified) and regulated systems, to identify the most important categories of change in flow characteristics within each regional flow category. These flow regime classifications would form the basis of a national program to assess the feasibility of benchmarking in different areas of Australia, as part of a national approach to environmental flow assessment using the proposed bottom-up – top-down approach.
2. Assemble all existing data sets on the effects of flow regulation on river systems throughout Australia, collating types of river flow regime, types of change in flow regime, types of data available (eg. geomorphology, plants, fish), length of data sets, and reliability of the data. Categorise data sets into those that report responses to flow regulation alone and those that are confounded by other types of disturbance (eg. loss of riparian zone functions, presence of barriers to fish migration, water pollution).
3. Commission analyses of the strictly flow-related data sets to determine and summarise the types of responses of key indicators to flow regulation. Then run a workshop to review how each river system has responded to flow regulation, and the types of responses observed (eg. do river systems change from one state of dynamic equilibrium to another when the flow regime is changed beyond some critical level, or do some systems respond to disturbance gradually and in a linear fashion (Figure 1)?)

   The workshop would address this question for key ecosystem components (geomorphological features of rivers, algae, aquatic plants, riparian plants, invertebrates, fish, attributes of water quality). Each participant would present response curves based on key indicators (eg. fish diversity, an index of recruitment, abundance of particular species, proportion of native versus exotic species) and levels of departure from 'natural' key flow statistics (eg. size of flows required to trigger spawning, frequency of riparian, wetland or floodplain inundation). The workshop would produce a national summary of the impacts of flow regulation on a catchment, regional, state and national spatial scale, and identify critical knowledge gaps.

4. Use the workshop summary of critical knowledge gaps to establish a coordinated national program to collect field data and build predictive models of responses to flow regulation in regional river types with different types of flow regime. Field sites would be selected to provide a range of levels of change in key flow statistics, so that a graded ecological response to flow regulation could be documented. This field research and modelling program would produce a series of models quantifying how much change in key flow statistics is possible before key ecological indicators reach a critical point. Models could be tested using the AUSRIVAS protocols, that is, by developing each model using a reduced set of sites, and testing it against other sites in the same catchment and in sites from an adjacent catchment to determine the range of applicability of the model.

   Outcomes would have three major uses:
   (i) identification of changes in flow regimes that have severe ecological impacts and should never be implemented in new development schemes;

Figure 1: Pressure-State-Response (PSR) curve



Note: Curve shows the 'edge of the cliff' (arrow) where condition suddenly and significantly deteriorates as a result of pressure. The thinner line indicates more gradual deterioration with increasing pressure.

(ii) identification of the potential impact of flow regulation in new development schemes before any particular environmental flow scenario is implemented; and (iii) identification of the critical features to be restored in rivers with modified and regulated flow regimes.

5. Models defining critical response curves could then be built into the environmental flow nodes of hydrological models such as Integrated Quantity Quality Model and be used to identify acceptable and unacceptable flow scenarios. When unacceptable flow scenarios are identified by some trigger process built into the Integrated Quantity Quality Model, the next step would be to run a series of flow scenarios wherein alternative strategies are tested as a means of providing both consumptive and environmental water requirements. This approach has been taken in Queensland Water Allocation and Management Planning studies and in the Flow Restoration Methodology. Alternatives might involve different water infrastructure, physical interventions to deliver water, provision of critical habitat areas for riverine biota, or fish stocking, and so on.

6. The final stage of the R&D program would be to implement a series of demonstration flow restoration projects in focus catchments around Australia with significant problems due to flow regulation and realistic opportunities for flow restoration. Each case study would be run according to a standard format for monitoring and assessing critical variables related to flow and flow-driven ecological processes. The monitoring and assessment program would be designed to determine the outcomes of particular changes in key flow characteristics (described by key flow statistics) representing the major types of changes being made in flow regimes in different areas of Australia. Such trials are essential to validate the models relating change in flow to geomorphological and ecological response. The Campaspe River Project is an example of this approach.

7.4 R&D strategy to support the best practice framework

This study has described a single overarching best practice framework for environmental flow assessment (Arthington et al. 1998). The framework presents:

- a structured and systematic methodology for developing environmental flow recommendations, incorporating the three-tiered hierarchy of assessment;
- a process for considering of factors other than flow which may influence river condition and the effectiveness of flow allocations and flow management;
- a process for addressing human use and water infrastructure constraints in a realistic fashion;
- a phase of social and economic evaluation;
- an ongoing interface with stakeholders;
- a monitoring phase to assess the outcomes and benefits of environmental flows, plus a phase of special investigations and/or research, with a feedback loop to ensure that flow management strategies are revised and adjusted as new information becomes available.

Within the framework, environmental flow assessments can be undertaken with various degrees of scientific rigour. A three-tiered hierarchy of assessment is suggested:

Level 1: Rapid methods for basin-wide assessment of development options, or scoping of opportunities to restore environmental flows in rivers with modified flow regimes.

Level 2: Holistic assessment of flow requirements at sub-catchment scale.

Level 3: Quantitative assessments at any scale, plus special investigations and research.

A standard but flexible best practice framework for environmental flow assessments in Australia would have several advantages. The most obvious is that outcomes from many case studies would be amenable to comparison of outcomes in many different catchments and types of flow environments around Australia. Regional principles for river flow management might be expected to emerge, and any such principles would strengthen basin-wide assessments and other rapid assessment processes based on less rigorous methods.

The following R&D strategy is recommended to support the best practice framework.

1. A combined bottom-up – top-down approach should be incorporated into existing holistic methodologies used in Australia (eg. Scientific Panel Assessment Method, Flow Restoration Methodology), and at least considered as an element of the Environmental Flows Decision Support System (Young et al. 1995), by adapting and improving the benchmarking methods developed in Queensland.
2. Several trials of these combined bottom-up – top-down approaches should be run in association with existing holistic methodologies.
3. These trials should be evaluated to determine the feasibility and utility of developing a standard methodology and prescriptive approach for Australian environmental flow assessments.
4. The trials should be run within the broader structure of the proposed best practice framework, and the utility of the best practice framework evaluated.
5. If appropriate, the best practice framework, the three-tiered hierarchy for environmental flow assessment and the most useful combined bottom-up – top-down approach, and any other useful innovations, should be developed into a set of standard procedures for routine application in Australia.

Appendix

Author contact details

Professor Angela H. Arthington
Centre for Catchment and In-Stream Research
Griffith University
Nathan Qld 4111
Telephone: (07) 3875 7403
Facsimile: (07) 3875 7615
Email: a.arthington@mailbox.gu.edu.au

Dr Sandra O. Brizga
Brizga and Associates Pty Ltd
PO Box 68
Clifton Hill Vic 3068
Telephone: (03) 9859 7403
Facsimile: (03) 9482 6885
Email: sbrizga@mpx.com.au

Associate Professor Stuart E. Bunn
Centre for Catchment and In-Stream Research
Griffith University
Nathan Qld 4111
Telephone: (07) 3875 7402
Facsimile: (07) 3875 7615
Email: s.bunn@mailbox.gu.edu.au

Dr Ivor O. Growns
Australian Water Technologies
PO Box 1357
Albury NSW 2640
Telephone: (02) 6058 3878
Facsimile: (02) 6058 3888
Email: Igrowns@awcnet.aw.latrobe.edu.au

Robert O. McCosker
LANDMAX
19 Bell Street
Kangaroo Point Qld 4169
Telephone: (07) 3217 4348
Facsimile: (07) 3392 2672
Email: landmax@tpgi.com.au

Dr Bradley J. Pusey
Centre for Catchment and In-Stream Research
Griffith University
c/– DPI Fisheries
Kennedy Highway
Walkamin Qld 4111
Telephone: (07) 4092 9924
Facsimile: (07) 4093 3903
Email: puseyb@dpi.qld.gov.au

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