Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods

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Contents

List of tables

List of figures

List of abbreviations

ANZECC	Australian and New Zealand Environment and Conservation Council
ARI	Annual series recurrence interval
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
AWWA	Australian Water and Wastewater Association
CWPR	Centre for Water Policy Research, University of New England
DNR	Department of Natural Resources, Queensland
DPI	Department of Primary Industries
IFIM	In-stream Flow Incremental Methodology
IFR	In-stream flow requirement
LWRRDC	Land and Water Resources Research and Development Corporation
WAMP	Water Allocation and Management Planning
WUA	Weighted usable area

1. Introduction

Angela H. Arthington

1.1 Project background and objectives

In 1994 the Council of Australian Governments reviewed water resource policy in Australia and agreed to implement a strategic framework to achieve an efficient and sustainable water industry. One of the major recommendations of the review was the introduction of comprehensive systems for water allocations addressing water entitlements, water trading arrangements and the provision of water for the environment.

The Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) and the Australian and New Zealand Environment and Conservation Council (ANZECC) subsequently commissioned a set of National Principles for the Provision of Water for Ecosystems. The purpose of the national principles is to provide policy direction on how the issue of water for the environment should be addressed in the general context of water allocation decisions. The goal for providing water for the environment is "to sustain and where necessary restore ecological processes and biodiversity of water dependent ecosystems" (ARMCANZ & ANZECC 1996).

Implementation of the Council of Australian Governments water reforms and national principles has stimulated a wide range of responses from the Australian states and territories (Allan & Lovett 1996). A key issue has been the definition of conceptual frameworks and practical methods for assessing the water requirements of environmental systems. To date, no set of techniques or conceptual framework has proved acceptable to all water agencies or suitable for all circumstances. There is concern that the most suitable methods are not being used universally, with many assessments relying almost entirely on rapid expert panel approaches rather than the best scientific information available (as required under Principle 2, ARMCANZ & ANZECC 1996).

The project 'Comparative Evaluation of Environmental Flow Assessment Techniques' was commissioned to address these concerns. It is an initiative of the National River Health Program, a cooperative research and development program of Environment Australia and the Land and Water Resources Research and Development Corporation (LWRRDC). One of the principal aims of the program is to enhance the management of river flows and water allocation to ensure the sustainability of riverine ecosystems. The program has supported research and development projects throughout Australia, and in 1995 organised a national seminar on 'Techniques for Environmental Flow Assessment' held at Cooma, New South Wales. Speakers from Australia, New Zealand, the United States and South Africa reviewed specific techniques and methodologies, and discussed their origins, theoretical basis, applications, advantages and limitations.

The Cooma seminar concluded by identifying several priority areas for R&D, including a critical comparative review of the techniques used by water agencies to assess environmental flow requirements in Australia. The project 'Comparative Evaluation of Environmental Flow Assessment Techniques' has been funded by Environment Australia, LWRRDC and the National Landcare Program.

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.

1.2 Structure of review

1.2.1 Scope of review

Techniques for assessing environmental flow requirements range from simplistic use of the hydrological record to establish minimum and flushing flows to sophisticated modelling procedures linking changes in river discharge with geomorphological and

ecological response. Recent studies have combined a number of techniques within a broader methodological framework designed to provide comprehensive recommendations on water allocations for ecosystem protection. Tharme (1996) distinguished the two levels of assessment as "methods" ("procedures or techniques used to measure, describe or predict changes in important physical, chemical or biological variables of the stream environment") and "methodologies" ("collections of several instream flow methods which are arranged into an organised iterative process which can be implemented to produce results").

Several reviews of international literature concerned with environmental flow determination have been published recently (Tharme 1996; Jowett 1997; Dunbar et al. 1998). The present review differs from these in the following respects.

1. It reviews the flow requirements of the riparian zone, floodplain wetlands, estuaries and coasts as well as in-stream freshwater requirements.
2. The application of various assessment methods in Australian environmental flow studies is examined in detail, with reference to international literature, where relevant.
3. Holistic methodologies of very recent origin and application in Australia are reviewed for the first time.

A list of the Australian environmental flow studies examined is presented in Table 1 (page 3). Most of the existing work on environmental flows has been carried out in the eastern mainland states.

1.2.2 Review of methods

Many environmental flow assessment methods have been applied in Australia, and modified according to circumstance. Reviews can be found in Kinhill (1988), Pusey and Arthington (1991), Arthington and Pusey (1993), AWWA (1994) and Arthington and Zalucki (1998a). This review set out to present these methods under the headings of geomorphology and channel morphology, wetland and riparian vegetation, aquatic invertebrates, freshwater and estuarine fish, water-dependent wildlife and water quality. Six reviews were commissioned to cover the key issues and those deemed suitable for publication by LWRRDC have been included in this report. The review on water quality was considered too preliminary to publish at this time and has been submitted to LWRRDC for internal reference only. The review of issues and methods relating to water-dependent wildlife was abandoned when it was realised that these topics would be covered by CSIRO reviews on platypus, water rats and waterbirds (eg. Scott 1997) as part of the Ecology-Flows Handbook commissioned to support the Murray-Darling Basin Commission's Decision Support System for environmental flow management (Young et al. 1995).

The methods reviews are presented in this Occasional Paper. Chapter 2 by Sandra Brizga reviews links between flows and geomorphological forms and processes, the geomorphological impacts of flow regulation, and methods for determination of the flows required for geomorphological purposes. Chapter 3 by Rob McCosker reviews wetland hydrology, water budgets and techniques for determining the flooding requirements of wetland vegetation, followed by a discussion of riparian zone ecology and environmental flow assessment techniques for riparian systems. Chapter 4 by Bradley Pusey reviews methods used to assess the flow requirements of fish, including maintenance of habitat and reproductive processes, flushing flows and fish passage requirements. Chapter 5 by Stuart Bunn reviews the influence of river flows on estuarine fishery production and describes new methods developed to quantify these relationships. Chapter 6 by Ivor Growns reviews methods for assessing the environmental flow requirements of aquatic invertebrates.

1.2.3 Review of methodologies

The review of holistic environmental flow methodologies (conceptual frameworks) takes two forms. Certain methodologies are discussed within the individual methods chapters, in order to place various assessment techniques into the context of the framework in which they have been applied. The major methodological frameworks developed or applied in Australia are reviewed and compared in LWRRDC Occasional Paper Number 26/98: *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Holistic Methodologies* (Arthington 1998).

These methodologies include the Holistic Approach (Arthington et al. 1992a), the Building Block Methodology (King & Tharme 1994; King & Louw 1998), the Expert Panel Assessment Method (Swales & Harris 1995), the Scientific Panel Assessment Method (Thoms et al. 1996), the Habitat Analysis Method (Walter et al. 1994; Burgess & Vanderbyl 1996), and the Flow Restoration Methodology (Arthington & Zalucki 1998b).

Table 1: *List of Australian studies examined in this review of methods*

State	River/Catchment	References
New South Wales	Barwon-Darling River	Thoms et al. (1996)
	Cudgegong River	Grose (1993)
	Gwydir River	Bennett & Green (1993), Keyte (1994), McCosker & Duggin (1993)
	Lachlan River	Denham & McAuliffe (1994)
	Lower Darling	Ardill & Cross (1994), Green et al. (1997)
	Macquarie Marshes	Bacon (1996)
	Snowy River	Snowy River Expert Panel (1996), CWPR (1996)
	Wingecarribee River	Erskine et al. (1995)
Queensland	Barker-Barambah Creek	Arthington et al. (1992b), Arthington (1994) Blühdorn & Arthington (1994)
	Barron River	Brizga (1997a, 1997b)
	Brisbane River	Arthington & Zalucki (1998b)
	Condamine-Balonne System	Burgess & Thoms (1997)
	Fitzroy System	DNR (1998a, 1998b)
	Logan River	Arthington & Long (1997), Arthington & Lloyd (1998)
	Tully-Millstream System	Arthington et al. (1994)
Victoria	Armstrong, Badger and Starvation Creeks	Gaynor et al. (1995)
	Campaspe River	Kelly (1996)
	Gellibrand River	Tunbridge & Glenane (1988)
	La Trobe, Thomson, Mitchell, Snowy Rivers	Hall (1989)
	Tambo River, Gippsland	Hall & Harrington (1991)
	Tanjil River, Gippsland	Hall (1990, 1991)
	Thomson River	Tunbridge (1980)
	Thomson River (Thomson Dam)	Gippel et al. (1992, 1993), Gippel & Stewardson (1995)
	Wimmera River	Anderson & Morison (1989)
Tasmania	Meander, Macquarie and South Esk Rivers	Davies & Humphries (1995)
Western Australia	North Dandalup River	Davies et al. (1996)

The research project was also required to review the degree to which water management agencies involved in water allocation for environmental purposes would benefit from a Decision Support System of the type being developed by the Murray-Darling Basin Commission and the National River Health Program (Young et al. 1995). To this end, the concept and structure of the Environmental Flows Decision Support System are compared with other frameworks for environmental flow assessment and water allocation used in Australia, and similarities and differences are noted.

1.3 Best practice framework

Objective 2 of the research project requires a synthesis of the various methodologies to produce a best practice framework for the application of techniques to environmental flow assessment. The framework proposed aims to addresses the shortcomings of existing approaches which have become apparent through this review and the authors' participation in a number of environmental flow studies conducted in Australia, or which have been identified in the literature.

LWRRDC Occasional Paper Number 25/98 presents this material: *Comparative Evaluation of Environmental Flow Assessment Techniques: Best Practice Framework.* (Arthington et al. 1998b).

1.4 R&D requirements

Research and development priorities are proposed on the basis of the conclusions of each chapter in the methods review, and in relation to the deficiencies of the methodological frameworks used to assess environmental flows in Australia. This section of the review also places in context the development of the Environmental Flows Decision Support System in relation to the need for further research and development of this approach.

LWRRDC Occasional Paper Number 24/98 presents this material: *Comparative Evaluation of Environmental Flow Assessment Techniques: R&D Requirements.* (Arthington et al. 1998a).

1.5 List of reports

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 1998b).
- *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Holistic Methodologies* (Arthington 1998).
- *Comparative Evaluation of Environmental Flow Assessment: Review of Methods* (Arthington & Zalucki 1998c, this report).

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2. Methods addressing flow requirements for geomorphological purposes

Sandra O. Brizga

2.1 Introduction

2.1.1 Background

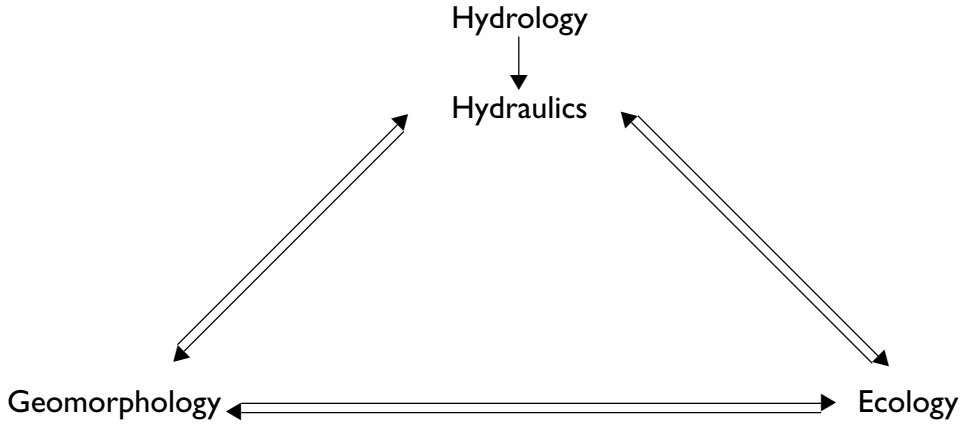
Flow is the key driver of fluvial geomorphological processes and exerts significant control on stream channel morphology. There is a large body of literature which examines how changes in hydrological regime lead to geomorphological changes. Channel morphology is a key determinant of habitat structure, and geomorphological processes (eg. erosion, sedimentation) have ecological implications. Geomorphological processes also have implications for human uses of streams and adjacent land (eg. navigation, river crossings, sand and gravel mining, frequency of overbank flooding, bank erosion). Hydraulic, geomorphological and ecological responses to hydrological changes are interdependent (see Figure 1 below). Determination of the flow required for geomorphological purposes therefore must be a vital component of environmental flow assessment.

This chapter is concerned with the determination of environmental flow requirements for geomorphological purposes in Australia, and is based on a review which focuses on Australian literature. Because of the limitations of the Australian literature in many areas, it has been necessary to draw upon the international literature to develop a broader contextual framework. However, this paper does not attempt to provide a comprehensive review of international literature on environmental flows.

The published Australian literature on environmental flow assessment for geomorphological purposes is extremely limited. There are two published papers which fall into this category: a paper on the use of a trial release in environmental flow determination (Erskine et al. 1995), and a general environmental flow study of which a subsection deals with flows for geomorphological requirements (Gippel & Stewardson 1995). The majority of the literature on environmental flow requirements of Australian rivers for geomorphological purposes is contained in unpublished reports.

Within the field of geomorphology, environmental flow studies appear to have been treated largely as an area where the results of research on the role of flows in channel morphology and processes and the impacts of regulation can be applied, rather than as a research focus

Figure 1: *Diagram illustrating relationships between hydrology, hydraulics, geomorphology and ecology within a stream reach*



in their own right. This is consistent with geomorphology's origins as a science concerned with description and explanation rather than the development of practical solutions. There have been recent moves within the discipline to strengthen the applied role of geomorphology (eg. the 1997 Binghampton Symposium on 'Geomorphology and Engineering').

A distinction is made in this chapter between 'regulated' and 'unregulated' streams. A regulated stream is defined here as a stream in which flows are affected by a major dam, and/or diversion weirs or pumps associated with a water resource scheme. Unregulated streams are not affected by major dams or water resource schemes, but their flow regimes may be far from natural due to 'incremental development'. Forms of incremental development include farm dams and other small dams, diversions (pumped or gravity) to individual properties, and groundwater development by individual extractors.

Environmental flows appear to be sometimes thought of as applying predominantly to regulated situations. For example, Stewardson & Gippel (1997, pp. 92–3) defined an environmental flow as "a set of operational rules for water resource schemes to limit adverse ecological impacts to acceptable levels" which "may be designed for a river subject to a new water resource development or more commonly, a historical development for which insufficient consideration has been given to the ecological impacts".

However, in addition to methodologies for streams which are currently regulated or will be subject to regulation in the near future, Australian water reform processes require methods for determining environmental flow requirements for unregulated streams which are subject to incremental development and may possibly be subject to major water resource developments in the longer term (eg. 20–50+ years time frame). The basic specifications used for environmental flows in regulated systems (typically a minimum base flow requirement plus an annual or biennial flood pulse) are too narrow to adequately characterise the many and varied parameters of geomorphological and ecological significance which could be managed by constraining development in unregulated systems.

Several reviews of international literature concerned with environmental flow determination have been published recently (Karim et al. 1995; Tharme 1996; Jowett 1997; Stewardson & Gippel 1997; Dunbar et al. 1998). The present review differs from these others in several respects:

- the scope of the review is restricted to geomorphological issues;
- the application of geomorphological methods in Australian environmental flow studies is examined in detail; and
- flow requirements for floodplains, estuaries and coasts as well as in-stream requirements in non-tidal channels are considered.

2.1.2 Objectives

The review presented in this chapter has three objectives.

- To review currently available techniques for assessing river flow as they relate to river channel morphology, habitat structure, substrate condition, flushing flows and estuaries, so that water managers have the key information and recommendations on which techniques are suitable for different situations, their limitations, advantages and cost-effectiveness.
- To assist in the selection of a 'best practice' framework for the application of techniques to environmental flow assessment.
- To provide research and development priorities for the refinement, development and integration of the techniques to facilitate their use in water allocation and water reform.

2.1.3 Methodology

All available documented Australian environmental flow studies have been reviewed with the aim of identifying the methodologies which have been used to address geomorphological issues, and examining the application of those methods. The methods used in Australian studies were examined in relation to the range of methods available in the international literature. A list of Australian environmental flow studies examined in this review is presented in Table 2 (page 10). From this table it can be seen that most of the existing work on this issue has been carried out in the eastern mainland states. No documentation of any environmental flow studies was available for South Australia, Tasmania, the Northern Territory or the Australian Capital Territory. A significant proportion of the previous work in Victoria has focused exclusively on fish (Tunbridge & Glenane 1988; Anderson & Morison 1989; Hall 1989, 1991; Hall & Harrington 1991). The other studies listed in Table 2 have generally taken a broader approach.

Table 2: *List of Australian environmental flow studies examined in geomorphological review*

State or Territory	River/Catchment	References
New South Wales	Barwon-Darling River	Thoms et al. (1996)
	Cudgegong River	Grose (1993)
	Snowy River	Snowy River Expert Panel (1996), CWPR (1996)
	Wingecarribee River	Erskine et al. (1995)
Queensland	Barker-Barambah Ck	Arthington et al. (1992)
	Barron Catchment	Brizga (1997a, 1997b)
	Brisbane River	Arthington & Zalucki (Eds) (1998)
	Condamine-Balonne Catchment	Burgess & Thoms (1998)
	Fitzroy Catchment	DNR (1998a, 1998b)
	Logan Catchment	Arthington & Long (Eds) (1997), Arthington & Lloyd (Eds) (1998)
	Tully-Millstream Scheme	Arthington et al. (1994)
South Australia	na.	
Tasmania	na.	
Victoria	Armstrong, Badger and Starvation Creeks	Gaynor et al. (1995)
	Campaspe River	Kelly (1996)
	Gellibrand River	Tunbridge & Glenane (1988)
	Major Gippsland Rivers	Hall (1989, 1991)
	Tambo River	Hall & Harrington (1991)
	Thomson River (Thomson Dam)	Gippel et al. (1992, 1993), Gippel & Stewardson (1995)
	Wimmera River	Anderson & Morison (1989)
Western Australia	North Dandalup River	Davies et al. (1996)
Northern Territory	na.	
Australian Capital Territory	na.	

In order to identify the strengths and limitations of the geomorphological concepts and methods which have been applied in Australian environmental flow studies, it is necessary to understand how they relate to existing knowledge in the following areas:

- links between flows and geomorphological forms and processes; and
- geomorphological impacts of regulation.

An understanding of these broader issues is particularly important for determining the comprehensiveness and completeness of the methodologies used. Therefore, overviews of these issues are presented, based on Australian and international literature. These overviews are intended only to highlight key issues and are not comprehensive reviews.

A best practice framework for environmental flow studies is proposed which addresses shortcomings of existing approaches which have been previously identified in the literature, or have become apparent through this review, or through the author's participation in a number of environmental flow studies in Queensland and Victoria. Best practice in the use of geomorphological techniques is also discussed.

Research and development priorities are proposed on the basis of the conclusions of the review.

2.1.4 Structure of this chapter

This chapter falls into seven main sections: in-stream flow requirements of non-tidal streams (2.2); flow requirements for floodplain processes (2.3); flow requirements for estuarine and coastal processes (2.4); environmental flow methodologies for quantifying geomorphological requirements (2.5); best practice recommendations (2.6); conclusions (2.7); and R&D priorities (2.8).

2.2 In-stream flow requirements of non-tidal streams

The in-stream flow requirements of non-tidal streams are discussed in this section, with particular reference to sediment motion, channel morphology, bank stability, hydraulic biotopes, tributary base level and large woody debris. For each of these issues, this section outlines the general principles concerning the relationship between flow and the factor in question, reviews the impacts of water resource development, with an emphasis on impacts documented in the Australian literature, and identifies the relevant environmental flow methodologies and alternative management techniques.

2.2.1 Sediment motion

Sediment motion is an important consideration in environmental flow determination due to its implications for:

- substrate characteristics (eg. gravel bed, sand bed, mud bed);
- channel morphology;
- channel stability; and
- downstream sediment delivery, including estuarine and coastal sediment supply.

2.2.1.1 Role of flow in sediment motion

Flow is the key driver of downstream transport of sediment in river systems. Sediment motion has three stages:

- sediment entrainment (erosion);
- sediment transport; and
- sediment deposition.

The critical state for sediment entrainment can be described in terms of lift and drag forces, critical velocity, critical shear stress or stream power (Gordon et al. 1992). These factors vary with flow magnitude, as well as in response to other hydraulic controls such as energy gradient, hydraulic roughness and flow confinement.

Sediment transport can be measured in several ways. Two key aspects are flow competence and transport capacity. Flow competence is the maximum particle size which can be transported at a specified location by any given flow. It is controlled by stream energy, which is related to flow magnitude as well as other hydraulic factors. Sediment transport capacity is a measure of the volume of sediment of a particular grading which can be transported by a stream at a specified location. It is related to the duration of flows greater than or equal to the flow competent to transport the grading in question.

Deposition occurs when the stream lacks the energy to carry sediment of a given size any further. This can occur as the result of a change in flow or other hydraulic controls.

Over longer time frames, flow regimes also affect sediment motion through their effects on sediment packing, vegetation, and channel morphology, which has implications for controls such as flow confinement, energy gradient and hydraulic roughness.

2.2.1.2 Impacts of water resource development on sediment motion

Water resource development affects sediment motion in two main ways:

- dams and weirs disrupt the downstream continuity of sediment transport; and
- changes in flow regime affect entrainment, transport and deposition processes.

Often both types of impacts are present. Dams and weirs obstruct sediment transport continuity and generally also affect sediment entrainment, transport and deposition processes by alterations to the flow regime. However, in cases where no significant barrier is erected in the stream (eg. pumped diversions), only the second type of impact occurs.

Disruption of downstream continuity of sediment transport

Dams and weirs impound sediments as well as water. The effect has been described graphically by Kondolf (1997) who likened a river to a conveyor belt transporting sediments from source areas in the catchment to the coast (or to terminal lakes in the case of inland draining streams such as Cooper Creek). The construction of a dam or weir across the river disrupts the longitudinal continuity of the conveyor belt. Deposition occurs upstream of the structure and, as a result, the water released downstream has a reduced sediment load.

Dams and weirs induce upstream deposition in two main ways:

- by reducing flow velocities upstream of the impoundment, thus making conditions more conducive for deposition; and

- by acting as a physical barrier to the downstream movement of bedload, which is that part of the sediment load of a river which is transported along the river bed by rolling, sliding or saltation.

Aggradation of the river bed is commonly observed upstream of dams and weirs, often many kilometres upstream of the structure, in the form of a delta near the upstream limit of the backwater pool. Deltas can also develop where tributaries discharge into weir pools and impoundments.

A broad indication of the efficiency of a dam or weir as a sediment trap can be obtained by using a method developed by Brune (1953), which determines trap efficiency on the basis of the ratio of dam or weir capacity to mean annual inflow. The capacity–inflow ratio is essentially a means of assessing the scale of the dam in proportion to the scale of the stream on which it is situated.

Dams which have relatively large capacity–inflow ratios store almost all of the sediment inputs they receive. Assessments of a number of major dams throughout Australia have indicated trap efficiencies of around 99% – these dams include Jindabyne Dam on the Snowy River (Brizga & Finlayson 1992, 1994), Glenbawn Dam on the Hunter River (Erskine 1985), and the four large dams in the Upper Nepean Water Supply system (Sammut & Erskine 1995).

Even weirs with relatively small capacity–inflow ratios, and thus relatively low total trap efficiencies, may have a filtering effect on sediment gradings which pass downstream. For example, if a weir has no gates and has not been filled with sediment to the extent that bed materials can pass over the crest, the coarse fraction that travels as bedload cannot pass downstream. Gated weirs can sometimes be managed to pass bedload during floods (Section 2.2.1.4).

Erosion downstream of dams and weirs due to sediment starvation (sometimes referred to as 'clearwater erosion') occurs when the water released or spilled has sufficient energy to move sediment, but carries a negligible sediment load due to the sediment trapping effect of the impoundment (Galay 1983; Kondolf 1997). Erosion continues until the bed eventually becomes armoured due to the selective removal of erodible fine materials, and the remaining lag deposit of boulders, cobbles or coarse gravels is too coarse to be shifted often (Kondolf 1997). This effect persists downstream until the stream has been able to pick up sufficient sediment to compensate for the deficit caused by the dam, and can therefore extend for a considerable distance as development of an armour layer limits in-stream sediment availability.

Clearwater erosion has been widely reported in the overseas literature (eg. Galay 1983; Germanoski & Ritter 1988). It has been observed to be most pronounced where the rivers have fine-grained bed materials, and where the effects of the dam on flood peaks are relatively minor (Williams & Wolman 1984).

There have been relatively few reports of clearwater erosion downstream of dams in Australia. Erskine (1985) observed evidence of clearwater erosion in the Hunter River downstream of Glenbawn Dam, a flood mitigation and water supply storage on the Hunter River, which has an estimated trap efficiency of around 99%. Evidence of clearwater erosion included lateral migration, bed degradation and progressive coarsening of bed material, consistent with degradation processes. Erskine's assessments were based on repeated cross-section surveys and the results of a bed material sampling program which was initiated by the New South Wales Water Resources Commission at the time the dam was completed. Thoms & Walker (1993) and Walker & Thoms (1993) observed that the lower Murray River was developing a stepped bed profile due to active deposition and erosion associated with a series of weirs.

There are at least four possible reasons for the relative scarcity of reported instances of clearwater erosion in Australia.

1. Post-regulation flows must have sufficient energy to erode the stream bed in order to cause clearwater erosion. In Australia, flows are often dramatically reduced downstream of major dams as the result of diversions into separate channel or pipe systems, or inter-basin transfers, so that there are significant reductions in competence and sediment transport capacity. Overseas studies have also noted that in instances where dams have led to dramatic reductions in flood magnitudes, no significant clearwater erosion has been reported (Kondolf 1997).
2. Clearwater erosion requires erodible channel boundaries. Many Australian dams are located in bedrock reaches which are relatively resistant to erosion. Some of the worst overseas examples of clearwater erosion occur in streams with easily erodible beds, for example, Williams and Wolman (1984) reported bed incision by up to 6 m in a sand bed stream in California.

3. Geomorphological assessments of the impacts of dams and weirs have been carried out for only a small number of Australian rivers, and no assessment has been made of the representativeness of the examples selected for study. Thus the scarcity of documented examples of clearwater erosion cannot necessarily be taken to demonstrate that this phenomenon has seldom occurred.
4. A lack of historical survey data in the vicinity of many dams has precluded assessment of changes in bed levels and channel cross-sections using repeated surveys. Historical sediment grading data, such as used by Erskine (1985) in his assessment of Glenbawn Dam, are seldom available. Field evidence therefore becomes the key information source in most instances. As *post-hoc* geomorphological assessments of impoundments are often carried out a considerable period of time after the impoundments have been completed, adjustments in areas proximate to the dam may be well advanced and field evidence of clearwater erosion may not be readily apparent. Field evidence could be subtle (eg. relatively coarse bed materials) and difficult to confidently distinguish from natural conditions without pre-dam baseline data.

Trapping of sediment inputs from the upstream catchment in impoundments makes the stream below the impoundment more dependent on local sources of sediments. This may have implications for sediment grading, depending on the nature of the sediments available in bed and bank deposits or supplied by downstream tributaries compared with those produced by the upstream catchment. The impact of the tributary inputs on substrate character may be amplified as the result of a reduction in the ability of the river to efficiently move these materials further downstream. For example, in the Brisbane River, inputs of sand and mud from tributaries below Wivenhoe Dam are contributing to buildups of fine sediments which are resulting in the loss of riffle habitat (Brizga 1998).

Gaynor et al. (1995) observed accumulations of fine sediments downstream of diversion weirs on headwater tributaries of the Yarra River. They suggested that these sediments may have been transported downstream past the weirs via flows through scour pipes near the bases of the weirs.

Impacts on sediment entrainment, transport and deposition

By altering the downstream hydrological regime, water resource development affects sediment entrainment, transport and deposition processes, as these are all partly determined by flow. Some examples of change have already been provided in Section 2.2.1.2.

Changes in the frequency and duration of flows competent to move the pre-existing bed materials have implications for substrate character. For example, if riffles are not flushed on a reasonably regular basis, fine sediment deposits tend to accumulate in the interstices (gaps) between the gravels, reducing and eventually eliminating the interstitial habitats. Over the longer term, the interstitial deposits may become colonised by macrophytes, which then anchor the existing sediments and protect them from scour and also trap more fine sediments, eventually burying the riffle substrate and leading to the loss of riffle habitat. This process has been observed on the Brisbane River downstream of Wivenhoe Dam (Brizga 1998).

Such changes in riffle sedimentology are not only relevant from the viewpoint of their implications for habitat suitability of the substrate, but also because of their implications for future sediment entrainment. The critical force required to entrain sediments depends on sediment packing (Gordon et al. 1992). Filling of interstitial voids and vegetation establishment on riffles increases the magnitude of the flow required for entrainment, thus decreasing the future frequency of entrainment.

Reductions in the frequency or duration of flows competent to transport tributary sediment inputs further downstream have implications for sedimentology and channel morphology, as sediment bars will develop or become enlarged near tributary junctions. For example, Grose (1993) reported that on the Cudgegong River downstream of Windamere Dam, deposition of coarse gravel bars at tributary mouths has occurred because flood releases from Windamere Dam have become too infrequent to remove them. In the Snowy River, bed sediments at Dalgety are dominated by inputs from Wullwye Creek, a local tributary, rather than the Snowy River (Brizga & Finlayson 1994). In the Yarra River, the channel has become constricted by sand bars at the mouth of the Little Yarra River (Brizga & Craigie 1997). Buildups of bars at tributary confluences may have adverse impacts on human uses as the result of bank erosion due to the deflection of flows by the bars, increased frequency of overbank flooding or, in extreme

cases, cutoffs or avulsions resulting from flows being forced out of the channel by the blockage.

Changes in hydrological regime resulting from flow management and flow augmentation may increase the frequency and duration of competent flows, resulting in accelerated erosion.

2.2.1.3 Methods for determining flow requirements

It has been previously argued that sediment load and transport are often overlooked in river management studies, including environmental flows studies (Carling 1995). The only aspect of sediment motion which has been widely addressed in environmental flow studies is sediment entrainment. A minor flood pulse referred to as a 'flushing flow' or 'channel maintenance flow' is often provided for the maintenance of gravelly or sandy substrates by flushing out accumulations of fine sediments. Often the same pulse is expected to perform other functions, ranging from maintenance of channel size by scouring out encroaching vegetation to flushing salt wedges out of estuaries. Methodologies for determining flushing and channel maintenance flows are discussed in Section 2.5.

The issue of sediment transport capacity was raised by Brizga (1997a) in a discussion of the environmental flow requirements of the Barron River, Queensland. She suggested that the implications of various flow management scenarios for sediment transport could be estimated with sediment transport modelling.

Channel maintenance flows are necessary, but not necessarily sufficient, for maintaining an existing channel (Andrews & Nankervis 1995). The existing methodologies do not address the full range of flow-related impacts of water resource development on sediment motion. For example, no rigorous method has been proposed for determining the flows required to redistribute sediment buildups resulting from tributary inputs, although it is sometimes assumed that the flood pulse specified as the flushing or channel maintenance flow will somehow perform this function.

Management measures based on flow provision alone will not address the impacts arising from the disruption of sediment transport continuity by dams and weirs. Unless this impact is satisfactorily addressed, it may void some of the benefits which might otherwise be provided by an environmental flow.

An example of this problem is provided by the issue of sediment supply by the Barron River to the Barron Delta coastline (Brizga 1997a). The Barron River is the key source of sand supply for the northern beaches of Cairns, which are situated along the edge of the Barron Delta. While it is possible to determine a flow regime which would be capable of transporting sufficient sand to meet coastal system requirements, such volumes of sand are not likely to be supplied under present conditions even if appropriate flows were provided, due to disruption of the downstream continuity of sediment transport by the Barron Gorge Weir and historical in-stream sand and gravel extraction from the lower reaches of the Barron River below the weir. A source of sand downstream of Barron Gorge Weir would need to be available in order to make it worthwhile to include a specific environmental flow provision to ensure sufficient transport capacity to deliver sand to the coast.

A similar point about the dependency of the effectiveness of environmental flows on other factors also applies in situations where a stream is subject to an elevated sediment input (eg. as a result of catchment disturbances or accelerated erosion). In such cases it may be desirable for measures to be taken to reduce sediment inputs instead of, or in addition to, measures to maintain or increase the ability of the river to move the imposed sediment load.

2.2.1.4 Other management measures

Two types of management measures related to sediment motion, other than flow management, are discussed here:

- measures other than flow management which could assist in addressing the impacts of flow regime change on sediment motion; and
- measures to address the disruption of sediment transport continuity by dams and weirs.

Buildups of sediments could be managed by physical intervention. This may be useful in situations where infrastructure constraints or established commitments make it impossible to deliver an adequate environmental flow. For example, it may be possible to facilitate the flushing of fine sediments from riffles by reducing the packing of the riffle sediments by mechanical raking (Brizga 1998), and tributary bars can be reduced in size by excavation. The latter would affect the overall sediment budget of the stream in question, so the risk of adverse impacts and their implications would need to be carefully assessed. No trials of these techniques have been reported in Australia, so any application at this stage must be regarded as experimental. It would be important for all possible precautions to be taken to minimise associated environmental disturbance (eg. vegetation damage, pollution).

Sediment inputs from developed catchments are generally higher than natural inputs unless intercepted by dams or weirs. Restoration of more natural levels of sediment inputs would reduce the demand imposed on streams to transport and rework elevated sediment loads. Appropriate catchment management measures include:

- treatment of point source inputs, including road drainage;
- soil conservation measures; and
- stabilisation of eroding tributaries.

A range of options for the transfer of sediment past dams has been reviewed by Kondolf (1995, 1997), including gravel replenishment below dams and sediment sluicing or bypass. A brief summary is presented here.

Gravel replenishment has been attempted overseas in the United States and Europe (Kondolf 1997). In the United States, gravels have been artificially supplied downstream of dams on at least 13 Californian rivers in order to enhance habitat for salmon spawning. The quantities supplied have been small relative to the total bedload deficit created by the dams. In the examples studied by Kondolf, continued importation of gravel was required because the introduced gravel washes out and is carried downstream during high flows. Larger gravels, which would be more likely to remain in place, are not suitable for salmon spawning. In Europe, gravel is artificially supplied to the Rhine River downstream of Barrage Iffezheim to address sediment deficit problems resulting from a series of hydroelectric dams. Around 170,000 tonnes of gravel are introduced each year, the exact volume being dependent on run-off. The quantity supplied has been calculated to be sufficient to satisfy the transport capacity of the river under the regulated hydrological regime. This strategy has been reported to have been successful in preventing further incision of the river bed resulting from clearwater erosion.

Kondolf (1997) reported on various methods which have been used for passing or sluicing sediment through reservoirs. These methods have generally been developed for the purpose of solving reservoir sedimentation problems rather than supplying bedload downstream.

Methods for passing sediments through reservoirs during floods have included:

- keeping large-capacity, low-level outlets open at the start of a flood, with the reservoir drawn down, so that the reservoir effectively behaves as a reach of the river;
- using diversion tunnels to route sediment-laden flood waters around reservoirs; and
- passing sediment laden floodwaters through a reservoir as a density current vented through a bottom sluice on the dam.

An alternative to releasing sediments during the course of a flood is to allow sediments to accumulate and subsequently discharge them as a pulse (Kondolf 1997). This may have significant detrimental ecological effects, particularly if the release is made under baseflow conditions when the imposed load cannot be transported. The impacts are less severe if the sediment is flushed during a high flow event. In larger dams, the sediment accumulated near the outlet is generally mud, the sluicing of which may have detrimental impacts on downstream biota and water quality.

Kondolf (1997) noted that the greatest potential for the application of pass-through and sluicing methods exists in the case of small dams situated in narrow v-shaped valleys. The methods are unsuitable for reservoirs designed for flood mitigation, or where flood storage is an important source of water supply. Large reservoirs cannot generally be drawn down sufficiently to transport sediment through their length to the outlet works as this would eliminate carryover storage from year to year. Sediment pass-through during high flows is not normally carried out in North America because of the limited capacity of many low-level outlets, and concern that debris may become stuck in the outlets (Kondolf 1997).

Another possible approach to sediment pass-through is to allow weirs to become infilled by sedimentation processes so that bedload can pass freely over the weir crest, as in the case of a natural waterfall. This approach would only be applicable to diversion weirs where no storage capacity is required.

2.2.2 Channel morphology

Channel morphology is defined here as the size and shape of the stream channel. Variables included in this category include:

- cross-sectional size and shape – for example, width, depth, width–depth ratio;
- planform attributes – for example, meander wavelength, meander amplitude, sinuosity, braiding;
- bars – for example, point bars, mid-channel bars; and
- bedforms – for example, riffle-pool sequences, dunes.

Channel morphology is an important consideration in environmental flow studies because:

- it determines habitat structure and habitat availability, for example, channel contraction leads to loss of in-stream habitat;
- it affects floodplain processes, for example, channel contraction may lead to increased overbank flooding, and possible increased risk of avulsion;
- it can affect bank stability, for example, deflection of flow towards the stream banks by bars can lead to increased erosion; and
- it affects sediment motion via effects on hydraulic variables such as energy grade and flow confinement.

2.2.2.1 Role of flow in channel morphology

Channel morphology at any given point in time is determined by a number of factors:

- flow regime;
- sediment load;
- vegetation;
- valley form and gradient;
- boundary materials (eg. bedrock, clay, sand, gravel); and
- inherited features from past environmental regimes.

Sediment load and vegetation are subject to change as the result of changes in flow regime, although they are partly controlled by other factors also. For example, sediment load is related to catchment lithology and weathering processes as well as to transport processes, and while the latter depend on flow, they are also affected by other hydraulic controls (Section 2.2.1). Vegetation is determined by factors such as climate and soil as well as flow.

Relationships between channel morphology and flow have been a major focus of interest in the fluvial geomorphological literature since the 1950s (a seminal paper was published by Leopold & Maddock in 1953). Key concepts in relationships between flow and channel morphology are reviewed with reference to (i) the concept of 'channel forming discharge', (ii) the role of floods, and (iii) the role of low flows.

Channel forming discharge

Much of the early work exploring relationships between streamflows and channel morphology was based on principles established in regime equations that had been developed for irrigation canals. Relationships between flow and morphological variables were described by power functions derived from regression analysis, in the form illustrated by the following hydraulic geometry equations:

$$w = aQ^b \qquad (1)$$

$$d = cQ^f \qquad (2)$$

where w and d are width and mean depth respectively; Q is discharge; and a, b, c and f are empirically derived constants (Leopold & Maddock 1953). Different values of a, b, c and f can be expected to apply in different environmental settings.

Relationships in a similar form as shown in Equations 1 and 2 have been found to apply to meander wavelength (Knighton 1984). Riffle spacing is also related to flow via channel width, and riffle-to-riffle spacings of five to seven times channel width have typically been reported (Knighton 1984), although this may be distorted by factors such as inputs of sediment from tributaries or the localised occurrence of coarse floodplain deposits (Richards 1982).

Schumm (1969) moved a step further away from the irrigation canal model by developing empirical equations relating morphological characteristics to flow and sediment load (size and quantity). He used multiple regression models to explore these relationships.

In the regime equations for irrigation canals and the empirical models of channel morphology derived from them, it is necessary to define hydrological regime in terms of a single representative flow. In contrast to irrigation channels, which are subject to relatively constant flows, natural river channels are subject to a much wider range of flows as well as varying degrees of flow variability. Thus a significant body of geomorphological literature arose from the need to identify the key formative discharge. Central concepts in this literature include 'dominant discharge', 'bankfull discharge', and 'effective discharge'.

'Dominant discharge' has been defined as the steady flow that would produce the same channel dimensions (specified in terms of parameters such as width, depth and meander wavelength) as the range of flows to which a stream is exposed (Knighton 1984). It has often been equated with bankfull discharge.

'Bankfull discharge' is the flow that fills the bankfull channel. It often corresponds to a flood with an annual series recurrence interval (ARI) in the range one to two years, although a wide range of recurrence intervals has been reported. For example, a review by Williams (1978) identified recurrence intervals from less than 1 year to over 30 years. Page (1988) analysed the

frequency of bankfull discharge in North American data sets published by Wolman and Leopold (1957), Leopold et al. (1964) and Williams (1978), and found that a significant minority of sites in each data set (35%, 20% and 38% respectively) had a bankfull discharge with an ARI greater than two years. Pickup and Warner (1976) found that small streams in the Cumberland Basin in New South Wales were characterised by bankfull discharge return periods of between four and ten years on the annual series.

A wide range of definitions of the bankfull stage has been used, including morphometric criteria, sedimentological criteria, vegetation limits (including lichen limits), and flow frequency. Subjective expert judgements need to be applied at many sites, even where criteria are clearly specified, as sharp boundaries often do not exist. The magnitude and thus the recurrence interval of bankfull discharge is significantly affected by the method used to determine the bankfull stage.

Different methods often give contradictory results, for example, in the humid tropics it is not uncommon for large trees to occur within the area defined as the bankfull channel on the basis of morphological criteria and flow frequency. Another example is provided by incised streams, where the bankfull stage defined in terms of flow frequency occurs well below the hydraulic discontinuity associated with the major break in slope separating the channel from adjacent floodplains or terraces.

Multiple significant flow levels have been identified in some instances. Knighton (1984) noted that morphological parameters do not necessarily all correlate equally well with the same 'bankfull' level. Woodyer (1968) identified the existence of several bench levels within the bankfull channel in streams in the Murray-Darling Basin. Newbury and Gaboury (1993) identified a second significant flow level, which they called the 'channel maintenance flow' level, which corresponds to the lower limit of permanent terrestrial vegetation or the upper limit of surfaces abraded by bedload, and occurs within the larger 'bankfull' channel.

'Effective discharge' is defined in terms of the magnitude and frequency of sediment transport. It is calculated by multiplying together sediment rating curves and flow duration curves. Effective discharge is the discharge at which the product of magnitude and frequency is at a maximum (Wolman & Miller 1960). Smaller events have less sediment transport capacity than the effective discharge, and larger events occur less frequently than the effective discharge. Thus while individual events have higher sediment transport capacities, the total volume of sediment that they transport is less than in the case of the more moderate effective discharge events which occur more frequently (Wolman & Miller 1960).

The effective discharge may be the same as bankfull discharge (Wolman & Miller 1969; Andrews 1980), but this is not necessarily the case. Baker (1977) found that in streams characterised by highly variable flow regimes and resistant boundary sediments, effective discharge occurred less frequently than bankfull discharge, while Pickup and Warner (1976) found that in sand and fine gravel bed streams in New South Wales it occurred more frequently, about three to five times per year on average.

Overall, the difficulties which have been encountered in attempts to define a single channel forming discharge strongly suggest that there is more than one morphologically significant flow level.

Role of floods

The impact of floods on stream channels has attracted the attention of geomorphologists in Australia and abroad, and there is a significant body of literature dealing with 'flood geomorphology' and related issues.

A key point which is apparent from the literature on flood geomorphology is that the role of floods in shaping channel morphology varies between streams. Variations in response to floods may also be apparent between different reaches of the same stream. In some instances major floods totally transform channel morphology by carving out an enlarged flood channel, and subsequent minor and moderate events gradually reconstruct the stream channel to its pre-flood dimensions. Thus at any given point in time, channel morphology will depend on flood history, as different morphologies will be apparent at different stages in the flood impact and recovery sequence. In other situations, floods, even large infrequent events such as the 50 or 100 year ARI flood, cause minimal change.

Inter-annual flood variability has been argued to be a significant factor in determining the responsiveness of streams to floods (Baker 1977). In the case of streams characterised by high inter-annual flood variability, large infrequent floods (eg. the 100 year ARI flood) are many times greater in magnitude than average events, and can thus produce significantly greater disturbance. Streams with high inter-annual flood variability are therefore likely to be affected by catastrophic erosion during major floods, undergo natural temporal variations in

channel morphology, and feature a wide gradational zone between the low flow channel and the floodplain. Streams characterised by low inter-annual flood variability tend to be relatively unaffected by rare events, because the difference in magnitude between these events and average events is not large. Channel morphology is likely to be characterised by a higher degree of temporal stability, and the streams are likely to have more sharply defined channel/floodplain boundaries than streams subject to a high degree of inter-annual flood variability.

An issue that needs to be explored is the extent to which variations in stream behaviour coinciding with differences in flood variability are dependent on associated climatic factors and vegetation growth rates rather than just differences in hydrological variability *per se*.

Another factor affecting the effectiveness of large floods is the channel/floodplain relationship (Brizga & Finlayson 1990). Reaches where flood flows are confined into the stream channel (eg. gorges, narrow valleys, incised channels) are subject to the full range of flood flows generated by the upstream catchment. In the case of reaches where the stream channel is perched above a broad floodplain, the channel is only affected by floods up to bankfull capacity as the rest of the flow is carried by the floodplain. The maximum stream power to which confined channels are exposed is determined by flood magnitude, whereas in the case of perched channels it is limited by bankfull capacity. Not unexpectedly, morphological differences are generally apparent between these types of channels.

A given reach of a stream can be transformed from having a perched channel to an incised channel as the result of the impact of human activities (eg. channelisation or straightening) or natural processes (eg. avulsion or in-situ erosion during a major flood). The susceptibility of the reach to flood impacts will be increased and channel morphology will be altered as a result.

Flood duration may be almost as important as flood magnitude in determining flood impacts. Costa and O'Connor (1995) developed a conceptual model combining flow duration, peak stream power, flood energy and erosion thresholds, which showed that floods of medium to long duration with medium to large total energy expenditure and large peak stream power were the most effective. Floods with equally large peak stream power but short duration and low total energy expenditure were relatively ineffective, as were floods with long duration, moderate to large energy expenditure, but low peak stream power.

Shifts in hydrological regime, from flood-dominated regimes to drought-dominated regimes (or phases of above and below average flood activity) have been identified in many eastern Australian river systems (eg. Warner 1995). Flood-dominated regimes are associated with channel enlargement and erosion; drought-dominated regimes with channel contraction and sedimentation. Different morphological conditions prevail under these differing hydrological regimes.

Role of low flows

Flow influences stream channel morphology in two ways:

- by affecting erosion and sediment transport processes; and
- by precluding the growth of terrestrial vegetation.

In the geomorphological literature, the role of flows in shaping channel morphology through erosion and sediment transport processes has been emphasised, to the virtual exclusion of any discussion of effects of low flows on channel morphology via their effects on vegetation zonation. Stewardson and Gippel (1997, p. 34) summarised the thrust of existing literature as follows: "channel form is a complex function of flood frequency, flood duration and sediment transport".

Prevailing low flow conditions are significant for aquatic and riparian vegetation, as discussed in other chapters of this report. Vegetation affects geomorphological processes by altering erosion thresholds and hydraulic roughness. For example, dense aquatic or riparian vegetation will increase erosion thresholds and increase hydraulic roughness, thus reducing flow velocity and inducing deposition.

A possible reason why low flows have not previously been considered in the literature on channel morphology is that in temperate settings, terrestrial vegetation may take more than a year to become established in stream channels to such a degree that it cannot be easily removed by minor floods (1–2 year ARI). However, in humid tropical and subtropical environments, the colonisation process may be very rapid, increasing the significance of low flows as a control on vegetation, and hence channel morphology.

2.2.2.2 Impacts of water resource development on channel morphology

Principles derived from the regression models quantifying relationships between dominant discharge

and channel morphology can be used to predict changes in channel morphology resulting from changes in flow. If the dominant discharge is increased, then channel size can be expected to increase, and if the dominant discharge is decreased, then channel size can be expected to decrease. Similarly, models linking channel morphology to flow and sediment load (eg. Schumm's 1969 equations) have been used to predict morphological impacts resulting from changes in both of these parameters which generally occur as a result of regulation.

It must be noted that for these models to apply, it must be assumed that stream channel morphology was in equilibrium with the prevailing flow regime prior to the disturbance caused by water resource development. This is not always the case. For example, in the case of the Brisbane River downstream of Wivenhoe Dam, it was noted that pre-regulation channel morphology was still in many areas dominated by features apparently related to ancient conditions when larger flows prevailed, and appeared to be in the process of undergoing further natural adjustments (Brizga 1998). The impacts of regulation in this instance appear to have been superimposed upon natural adjustment processes.

Implications of water resource development for sediment motion have been discussed in Section 2.2.1. Morphological inputs resulting from changes in sediment motion include:

- channel widening and deepening as the result of clearwater erosion below dams and weirs;
- sediment buildups at tributary junctions if the tributaries supply sediment at a rate faster than the main stream can remove it; and
- bed aggradation and bank accretion resulting from reductions in flow competence and interactions with vegetation.

Different types of regulation have different hydrological impacts. Most existing research has focused on major dams and water resource developments, probably because these have had the most spectacular impacts. Similar forms of infrastructure (eg. large dams) may have varying impacts depending on how they are operated. For example, Jindabyne Dam, Upper Yarra Dam, Eildon Dam and Wivenhoe Dam may superficially appear to be similar as they are all large dams. However, in the case of Jindabyne Dam and Upper Yarra Dam, flow is diverted out of the river into a pipe or aqueduct system, resulting in reductions across the full range of flows. In the case of Eildon Dam and Wivenhoe Dam, the dam is used to regulate flows in the river, resulting in elevated baseflows and reduced flood peaks. The Jindabyne and Upper Yarra type of regulation leads to an overall reduction in channel size, while the Eildon and Wivenhoe type of regulation leads to enlargement of the low flow channel but reduction in the size of the high flow channel (Erskine 1993; Brizga 1998).

Two main types of reduction in channel size have been identified (Petts 1979): accommodation adjustment (the invasion of channel airspace by vegetation) and channel contraction as the result of sediment buildup within the pre-regulation channel. The latter may occur in the form of localised aggradation at tributary confluences (as discussed in Section 2.1) or widespread morphological adjustment involving the development of benches within the pre-dam channel and eventually more appropriate planform dimensions and riffle-pool spacing. Rates of channel contraction by sediment buildup depend on the availability of sediment. In many cases it appears to be a slow process, requiring decades or centuries before full adjustment has taken place. For example, significant sections of the Snowy River (affected by Lake Jindabyne since 1967) and Yarra River (affected by the Upper Yarra Dam since 1957) have primarily undergone accommodation adjustment to date.

An important issue related to reduction in channel size is the tendency for exotic species to be the first to colonise areas of river bed freshly exposed by a decrease in flow. For example, in the Barron River in northern Queensland, para grass has played an important role in colonising parts of the river bed which were exposed by the reduction in flows resulting from Tinaroo Dam (Brizga, 1997b; Yu, in press). In the Snowy River (south-eastern Australia), upper Hunter River (New South Wales) and Yarra River (Victoria), encroachment by willows has occurred (Erskine 1985; Brizga & Finlayson 1992, 1994; Brizga & Craigie 1997).

Channel enlargement may occur in stream systems receiving additional flows from inter-basin transfers (Galay 1983). Channel enlargement may simply be accomplished by the occupation of a larger wetted area or it may involve erosion processes. The actual type of response that will occur depends on the available energy and the resistance of the bed and bank materials. Bed armouring may limit the extent of deepening.

The downstream impacts of water resource development may be spatially variable, depending on factors such as sediment availability, bed and bank

materials and stream power. For example, different reaches of the same stream may simultaneously exhibit accommodation adjustment, degradation and contraction (Petts 1979; Erskine 1985).

Not all of the changes in channel morphology that have been reported to be associated with flow regulation are well understood. For example, in the lower Snowy River regulation coincided with a change in bed morphology from pronounced alternate bars to a relatively flat sand bed (Brizga & Finlayson 1992, 1994; Erskine 1996). There are no simple, well-established geomorphological principles which could be readily applied to assess links between this morphological change, flow regulation and other disturbances which have affected the lower Snowy River. Detailed studies have produced explanations related to hydrograph shape and flood duration (Stewardson et al., in prep). In cases such as this one, relationships of morphological changes to flow and possible confounding variables must be elucidated before meaningful environmental flow provisions can be determined.

Studies of the Yarra River have shown the Upper Yarra Dam initially resulted in reduced frequency of overbank flooding (Brizga et al. 1995). Over the four decades or so during which flows have now been regulated, an expectation of relatively infrequent flooding of the floodplain has developed and adjacent land uses adapted to the post-regulation overbank flooding regime. However, as encroachment of terrestrial vegetation and bar development reduces the size of the channel, in the absence of management intervention the frequency of overbank flooding is likely to increase over the longer term, eventually returning to a level more like the original level, with adverse implications for the land uses which have adapted to less frequent inundation of the floodplain (Brizga & Craigie 1997).

2.2.2.3 Methods for determining flow requirements

The maintenance of channel morphology is generally addressed in environmental flow studies through the provision of a flushing or channel maintenance flow. Often the same flow which is provided for periodic entrainment of the substrate (Section 2.2.1.3) is expected to be adequate for maintenance of channel morphology. Methodologies for determining flushing and channel maintenance flows are discussed in Section 2.5.

Channel maintenance and flushing flows are generally annual or biennial events, similar to the common frequency of bankfull discharge (Section 2.2.2.1). The importance of larger floods is generally acknowledged by geomorphologists participating in environmental flow studies. However, in the majority of studies large floods are not specifically requested because it is assumed that they will occur anyway, despite regulation.

Generally, no recommendations are made with regard to minimum low flows from a geomorphological viewpoint. However, in Water Allocation and Management Planning (WAMP) technical panel discussions, Brizga argued that minimum low flow provisions were necessary for geomorphological purposes in the Logan (Brizga 1997d) and Barron Rivers because of implications of low flows for channel morphology via effects on vegetation zonation.

Upper limits for low flows have been examined in relation to the likelihood of bed and bank erosion.

2.2.2.4 Other management measures

In situations where a stream is subject to elevated sediment input, reduction of that input would assist in reducing rates of channel contraction.

Physical works to address morphological impacts of regulation fall into three broad categories:

- removal of obstructions in order to restore original capacity;
- use of in-stream structures to assist in re-establishing significant morphological features; and
- channel stabilisation works.

Restoration of original capacity may be a desired goal in situations where increased frequency of overbank flooding has adverse impacts on human uses on the floodplain, or where there is a risk of a cutoff or avulsion. The types of works which have been discussed in relation to restoration of channel capacity include the removal of encroaching willows and weeds (Brizga & Craigie 1997), and trimming or removal of bars at tributary junctions. Removal of sediment from the active channel system may potentially have adverse impacts.

No works to restore significant morphological features are known to have been carried out in Australia. A detailed discussion of works of this type is presented by Stewardson et al. (in press) who identified a change in bedform type in the lower Snowy River from alternate bars to a uniform bed as a key impact of the Snowy Mountains Scheme. They proposed that even if an optimal channel maintenance flow is not provided, the alternate bars could be restored by a smaller, sub-optimal

channel maintenance flow accompanied by construction of submerged vanes or timber pile deflectors to enhance alternate bar forming processes. They pointed out that from an ecological viewpoint it would be preferable to restore the bars solely through the provision of flow, but this may not be feasible on economic grounds.

Erosion due to channel enlargement resulting from clearwater erosion or increased flows has traditionally been addressed by erosion control works such as rock lining of stream banks.

2.2.3 Bank stability

Bank erosion is generally viewed negatively from a human-use viewpoint as it may threaten assets situated near a stream, such as roads and bridges, and lead to loss of streamside land. From an ecological viewpoint it may be considered to have adverse impacts in situations where riparian vegetation is limited to a single row of mature trees, and erosion causes the loss of these trees. Also, elevated sediment inputs resulting from accelerated bank erosion may have deleterious impacts on in-stream habitats and biota. However, bank erosion is a natural process and erosion not exceeding natural levels may be an ecologically desirable form of disturbance.

2.2.3.1 Bank stability, flow and water resource development

Bank stability is affected by water resource development, both directly as a result of hydrological changes and indirectly as a result of changes in sediment transport processes and morphological adjustments such as channel enlargement and contraction. Relationships between bank stability and flow are examined here in the context of impacts of water resource development.

The shape of the hydrograph recession limb is important. Rapid recession is more likely to lead to bank slumping than gradual recession. Rapid drawdown due to regulation has historically contributed to bank slumping on the Brisbane River downstream of Wivenhoe Dam (Brizga 1998).

Flood timing and duration affect the degree of pre-wetting of the banks. Soil moisture conditions are a significant factor in bank slumping. Banks that already hold water because of a previous recent event, or have undergone thorough wetting because of prolonged flood duration, are more likely to fail than dry banks subject to a short flashy event, all other things being equal. Rapid drawdown may not have major effects on bank stability if flood peaks are very flashy, but would be expected to have much greater effects if flood duration is prolonged.

Flood duration is also relevant to bank erosion via its effect on the duration of competent flows, as rates of meander migration are related to rates of bed sediment transport (Hickin & Nanson 1983). Increased frequency of competent flows could therefore be expected to increase rates of bank erosion related to meander migration, while decreased frequency of competent flows may reduce meander migration rates.

Changes in channel morphology resulting from regulation have important consequences for bank stability. Channel enlargement in response to increased flows may involve bank erosion. Clearwater erosion downstream of dams may involve direct attack on the banks by flows, or may have an indirect effect via bed lowering, which increases the effective slope of the banks and thus increases the risk of bank failure.

Channel contraction in response to a reduction in low to moderate flows can lead to increased risk of bank erosion in high flows (Brizga & Craigie 1997). Channel contraction alters channel hydraulics, for example, narrowing increases flow confinement, and thus unit stream power for a given flow. Point bars or mid-channel bars which may develop or enlarge as the result of reduced flows may divert the main current towards the banks. Opportunistic vegetation growth associated with the contraction process also may deflect flows towards the banks. This type of instability may be particularly important in situations where regulation leads to increased flood variability by reducing smaller floods but allowing large events through at near their full natural magnitude.

2.2.3.2 Environmental flow assessment methods

Impacts related to rapid drawdown are generally addressed in environmental flow studies by stipulating that drawdown rates should not exceed natural hydrograph recession rates. Maximum event durations are also sometimes specified. For example, Grose (1993) specified maximum durations of transfer releases from Windamere Dam with the intention of minimising adverse impacts on bank stability.

Methods for addressing changes in channel morphology have been outlined in Section 2.2.2.

2.2.3.3 Other management measures

Flow management is often not the sole or principal cause of bank erosion on a regulated river. Other factors include natural meander processes, past channel

modifications (eg. straightening, channelisation), groundwater seepage, irrigation water seepage, and stock damage.

Structural works (eg. concrete lining, rock lining, groynes) are commonly carried out to address bank erosion. Riparian revegetation and measures to reduce stock pressures are also often carried out. Non-structural measures involve eliminating the conflict between erosion and adjoining land uses, and entail modification of the conflicting land use (eg. moving an asset which is at risk from erosion processes further away from the stream).

2.2.4 Hydraulic biotopes

Hydraulic habitat is a key element of most environmental flow methodologies. The criteria for determining hydraulic habitat requirements often relate to biological rather geomorphological factors. For example, methods based on wetted perimeter or wetted habitat area have the objective of maximising macroinvertebrate production, and depth-velocity methods are based on habitat suitability for target fish species.

Geomorphology intersects with lotic ecology and hydraulics in the concept of hydraulic biotopes (Anderson & Morison 1989; Wadeson 1995). Examples of hydraulic biotopes include riffles, runs, pools, glides, cascades, rapids and backwaters. Hydraulic biotopes are controlled by channel morphology, substrate and flow conditions, and are thus susceptible to changes in any or all of these factors resulting from water resource development.

Brizga (1998) examined the question of change in hydraulic biotopes in the Brisbane River downstream of Wivenhoe Dam resulting from flow regulation, and established that many former riffles now essentially function as runs. This change has involved drowning of the riffles under greater depths of flow due to elevated baseflows, as well as changes in substrate, including the establishment of dense beds of macrophytes on former riffle surfaces.

Hydraulic biotopes are subject to change as the result of longer term adjustments in channel morphology. Stewardson and Gippel (1997) noted that if a channel contracts in response to altered flow regime, models of habitat availability as a function of discharge developed pre-regulation will no longer apply. A similar point applies to channel enlargement or other morphological adjustments.

2.2.4.1 Environmental flow assessment methods

Most existing environmental flow methodologies emphasise the biological aspects of hydraulic habitat. Hydraulic biotopes were considered in the Brisbane River environmental flow study (Arthington & Zalucki 1998), and recommendations were made to mitigate existing impacts of regulation on the riffle biotope as well as minimise potential impacts of future development on this biotope.

2.2.4.2 Other management measures

Flow depths can be increased by narrowing the flow cross-section or reducing flow gradient, while flow depths can be decreased by widening the flow cross-section or steepening the flow gradient. No Australian examples are known where this type of intervention has been carried out with a primary purpose of modifying hydraulic biotopes.

Measures to address issues related to substrate conditions or channel morphology have been discussed in Sections 2.2.1.4 and 2.2.2.4. respectively.

2.2.5 Tributary base level

2.2.5.1 Impacts of water resource development on tributary base levels

Incision of tributaries entering regulated streams downstream of major dams has been reported in many overseas studies. A list of examples is cited by Germanoski and Ritter (1988), who carried out a relatively detailed study of this issue, and some dramatic examples were also presented by Galay (1983). Links between tributary incision and main stream regulation have been inferred in studies of several Australian examples, including tributaries of the Murray River, Goulburn River and Yarra River (Brizga 1996, 1997c; Brizga & Craigie 1997).

Tributary incision may occur downstream of dams due to lowered base level in the main stream, as the result of any of the following four factors:

- water levels in the main stream are lowered by bed degradation;
- water levels in the main stream are lowered by channel widening;
- water levels in the main stream are significantly lowered by reduced flows; and
- peak flows in the main stream are out of phase with peak flows in tributaries, as the result of regulation.

In the Australian examples reported above, suspected links between tributary incision and main stream regulation relate to significantly reduced flows (eg. Yarra River tributaries – Brizga & Craigie 1997), or to peak flows in the main stream being out of phase with peak flows in tributaries (eg. Kiewa River [Murray River tributary] – Brizga 1996; Seven Creeks [Goulburn River tributary] – Brizga 1997c). In the Kiewa River the link is unclear because of other possible contributing factors, including artificial meander cutoffs near the confluence.

There is always a possibility under natural conditions of tributary incision occurring due to a flood in the tributary being out of phase with mainstream floods, but the probability is much increased by regulation.

Tributary base level may also be altered upstream of dams and weirs, where the base level of tributaries discharging into the pondages is increased. Major fluctuations in water levels could have destabilising effects on the tributaries.

2.2.5.2 Environmental flow assessment methods

There is no established procedure within any of the existing environmental flow methodologies for provision of flows or any other measure to prevent tributary incision in response to dam development. In many environmental flow studies this issue has not been considered at all. In some instances the risk of tributary incision is minimal due to bedrock controls.

2.2.5.3 Other management measures

Germanoski and Ritter (1988) argued that tributary incision is not reversible by aggradation in the main trunk stream, as the incision propagates upstream throughout the catchment as a zone of intense erosion, whereas the upstream extent of aggradation is limited to the upstream extent of backwater effects. However, some recovery is possible by deposition of sediments eroded further upstream within the tributary system.

Bed and bank erosion resulting from changes in tributary base levels are normally dealt with using standard erosion control techniques.

2.2.6 Large woody debris

The dynamics of large woody debris in streams are affected by flow. Bank erosion rates, which affect large woody debris input rates, are partly determined by flow. The downstream transport of large woody debris is closely related to flow conditions. Despite these linkages to flow, the dynamics of large woody debris do not appear to have been discussed in any detail in assessments of impacts of water resource development or in environmental flow studies in Australia.

2.3 Floodplain processes

This section is concerned with geomorphological processes affecting floodplains and the channel–floodplain interface, and their flow requirements. Particular reference is made to meander migration, meander cutoffs, avulsion, and overbank deposition.

2.3.1 Meander migration

Meandering alluvial rivers have a natural tendency to migrate. Meander migration generally involves erosion at the outer banks of bends and deposition on the inner banks. Under certain circumstances deposition may also occur on the inner banks of bends in the form of concave benches. Meander migration rates are affected by flow, as well as by a variety of factors, including stream power, sediment transport capacity, bank materials and bank vegetation. Many of these factors are related to flow.

In natural environments, meander migration has the beneficial effect of enhancing biodiversity by leading to the development of a variety of successional stages of riparian communities reflecting the varying ages of different parts of the point bar and floodplain surfaces (Everitt 1968; Nanson & Hickin 1974). Also, in situations where riparian trees or forests are present, bank erosion contributes to large woody debris inputs into the stream channel.

Whilst meander migration may bring ecological benefits in natural settings, it can have adverse impacts in settled areas, particularly in situations where significant assets such as houses, roads and bridges are threatened. Across Australia millions of dollars have been spent on structural bank protection works, such as groynes and rock lining, to restrain meander migration. In the case of floodplains which have been cleared, except for perhaps a line of bank-side trees, and where point bars are used for grazing or agricultural purposes or are infested by weeds, meander migration is likely to bring little, if any, ecological benefit. Indeed, it may lead to detrimental impacts by causing the single remaining row of bank-side trees to progressively fall into the river, resulting in increasingly large gaps in bank vegetation.

The provision of flows specifically for the purpose of enabling meander migration processes to continue at

natural rates has not been seriously entertained in any of the Australian environmental flow studies reviewed, and no efforts have been made to quantify flow requirements. In a background paper to the Barron WAMP project, one of the few places where meander migration has been discussed in relation to environmental flows, Brizga (1997a, p. 12) concluded that: "Although river channel migration is a natural process, it would be difficult to obtain community support for the provision of environmental flows specifically to maintain this process on the Barron Delta. Bank erosion has socially and economically undesirable consequences and there has already been considerable investment in works to prevent erosion."

There has been greater interest in measures to counter the risk of increased rates of meander migration resulting from water resource management. Flow regulation can contribute to bank erosion related to meander migration in two ways: (i) increased flows leading to increased stream power, as may occur when flow is added to a stream in an interbasin transfer; and (ii) increased flow variability involving reduction in low to moderate flows and minor floods but retention of large floods, resulting in channel contraction or vegetation encroachment which then confines or deflects flows during high flow events.

2.3.2 Meander cutoffs

Meander cutoffs are a natural phenomenon associated with meander migration. Two main types of cutoffs are recognised: neck cutoffs and chute cutoffs. Neck cutoffs occur when bank erosion results in two adjacent reaches impinging on each other and ultimately breaching the meander neck between them. Chute cutoffs involve the short-circuiting of a meander by the development of a new channel on the inside of the bend. Both types of cutoffs generally occur during floods, although other flow levels are relevant in terms of the development of antecedent conditions which contribute to the occurrence of the cutoff, such as the development of blockages within the main channel.

Meander cutoffs have ecological significance because they lead to the creation of wetland habitats such as oxbow lakes and billabongs. These habitats are subject to infilling, thus ongoing cutoffs are important for the maintenance of a diversity of floodplain wetland habitats.

Meander cutoffs are often regarded unfavourably in settled areas from a waterway management viewpoint, and in some instances works have been undertaken to prevent them. Reasons include implications for land ownership in situations where a stream is used as a property boundary, and concern about the possibility of other instabilities being triggered by the cutoff. This attitude contrasts with the historical situation, where artificial cutoffs were carried out on many streams in attempts to improve flood conveyance.

The implications of water resource development for meander cutoffs have received little consideration in the literature. Brizga and Craigie (1997) suggested that in the Yarra River flow regulation may have led to increased risk of chute cutoffs by enabling local buildups of bedload to occur in areas of relative hydraulic inefficiency, which then divert larger floodflows out of the channel.

Meander cutoffs have generally not been considered in Australian environmental flow studies. There are no existing methodologies for determining environmental flow provisions in relation to meander cutoffs.

2.3.3 Avulsion

Avulsion, or river breakaway development, is the process by which a river abandons a significant length of its existing course (often kilometres to tens of kilometres) for a new course elsewhere on the floodplain. Alluvial rivers throughout Australia are affected by avulsions.

Avulsions are responsible for the formation of anabranches. Two types of anabranches exist: (i) old river courses abandoned by avulsion; and (ii) new developing river courses.

As in the case of cutoffs, abandoned river course anabranches are subject to infilling, and ongoing avulsions are required to provide habitats of various ages. Avulsions generally occur much less frequently than cutoffs, for example, on the Thomson River in Gippsland, Victoria, thousands of years are likely to elapse between avulsions on any given reach (Brizga & Fabel, in prep).

New developing river course anabranches range in morphology from chains of lagoons and scourholes to almost continuous channels, into which a breakaway is imminent.

From a waterway management viewpoint, avulsions in settled areas are considered to be undesirable because of the high degree of disruption they cause. However, because of the large scale of the process, it is generally not feasible to prevent them.

Flows play a significant role in avulsion:

- avulsions often occur during large floods; and

- a loss of capacity or blockage in the old course is often a predisposing factor, and this can be significantly affected by flows, as discussed in Section 2.2.

No rigorous study of the effects of water resource development on avulsion has yet been carried out. From general principles, it appears likely that flow management can increase or reduce the risk of avulsions. For example, a reduction in flood frequency, including major floods, could be inferred as being likely to reduce the risk of occurrence of avulsion. However, a reduction in the magnitude of only small to moderate floods may increase the risk of avulsion by enabling channel contraction or encroachment in the main channel, thus forcing more water out of the channel during large floods, and thereby increasing the probability of the development of a new channel elsewhere on the floodplain.

The process of avulsion is rarely mentioned in environmental flow studies. In a background paper prepared for the Barron WAMP study, Brizga (1997a) discussed avulsion processes on the Barron delta, and concluded that it would be difficult to obtain community support for an environmental flow provision to enable avulsion. She noted that in order to avoid increased risk of avulsion resulting from regulation, environmental flows would need to be provided to prevent the contraction of the main river channel.

2.3.4 Floodplain sedimentation

Floodplains are constructed by processes of lateral and vertical accretion. Lateral accretion refers to deposition related to meander migration, which has been discussed above in Section 2.3.1. Vertical accretion occurs as the result of overbank deposition.

Under natural conditions, floodplain sedimentation processes contribute to floodplain ecology. The variety of depositional forms (eg. sand and gravel splays, levees, silt and mud deposits in backswamp areas) helps to maintain the diversity of floodplain communities and habitats.

In settled areas, overbank flooding is viewed as a problem or nuisance. While silt deposition is viewed as beneficial in agricultural areas, sand and gravel deposition is generally not welcomed. The provision of flow to maintain or increase frequency of inundation of developed areas would be a contentious issue, particularly if the purpose were to allow unpopular depositional processes such as sand splay development to occur.

Floodplain sedimentation can be affected by water resource development, particularly if the frequency and duration of floodplain inundation is affected. Sediment supply and delivery issues are also relevant. Human impacts other than flow regulation may be important, for example, land use changes which lead to accelerated erosion or increased mobility of sediment, or drainage modifications which affect sediment delivery processes or overbank flooding regimes.

Floodplain sedimentation has been considered in few environmental flow studies, and none have attempted to quantify flow requirements.

2.3.5 Floodplain stability

Under natural conditions, many eastern Australian rivers have confined narrow floodplains subject to periodic natural stripping which occurs during major floods (Nanson 1996). Regulation may have an impact on this process by reducing or eliminating floods capable of this type of erosion. In the Brisbane River downstream of Wivenhoe Dam, it was noted that the floodplains appeared more stable than they were under natural conditions, and more stable than floodplains upstream of the dam, and it was suggested that this change was probably related to regulation (Brizga 1998; McCosker 1998). No provision could be made in the environmental flow regime to restore the stripping process because of constraints imposed by human use requirements, including the dependence of suburban areas of Brisbane on the flood mitigation effects of Wivenhoe Dam.

2.4 Estuarine and coastal zones

The freshwater flow requirements of estuaries and coasts for geomorphological purposes are discussed in this section. Particular reference is made to channel morphology, salinity structures, river mouth processes, and fluvial sediment supply.

Estuarine and coastal requirements have been considered in recent environmental flow studies in Queensland, including the Barron and Fitzroy WAMP studies, the Logan trial of the Building Block Methodology (Arthington & Lloyd 1998), and the Brisbane River environmental flow study (Arthington & Zalucki 1998). Many environmental flow study areas do not have a coastal component (eg. Condamine-Balonne and Border Rivers WAMPS). However, estuaries and coasts are often not considered even where the river in question is linked to a significant coastal system. For

example, Casanova and Brock (1996) drew attention to the Snowy River Expert Panel's failure to consider the implications of their proposed new environmental flow regimes for estuarine and lagoonal landforms in the tidal section of the Snowy River.

2.4.1 Channel morphology in estuaries

Discussions of relationships between the dimensions of non-tidal streams and the flows that they carry are often based on the assumption that channel morphology is in equilibrium with the prevailing flow regime, or fluctuates about an equilibrium state. Of course the assumption of equilibrium does not always hold true in non-tidal streams, as discussed in Section 2.2.2.2. Estuarine channels cannot be assumed to be in equilibrium with the freshwater flow regime. They are depositional environments which are subject to progressive infilling with sediments, and are occupied partly by freshwater flows and partly by tidal flows. The component of the channel which accommodates tidal flows will be reduced by depositional processes until eventually tidal flows are excluded and the channel becomes a freshwater stream channel with dimensions which are in equilibrium with the freshwater flow regime (Roy 1984). The infilling of estuaries is a long-term process, extending over thousands of years.

Freshwater flows are important in estuaries as they define the minimum size to which the channel will eventually contract. They also affect the rates and processes of contraction. In many estuaries, high flows (river floods) have greater power to transport sediments and erode the bed and banks of estuaries than tidal flows, thus providing a mechanism for the removal of sediment accumulations built up by tidal processes. Therefore, high flows appear to be important for channel 'maintenance' in these estuaries, just as they are in non-tidal reaches.

The impacts of water resource development on channel morphology in estuaries have not been studied in Australia, except in relation to river mouth processes as discussed in Section 2.4.3. No methods currently exist for quantifying flow requirements for maintenance of channel morphology in estuaries. Methodologies for freshwater channels may not be directly transferable, for example, methods based on sediment entrainment will produce different threshold flows depending on tide level.

2.4.2 Salinity structures in estuaries

The salinity structure of an estuary is an important control on sediment deposition processes because of the role of the water chemistry in the flocculation and deflocculation of clays. In salt wedge estuaries, the upstream tip of the salt wedge is generally a zone of preferential deposition of fine sediments. As well as being affected by tides, the location of the tip of the salt wedge is affected by freshwater flows, with the salt wedge moving landward during periods of low flow and seaward during floods. Changes in flow regimes will alter the position of the salt wedge, thus altering patterns of deposition of fine sediments.

The impacts of water resource development on salinity structures in estuaries have not been studied in detail, although there has been some discussion of this issue. For example, the Department of Harbours and Marine (1980) reported that hydropower generation in the Barron River caused very low flows to occur less frequently than under natural conditions, and inferred that as a consequence, saltwater may not intrude as far upstream in the estuary under regulated conditions as it would have done in the dry season under natural conditions.

Some estuaries have been subject to extensive historical channel modifications and management intervention such as dredging to maintain navigability. For example, in the Yarra River estuary in Melbourne the removal of natural rock bars has allowed the salt wedge to penetrate many kilometres further inland than it did than under natural conditions (Brizga et al. 1996). In these situations it may be difficult to determine the impacts of flow regulation, which may be relatively insignificant compared to other factors. Also the development of environmental flow objectives is made difficult, as a return to something resembling the natural condition is not feasible.

No methods currently exist for determining flow requirements in relation to salinity structures in estuaries.

2.4.3 River mouth processes

River mouths are affected by fluvial, tidal and coastal processes, and their interactions. Variations in any of these factors have implications for geomorphological processes. For example, Brizga (1997a) identified relationships between flow and flood history and the dynamics of the mouths of the Barron River and its distributaries over a period of some 50 years, as

identified from analysis of sequential aerial photographs. During flood-free periods, the river and distributary mouths became deferred or blocked by the development of sand spits. Large floods eroded or breached the spits and barriers. The threshold size of flood required to erode or breach the spits and barriers varied depending on antecedent conditions such as size of barrier and extent of vegetation growth. During periods of frequent flooding, the mouths did not become blocked or significantly deferred.

River mouth processes have implications for estuary hydrodynamics and salinity structures, and for fluvial sediment supply to the coast.

The impacts of flow regulation on river mouth processes have been examined in some detail in relation to the mouth of the Murray River, where a reduction in river flows has occurred due to regulation (Harvey 1988, 1996; Walker & Jessup 1992; Bourman & Barnett 1995). This has resulted in increased dominance of coastal processes, including the development and stabilisation of a flood-tidal delta (Bird Island), the migration of the river mouth due to spit development, and sediment accretion at the river mouth (Harvey 1996). Harvey argued that coastal processes such as littoral drift, tidal flux and sea state are important in explaining the position and morphology of the river mouth, particularly at times of low river flow. The effects of regulation are complicated by the effects of the barrages on tidal prism (the barrages are situated in the estuary, and a reduction of over 85% in tidal prism occurs when the barrages are closed), as well as by excavation works to artificially open the river mouth.

No widely accepted methods currently exist for determining flow requirements in relation to river mouth processes. Huzinga (1996) suggested that in the Tugela River, South Africa, river mouth closure could be directly related to flow rates, and identified four flow ranges in relation to river mouth conditions based on one year of data only: (i) mouth will stay open; (ii) mouth closure will occur occasionally; (iii) mouth closure will occur; and (iv) mouth will normally be closed. In the case of the Barron Delta, Brizga (1997a) offered broad guidelines based on the conclusions from the aerial photograph analysis discussed above, but was unable to identify a simple relationship between flow rates and river mouth state due to the role of antecedent conditions in determining the effectiveness of flows.

2.4.4 Fluvial sediment supply

The role of river flows in delivering sediments to estuarine and coastal environments has been highlighted in previous literature concerned with relationships between river flows and geomorphological processes in estuaries (Kulm & Byrne 1966; Boggs & Jones 1976; Nichols 1977, 1988; Adams et al. 1988; Jones et al. 1993; Longley 1994). High flows have been found to be particularly important for sediment delivery because of their relatively high competence and transport capacity. High flows mobilise coarse sediments which are not entrained by low flows, and also carry larger volumes of sediment than low flows.

Dams and weirs affect the delivery of sediments to estuaries, not only by altering river flows, but also by trapping sediments (Section 2.2.1). The trapping is selective. Unless a structure has gates which are kept open during floods, all of the bedload is retained behind the structure. However, only a portion of the suspended load settles out, and the rest is carried downstream. Some of the material deposited behind the dam or weir may be re-suspended and carried past the structure by large floods. In estuaries immediately downstream of dams or weirs, the overall rate of sediment supply from the upstream catchment could be expected to be reduced, while the relative proportion of fine sediments may be increased.

Changes in sediment supply from upstream can be expected to eventually lead to changes in estuary substrate, which has ecological implications. Coastal sediment supply can also be affected by flow regulation. A classic example from the international literature is the role of the Aswan Dam in leading to erosion of the Nile Delta by trapping much of the sediment load of the Nile River (Kashef 1981).

Issues related to the determination of flow requirements and other management measures to maintain sediment delivery processes have been discussed in Section 2.2.1. The quantity of sediment necessary to satisfy coastal requirements can possibly be determined with reference to rates of coastal processes such as longshore drift. However, sediment supply and longshore drift rate calculations generally both have wide error bands, which will introduce uncertainty into the conclusions drawn from them.

2.5 Quantification of environmental flow requirements

In Sections 2.2 to 2.4 the review of relationships between geomorphological forms and processes, and flow, has shown these to be numerous and complex and, in many cases, not fully understood. It is apparent from these Sections that methodologies for quantifying flow requirements exist for only a sub-set of factors which are related to flow. In some cases this is because of conflicts between natural processes and human uses, in other cases because the relationships are difficult to quantify, or because the issues in question have been outside the scope of many environmental flow studies (eg. estuarine and coastal processes).

Environmental flow studies operate at a number of scales, ranging from basin-wide guidelines to detailed management strategies for individual reaches of regulated rivers. Different methods may be appropriate at these different scales (Dunbar et al. 1998).

The quantification of environmental flow requirements can be approached in two ways:

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

Bottom-up approaches are most commonly used. All of the conventional methodologies, including the original Holistic Approach, the Building Block Methodology and the In-stream Flow Incremental Methodology (IFIM) take a bottom-up approach. The type of flow regime developed on the basis of bottom-up methodologies is dependent on the knowledge of the participants in the process and the availability of reliable data about the stream system in question. It has been noted that the more that is known about a system, the closer the environmental flow regime is likely to come to the natural regime (Bunn 1998).

A top-down approach was developed by the Queensland Department of Natural Resources (DNR 1998a, 1998b) in the Fitzroy Basin WAMP, where the degree of departure from the natural regime under various management scenarios was quantified in relation to key indicators, and then the acceptability of the deviation from the natural regime was examined. Limits on the acceptable deviation from the natural regime were identified by comparison with other river systems which are widely considered to have been seriously degraded by flow regulation. This process has been termed 'benchmarking' (Vanderbyl 1998).

The most rigorous approach may be a 'bottom-up – top-down' approach, where an environmental flow regime is initially developed using a bottom-up approach and is then tested by cross-checking against a top-down assessment. Two environmental flow studies in Australia have used a bottom-up – top-down approach, the Fitzroy Basin WAMP (DNR 1998a, 1998b) and the Brisbane River study (Arthington & Zalucki 1998).

Bottom-up approaches generally consider two or three flow bands: low flows, medium flows (sometimes) and high flows. The top-down approach used in the Fitzroy Basin WAMP was based on key indicator statistics tied to geomorphological and ecological outcomes rather than flow bands.

This section is concerned with methodologies for quantifying flow requirements. Relationships between these methodologies and specific objectives have been outlined in Sections 2.2, 2.3 and 2.4. The discussion of methodologies is structured according to three key flow bands: low flows, medium flows and high flows. Flow variability and flow seasonality are also considered.

2.5.1 Low flows

The primary motivation for low flow requirements in environmental flow studies is generally based on ecological considerations, such as the availability of in-stream habitat or suitability of habitat for target species. The methods which have been used in determining flows in relation to these requirements include the wetted perimeter method and hydraulic habitat rating methods (Tharme 1996; Stewardson & Gippel 1997).

In the Brisbane River environmental flow study, the implications of changes in low flow conditions for hydraulic biotopes were examined, and it was noted that many former riffles now effectively function as runs because of elevated baseflows (Brizga 1998). The reduction in baseflows required to return the post-regulation runs to riffles was quantified on the basis of rating curves for two representative sites (Arthington & Zalucki 1998).

Low flow requirements are often not requested or defended from a geomorphological viewpoint, even though low lows are relevant to geomorphological processes for at least three reasons, as discussed earlier in this review:

- low flows affect in-stream and riparian vegetation zonation which, in turn, has implications for resisitance to erosion and channel and floodplain hydraulics, and therefore sediment transport processes and morphology;
- low flows play a major role in determining prevailing hydraulic biotopes; and
- low flow water levels in the main stream are controls on tributary base level.

Further research is required to develop and refine methodologies for determining low flow requirements for geomorphological purposes.

2.5.2 Medium flows

Medium flows are often capable of entraining and transporting sand, so specification of medium flow requirements may be particularly important in sand bed rivers. Davies et al. (1996) used shear flows based on near-bed velocity and water depth required to mobilise sandy sediments colonised by benthic microbial mats and algae as a reference point in the development of an environmental flow for the North Dandalup River, Western Australia. They considered the frequency, timing and seasonal distribution of flows exceeding the threshold flow for channel shear.

Medium flows for geomorphological purposes have been ignored in many Australian environmental flow studies, particularly those concerned with gravel bed rivers.

2.5.3 High flows

High flows are generally emphasised in geomorphological assessments of environmental flow requirements, and are typically made with regard to the following environmental objectives:

- to maintain channel size and form;
- to limit vegetation encroachment; and
- to remove fine sediment buildups from the stream bed to maintain substrate character in gravel and sand bed streams.

Flows to achieve these objectives are commonly referred to as 'flushing flows' or 'channel maintenance flows'. Stewardson and Gippel (1997) made a distinction between 'flushing flows' which remove fine sediment from the bed surface, check vegetation encroachment and rearrange small-scale bed forms, and 'channel maintenance flows' which have the capacity to maintain the overall channel form by mobilising bed and bank sediments. However, not all researchers distinguish between these terms on the basis of the same criteria.

Flushing flows or channel maintenance flows are typically minor flood events, with ARIs in the order of one to two years. Reasons for their provision include:

- to prevent a major rise in flood variability which could lead to catastrophic stripping;
- to maintain the available area of habitat; and
- to maintain flood capacity.

High flows are also necessary for floodplain processes but, because of human use constraints, generally no provisions for these are specified, as discussed in Section 2.3.

A single flow event is sometimes specified as being required to perform a wide range of functions. For example, the environmental high flow for the Snowy River recommended by Erskine (1996) was calculated on the basis of sediment entrainment thresholds, but was expected to perform a range of other functions, including to prevent biogenic sediment buildup in pools, to scour and at least partially remove tributary mouth bars, to episodically mobilise bed material, to maintain vegetation which has already encroached into the channel, to improve downstream water quality, to maintain or reinstate hydraulic and sedimentologic differences between pools, riffles, runs and rapids, and to reverse the trend of channel shrinkage by removing recent sediment deposits.

In many cases, even though a single high flow event is specified, a broader range of flows is actually likely to be important, as discussed in Section 2.2. Petts (1996, p. 360) argued that "channel morphology is affected by the full range of flows", and specified a number of potentially significant floods, including the bankfull flood (1.5 year ARI) which determines macro-scale structural features, and rarer floods (say 1 in 20 years) for causing major erosion (including cutoffs) and deposition. Large rare floods (with ARIs of, say, greater than 25 years) bring about changes which are qualitatively different to smaller events, such as floodplain stripping in narrow valleys. Stewardson and Gippel (1997, pp. 34–5) argued that the maintenance of river morphology is performed by the range of flows between the channel maintenance level (Newbury & Gaboury 1993) and bank top level. On the basis of hydraulic factors, incised channels are likely to be

subject to a wider range of channel forming flows than channels with a limited capacity.

The mode of delivery of the flushing or channel maintenance flow is another important issue. High flow requirements may be used to place a constraint on development in a basin, or may be intended to be at least partly provided by releases. An example of the latter is provided by the Snowy River Expert Panel's recommendation for a flushing flow at Dalgety, which required a release of 12,000 MLd^{-1} from Lake Jindabyne (Snowy River Expert Panel 1996). In these cases, there is a significant risk of clearwater erosion occurring as the result of the delivery of the environmental flow.

Some geomorphologists recommend environmental flow regimes which include initial flood pulses to remove the historically accumulated sediments in streams which have already begun to adjust to reduced flows in a regulated regime. However, this is controversial, as it may potentially have adverse impacts. For example, Erskine (1996) suggested that in the Snowy River the duration of high flows should be increased above natural so as to erode and transport the sediment which had already accumulated in the channel. However, he noted the issue of poor water quality resulting from mud and organic matter being flushed from storage sites. Haworth (1996) drew attention to the potential for ecological damage further downstream, and noted that one possible long-term outcome would be an increasing sediment deficit and continuing erosion as the existing stores of sediment are progressively moved further downstream.

Human use constraints may place upper limits on high flow provisions in developed areas. Restoration of overbank flood flows may be problematic in situations where there are human uses on the floodplains. This problem has arisen in a number of Australian environmental flow studies, including the Brisbane River study (Arthington & Zalucki 1998) where, due to flood mitigation requirements, it is not feasible to provide a major flood flow for environmental purposes.

High flows have at least seven degrees of freedom which can be specified: magnitude, frequency, timing, duration, rate of hydrograph rise, rate of hydrograph recession, and inter-annual variability.

2.5.3.1 Magnitude

There is no widely accepted standard methodology for determining the magnitude of flushing or channel maintenance flows. Existing methods fall into five classes:

- field observations/controlled release;
- sediment entrainment calculations;
- hydraulic geometry;
- hydrological methods; and
- professional judgement.

Field observations and controlled releases

Arguably the most reliable method for establishing flushing flows involves the observation of the study stream at a series of discharges (Tharme 1996; Wesche et al. 1977). Field observations are recommended for verification and refinement of recommendations made on the basis of desk methods (Tharme 1996).

Controlled releases have been used to determine high flow requirements in overseas studies (eg. Wilcock et al. 1996). One Australian study concerned with the morphological effects of a trial release has been carried out (Erskine et al. 1995).

Hey (1981, cited in Stewardson & Gippel 1997) outlined a methodology involving tracing the movement of marked stones to determine sediment transport thresholds in gravel bed streams. So far this type of method has not been used in Australian environmental flow studies.

Constraints on controlled releases include the following:

- only possible on regulated streams;
- the characteristics of the dam are important – it must have outlet works capable of releasing the specified flows and many dams do not have the capability to make a controlled release of a high flow; and
- the cost of water for release may also be an issue.

In situations where existing infrastructure is not suitable, it may still be possible to observe streams under different flow conditions resulting from natural flow variations or by piggybacking a small release onto a natural flood.

Unregulated streams can also be studied under a variety of flow conditions. However, the monitoring program would be dictated by natural variations in flow and thus the timing of outcomes would be unpredictable, which would make this inappropriate as a stand-alone method in studies where the time frame is critical.

Sediment entrainment calculations

Sediment entrainment calculations have been used in a number of Australian environmental flow studies (eg. Erskine 1996; Brizga 1997d, 1998). The two main methods of sediment entrainment calculations used in environmental flow studies are based on critical velocity and critical shear stress for entrainment.

The critical velocity method may be applied using Hjulstrom curves which show limiting mean velocities for entrainment, transport and deposition in relation to particle size (Hjulstrom 1939) or an equation developed by the United States Bureau of Reclamation (1977) for sediments with particle sizes greater than 1 mm. Limitations of the critical velocity method include (from Gordon et al. 1992; Bovee et al. 1978, cited in Tharme 1996):

- the Hjulstrom curves were developed for sediments of uniform grain sizes, whereas natural streams generally carry a wide range of sediment sizes;
- the Hjulstrom curves were developed for streams with flow depths greater than 1 m, and may not be applicable to shallower flows because shear stress is related to depth;
- the implications of mean velocities for sediment transport within a specific cross-section will vary depending on the configuration of the cross-section and local currents – at any given cross-section a large range of particle sizes will move at a single given mean velocity; and
- the effects of sediment packing are not considered.

Critical shear stress is a measure of the force required to counterbalance the submerged weight of a particle and just initiate movement. Actual shear stress must exceed critical shear stress for movement to occur. The Shields equation is often used, or a simplified approach based on it which assumes that critical shear stress required to move a particle (in Nm^{-2}) is approximately the same as particle diameter in millimetres. Milhous (1986, 1989 cited in Gordon et al. 1992) argued that if enough shear stress were applied to just move some of the larger particles in a surface armour layer, the finer materials between them would be flushed out.

The critical shear stress method is affected by a number of complicating factors and limitations (from Gordon et al. 1992; Erskine 1996):

- shear stress is affected by flow roughness – critical shear stress is higher in hydraulically smoother conditions than hydraulically rough conditions;
- the method was originally developed for uniform sands;
- critical shear stress is affected by the packing of the bed sediments. Gordon et al. (1992) set out a four-step ranking of critical shear stress in relation to packing. In order from least erodible to most erodible, the categories are as follows: (i) highly imbricated sediments; (ii) closely packed sediments with smaller materials filling the voids between larger particles; (iii) uniform sediments or random grain arrangements; and (iv) loosely packed sediments such as quicksands;
- shear stress is unevenly distributed across the channel, so a large range of particle sizes will move at a given mean shear stress for a cross-section; and
- encroaching vegetation can affect flow hydraulics and shear resistance.

To account for effects of bed vegetation on entrainment thresholds, Erskine (1996) adopted a larger grain size than indicated by his measurements.

The application of sediment entrainment methods in determining flushing or channel maintenance flow requirements is limited by the availability and suitability of hydraulic data. In some environmental flow studies it has not been possible to use these methods because of a lack of suitable data (eg. Gippel & Stewardson 1995). Erskine (1996) determined flushing flow requirements for the Snowy River using Neill's (1968) method as this was the only method for which suitable data were available. Brizga (1996) calculated entrainment flows for the Logan River using both the critical velocity method and critical shear stress method and found major discrepancies, which she attributed to inconsistencies in the available hydraulic data.

A weakness in many environmental flow studies relates to the quality of the information about high flow hydraulics. Generally, the available data only relate to a single site rather than a reach, even though considerable variability in hydraulic conditions is generally evident in a river (eg. through a riffle-run-pool sequence). The hydraulic information may be based on extrapolation of gauging station data (Arthington & Long 1997), crude modelling (Johansen 1998), or simple calculations based on channel roughness (Erskine 1996). Reach-based hydraulic modelling and inputs from a hydraulics expert would provide a sounder hydraulic basis and would produce more reliable results from sediment entrainment calculations.

The notion of determining flushing flows on the basis of bed sediment entrainment thresholds arose from work on gravel bed rivers. Riffle surface entrainment flows in gravel bed rivers commonly have natural ARIs between one and five years. In these situations it may be appropriate to use the entrainment flow as the basis for specifying a single key high flow event. Flows which entrain sands occur much more frequently so they could not necessarily be used interchangeably with channel maintenance flows, as may be the case in gravel bed rivers. The issue of entrainment thresholds and their implications in streams with naturally muddy beds has not previously been discussed in the Australian literature. Sediment entrainment thresholds are not a particularly useful measure in the case of bedrock channels.

Kondolf (1997) identified the following in-principle problem with entrainment flows. A discharge that is capable of mobilising the stream bed to flush interstitial fine sediment will often transport both sand and gravel, eliminating the selective removal of sand and resulting in a net loss of gravel from a reach if supply from upstream has been reduced or cut off by an impoundment.

Hydraulic geometry

Gippel and Stewardson (1995) used hydraulic geometry models established for a neighbouring catchment to determine the channel maintenance flow for the Thomson River below the Thomson Dam. Arthington et al. (1994) used a hydraulic geometry approach to determine the impact of regulation on streams in the Tully-Millstream area, and used this as the basis for arguments for an environmental flow provision to maintain the bankfull channel.

Hydrological methods

Methods requiring limited field work are needed for basin-wide planning purposes (Orth & Leonard 1990). Situations in Australia where this would apply include WAMP studies in large catchments such as the Fitzroy and Burdekin.

Overseas 'rule of thumb' methods based on hydrological indices include the Montana Method and Hoppe Method. The transferability of these methods to other environmental settings has been queried (Gordon et al. 1992).

The Montana Method and Hoppe Method were not applied in any of the Australian studies reviewed for this present paper. A hydrological approach based on channel morphology has been used in two of the WAMP studies in Queensland. In the Logan River project, the 1.6 year ARI flood was adopted by Brizga (1997d) as a morphologically significant flow on the basis of previous work by Dury et al. (1963). In the Fitzroy WAMP project, the 2 year ARI flood was adopted as a key indicator for channel morphology on the basis of being a moderate-sized flood event. The latter was not specified as a discrete event to be provided (*cf.* the Hoppe and Montana methods), but rather as an indicator level for measuring upward or downward shifts in flood frequency resulting from various water allocation and management scenarios.

Professional judgement

Professional judgement as a stand-alone methodology is less defensible than other methods for determining high flow requirements. However, this approach has been used in several Australian environmental flow studies.

Grose (1993) reported on the evaluation of potential benefits of transfer release from Windamere Dam on the Cudgegong River to Burrendong Storage. Transfer releases are limited by the outlet valve capacity. Expert judgements indicated that the transfer flows may increase channel capacity by scouring submerged macrophytes and damaging invading cumbungi beds, cause bank erosion, and entrain tributary gravel bars, bedload, gravel, mud and sand. No supporting evidence was presented in the report. It was recommended that transfer releases be closely monitored to ensure they do not result in significant adverse impacts.

Thoms et al. (1996) made recommendations regarding flow management in the Barwon-Darling system for ecological benefit using a top-down approach. They indicated percentage reductions in various flow parameters which would be acceptable. No scientific basis for the magnitude of the proposed reductions was provided in their report, although they emphasised the importance of in-channel flow heights as reference levels. No significant discussion of geomorphological processes was included in the report.

General issues

The use of different methods for determining high flow requirements may produce great disparity in results. Tharme (1996) noted differences of up to 900%. This is likely to be at least partly due to the fact that a range of flows, and not just a single flow, is important for stream geomorphology.

Desk-based methods produce hypotheses about flushing flow requirements. Monitoring to test these hypotheses is important, particularly in light of the wide

disparity in results which may be produced by different desk study methods.

Combinations of desk and field methods have been previously recommended because of concerns about inaccuracy of desk methods. Gordon et al. (1992) recommended that the best approach would be to develop flushing flow estimates using several methods, adopt a conservative figure, then test it out in the field, and then monitor it to determine its effectiveness. However, practical and cost constraints preclude detailed trials and monitoring in every situation. There is a need for trials to be carried out and properly documented for a variety of stream settings, so that there is a reliable knowledge base upon which to develop future recommendations.

2.5.3.2 Frequency

Different considerations apply to the specification of the frequency of identified high flow events (such as channel maintenance or flushing flows), depending on how they will be applied.

In highly regulated rivers where the flow is provided at least partly by a reservoir release, it can be specified in terms of release frequency. For example, Gippel and Stewardson (1995) specified that in the Thomson River, a single channel maintenance release should be made from the Thomson Dam every year during the normal wet season. Erskine (1996) requested that specified flushing flows for the Snowy River be released at least once, preferably twice, a year.

In unregulated rivers, the frequency of significant high flow events may be specified in terms of partial or annual series recurrence intervals. In these situations, a request for an event to be provided with natural frequency implies that no modification to the flow regime should be permitted, as any change to the flow regime will alter the flood frequency statistics (G. Burgess, DNR, pers. comm.). The problem in these situations is to determine the magnitude of an acceptable departure from the natural regime. This has been addressed in the Fitzroy WAMP study using a benchmarking approach based on key indicators (DNR 1998a, 1998b). Further work is required in this area.

2.5.3.3 Duration

The duration of a high flow event is an important determinant of its geomorphic effectiveness (Costa & O'Connor 1995). Environmental flow recommendations, where they specify flood duration, often indicate that the duration of the flood events provided should be similar to the natural duration of events of similar magnitude (eg. Erskine 1996; Gippel & Stewardson 1995). An issue that has not been widely discussed is the extent of variability in natural flood durations, and the implications of this for managed environmental floods.

Event duration is also important where the environmental flow specifications are used to cap high flows. Grose (1993) recommended that maximum durations for transfer releases from Windamere Dam to Burrendong Dam via the Cudgegong River should not exceed maximum historical durations for flows of the same magnitude. The following rules were proposed. Maximum durations were specified for flows of 250, 500, 1,000 and 2,000 MLd^{-1}. If flows of 1,000–2,000 Mld^{-1} are to be released more frequently than one in ten years, then the durations should not exceed the 90^{th} percentile durations as determined from historical records.

2.5.3.4 Timing

Timing of floods is generally determined on biological rather than geomorphological grounds (eg. fish migration and spawning cues) and high flow events are commonly requested to occur at times when they would naturally occur. However, Grose (1993) noted in her report on proposed transfer releases from Windamere Dam into the Cudgegong River that the likelihood of bank erosion could increase if the banks are already wet when the transfer release starts.

2.5.3.5 Hydrograph rise and recession rates

Rates of hydrograph recession are an important control on bank stability, particularly in the case of prolonged elevated flows. Australian environmental flow studies have generally recommended that rates of hydrograph recession in regulated streams should not exceed natural rates.

Rates of hydrograph rise are sometimes also recommended as approximating natural rates, although no clear justification has been given.

2.5.3.6 Inter-annual variability

Inter-annual variability in high flows is very important from a geomorphological viewpoint, as discussed in Section 2.2. This has generally not been directly addressed in Australian environmental flow studies, although it is partly covered by provisions for a minor flood which will guard against major increases in inter-annual variability resulting from the absence of high flows in some years. Indicator statistics such as Iv (an index of inter-annual flood variability based on the

standard deviation of the annual flood series in the log domain) can be used to compare flow regimes in relation to this parameter.

2.5.4 Seasonality of flow

Flow seasonality is relevant from a geomorphological viewpoint as the main stream provides base level control for its tributaries, as discussed earlier in this review. This geomorphological issue has not been raised in any of the Australian environmental flow studies reviewed in this chapter. It is more important in situations where the tributaries are alluvial streams than where they have a hard bedrock bed.

2.6 Towards a best practice approach

2.6.1 Overall framework

Environmental flow assessments in Australia are carried out in two types of situations: (i) streams subject to existing or proposed future regulation; and (ii) unregulated streams affected by incremental development and possibly major dams or water resource schemes in the longer term. Study areas vary greatly in scale, from a single reach of regulated river to whole-of-catchment water resource planning for large basins.

No single framework for determining environmental flow requirements has yet become accepted as the preferred approach in Australia. A variety of frameworks have been used in Australia, including the Flow Restoration Methodology (Arthington & Zalucki 1998), Building Block Methodology (Arthington & Long 1997; Arthington & Lloyd 1998), Expert Panel Assessment Method (eg. Swales & Harris 1995; Thoms et al. 1996), and IFIM (Arthington et al. 1992). An assessment of the strengths and weaknesses of existing methodologies has been presented by Stewardson and Gippel (1997).

Concerns about the unsuitability of existing methodologies are reflected in the development of new and hybrid methods. Alternative methods which have been proposed but not yet trialled include the Rapid Assessment Methodology which is being developed by the Victorian Department of Natural Resources and the Environment for streams which are not regulated by major impoundments, and a method for regulated rivers proposed by Stewardson and Gippel (1997). An example of a hybrid approach is the environmental flow component of the Barron WAMP project in Queensland. This started as an expert panel process, but more detailed investigations have been commissioned during the course of the study, including a trial release from Tinaroo Dam. A top-down benchmarking type of approach is now also being incorporated.

Most existing methods were developed for use in regulated rivers. A regulated situation is even implied in some definitions of 'environmental flow', for example, Stewardson and Gippel (1997, p. 923) defined an environmental flow as "a set of operational rules for water resource schemes to limit adverse ecological impacts to acceptable levels" which "may be designed for a river subject to a new water recourse development or more commonly, a historical development for which insufficient consideration has been given to the ecological impacts". The water reform process currently under way in Australia requires methodologies which are applicable to both unregulated and regulated rivers.

Previous 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. This stems partly from the definition of the scope of environmental flow studies within their terms of reference, as well as from the narrow focus on flow which is inherent in the majority of existing environmental flow methodologies.

A proposed new framework suitable for use in regulated and unregulated river systems is outlined in Figure 2 (page 36). Key features of this framework include:

- applicability to unregulated and regulated systems;
- a multidisciplinary approach;
- the steps shown in Figure 2 define the key issues which need to be considered – the scale of the study can be varied depending on available resources and the degree of rigour required in the selection of appropriate methods to complete each step (eg. expert opinion *versus* detailed scientific investigations);
- inclusion of a scoping stage after the completion of background studies and prior to 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 – Haworth (1996) criticised the requirement in the study brief for the Snowy River Expert Panel to recommend flows to "maximise ecological benefit" as being too vague to provide adequate focus for key inputs;
- provision is made for the acknowledgment of all significant factors, including those which are not flow-related;
- provision is made to consider the full range of flows in so far 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 could be incorporated into the process if desired – hold points 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; and
- the process provides an ongoing interface with stakeholders through the staged reporting process, and by seeking stakeholder inputs at the scoping workshop.

The framework set out in Figure 2 (page 36) has eight main steps, including four multidisciplinary workshops. Square boxes indicate work carried out individually by individual team members; rounded boxes indicate workshops involving all members of the environmental team. Disciplines which should be included in the environmental team include hydrology, hydraulics, geomorphology and ecology. Close interaction between the disciplines is considered to be necessary because of interdependencies between physical and ecological processes. Workshops are seen as an efficient means of fostering such interaction. There may need to be some individual follow-up work and consultation amongst the team members after the workshops to finalise outcomes at each stage.

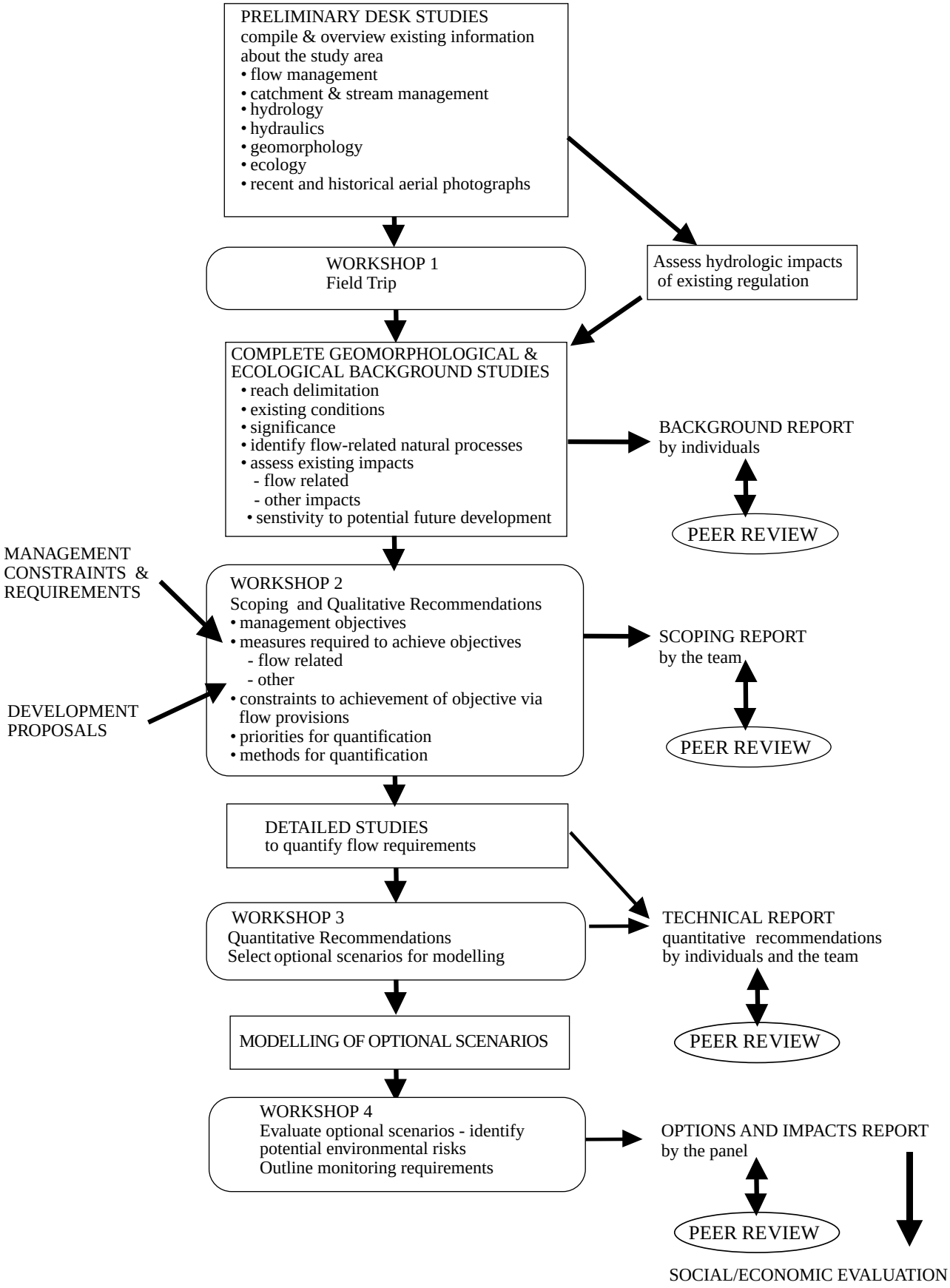
The first step in the process is the compilation and overview of existing relevant information. The next step is a field inspection of the stream(s) in question, carried out together by the whole environmental team.

The completion of the geomorphological and ecological background studies is carried out on the basis of existing information, the group field inspections, and the results of the assessment of hydrological impacts of existing regulation. Relatively homogenous reaches are identified on the basis of geomorphological criteria. 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 the level of resources available to the project.

The second workshop is held after the completion of the background studies and circulation of the background papers. 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%". The geomorphological and ecological objectives which need to be met to achieve the vision should be outlined in detail to assist in identifying optional management strategies.

The next 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 addressed more satisfactorily 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 values.

Figure 2: *Framework for assessing environmental flows in regulated and unregulated river systems*



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. 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 implementating a specific recommendation. As the geomorphological review has shown, 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 top-down or bottom-up approach, as well the specific techniques to be used (eg. rule of thumb, hydraulic assessments, trial release).

An example of the feasibility of implementation issue is provided by considering a reach controlled by a large ungated 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 it as an issue and maybe give a ballpark estimate of the required flow.

Step 5 consists of detailed studies to quantify flow requirements, using the procedures agreed at the workshop. 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 recommendations are written up in a Technical Report.

A set of optional flow management strategies needs to be outlined, with indications of their ecological and water resource management implications, to provide a basis for the social and economic evaluations. Optional management scenarios for hydrological modelling and ecological assessment are selected at Workshop 3. The modelling would be carried out after Workshop 3, and the results presented and evaluated by the environmental team in Workshop 4. 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 four reports indicated in Figure 2 can be bound together to provide a complete record of the process.

2.6.2 Geomorphological techniques

The existence of a wide range of geomorphological factors which are related to flow, and the unavailability of reliable methods for quantifying more than a small subset of these, emphasises the importance for the geomorphological components of environmental flow studies to begin with a qualitative overview of flow-related issues in the study area.

The selection of appropriate methods for quantification depends on the purpose and scale of the study. The limited development of existing methodologies with regard to many factors means that quantitative estimates are likely to have wide error margins. The literature review indicates a consensus opinion that the most reliable estimates of flow requirements for specific processes include field assessments.

The potential for high flow provisions to have unintended detrimental impacts on the stream system needs to be accounted for.

2.7 Conclusions

1. 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.
2. 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.
3. 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 in 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.

4. 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.

5. 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.

6. The author's present understanding is that no environmental flow regime which makes provisions for geomorphological purposes has yet been implemented in Australia. 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 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 time 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 adaption in response to monitoring outcomes.

7. 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: (i) the long-term implications of reduced sediment delivery to estuaries and coasts; and (ii) 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.

8. 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 impacts 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 WAMP 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 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 1997a). The Brisbane River study also identified a broader range of issues affecting the river system (Arthington & Zalucki 1998).

9. There is a need for open acknowledgment of human use constraints. Environmental flow studies often state a requirement for scientists to focus exclusively on maintaining and enhancing ecological values. However, assumptions about social and economic values are implicit in the majority of environmental flow recommendations.

   The inevitability of continued existence and operation of existing infrastructure and, in many cases, some level of additional future development influences environmental flow recommendations even where this is not explicitly stated. For example, the brief of the Snowy River Expert Panel was to "develop a set of recommendations for flow management to maximise ecological benefits" (Snowy River Expert Panel 1996, p. 4). However, the panel did not suggest removal of Jindabyne Dam, presumably because of an unwritten assumption that it would be unacceptable for them to make environmental flow recommendations which would jeopardise the continued operation of the Snowy Mountains Scheme.

   McMahon and Finlayson (1995) argued that environmental flows on regulated streams should recognise constraints imposed by existing regulation and develop the best possible strategy for the environment within recognised operational constraints, rather than return to ecological conditions as they existed prior to development.

   Other human use values also bias environmental flow recommendations. This is particularly the case for macro-scale geomorphological processes, as discussed in Section 4 above. For example, bank erosion due to meander migration is a natural process and has some ecological benefits, yet environmental flows expressly to allow this process to continue are not normally requested. Particularly

in settled areas and where there has been significant investment in erosion control works, provision of a flow for the purpose of encouraging bank erosion due to natural meander processes would be socially unacceptable. In these instances, although environmental flow recommendations may purport to have the intention of purely maximising ecological benefits, the omission of specific flow provisions for socially unacceptable processes indicates that the flow recommendations have been significantly influenced by human use values. However, such compromises are seldom detailed in written documentation of the environmental flow process.

2.8 R&D priorities

Priority issues for research and development arising from this review are as follows.

- Clarification of 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.
- No environmental flow regime for geomorphological purposes has yet been implemented and monitored. There is a need to determine whether recommended flows actually achieve their objectives.
- 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 in a range of streams to be carried out as a research exercise, and the results documented in detail and disseminated.
- 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.
- Studies are required to determine the feasibility of sediment bypassing around dams and weirs, and to develop guidelines in relation to this matter. Field experiments would probably be required.
- The integration of hydraulics, including hydraulic modelling techniques, into environmental flow studies needs to be developed.
- Development of a checklist of geomorphological issues and potential impacts to be considered in environmental flow studies would help ensure a systematic approach.

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3. Methods addressing the flow requirements of wetland, riparian and floodplain vegetation

Robert O. McCosker

3.1 Introduction

Water availability is the key factor influencing the structure and floristic composition of vegetation communities in wetland, riparian and floodplain ecosystems. Wetlands can be considered distinct from riparian and floodplain communities on the basis of standing water being the primary force determining plant assemblages in wetlands. While flooding plays an important role in the ecology of riparian and floodplain plant communities, water drains off the land occupied by these communities soon after the recession of floodwaters. Wetlands can be considered as water storage systems, while riparian zones and floodplains act as conduits for water transmission.

This fundamental difference between wetland and riparian ecosystems necessitates different techniques for determining the flooding requirements of wetland vegetation and riparian vegetation. Because of this difference, the two systems are treated separately in this review.

3.2 Wetland vegetation

3.2.1 Wetland hydrology

Virtually every structural and functional characteristic of a wetland is directly or indirectly determined by the hydrological regime (Gosselink & Turner 1978; Carter 1986; Gopal 1986; Mitsch & Gosselink 1986; Hammer 1992; Gilman 1994) which, in turn, is controlled by regional hydrological cycles and the landscape (Bedford & Preston 1988). Water regime is often considered the single most important ecological factor for wetlands (Breen 1990; Roberts 1990).

Floristic composition and vegetation community structure in wetlands are determined by frequency, duration, depth and season of flooding. The assemblages of plant species in a wetland habitat are the result of a particular flooding regime occurring through time. Trees, shrubs and herbaceous plants respond to hydrological stress caused by either excess or insufficient moisture. Herbaceous vegetation is quick to respond to changes in inundation frequency, duration and depth, while woody vegetation tends to reflect long-term trends in these parameters (Carter 1986). Changes in water regime often result in changes to the floristic composition of a wetland (Chesterfield 1986; Bren 1992; Weiher & Keddy 1995; Casanova & Brock 1996; Nielsen & Chick 1997).

The physical, chemical and biological functions which give wetlands their unique character and habitat value are driven by water availability (Gippel 1992). Both seasonal and year-to-year variations in rainfall and run-off produce natural cycles of water level fluctuation in wetlands. Fluctuations in water level, including the complete drying of the bed, have been shown to have beneficial effects on the productivity of wetlands (Braithwaite 1975; Maher & Carpenter 1984; Briggs & Maher 1985; Briggs et al. 1985; Pressey 1986). Desiccation of organic matter during dry periods releases nutrients, which produce a flourish of biological activity when the wetland is re-flooded. Intensive breeding activity in some species of ducks has been observed in swamps that have filled following complete drying out, whereas a rise in water level in permanent swamps has resulted in less bird breeding activity (Crome 1986, 1988).

Consideration of water regime is a fundamental component of wetland management, as the ecological processes occurring in wetlands are driven by hydrology. Disturbance to hydrological processes is the greatest threat to wetland conservation values and, historically, has caused most wetland degradation (Briggs 1983; Bedford & Preston 1988; McComb & Lake 1988; Wong & Roberts 1991; Gippel 1992; Martin & André 1993). Wetland water regime was identified as the number one priority issue for the National Wetlands R&D Program (Bunn et al. 1996).

Wetlands can be considered in two broad categories for the purposes of this review:

- riverine floodplain wetlands, which are depressions within the floodplain that are fed by the adjacent river (eg. billabongs); and

- terminal wetlands, which lie at the lowest point in a catchment and receive water that drains from the catchment. These can vary enormously in size depending on the area of catchment feeding them.

3.2.2 Wetland water budgets

A water budget is a simple model of the inputs and outputs of water to a wetland (Carter, 1986; LaBaugh, 1986). It can be expressed by the following equation such that over a specified time interval (t):

$$\Delta S(t) = P + Q_i + G_i - E - Q_o - G_o$$

where:

- ΔS = change in water quantity stored in the wetland
- P = precipitation falling on the wetland
- Q_i = surface water flowing into the wetland
- G_i = groundwater flowing into the wetland
- E = evapotranspiration volume
- Q_o = surface water flowing out of the wetland
- G_o = groundwater flowing out of the wetland.

Water additions to and losses from wetlands tend to vary seasonally. This gives rise to seasonal variations in the depth of water and area inundated in wetlands. Fluctuations in water level also occur within seasons, in response to random inputs. In the longer term, the water level may be low or high for unusually long periods, or at unseasonal times, in response to erratic weather patterns or extended wet or drought years (Gippel 1992).

Knowledge of the typical pattern of water level variation through time is crucial for wetland management. This pattern can be characterised in terms of the frequency of wet and dry periods, the average and extreme duration of wet and dry periods, and the seasonality of wet and dry periods (Gippel 1992). Because the Australian climate is typically variable, this information needs to be obtained from long periods of observation. Unfortunately, wetland water level is rarely recorded and, where records are available, they are usually too short for reliable conclusions to be drawn.

Wetland vegetation condition is a good indicator of changes in wetland hydrology. Changes in the floristic composition or vegetation community structure of a wetland are most likely to be caused by hydrological change. Factors affecting wetland hydrology include natural long-term climatic variability, regional or catchment impacts (eg. vegetation clearing, land use changes, river regulation, river improvement) and local impacts (eg. drainage, levee construction, groundwater pumping).

3.2.3 Terminal wetlands

Water budgets have been used to estimate volumes of water required to inundate terminal wetlands in river systems that have been subjected to hydrological changes as a result of river regulation (eg. McCosker & Duggin 1993; Keyte 1994). Determining the volume of water required is a relatively straightforward exercise once the area of the wetland and required depth of flooding have been established. The water budget inputs and outputs can be quantified mathematically. However, wetland management should aim to preserve or restore vegetation communities that existed in the wetland prior to hydrological changes being imposed upon the system. This goal requires knowledge of the hydrological requirements or tolerances of the plant species present.

A restored flooding regime that does not mimic the natural seasonal, frequency and duration patterns may alter the plant communities present in the wetland system. For example, if the duration or frequency of flooding is reduced, the native species may lose their competitive edge and the system will become vulnerable to invasion by exotic species. This has occurred in the Gwydir wetlands in north-western New South Wales, where water couch (*Paspalum distichum*) and spike-rush (*Eleocharis plana*) meadows have been extensively invaded by the exotic lippia (*Phyla canescens*) as a result of reduced frequency and duration of flooding following river regulation (McCosker & Duggin 1993).

Calculated estimates of terminal wetland water requirements can be verified with the aid of historical flow data and remote sensing. Bennett and Green (1993) used remote sensing to establish a relationship between the area of wetland inundated and the volume of water in a particular flow event in the Gwydir wetlands. Using 10 Landsat Multispectoral Scanner images recorded over a range of wetland flooding conditions, the area inundated was visually assessed and measured by planimeter. The area estimates derived from the satellite images were plotted against the volume of recorded flow in the Gwydir River at Yarraman Bridge (about 20 km upstream of the wetland inflow point) for the month prior to the image (Bennett & McCosker 1994).

Application of the water budget and remote sensing methods produced comparable results. The volume of water required to inundate 20,000 ha of water couch and spike-rush meadows was calculated by the water budget method as being 3 to 6 ML/ha, depending on antecedent conditions. The remote sensing approach determined that 5 ML/ha would be required. The

similar results from both methods added a degree of confidence to the volumes determined.

Satellite remote sensing was used by Shaikh et al. (1997) to develop a relationship between historical streamflow data, meteorological data and wetland inundation in the Great Cumbung Swamp in the Lachlan Valley, south-west New South Wales. A high correlation was found to exist between the magnitude of 12 flood events (determined from upstream flow data) and the area of wetland inundated by each event. The authors claimed that the study demonstrates the value of remote sensing in providing information on wetland hydrology using existing upstream hydrological data. They suggested that remote sensing provides a practical means of observing a number of actual events in a wetland that may be hydraulically complex, have no gauging records, or be inaccessible and expensive to survey topographically.

Johnston and Barson (1991, 1993) used Landsat Thematic Mapper™ data to assess the effectiveness of remote sensing for mapping and monitoring wetlands. They concluded that satellite remote sensing has advantages in reconnaissance mapping programs for wetlands and in monitoring known wetland areas. However, for detailed mapping of the distribution of wetland vegetation species, satellite remote sensing is unlikely to replace conventional mapping methods that use aerial photography interpretation and field survey (Johnston & Barson 1991).

Shaikh et al. (1997) identified limitations of remote sensing as being the large numbers of images required to develop a reliable area–volume relationship. Also, remote sensing only provides information on flood extent, unlike hydraulic modelling which can predict other hydrological information such as height and duration of flooding, parameters that are important determinants of vegetation communities, and other processes such as bird breeding events. None of the studies using satellite imagery examined the response of wetland vegetation to seasonality or frequency of inundation. The focus to date has been on establishing a relationship between streamflow records from an upstream gauging station and area of wetland inundated. This has been driven by the need to establish quantities of water required to restore or maintain important wetlands.

3.2.4 Riverine floodplain wetlands

Methods for assessing water regime requirements of floodplain wetlands mainly utilise analysis of historical data, including aerial photography and streamflow records. Comparison of historical and recent aerial photography enables an assessment of changes to the vegetation that may have occurred in a wetland over time. Analysis of historical streamflow data from a nearby gauging station enables determination of the frequency and season of wetland inundation if the stage height at which overbank flows commence to enter the wetland is known.

If the threshold wetland flooding height is unknown, the discharge at which a river overtops its banks (and therefore inundates wetlands) can be estimated by using a uniform flow resistance formula, the most popular being the Manning Formula (Gippel 1992). In cases where there is no river gauge in the vicinity of the wetland of interest, it is necessary to develop a flow routing model which will, on the basis of flow data available for other parts of the catchment, generate a modelled flow record for the river adjacent to the wetland. In cases where the river in the vicinity of the wetland is ungauged, and a flow modelling approach is unwarranted, flow records from an upstream gauge can be used as a guide to the frequency and season of wetland filling (Gippel 1992).

Gippel et al. (1991) compared local observational evidence of river levels at which floodplain wetlands become inundated with historical river gauging data for the Goulburn River in Victoria. The characteristics of both wetland inundation and the dry spells between were examined. The emphasis of the study was on the impact of flow regulation on wetland inundation. This required access to river flow records for a reasonable length of time before and after the commencement of regulation. A single threshold flooding level was assigned to represent the wetland area in the vicinity of each gauging station. The authors noted that local information about levels at which wetlands fill may be unreliable. Where the wetlands of interest are close to gauging sites, surveyed levels can be related directly to gauge heights.

The analysis by Gippel et al. (1991) contained the following five components.

1. Comparison of regulated stations and unregulated control stations using yearly flow or rainfall data.
2. General comparison of regulation phases using descriptive statistics derived from yearly and monthly flow data.

3. Detailed comparison of regulation phases using descriptive statistics derived from daily flow data, combined with wetland filling threshold information and evaporation data.
4. Investigation of downstream extent of the effect of regulation.
5. Sensitivity check by repeating analysis using the upper and lower confidence bounds of the threshold flooding level.

The study by Gippel et al. (1991) found that at Eildon, wetland flooding events now occur, on average, once every three years compared to annual flooding prior to regulation. Wetlands of 1 m depth dry out, on average, once every three and a half years, with an average duration of just over three years under regulation, compared with the pre-regulation situation of no dry spells. The authors noted that the method had a number of simplifying assumptions consistent with its intended use for reconnaissance. It was suggested that the analysis would not be valid if the wetlands interacted significantly with groundwater. Stated advantages of the method were that it is rapid and utilises existing data that can be readily and inexpensively acquired.

Studies of floodplain wetlands along the Darling River used a combination of streamflow records and satellite remote sensing to determine the stage height at which the wetlands commence to fill from the main river channel (Cooney 1994; Green et al. 1997). The method for both studies involved identifying past flood events that resulted in wetland inundation and securing flow data for those events. Comparison of satellite images from before and during the peak of events enabled identification of wetlands that had filled during the event. Streamflow bands considered important for achieving wetland inundation were identified by comparing images and flow data from several events of different magnitude.

The study found that the near infra-red and middle infra-red bands of the Landsat Thematic Mapper™ images are best for identifying inundated areas. Of the seven available bands, the middle infra-red (TM5) provides best results and is the most cost-effective. Green et al. (1997) used a density slicing technique to enhance the distinction between flooded and non-flooded areas. This technique had previously been used and described by Bennett (1987) and Johnston and Barson (1993).

Aerial photographs taken in 1945, 1957, 1970 and 1985 were used by Bren (1992) to examine the invasion of river red gum (*Eucalyptus camaldulensis*) into an extensive natural grassland at a high flood frequency site adjacent to the River Murray. Analysis of historical streamflow data from a nearby gauging station indicated that increased summer flooding and reduced winter–spring flooding as a consequence of river regulation were the principal factors allowing red gum to invade the grasslands.

Management plans have either been prepared or are in preparation for many wetlands on the River Murray floodplain. Many of these wetlands became degraded as a result of changes to seasonal flooding patterns following river regulation (Pressey 1986). Restoration of these wetlands has hinged on restoring natural flooding regimes. In most cases this has been achieved by analysing historical streamflow data to determine the natural frequency, duration and season of flooding. Where necessary, engineering structures have been installed to allow controlled flooding and drying of the wetlands, to mimic natural conditions.

3.3 Floodplain and riparian vegetation

3.3.1 Riparian zone ecology

Riparian vegetation occupies one of the most dynamic areas of the landscape. The distribution and composition of riparian plant communities reflect histories of both fluvial disturbance from floods and the non-fluvial disturbance regimes of adjacent upland areas, such as fire, wind, plant disease and insect outbreaks (Gregory et al. 1991; Tabacchi et al. 1996). Soil properties and topography of valley floors are extremely varied. Soil moisture availability within the riparian zone can range from perennial saturation to occasional saturation. Consequently, riparian plant communities normally exhibit a high degree of structural and floristic diversity.

The structure and floristic composition of riparian plant communities are influenced by environmental gradients that exist within the riparian zone. These gradients are related to fluvial dynamics, floods and soil moisture availability. They extend from upland terrestrial conditions through to the in-stream aquatic environment (Malanson 1993).

Malanson (1993) identified two major gradients that exist in riparian areas. One is a stress gradient related to moisture availability. The second is

disturbance resulting from dynamic fluvial geomorphology. Riparian plant species occupy different niche spaces along axes related to both of these factors. The different hydrological regimes that occur along the moisture gradient create a variety of conditions which are advantageous for establishment and growth of species differing in their specialisation (Blom et al. 1990). Plant species also exhibit a variety of mechanisms enabling them to withstand the physical forces of floodwaters and recolonise areas following floods (Gill 1970). Hughes (1990) noted that a fine balance exists between *dependence on* and *tolerance to* flooding.

Disturbance is considered an important factor in riparian zone ecology as it maintains plant diversity through increasing environmental heterogeneity (Bornette & Amoros 1996; Resh et al. 1988). In stable environments the superior competitors eliminate inferior competitors, reducing the species richness of the system. At an intermediate level of disturbance frequency and magnitude, a balance between competitive species adapted to long-term stable environments and coloniser species adapted to frequent disturbances is reached, and diversity is maximised. Flooding is the primary agent of disturbance in riparian plant communities. Alternative mechanisms have evolved amongst riparian plant species to enable them to cope with flooding disturbance. Essentially, a particular flooding regime is a disturbance only to those species that cannot tolerate it (Menges & Waller 1983).

Elevation above the stream channel is a major factor determining species patterns (Hupp & Osterkamp 1985). Small changes in elevation often reflect substantial variation in hydrological conditions. Mitsch and Gosselink (1986) proposed that floods and groundwater levels are the main determinants of the type and productivity of riparian vegetation. Rate of flow, seasonality of flooding and duration of flooding have been found to be particularly critical (Hughes 1990). Kondolf et al. (1987) stated that an understanding of the nature of interactions between streamflow and the alluvial water table is necessary in order to determine the effect of streamflow changes on the availability of water to riparian plants.

Riparian plant communities are known to be sensitive to changes in the hydrological regime (Décamps et al. 1995; Nilsson et al. 1997). Natural fluctuations between the high and low water levels generally produce high species-richness of plants and relatively dense vegetation in the riparian environment (Wisheu & Keddy 1989). However, deviations from the natural regime of water level fluctuation reduce species-richness and vegetation cover (Nilsson et al. 1991). Factors causing such declines include drought stress, which may affect seedlings and old trees (Décamps 1996). Sustained high flows associated with river regulation provide favourable conditions for plant growth in a narrow band of the riparian zone at the regulated flow level. These conditions can lead to increased vigour and recruitment of specific species that may be adapted to perennially stable water levels.

Studies in the American and African sub-continents have found that certain bottomland species of woody vegetation have predictable distribution patterns which correspond to observable fluvial landforms (eg. Hupp & Osterkamp 1985; Bradley & Smith 1986; Harris 1986, 1988; Hughes 1990). This correlation has been used in association with historical hydrological data to assess the impact of flow diversions on riparian vegetation (Bradley & Smith 1986; Kondolf et al. 1987; Hughes 1990) and to determine in-stream flow requirements in rivers which have been subjected to altered flow regimes (Stromberg & Pattern 1990).

3.3.2 Environmental flow assessment techniques

The concept of determining in-stream flow requirements of rivers emerged from the need to establish the extent to which the flow regime of a river can be altered from the natural condition while still maintaining the integrity of the riverine ecosystem. Such requirements are calculated by means of an in-stream flow assessment, the essence of which is to ascertain the amount of water that must be left in a regulated river system during different times of the year to maintain the aquatic resources at some designated desirable level (Tharme 1996). The original natural flow regime is often used as a guide for determining the elements of a flow regime that are considered essential for maintenance of the riverine biota.

A number of methodologies have been developed worldwide for assessing in-stream flows for a variety of aquatic species and components of riverine ecosystems. Commonly used methodologies fall into four categories: historical flow record methodologies, hydraulic rating methodologies, habitat rating methodologies, and holistic methodologies (Tharme 1996).

Historical flow record, hydraulic rating and habitat rating methodologies were developed mainly to determine the requirements of either individual species or assemblages of species of fish. As they are not directly applicable to riparian vegetation, and because they have

been thoroughly reviewed in the literature (eg. Estes & Orsborn 1986; Bleed 1987; Arthington & Pusey 1993; Karim et al. 1995; Jowett 1997), these methodologies will not be considered in this review.

Early assessments of environmental flow requirements of rivers in Australia focused mainly on the needs of fish. Although it is well established that riparian vegetation plays a pivotal role in stream ecology and maintaining bank stability (see Bunn et al. 1993), few studies have considered the hydrological requirements of individual plant species. Riparian vegetation is often viewed as a single entity comprising a suite of species. Scant attention has been given to individual species and their specific ecological niche preferences on the hydrological gradient between the aquatic and terrestrial environments. Consideration of riparian vegetation is often restricted to an assessment of the degree of disturbance through clearing and grazing, and the extent of invasion of the riparian zone by exotic species (eg. Snowy River Expert Panel 1996).

Environmental flow assessment studies in Australia that have included consideration of riparian vegetation have generally been of the multidisciplinary holistic ecosystems approach. Variations of this methodology have been developed in recent years. They include the Expert Panel Assessment Method (Swales et al. 1994; Swales & Harris 1995), Holistic Approach (Arthington et al. 1992; Arthington & Pusey 1993), Building Block Methodology (King & Tharme 1994) and Habitat Analysis Method (Burgess & Vanderbyl 1996).

3.3.2.1 The Expert Panel Assessment Method

The Expert Panel Assessment Method was formulated by New South Wales Department of Fisheries and first tested experimentally at sites on regulated rivers below six headwater storages on tributaries of the Murray-Darling River in eastern New South Wales (Swales et al. 1994). The method draws on the professional experience of specialists in fluvial sciences to assess the suitability of in-stream flows for river ecosystem processes. In the first application of the method, the suitability of streamflows for the survival and abundance of native fish was taken as the primary criterion of the suitability of the discharge as an environmental flow. This was based on the premise that fish communities are a good indicator of river 'health' (Swales & Harris 1995). Expert panels in the trial of the method comprised three specialists in the fields of freshwater fish ecology, river invertebrate ecology and fluvial geomorphology.

An expert panel was established to review the environmental values and identify management changes required to provide additional flows within the Campaspe River Basin in Victoria (Kelly 1996). However, water requirements of aquatic plants and riparian vegetation were not studied. The primary objective of the recommended environmental flows was to improve conditions for existing biota and restore populations of golden perch and Murray cod. It was assumed that by improving conditions for golden perch and Murray cod, conditions would be improved for other biota. Implicit in this assumption was that provision of a flow broadly mimicking natural flow patterns would provide adequate protection for vegetation.

Other recent applications of the method have included riparian vegetation specialists. Examples include in-stream flow assessments of the Barwon-Darling River (Thoms et al. 1996) and the Snowy River (Snowy River Expert Panel 1996). In these studies, a panel of scientists conducted a study tour of the section of river in question, reported on the condition of the river from their observations, and made recommendations for flow management. No prior quantitative studies had been undertaken by the panel members, and hence recommendations were based on observations and existing knowledge of these and similar rivers.

The Barwon-Darling study recorded tree species present in each of three reaches between Mungindi and Menindee, and identified their general location in relation to the active channel. The distribution of trees was reported as being linked to certain geomorphic features. Black box (*Eucalyptus largiflorens*) and coolibah (*Eucalyptus coolabah*) were usually found on the older, heavier clay of the pre-existing Darling floodplain, whereas river red gum (*Eucalyptus camaldulensis*) and river tea tree (*Melaleuca trichostachya*) occurred on younger features beside and within the present active channel of the Darling River (Thoms et al. 1996). The general health and recruitment success of trees was also discussed. However, the study fell short of identifying specific flow regime requirements of individual species. The principal threat to trees in the riparian zone and floodplains of the Barwon-Darling River was considered to be restricted regeneration due to an interplay of altered flow regime, grazing pressure, clearing, weir pools and exotic invasive shrub species.

The Snowy River study (Snowy River Expert Panel 1996) reported that the riparian zone of the river had

been invaded for much of its length by exotic species, including willows and blackberries. The original native vegetation had been extensively cleared. While flow regulation was identified as contributing to changes in riparian vegetation, clearing, grazing and disturbance by stock also were considered to have had a major impact. It was noted that flow regulation had allowed both native and exotic plant species, to stabilise sand banks. Other than suggesting that an enhanced flow regime would assist in clearing out vegetation that had colonised the active channel and sand banks, the study fell short of identifying flow regime requirements of individual plant species.

In reviewing the application of the Expert Panel Assessment Method to the Snowy River, Pigram (1996) concluded that while the method had some merits in the area of fluvial geomorphology and assessment of ecological conditions for macroinvertebrates, methodological and information deficiencies were evident in aspects of the assessment of hydrology, fish ecology and riparian vegetation ecology.

3.3.2.2 The Habitat Analysis Method

The Habitat Analysis Method was developed in Queensland to determine environmental flows for water allocation and management plans (Burgess & Vanderbyl 1996). The method is based on the 'panel of experts' approach, with a workshop being the centrepiece of the process. The panel would typically include specialists in geomorphology, aquatic biology, freshwater fish biology, marine biology (for coastal rivers), riparian ecology and wetland ecology. A support group would include facilitator, system manager or operator, hydrologist, hydrographer, recorder and a catchment group representative.

The workshop is conducted to achieve four distinct outcomes: (i) identification of generic habitat types existing within the catchment; (ii) determination of the flow-related ecological requirements of each of those habitats; (iii) formulation of bypass flow strategies to meet those requirements; and (iv) development of a monitoring strategy to check on the effectiveness of the flow strategies (Burgess & Vanderbyl 1996).

The workshop is preceded by a data collection phase. All available data relevant to the workshop are reviewed, collated and dispatched to workshop participants prior to the workshop being held. The data would either be flow-related or linked to the condition of the riverine habitats.

A post-workshop stage of the methodology includes modelling the flow provision options formulated by the panel in terms of flow quantity, duration and timing. The quantified options are then assessed during a community consultation phase in relation to: (i) effectiveness in meeting critical environmental requirements; (ii) impact on water resource entitlements; and (iii) limitations of supply infrastructure.

Finally, the specified environmental flow provisions are presented back to the original panel members to: (i) verify that the specific environmental flow provision options are consistent with the intention of the workshop; and (ii) qualify the sensitivity levels associated with the effectiveness in meeting the critical environmental flow requirements.

Workshops applying the Habitat Analysis Method have been conducted for the Dawson, Barron, Condamine-Ballone and Border Rivers (Macintyre and tributaries) at the time of writing. However, none of these applications has been completed to the stage of specifying environmental flow provisions.

The Habitat Analysis Method identifies habitats as generic types within each of the geomorphic zones. Documents prepared and circulated to panel members prior to the workshop include descriptions of the vegetation communities in the different habitat types. Ideally, this description would include an analysis of the relationship of the vegetation communities to the river system in regard to hydrological requirements of key species. The method does not include specific guidelines for determining the hydrological requirements of riparian and floodplain vegetation.

From the writer's involvement in two of the workshops (Condamine-Balonne and Border Rivers) it appears that the Habitat Analysis Method is still in a developmental phase. Shortcomings identified in early applications of the method have resulted in improvements being incorporated into subsequent applications. One of these has been the assessment of specific sites that are considered representative of each geomorphic zone, an approach derived from the Logan River trial of the Building Block Methodology (Arthington & Long 1997). River cross-sectional diagrams showing stage height and discharge rating curves are prepared for each of these sites and made available to panel members during the workshop. Historical flow data is also made available to allow an appraisal of the natural flow regime. A catchment tour by panel members immediately prior to the workshop includes inspection of representative sites.

3.3.2.3 The Holistic Approach and Building Block Methodology

The Holistic Approach and Building Block Methodology have a common origin and similar applications. Because of their similarities they are treated together in this review. The approach is based on the natural hydrograph of the river, which is used as a fundamental guide to the environmental conditions that have maintained the river in its characteristic form (Arthington et al. 1992). It assumes that the natural flow regime of a river maintains, in a dynamic manner, all of the in-stream biota, riparian vegetation, floodplain and wetland systems, and any estuarine and offshore systems affected by flows. Implicit in this assumption is the notion that if certain essential features of a river's natural (unregulated) flow regime can be identified and adequately incorporated into the modified or regulated flow regime, the extant biota should persist and much of the 'functional integrity' of the riverine ecosystem should be maintained (Arthington et al. 1992).

Application of the Australian Holistic Approach and South African Building Block Methodology involves the systematic construction of a modified flow regime, month by month (or on a shorter time scale) and element by element, each element representing a well-defined feature of the flow regime intended to achieve particular ecological, geomorphological or water quality objectives in the modified river system (Arthington 1996).

The conceptual basis and key elements of the Building Block Methodology are described by Tharme (1996). The methodology is based on the concept that some flows within the complete hydrological regime of a river are more important than others for maintenance of the riverine ecosystem. These flows can be identified and described in terms of their magnitude, duration, timing and frequency. In combination, these flows form a river-specific modified flow regime, linked to the desired future state of the river.

The following assumptions are explicit in the methodology (Tharme 1996).

- The biota associated with a river can cope with baseflow conditions naturally occurring often, and may be reliant on higher flow conditions that naturally occur in it at times (eg. specific floods).
- Identification of the most important characteristics of the natural baseflows and floods, and combining them as the modified flow regime, will facilitate maintenance of the river's natural biota and processes.
- Certain flows influence channel geomorphology more than others, and incorporating such flows into the modified flow regime will aid maintenance of natural channel structure and diversity of physical biotopes.

The main procedures comprising the Building Block Methodology are as follows (Tharme 1996).

- Identification of a desired future state for the river or reaches.
- Riparian and in-stream habitat integrity assessment and site selection.
- Geomorphological catchment and river reach analysis, and compilation of information on the geomorphology and hydraulics of sites.
- Collection of hydraulic data at established in-stream flow requirement (IFR) cross-sections at sites, including stage-discharge data, depths, velocities, *inter alia*, followed by modelling of local hydraulics. Provision of cross-section plots and graphs of hydraulic relationships (eg. discharge versus maximum depth or wetted perimeter).
- Compilation of historical records of virgin and present-day daily average discharge data and other hydrological information, in various formats (eg. plots of time series of daily discharge and flow duration curves).
- Compilation of flow-related information on designated ecosystem components, with field collections if required. Information on social dependence on the river is also compiled.
- Development of a statement of the river's economic, conservation and cultural importance.
- Presentation of summaries of all of the above information in a Starter Document for workshop participants.
- Determination of the IFR at a workshop, including site visit, information session, recommendation of a quantified modified flow regime at each site, with explicit motivations by all specialists for each flow identified, matching the IFRs for all sites, descriptions of further work needed to increase confidence in the recommended IFRs, and a report of the workshop proceedings. Development of a quantified modified flow regime at each IFR site involves use of hydraulic data at cross-sections; site photographs at various discharges; historical virgin flow records; and specialist information on each

ecosystem component to recommend suitable baseflows and higher flows, for maintenance and drought IFRs. Flow variables considered in the assessment include depth, level or extent of inundation of the channel, velocity, duration, recurrence interval, magnitude and timing.

The Holistic Approach and Building Block Methodology differ from expert panel approaches by commissioning a team of experts to provide specific quantitative advice relevant to in-stream flow management, rather than drawing on opinions. For riparian vegetation, a detailed botanical survey is conducted at each IFR site. These sites are chosen as being representative of geomorphically homogenous reaches of the river. The location of plant species in relation to water level is recorded, as is any evidence of recruitment of dominant species, disturbance, or invasion by exotic species (eg. McCosker 1997). Many plant species display predictable patterns in their distribution within the riparian zone. These patterns reflect the hydrological regime favoured by the particular species and can be mapped onto channel cross-sectional diagrams of the IFR site. By superimposing a flow rating curve over the cross-sectional diagram, it is possible to determine the discharge at which different elevations of the riparian zone are inundated.

Long-term hydrological data on natural daily flow is provided for each IFR site to allow assessment of the flooding regime that occurred historically at the site. Long-term hydrological data are seen as ideal because they provide comprehensive information on the timing, magnitude, frequency and duration of flow conditions that occur often in the river (ie. conditions that the natural vegetation of the river has adapted to). Data on natural flow are considered ideal because the natural flow regime is one of the driving forces that has sculptured both the river channel and the character of its biological communities. An understanding of the regional character of the river, and the difference between its natural and present flow regime, will provide a guideline of the flow regime most suited to the river. It will also allow an assessment of the extent to which the most suited flow regime has been lost. Maintaining something resembling the natural flow pattern in a regulated river reduces the likelihood of costly ecological or geomorphological repercussions (King & Louw 1995). Daily flow data are considered ideal because these come closest to describing the instantaneous flow that the riverine biota experiences and to which they react.

The Building Block Methodology was trialled for the first time in Australia in 1996 in the Logan River catchment in south-east Queensland (Arthington & Long 1997; Arthington & Lloyd 1998). Riparian vegetation on the Logan River had been extensively cleared late last century. Historical records indicated that the river was originally fringed by a gallery of rainforest. Present vegetation is dominated by weeping bottlebrush (*Callistemon viminalis*) at the water's edge, with grasses prevailing on the banks. A workshop was conducted to determine monthly minimum drought flows, maintenance flows and capping flows required to maintain the riverine biota. The level of detail requested of the riparian vegetation specialist regarding flow requirements of the vegetation was difficult to justify, considering the degree of disturbance to which riparian vegetation had been subjected by anthropogenic factors and the lack of knowledge of hydrological requirements of plant species present (McCosker 1997). It was apparent that land management issues were possibly more important for maintaining and restoring riparian vegetation than setting river flow objectives, particularly considering that this was a highly disturbed system and the present vegetation represented a primary successional state. This application of the Building Block Methodology was not sufficiently flexible to incorporate non-flow-related issues into the recommendations for riparian vegetation.

The Holistic Approach was first applied in a limited way to the Tully-Millstream Hydroelectric Scheme in north Queensland. Currently, it is being used to develop environmental flow recommendations for the North Dandalup and Canning River systems in Western Australia, and to produce an environmental flow strategy for the Brisbane River below Wivenhoe Dam (Arthington & Zalucki 1998). The application of the Holistic Approach to the Brisbane River followed a similar procedure to the Building Block Methodology. Differences included a more intensive study of the riparian vegetation on the Brisbane River and a less formally structured workshop conducted to formulate flow management recommendations that were acceptable to all specialists. Vegetation surveys were conducted at IFR sites during summer, autumn and spring in order to develop an understanding of the seasonal characteristics of the vegetation, particularly for annual species.

Riparian vegetation along the regulated section of the Brisbane River downstream from Wivenhoe Dam displays typical adaptations to a regulated flow regime. Sustained higher than natural low flows throughout the year and a reduction in the severity of floods have allowed weeping bottlebrush (*Callistemon viminalis*) to extensively colonise point bars and banks slightly above the regulated flow level. Recommendations for management of flows were constrained by a requirement of the South East Queensland Water Board to deliver 600–700 MLd^{-1} to Mt Crosby pumping station, a few kilometres upstream of the tidal zone. Flow management recommendations for riparian vegetation focused on restoring critical flow bands that would inundate benches located at different levels within the channel, floodrunners and wetlands. These geomorphic features coincide with different suites of plant species. Periodic moderate and major floods were considered important for scouring the channel and removing young bottlebrush seedlings from point bars. Floods were also considered important for providing favourable conditions for recruitment of riparian species such as river oak (*Casuarina cunninghamiana*), on mid and upper banks.

3.3.2.4 Other approaches

Two methods devised in North America for assessing in-stream flow requirements of riparian vegetation differ in their approaches from the methods trialled in Australia. The first involves linking stream discharge to alluvial groundwater levels. The premise of this approach is that variations in the alluvial water table have the potential to affect riparian vegetation (Kondolf et al. 1987). Kondolf et al. (1987) postulated that determining the effect of streamflow changes on the availability of water for riparian plants requires an understanding of the nature of the interactions between streamflow and the alluvial water table. Where groundwater levels in the riparian zone can be measured (either by observing existing wells or by installing peizometers), their fluctuations can be compared with changes in streamflow as an indication of the degree to which the two are interrelated.

One of the most fundamental determinations to be made with this method is whether a stream reach is gaining water from the groundwater (a gaining reach), losing water to groundwater (a losing reach), or in equilibrium with respect to groundwater. The riparian vegetation in losing reaches is considered more sensitive to flow reductions than in gaining reaches. The shallow water table in a losing reach is probably dependent on flow, whereas in a gaining reach, riparian vegetation may be supported by in-flowing groundwater (Kondolf et al. 1987).

The second method devised in North America involves establishing a relationship between streamflow and riparian vegetation. Stromberg and Patten (1990, 1996) found that growth ring widths in two deciduous riparian species could be correlated with hydrological variables. It was shown that streamflow volume directly influenced the growth rate of riparian trees. The assumption implicit in this approach is that certain levels of growth are required to maintain both the individual tree and the population (Stromberg & Patten 1990).

Stromberg and Patten (1990) acknowledged that it is important to understand relationships of streamflow to plant processes other than growth rate (eg. tree mortality and recruitment success). They noted that because the reduction in growth during times of low flow results from reduced moisture within riparian soils, the relationship of stream flow and growth should be quantified with respect to distance of trees from the stream and height above the water table. They also suggested that the response of several species should be considered, as well as several aspects of the flow regime (eg. seasonal distribution of flow, magnitude of flood peaks, and annual variation in flow) when determining in-stream flow requirements for riparian communities.

In a similar attempt to directly link hydrological variables with riparian vegetation, Stromberg (1993) found that flow volume was the primary factor influencing riparian vegetation abundance and species richness in semi-arid areas of central Arizona. Although the abundance–discharge models are simplistic, it was suggested they could be refined to account for changes in critical hydrological components other than the mean or median flow volume. Such refinements could include the magnitude and duration of low or no flow periods. Flood flows of a given magnitude, frequency and seasonal timing are also considered important because of their roles in influencing species diversity patterns and in creating opportunities for riparian recruitment (Stromberg 1993).

The New South Wales Department of Land and Water Conservation adopted a multidisciplinary approach to determining the environmental flow requirements of the lower Darling River (Green et al. 1997). The recommendations form the culmination of studies that had taken place over a number of years. Although this is a study, rather than the application of a

method to determine the river's flow requirements, it is worth reviewing because of the multidisciplinary ecosystem approach adopted.

The study comprised analyses of floodplain wetland inundation, hydrology and ecology. The wetland component aimed to verify commence-to-flow heights of billabongs along the lower Darling River between Jamesville and Ashvale that had been documented earlier by Ardill and Cross (1994), and to develop a method for using satellite imagery in determining commence-to-flow heights for wetlands over the entire reach. This component of the study was discussed previously in Section 3.2.4 of this review.

Hydrological analyses conducted for the lower Darling River examined annual and monthly flow duration curves, flow frequencies for peak and low flows, and rate of recession following floods. The ecological components considered in the study were channel geomorphology, water quality, riparian vegetation, fish, macroinvertebrates and waterbirds. The section on riparian vegetation consists of a description of dominant species and their location within the riparian zone. A table is presented that outlines the water requirements of dominant species in terms of frequency, duration and seasonality (Table 3, page 58). The flooding recommendations appear to have been determined from the limited literature and observations of the authors. Notes are provided on the health of riparian vegetation and extent of regeneration (Green et al. 1997).

An environmental assessment of proposed Windamere Dam transfers down the Cudgegong and Macquarie Rivers to Burrendong Dam in central western New South Wales included a study of riparian vegetation (Grose 1993). A survey of vegetation at nine sites along the river divided plant species into three categories on the basis of elevation within the channel (bed, fringing and bank). The study found that fringing vegetation and aquatic macrophytes had encroached onto point bars and into the river channel as a result of a reduction in scouring flood flows and improved persistence of low flows. It was concluded that a combination of reduced flooding and grazing pressure was likely to affect the natural regeneration and general health of river red gums. It was recommended that transfers should be made during winter, in order to optimise river red gum recruitment opportunities and minimise effects on water quality, faunal breeding cycles, and water-based recreation on the storages. Winter floods that recede in spring are considered ideal for the germination and growth of river red gum seedlings (Leitch 1989).

3.4 Critique of available methodologies

3.4.1 Wetland vegetation

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 applying 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 exists 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 the 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 the water regime.

Table 3: *Water requirements of riparian vegetation species found on the Lower Darling River (reproduced from Green et al. 1997)*

Vegetation	Minimum duration	Maximum duration	Minimum frequency	Best time for effective flooding
River red gum				
low quality	2 weeks	18 months	3 years in 10	June to November
high quality	1 month	18 months	7 years in 10	(for regeneration)
Black box	0 months	1 month	0 years	any time
Lignum	3–5 months	3 years (?)	1 year in 10	winter – spring
Nitre goosefoot		can tolerate prolonged inundation		periodic
Spikerushes (*Eleocharis spp.*)		2 years in 3		winter – spring
Rushes (*Juncus spp.*)	2 months	30 months	3 years in 4	any time
Common reed			annually	summer
Cumbungi	6 months	permanent inundation	annually	summer
Water couch	4 weeks	8 weeks	annually	summer

Sources: Rankine & Hill 1979; Bren & Gibbs 1986; Cross & Keenan 1988; Leitch 1989.

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.

3.4.2 Riparian vegetation

The methods described in this review that have been used to determine flow requirements of riparian vegetation on 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 Assessment and Habitat Analysis Methods approaches 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 Assessment 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 Holistic Approach and Building Block Methodology require much more detailed knowledge of the riparian vegetation community at reach representative sites as a basis for making recommendations. By conducting a detailed botanical survey at IFR sites and recording 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 (eg. McCosker 1998).

An ability to make accurate predictions about the potential impact on riparian vegetation of a modified flow regime 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 or 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 toward 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; Chesterfield 1986; Dexter et al. 1986; Bren & Gibbs 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 the 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 give more attention to 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.

3.5 R&D recommendations

3.5.1 Wetland vegetation

- Further refine techniques for assessing terminal wetland water requirements to include consideration of timing, duration and frequency of flooding.
- Further research and collate existing information on the water regime requirements of common wetland plant species (eg. depth, duration, timing, frequency).
- Develop a list of indicator plant species of healthy and degraded wetlands for different climatic zones in Australia and document the water regime tolerances of these species.
- Develop techniques for assessing the interaction between surface water and groundwater in wetlands.

3.5.2 Riparian vegetation

- Collate into a single publication all existing information about water regime requirements and flooding tolerances of plants that occur in riparian zones.
- Direct a research effort toward assessing the role of groundwater in maintaining riparian plant communities.
- Improve knowledge 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.
- Prepare a prescriptive manual that outlines a step-by-step procedure for assessing the water regime requirements of riparian plant communities as a valuable addition to all methodologies.
- Increase knowledge of the most suitable timing, frequency, duration, and recession rates of floods for recruitment and maintenance of riparian vegetation.

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4. Methods addressing the flow requirements of fish

Bradley J. Pusey

4.1 Introduction

The assessment of the environmental flow needs of freshwater fishes in Australian rivers commenced in 1976 (Tunbridge 1997). Since that time, the field of environmental flow management has burgeoned due to developments in the number and sophistication of the methods used to evaluate and define flow needs, the critical state of the nation's rivers, projected increases in demand on, and an overall acceptance of the need for sustainable development of, this vital but scarce resource.

The purpose of the current review is to address the following three objectives.

1. Review currently used and available techniques for assessing flow requirements of fish, so that water managers have the key information and recommendations on which techniques are suitable for different situations, their limitations, advantages and cost-effectiveness.
2. Assist in the selection of 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.

4.2 Review and evaluation of methods

Kinhill (1988) recognised three groups of techniques or methodologies used to determine environmental flow requirements: rule of thumb, transect or passage, and available habitat. Tharme (1996) also broadly categorised the available methodologies into three groups. The first group consisted of methodologies that relied on the use of the historical flow record as a basis for determining in-stream flow needs. This group was termed hydrological methodologies. The second group was termed habitat discharge methodologies and contained the transect or passage methodologies and available habitat methodologies recognised by Kinhill (1988). The third group of methodologies were collectively grouped under the heading of holistic methodologies. This latter group has only been recently developed and thus was not considered by Kinhill (1988). In the following chapter, the three groups used by Tharme (1996) have been retained.

4.2.1 Hydrological methodologies

Hydrological methodologies are also known as 'rule of thumb', 'threshold' or 'standard setting' methodologies (Tharme 1996), with the former term being the most commonly used. This group of methods was developed in North America and a large array of individual methodologies have been described. All are based on the historical flow record, although their basis may differ from one methodology to another and may, in some cases, be obscure (Tharme 1996).

The Montana, or Tennant, Method (Tennant 1976) is the most frequently used method throughout the world and has been used, with modification, in Australia (Hall 1989, 1991). Tennant (1976) considered the three factors of wetted width, depth and velocity as being crucial for fish wellbeing. In developing the method Tennant (1976) measured variables concerning physical, biological and chemical parameters along 58 transects from 11 different streams at 38 different discharges (a total of 196 miles of stream). These data were gathered in three north-western states of the United States and augmented with additional data collected from a further 21 states.

Tennant (1976) believed that substantial congruous between discharge levels and the nature of the in-stream habitat existed over the range of streams examined. From this, he proposed that certain flows could achieve the maintenance of particular amounts of habitat which he termed "short-term survival habitat", "survival habitat" and "excellent-to-outstanding habitat". In its simplest form, these different qualitative categories were achieved by maintaining set proportions of the mean annual flow. Short-term survival habitat was maintained by preserving 10% of the mean annual flow survival

habitat at 30% of the mean annual flow and excellent-to-outstanding habitat at flows greater than or equal to 60% of the mean annual flow. This scheme was based on the observation that the greatest changes to habitat occurred between the flow range of 0–10% of the mean annual flow. Tennant (1976) considered biota other than fish in the formulation of these standards but was concerned chiefly with the maintenance of in-stream secondary production and recreational salmonid fisheries. This emphasis on salmonid species and/or species of recreational value is a theme that will recur in this review.

Tennant (1976) recognised that the flat allocation of a single discharge to a modified flow regime effectively removed all trace of any pre-existing pattern of seasonality. In accommodation, Tennant (1976) proposed a series of different flows for two six-month blocks (see Table 4 below).

The Montana Method in this form has not, to the author's knowledge, been applied in an actual assessment of the in-stream flow needs of an Australian river. However, Richardson (1986) did apply the Montana Method in the Tweed River, New South Wales, in a comparison of four different methods (see below) and noted that an equivalent database to that collected by Tennant (1976) was lacking for Australian rivers which were characterised by markedly different flow regimes and species of very different evolutionary histories.

Tharme (1996) lists several advantages of the Montana Method. These include that it is rapid, cheap and easy to apply; has moderate data requirements; and can be executed in the office but has the potential for field calibration. It was also suggested that it may have utility in situations where there is no negotiation phase in the allocation process. Tennant (1976) believed it to have wide applicability in the United States and elsewhere.

The disadvantages associated with the Montana Method are numerous, however, it is difficult to comparatively rank their seriousness. Tennant (1976) suggested that the method is most applicable for mountain streams with 'virgin' flow. If the flow regime is already partly regulated, then suggested allocations may be too low. Prewitt and Carlson (1980) reinforced this view and suggested that in streams where losses to off-stream uses and diversions are poorly known, there is a high potential for under-allocation. This has serious consequences in areas for which licences for abstraction of stream water for the irrigation of crops are granted on the basis of land area and works (ie. pump capacity) and for which there is poor or little accurate quantitative data on actual volumes abstracted for irrigation. Application of the Montana Method under such circumstances would be extremely unwise.

The Montana Method is dependent on the provision of extensive flow data. In many regions of

Table 4: *Temporal variation in proportion of mean annual flow allocated to achieve the maintenance of differing levels of habitat quality (after Tennant 1976)*

	Recommended baseflow regimes	
Flow category	**October to March**	**April to September**
flushing or maximum	200	200
optimum	60–100	60–100
outstanding	40	60
excellent	30	50
good	20	40
fair or degrading	10	30
poor or minimum	10	10
severe degradation	<10	<10

Australia such long flow records are not available. Furthermore, where long time series of data are available, then care must be taken in choosing which period of record is used as the basis for water allocations. For example, a substantial change in annual rainfall yields in south-eastern Australia occurred about 1946 (Pittock 1975). Similarly, Willcocks and Young (1991) present data which clearly show that total annual rainfall in many parts of northern Queensland cycles through periods when it is consistently greater than, or less than, the long-term average. The choice of which segment of streamflow data upon which to base an environmental allocation thus seems critical. In addition, the decommissioning of established stream gauges may also present some problems in the future.

The application of the Montana Method in areas other than those for which it was developed may be problematic and may be particularly limited in streams which are morphologically dissimilar to those originally examined (see Stalnaker & Arnette 1976). Richardson (1986) stressed that the relationship between habitat suitability and proportions of mean annual flow, which forms the basis of the Montana Method, has not been examined in Australia and that, therefore, there appears to be no theoretical or empirical basis for its implementation. Moreover, in regions with variable flows (ie. the mean flow is substantially different to the median flow), application of the Montana Method may result in allocations more generous than are required (Richardson 1986, cited *inter alia* in Tharme 1996).

The Montana Method has been criticised for offering an assessment of only low to moderate resolution, encompassing limited temporal differences in flow allocations (Stalnaker & Arnette 1976). In other words, only two 'seasonal' flows are possible, although there is the potential for modification to include provisions made in wet and dry years. However, the Montana method is generally for baseflows only and has little provision for recommending other ecologically important flows (eg. spates and floods).

Increased resolution may be built into a modified flow regime after examination of the historical flow record. Methodologies that use historical flow records are primarily focused on scrutiny of the flow duration curve and, for this reason, are frequently referred to as flow duration curve analysis methods (Tharme 1996). Swales et al. (1994) use the term "stream history analysis" method. The country of origin of methods that use historical analysis of the flow record was predominantly the United States and again, the main focus was on the maintenance of salmonid fisheries. Stalnaker and Arnette (1976) recommended that specific percentile flows be maintained in order to ensure sufficient water for specified ecological processes. The 80th exceedance percentile flow was recommended to ensure the maintenance of food production, the 40th percentile flow was recommended to maintain conditions necessary for salmonid spawning and migration, and the 17th percentile flow was recommended as a flushing flow. The choice of these levels of streamflow was based on empirical data concerning flow and salmonid habitat in the south-western United States.

The first step in this process is therefore the construction of monthly flow duration curves. According to which criterion is used (eg. spawning or maintenance), percentile values are then estimated for each month and a modified flow regime is constructed for the entire year.

Australian use of flow duration analysis in this sense (ie. construction of the modified flow based upon set cut levels in each month) has been limited (Richardson 1986; Hall 1989; Arthington et al. 1992a; Swales et al. 1994). A consistent criticism of this approach in these studies has been that, in addition to not accommodating high flow events, the method was developed in a region with a fundamentally different pattern of streamflow. Accordingly, several authors (Hall 1989; Arthington et al. 1992a; Swales et al. 1994) recommend that the 50th percentile flow rather than the 40th percentile be used. Arthington et al. (1992a) suggested that the 50th percentile flow for each month represented the ideal whereas the 20th percentile flow should be regarded as the lowest flow permissible in drought years. All flows into a storage facility that were less than or equal to the 20th percentile flow should be released downstream in very dry years.

An important advantage of such an approach is that incorporation of monthly percentile flows allows the maintenance of the natural temporal pattern of intra-annual variation, albeit the quantities are reduced. Furthermore, additional volumes may also be added to monthly allocations to achieve specific ecological purposes or to accommodate for downstream abstraction or diversion (Arthington et al. 1992a; Swales et al. 1994). In addition, such approaches allow for the formulation of rules associated with the actual delivery of environmental water. For example, Hall (1989) constructed a system of release rules for four Victorian rivers based on a comparison of the median flows with

flows necessary to maintain maximum habitat maintenance flow (see below for further discussion) wherein the recommended environmental allocation was equal to the maximum habitat maintenance flow if it was less than the median flow for a particular month. If the maximum habitat maintenance flow was greater than the median flow, then the recommended environmental flow was the median. During periods of drought, the environmental flow equalled the 80th percentile exceedance flow. The basis for this schedule of environmental flows was later strongly criticised by Gippel et al. (1992).

Arthington et al. (1992a) regarded the adoption of 20th, 50th and 80th percentile flows (drought, median and flood flows respectively) as defining the boundary conditions within an environmental flow allocation and, further, that the incorporation of variability within the monthly flow was needed. However, Arthington et al. (1992a) stressed that such a modified flow regime should be regarded as a first approximation or interim regime, and that further monitoring of its effects was necessary to refine the allocation and safeguard the environment.

Many of the criticisms levelled at the Montana Method also apply to slavish adoption of set cut-off points derived from flow duration curve analysis, such as those suggested by Stalnaker and Arnette (1976). Such criteria were developed for salmonid fishes in North American streams and may have little relevance for Australian systems. For example, Richardson (1986) noted that if 40th percentile flows were adopted as essential for fish reproduction, then such flows would need to be implemented throughout the year in the Tweed River as there were substantial inter-specific differences in the phenology of reproduction. Richardson (1986) also noted that the 40th percentile flow could be criticised as being excessive, based on a comparison with flows recommended by other methodologies. This problem of method transportability was discussed by Stalnaker and Arnette (1976), who suggested that the use of flow duration curve analysis is problematic unless the hydrological pattern of the stream in question is similar to that of the region for which it was developed. In the United States several methods have been devised, including the original procedure, which modify flow duration curve analysis to account for such differences in stream size and region (see Tharme 1996).

Flow duration curve analysis does seek to reintroduce some level of seasonality back into the modified flow regime and this is its greatest strength. A major disadvantage, however, is a questionable identification of exactly what flows are necessary to maintain certain aspects of the aquatic environment. At this stage of the development of ecological understanding of Australia's riverine ecosystems, it is unlikely that general agreement could be reached concerning percentile criteria necessary for ecological maintenance. In many cases, the necessary criteria would need to be developed anew for each separate area or river (Richardson 1986). In addition, flow duration curve analysis, as it stands, does not explicitly allow for a consideration of inter-annual variation of discharge.

A major assumption of flow duration curve analysis is that the most frequent conditions over a period of record are suitable for all life history stages without any examination of short-duration perturbations and species responses (Richardson 1986). Moreover, it also assumes that the prolonged imposition of a certain flow has the same ecological effect as a group of repeated but temporally discrete events of the same magnitude. There is little theoretical or empirical basis for these assumptions.

Overall, Tharme (1996) considered methodologies based on historical flow records to have substantial value in spite of the disadvantages described above. However, their major benefit was considered to be limited to the early reconnaissance phase of the allocation process and provided a way of 'block-booking' quantities of water which was rapid, simple and had only moderate data requirements.

4.2.2 Habitat discharge methodologies

Both the Montana Method (Tennant 1976) and flow duration curve analysis described by Stalnaker and Arnette (1976) are based on the premise that the amount and quality of habitat in a stream are related to the amount of water being transported down the stream channel. Rather than putting arbitrary limits on what is considered 'good' or 'excellent' maintenance of habitat based on proportions of the mean annual flow, habitat discharge methodologies seek to define the relationship between the discharge regime and the amount and type of habitat that is provided. Once this relationship is known, then a modified flow regime can be constructed

that maintains that habitat at either maximum suitability or at known and acceptable levels of habitat.

Tharme (1996) recognised two broad groups of habitat discharge methodologies: hydraulic rating methodologies and habitat rating methodologies. The former group is broadly classified by three main factors. First, it uses an intermediate level identification of the physical nature of the riverine environment as a surrogate for target biota. Second, it involves the use of simplified prediction techniques such as those based on stage discharge rating curves and Manning's equation (Loar et al. 1986, cited in Tharme 1996) to replace field survey needs. Third, it involves examination of site-specific aspects of the morphology of the stream channel. An implicit assumption of the method is that by ensuring some threshold value of a selected hydraulic parameter (such as wetted perimeter), the requirements of target taxa or ecosystem integrity will be met (Tharme 1996).

To the author's knowledge, no studies in Australia have completely relied on hydraulic rating methods to determine appropriate environmental flows. That is not to say that they have not been used. For example, Davies et al. (1996) estimated flow magnitude necessary to destabilise algal mats on unstable sand substrates in the North Dandalup River. However, this was not the only criterion used in the final assessment of the environmental flow needs of this river.

Habitat rating methodologies have been much more widely used in Australia and, to date, this is the most frequently used group of techniques. The degree of sophistication of habitat rating methodologies varies greatly from single transect studies designed to estimate changes in 'wetted perimeter' through to highly complex modelling procedures such as those found in the In-stream Flow Incremental Methodology (IFIM) developed by the United States Fish and Wildlife Service. These will be discussed separately below.

Both hydraulic and habitat rating methodologies are designed to assess the relationship between various conditions of physical habitat structure and discharge. The most simple, and historically most commonly used (Reiser et al. 1989), of the hydraulic rating approaches is the 'wetted perimeter or area' method. The wetted perimeter or area method has been used in Australia (eg. Tunbridge 1988; Tunbridge & Glenane 1988; Anderson & Morison 1989; Davies & Humphries 1995) but it must be emphasised that in these studies, this method was not the sole criterion upon which the environmental flow was ultimately based.

The wetted perimeter or area method usually involves the placement of a single transect per site at a location on the river most responsive to changes in flow. The relationship between wetted perimeter and discharge is then determined from measurements taken at several different stage heights. There are several important assumptions associated with use of the wetted perimeter or wetted area approach. First, it is assumed that single transects per site are adequate to describe the changes within that site that occur with changing discharge. Second, since those locations that are most responsive to changes in discharge are riffles, then the focus of the study tends to be on this habitat type. It is assumed, therefore, that consideration of one habitat type only is sufficient to fulfil the requirements of other biotopes or habitat types. In rivers of south-eastern Queensland, only about one-third, or less, of the fish species inhabit riffles and therefore a focus on this group could potentially be ignoring the majority of fish in these rivers (M. Kennard, pers. comm.). Third, the most important assumption is that stream area (or perimeter) is a surrogate for many other factors or processes that determine overall stream health or ecological integrity. When considered together, these inherent assumptions result in a highly simplified perception of the stream environment encompassed within a single variable.

The wetted perimeter or area method is based on a series of observations of changes in stream habitat structure with changing discharge and collectively grouped under the heading of wetted perimeter theory (Stalnaker & Arnette 1976). In this sense, it is similar to Tennant's (1976) proposal that there are general relationships between habitat quality and some aspect of the flow regime (in this case proportion of the mean annual flow). In wetted perimeter theory, there is an association between wetted perimeter and discharge, wherein wetted perimeter increases rapidly with increasing discharge, from a base level of zero flow and reaches an inflection point, whereafter increases in wetted perimeter occur much more slowly until bankfull stage is reached. This inflection point is taken to represent the optimal discharge. Tunbridge (1988), in a report on the environmental flow needs of freshwater rivers and lakes of south-western Victoria, found that such inflections in the relationship between flow and wetted perimeter were often absent or poorly defined, at best, and he arbitrarily defined the wetted perimeter occurring at the 20th percentile flow as that which is equivalent to 100% habitat suitability. Loss of wetted perimeter, given the plots presented in Tunbridge

(1988), would therefore only occur at flows less than the 20th percentile, that is, flows which historically were relatively infrequent. This gave a false impression that the maintenance of low, infrequently experienced, flows maintained a high amount of suitable habitat.

The wetted perimeter method was developed in North America and was strongly focused on salmonid fishes of recreational value and for which substantial information on habitat requirements was already known. Uncritical application to regions and species other than for which it was developed is not recommended.

Davies and Humphries (1995) used the wetted perimeter method in a novel and totally appropriate manner in an examination of the environmental flow needs of the Esk River, Tasmania. One of the target taxa in that investigation was the southern pygmy perch, and extensive biological study revealed that this species was restricted to and dependent on macrophyte beds found in pools. The wetted perimeter method was used to determine the flow needed to maintain inundation of macrophyte beds in the test reaches. Thus the maintenance of habitat conditions for pygmy perch was achieved by maintaining flow conditions for another taxonomic group, aquatic plants, upon which pygmy perch was critically dependent.

Multiple transect methods are an attempt to rectify the problems associated with a reliance on a single transect and a single variable such as wetted perimeter. This suite of methodologies is by far the most commonly used and abused in Australia to date. Multiple transect methods are an empirical means of determining changes in habitat with changing discharge. A series of transects is implemented within a stream and measurements of such variables as depth, velocity, substrate and cover are then made at intervals across the transect. Changes in these variables with discharge can then be determined. A map of the stream reach can be constructed from the data collected at all transects for each discharge, and the relationship between certain variables and discharge or between the proportion of the habitat within certain criteria can be ascertained. If the habitat requirements of a certain species of fish are known, then the change in suitability of an area at different discharges may also be determined.

In several Victorian studies the focus has been on identifying the optimal flow, that is, the flow which results in the maximum amount of a particular habitat for a fish species (Tunbridge 1988; Tunbridge & Glenane 1988). Flows which result in proportional reductions in available habitat can then be identified. Flows which maintained at least 90% of the optimum habitat were termed the optimum environmental flow, 70% maintenance was achieved by the minimum environmental flow and 50% maintenance was achieved by survival (short-term) flows. These criteria appear to be based on wetted perimeter theory, although this is not stated in either Tunbridge (1988) or Tunbridge and Glenane (1989) (Gippel et al. 1992).

Hall (1989) suggested that the imposition of environmental flow allowances on the basis of whether they maintained certain proportions of fish habitat (ie. 90% of all fish habitat) was scientifically indefensible for a number of reasons. Most importantly, Hall (1989) suggested that there were no data for Victorian streams which had established a quantitative relationship between habitat levels and fish numbers or biomass and that, moreover, if there were such a relationship, it would likely vary from river to river. Hall (1989) suggested that the only defensible position was the maintenance of the optimum available habitat.

Hall (1989) believed that habitat availability (or suitability – it is difficult to ascertain) was related to discharge in a 'dome shaped' manner wherein habitat increases with flow to a certain level and then decreases as increased velocities limit available habitat. From this, it followed that there is a natural optimum habitat availability for each species and that, if between-species compromises can be made, then a flow can be identified which leads to optimum fish habitat availability.

This approach has been used in assessments of the environmental flow requirements of several Victorian rivers (Tunbridge 1988; Tunbridge & Glenane 1988; Hall 1989, 1990, 1991). Four important fish habitat types are recognised in these studies: (i) rearing; (ii) resting; (iii) spawning; and (iv) passage.

Rearing habitat includes areas in which fish feed as well as those areas in which prey organisms are found. Hall (1989) argues that rearing habitat is the most critical habitat to be considered, although there seems little reason for maintaining rearing habitat if there is no suitable spawning habitat. Hall (1989) suggests that rearing habitat invariably encompasses the largest area and that reductions in size of the rearing area are likely to reduce the carrying capacity or the number of fishes a river could support. Research is needed to validate the assumption that fish abundance or biomass is indeed related to any proportion of rearing habitat, and to determine if fish populations are anywhere near the carrying capacity of their habitats. If this can be shown,

then information is needed to determine the mechanism (ie. competition?) by which reductions in habitat area result in changes in fish population density.

Resting habitat refers to those areas of a river in which fish seek refuge and includes such areas as deep pools with low water velocities, woody debris and macrophyte beds. Spawning habitat refers to habitat attributes such as certain depths, water velocities and substrates, plus conditions necessary to cue reproduction or initiate movement. Passage habitat refers to those conditions that either allow or prevent fish movement from one section of a river to another. The degree to which any one of these requirements takes precedence over the others is unknown, and the assumption that one can indeed take precedence may not be appropriate (Tharme 1996).

In the Victorian studies listed above, the various habitat requirements are based largely upon unpublished sources. Rarely were suggested requirements based upon data collected from the river in which they were subsequently being applied. It has been suggested that this has the potential to strongly bias the interpretation of changes in habitat availability with changes in discharge (Orth & Maughan 1982; Moyle & Balz 1985). Habitat use by fishes is influenced by many factors, including availability and the presence of predators and competitors. In some cases (eg. Hall 1989), the adoption of a suitable habitat criterion is clearly inappropriate, given that the source used originated from outside of Australia (ie. brown trout and redfin perch) and, in one case, was for a lake dwelling rather than a riverine population. Similarly, habitat criteria for two other native species, tupong and bass, were derived from literature reports of habitat use in populations many hundreds of miles to either the south or north respectively. It is impossible to judge the appropriateness of the habitat criteria for many of the remaining species as there are no supporting data (only listed as FFMB unpublished data). They do, however, appear to be relatively broad with respect to depth and especially substrates (species were often listed as requiring 'all types' of substrate) and narrow with respect to water velocity. No species was listed as requiring flows greater than 0.5 $m.sec^{-1}$ (ie. no obvious obligate riffle dwelling species).

Such habitat functions may be criticised at many levels, many of which will be dealt with below in a discussion of the IFIM. Foremost amongst these criticisms, however, is that in Victorian studies utilising the multiple transect method, the form in which habitat criteria are given is essentially dichotomous. Either the habitat is suitable if it fits within the defined limits for depth, velocity and substrate, or it is not. For example, if the velocity requirements of grayling are between 0 and 0.5 $m.sec^{-1}$, does this mean that a stream reach with a velocity of 0.49 $m.sec^{-1}$ is equivalent in terms of suitability to a reach with a velocity of 0.01 $m.sec^{-1}$? Similarly, is it appropriate to say that a mean flow of 0.51 $m.sec^{-1}$ is significantly different in suitability to 0.49 $m.sec^{-1}$?

The validity and/or transportability of the habitat criteria used in many Victorian in-stream flow studies has never been seriously questioned, even in the face of data which are clearly at odds with the predictions made concerning the amount of available habitat. For example, Tunbridge and Glenane (1988) estimated that at two sites on the Gellibrand River (Newling and McKenzie), flows were naturally high enough to result in the provision of no useable habitat suitable for blackfish (*Gadopsis marmoratus*) for substantial periods during winter. This is difficult to reconcile with the fact that these sites contained substantial populations of blackfish and the river in question is renowned for the size and abundance of it blackfish (Tunbridge & Glenane 1988). Moreover, comparison of the natural flow record with the flows required to produce 'optimum' habitat for blackfish reveals that such optimum flows are actually rarely experienced in the Gellibrand River. Flows recognised by transect analysis as resulting in the preservation of 70% of optimum habitat were even more infrequently experienced (less than 4% of the time over the period 1960–1981) whereas 'survival flows' (maintaining 50% of the optimum habitat) had never been experienced over the same 20-year period. Gippel et al. (1992) also noted that reliance on the maintenance of some identified percentage of 'optimum habitat' at a series of river reaches could result in the situation where it is impossible to simultaneously accommodate each reach because of spatially varying 'optimum' discharges (ie. a site located downstream of another requiring less water in order to maintain optimum habitat). Poorly developed species-specific habitat requirements will only increase the potential for errors of this type.

Gippel et al. (1992) were highly critical of the multiple transect approach employed by Hall (1989, 1990, 1991), Hall and Harrington (1991) and Tunbridge (1980), noting that in all of these studies, measured velocities were not the mean velocity but rather the velocity recorded at 0.1 X depth from the

stream bottom. Tunbridge (pers. comm. to Gippel et al. 1992*)* suggested that this was where most fish were located. However, near-bed flows are usually considerably lower than average flows (Gordon et al. 1992) and therefore flows measured at one-tenth of the depth from the bed are an unreliable estimate of the flow conditions elsewhere. Gippel et al. (1992) noted that one of the assumptions in multiple transect analyses is that water velocity (particularly that at 0.1 X depth) rises proportionally with increasing stage height, and also noted that this was unlikely to be so. Gore and Nestler (1988) suggest that the multiple transect method is prone to error because of the assumed proportional change in some habitat variables with increasing stage height. In addition, Tharme (1996) warns that the distance between transects and the total number of transects for each stream reach is critical in determining the reliability of estimated changes in habitat structure.

The assumption that conditions between each transect conform to the predicted changes becomes ever more tenuous with increasing distance between transects. The interval between adjacent transects is only rarely stated in many Australian in-stream flow studies (ie. between 11 and 16 m in Tunbridge & Glenane 1988), but it can be inferred from data presented concerning the length of study reaches and the number of transects that interval size is rarely less than 10 m. It thus seems that Tharme's (1996) concerns about the reliability of inferred changes in habitat are particularly appropriate with respect to Australian studies. In addition, the criteria for determining placement of transects are rarely stated and this can be problematic (Hankins & Reeves 1988). Furthermore, the presence of in-stream structures such as woody debris or macrophyte beds can greatly modify the behaviour of moving water and such structures are poorly accommodated in multiple transect analyses.

Of significant importance in determining the reliability of the multiple transect methodology is the number of different occasions upon which the relationship between habitat and discharge is based. The number of separate measurements of habitat at different discharges in Australian studies that employ this method are generally small and rarely exceeds five (Tunbridge 1980, 1988; Tunbridge & Glenane 1988; Hall 1989, 1990, 1991; Swales et al. 1994). In fact, very few exceed three and a significant number are based on measurements taken on only two occasions (eg. 9 of 26 assessments in Hall (1989) are based on only 2 different flows.). Some studies do not list the number of discharges (Swales et al. 1994) although in some cases the number can be inferred from the text. The use of so few points upon which to base such an important relationship as that between habitat and flow lends great scope for creative inter- and extra-polation. For example, in a study of the flow requirements of the Aire River, Victoria, Tunbridge (1988) measured habitat at one station at flows of 36 and 43 MLd^{-1}, yet extrapolated the findings over the range of 0-500 MLd^{-1}. In another, habitat was measured at flows of 97 and 146 MLd^{-1}, yet changes in habitat were extrapolated over this same range. Even more surprising is that the author can detect peaks in habitat availability for different taxa at different flows from these meagre data! This was a common approach in many Victorian studies (Hall 1988, 1990, 1991).

In none of the studies that employed the multiple transect approach reviewed here was there any indication of an attempt to statistically fit a curve or a straight line to the observed relationship or even determine whether there was a significant relationship between habitat and discharge. In all cases, the curves are drawn by eye and assumed to be completely free from error. The author's criticism of the methods employed in Victoria may appear to be overly vigorous, however, it is important to remember that the curves developed in these studies formed the basis from which the resultant environmental flows were derived. It is highly unlikely that such important conclusions based on such meagre data would ever be allowed in any peer-reviewed literature, but appear to be 'suitable' for the grey literature. This is an illogical circumstance given that decisions of considerable economic, social and environmental importance are being based on these conclusions.

Both Richardson (1986) and Swales et al. (1994) note that the multiple transect method tends to be conservative and result in recommendations that appear "over generous". Moreover, there is nothing inherent within the method that ensures it deals appropriately with temporal variability in flow and habitat structure. Thus the situation may arise where recommended flows, based on some arbitrary proportion of an arguably arbitrary 'optimal' habitat, may have rarely, if ever, occurred (see above).

4.2.3 Habitat modelling methodologies

4.2.3.1 The In-stream Flow Incremental Methodology

The IFIM can be thought of as a sophisticated, computer-driven version of the multiple transect method described above. In reality, it is much more than that; Bovee (1982), describes it as a thought process. Tharme (1996) considered it to be sophisticated and scientifically and legally defensible but also listed many areas of concern. The IFIM was developed in North America and was originally concerned primarily with salmonid species in snow-melt streams (Bovee & Milhous 1978; Bovee 1982) but has since been implemented in many other regions and many other types of streams (Tharme 1996).

Two versions of the IFIM have been used in Australia, differing only in the computer models used, PHABSIM II (Milhous et al. 1989) or RHYHABSIM (Jowett 1989), but not in overall philosophy and intent. Davies and Humphries (1995) stress that RHYHABSIM does not constitute a significant departure from the IFIM approach, rather the use of an alternative program for performing the same modelling procedure within a more straight-forward, standardised and better supported framework. Gan and McMahon (1990a) have compared PHABSIM II and RHYHABSIM and note that the latter is more limited in its application as it does not contain anywhere near the number of programs or options as in PHABSIM II, and has some hydraulic modelling limitations, but is overall a more user-friendly package. Much has been made of the user-unfriendly nature of the PHABSIM II package and the opaqueness of its supporting literature, and King and Tharme (1994) provide an instructive, even cautionary, account of its application in South Africa.

The IFIM consists of a set of analytical procedures and computer methods (including the component PHABSIM II, which many think *is* the IFIM) which seek to evaluate the effects of incremental changes in streamflow on channel structure, water quality, temperature and availability of suitable microhabitat using a combination of hydraulic, hydrological and biological data.

There are several steps in the IFIM process. The identification of study objectives, river study reaches and target species is the first step (Tharme 1996). Such a first step is not limited solely to this methodology but should be included in any study of the environmental flow needs of any river. Study objectives can, however, be highly constrained if the available biological information is limited or poor (Richardson 1986; Gan & McMahon 1990a). Tharme (1996) recommends that species from a wide array of trophic levels be included so as to improve the generality of the predictions made by the IFIM. It should be emphasised that no single flow recommendation will be possible in species-rich assemblages and therefore compromises will be necessary. It is important to note that habitat requirements differ between species and that manipulating the flow regime to suit one species may be to the detriment of another. Further discussion of target taxa is given below.

The second critical step in the IFIM process is determining whether the catchment is in equilibrium and whether macrohabitat conditions are suitable. The former concern has attracted much criticism (Richardson 1986; Bleed 1987; King & Tharme 1994; Tharme 1996). In essence, there is little point in modelling changes to in-stream habitat if the stream channel changes shape subsequent to flow regulation. King and Tharme (1994) state that while the concept of catchment equilibrium is sound in theory, it is difficult to apply. Tharme (1996) suggests that the assumption of channel stability may limit the applicability of the IFIM in many countries. The suitability of macrohabitat conditions is of critical concern also. If study sites are of an inappropriate macrohabitat type or located in regions of the catchment such that target species are unlikely to occur there, then it is unnecessary to proceed further with the more expensive and intensive modelling stage. A good example of this situation is reaches located above barriers to fish movement. Despite the critical nature of these 'pre simulation' concerns, most criticisms of the IFIM have ignored them and focused on the modelling process.

As with the multiple transect method, the location of study sites is critical in determining the outcome and utility of the IFIM procedure. It is assumed that the reference sites have substantial similarity to other parts of the river and that discharge-related changes in habitat that occur in the reference site may be extrapolated elsewhere in the catchment with confidence. Another similarity to the multiple transect method is that study sites are usually chosen on the basis of whether the habitat structure is likely to be responsive to changes in discharge. For this reason, most sites included in IFIM studies are riffles or runs (King & Tharme 1994; Tharme 1996). This may be appropriate if riffle

dwelling species are the major focus or target but is unlikely to be the case when riffles do not normally contain the target taxa. This focus on riffle/run habitat underscores the absolute necessity of preliminary studies to ascertain macrohabitat conditions within the study river. For example, if an inventory of habitat types within a study river revealed that riffle habitats were, in fact, only a minor and spatially restricted component in the overall distribution of habitat types, then there would be very little point in proceeding with an IFIM assessment based only on riffles. Moreover, if obligate riffle-dwelling fish species contribute only a small proportion of the total assemblage, which seems probable for most Australian streams (personal observations), then undue focus on this component of the biota may lead to flow recommendations detrimental to other species.

The procedure used in the IFIM to simulate changes in microhabitat conditions with changing discharge is contained within the module known as PHABSIM II (Physical Habitat Simulation), which consists of 240 separate programs covering depth, velocity, substrate and cover. Simulations are usually based upon transect data collected on one occasion (ie. one discharge) and a series of measurement relating discharge to river stage height. Thus transect placement, transect number and the accuracy of measurements have great potential to influence subsequent habitat simulation. King and Tharme (1994) recommend that an experienced hydraulics expert be involved in the initial phase of habitat quantification in order to advise on the placement of transects. Importantly, this potential problem is not overcome simply by increasing the number of transects used as this can interfere with the efficiency of the simulation procedure (Bovee & Milhous 1978).

Simulating the changes in suitability of a river reach for a particular species involves two separate procedures. The first is known as hydraulic simulation and the second is known as habitat simulation. In the hydraulic simulation phase, the stream reach is divided up into a series of cells defined by the number of measurements taken in the initial survey process. Well-defined hydraulic relationships such as between stream slope, bed roughness and water velocity and depth are then applied to simulate the changes that occur within the stream channel at different discharge points. Two assumptions are critical in this process. First, it is assumed that conditions measured at one point extend both laterally and longitudinally to the field of coverage of the next point of measurement; and second, that mean water velocities in individual cells change in the same way as do mean velocities for a cross-section. Tharme (1996) suggests that this first assumption may rarely be valid and that the potential error increases with cell size. Other studies have revealed this latter assumption to be particularly questionable and errors of up to 60% have been recorded (Bovee et al. 1978; see references in Scott & Shirvell 1987). Tharme (1996) suggests that there are no standardised criteria for defining cell size and that a lack of structured guidance in the IFIM procedure increases the potential for error in its application.

Other criticisms of the IFIM process relate to the actual hydraulic simulation phase and include concerns about the validity of the assumption that Manning's n remains constant at different discharge levels, the degree of precision at boundary layers and the assumption that channel shape does not change with increasing discharge (Shirvell 1986; King & Tharme 1994; Tharme 1996). In addition, the hydraulic simulation does not perform well in non-standard situations such as rapid expansions or contractions in channel width or the presence of secondary channels (ie. parallel anabranches) (King & Tharme 1994). Nonetheless, Gore et al. (1989) believed that application of the IFIM was rarely limited by concerns about the hydraulic simulation phase. Gan and McMahon (1990) provide examples to indicate that this may not be true but stress that good reliability (90%) can only be obtained with very accurate survey data and calibration.

Concerns about whether the programs contained within PHABSIM II accurately predict discharge-related changes in habitat structure in terms of water depth, velocity and substrate are relatively immaterial if these factors are not the most important microhabitat variables influencing the distribution and abundance of fish species. Petty and Grossman (1996) report that although mottled sculpin abundance and distribution appeared to be related to depth, velocity and substrate characteristics at the stream reach level, sculpin distribution and abundance were more closely related to, and presumably determined by, invertebrate distribution and abundance at finer scales (ie. the level of the patch). Modelling sculpin distribution and abundance would therefore be better achieved by modelling the distribution and abundance of its prey. Unfortunately, hydraulic parameters of importance to invertebrates are difficult to model (Orth 1987; Statzner et al. 1988) but attempts are being made to incorporate some factors

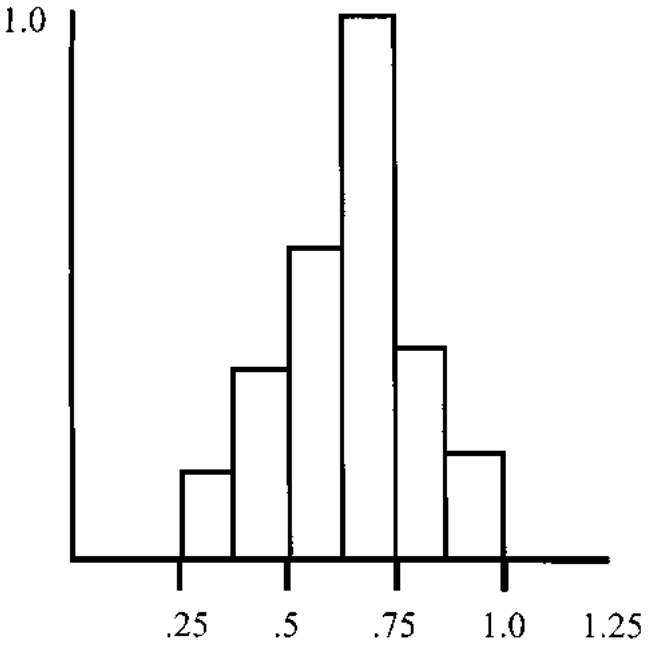
such as shear stress into the PHABSIM II module (Tharme 1996).

Pusey et al. (1993) stressed that unless hydraulic/habitat simulation techniques can be expanded to include such complex structures as woody debris, macrophyte beds and leaf litter, their full utility will not be realised. Such in-stream features are not only important substrates for microorganisms and macroinvertebrates and important sites of primary production (Thorpe & Delong 1994), but may also serve as food and ultimately determine in-stream secondary production. Leaf litter is especially important in this regard as it may have a fundamentally important role in the delivery of organic carbon to downstream food webs (Vannote et al. 1980). If in-stream flow assessments do not take into account such factors as the accumulation and processing of organic carbon in the aquatic ecosystem, and how this is related to discharge, then it is unlikely that predicted changes in habitat and suitability for individual fish species are of significance. For example, Davies et al. (1996) considered that the most important issue in an assessment of environmental flows for the North Dandalup River, Western Australia, was the maintenance of highly productive, stable algal mats over the unstable sand substrate. Similarly, the maintenance of water depths sufficient to inundate productive algal mats occurring in the shallow margins of the turbid Cooper Creek was considered the most important environmental flow issue in this system (S.E. Bunn, pers. comm.). In both cases, the algal mats were the basis of the food webs in these systems. Their maintenance therefore must take precedence over any perceived change in the suitability of fish habitat.

The most heavily criticised component of the IFIM process is the habitat simulation phase. In this phase, changes in physical habitat structure predicted by the hydraulic simulation phase are assessed to determine if they result in changes in the 'suitability' of the stream reach for a particular species. In order for this to occur, however, the habitat requirements of individual species must be known relatively precisely. The habitat simulation phase essentially combines the information derived from the hydraulic simulation phase with data on the preferred physical microhabitat of the target taxa to assess how much of the preferred microhabitat is available at different discharges (King & Tharme 1994). Thus the accuracy and quality of the data incorporated into habitat curves has an enormous potential to influence the outcome of the process.

Biological information on the habitat requirements of target taxa is summarised in a series of curves. For example, the velocity suitability function may be as depicted in Figure 3. In this case, it is indicated that flows below 0.25 m sec^{-1} are not suitable for this species, nor are flows above 1 m sec^{-1}. Curves with a narrow range theoretically indicate well-developed preferences for a particular range of conditions whereas broad curves indicate little preference. King and Tharme (1994) caution that there is a great deal of confusion concerning precisely what these curves depict or represent: preference or utilisation. It should be emphasised that utilisation and preference curves are distinctly different. King and Tharme (1994) suggest that, within the literature produced by the developers of the IFIM, the term "suitability" is most frequently used, although it may be associated with additional terms such as curves, functions, indices or criteria. In Australian studies, the terms "probability of use" (Richardson 1986) or "habitat preference" (Arthington et al. 1992a) have been used.

Figure 3: *Velocity suitability curve for a hypothetical species*



Bovee and Milhous (1978) recognised three different categories of microhabitat suitability criteria. Category I criteria are derived from information in the literature or from professional experience and are considered the least valuable. This was the method used to derive the habitat suitability curves used in Arthington et al. (1992a). The

curves used in this study were based on responses to a questionnaire mailed to over 50 aquatic ecologists and fisheries experts. A weighting function was applied to the data to take into account the number of sampling occasions and locations the individual response was based upon. Responses based on 1 sample occasion from 1 location were accorded a weight of 1 whereas responses based on more than 10 sampling occasions and 5 to 10 sampling locations or 1 occasion over more than 10 locations were given a weighting of 5. The responses were then amalgamated, averaged and modalised (or normalised as in Jowett 1989; Davies & Humphries 1995).

Category II criteria are based on empirical data of the microhabitat conditions utilised by the target species; they are thus termed 'utilisation' functions. Category III criteria take into account that the utilisation of particular microhabitat conditions may be constrained by the availability of alternative conditions. Thus the utilisation functions are then scaled to reflect the availability of the microhabitats and termed 'preference' functions. Habitat criteria for adult brown trout used in Davies and Humphries (1995) were generated in this fashion. Bovee (1986) recommended that Category III criteria be used in IFIM studies but lesser categories were acceptable when higher category criteria were unobtainable.

Habitat use is influenced by factors other than habitat availability including the presence of competitors and predators (Koehn et al. 1994). Therefore preference curves should be developed from data gathered in the same system for which the IFIM is intended to be applied (Moyle & Baltz 1985). In addition, observations should be collected over a reasonably long period of time to take into account temporal and ontogenetic changes in microhabitat use. Grossman et al. (1995) recommend long periods of record upon which to base microhabitat preferences as temporal changes in habitat structure are common. Antecedent flow conditions need to be considered also when constructing preference curves. Highly flexible patterns of microhabitat use necessitate that management decisions be based on data covering a range of environmental conditions (Grossman & Ratajczak 1998).

Gore and Nestler (1988) consider the use of accurate and appropriate suitability indices to be the most important constraint to the valid use of the IFIM. Without accurate curves or indices, no matter the level of sophistication and predictive power of the hydraulic simulations, there is no way in which to assess changes in habitat suitability for target taxa.

Assessment of changes in habitat suitability in the IFIM is achieved by examining discharge-related changes in weighted usable area. Weighted usable area is most often taken to represent a measure of the amount of habitat within the study reach that is suitable for use by a target taxon, and is derived by application of the depth, velocity and substrate preference indices to the simulated conditions at each discharge. For example, Gan and McMahon (1990a) list an example wherein a 10 m^2 cell of stream bed had simulated depth, velocity and substrate conditions corresponding to depth, velocity and substrate preference indices of 0.9, 0.85 and 1.0 respectively. Thus this cell had an overall suitability of 0.9 X 0.85 X 1.0 = 0.765 and therefore 7.65 m^2 of that cell could be considered suitable. The outputs of both PHABSIM II and RHYHABSIM are in the form of area, either as an absolute amount or expressed as a percentage of the total amount of habitat available. King and Tharme (1994) suggest an alternative interpretation that all of the 10 m^2 cell is 76.5% suitable, and further suggest that this is the logical interpretation given that the area of the cell does not change with discharge but rather its suitability changes. They suggest this is ecologically more relevant.

Important and frequent criticisms of the IFIM approach concern the manner in which habitat suitability or weighted usable area is estimated and interpreted. Note from the above example that habitat preferences for depth, velocity or substrate are essentially treated as independent of one another. Thus habitat preference curves are used as if they are probability functions and the underlying assumption is that organisms assess the suitability of a habitat with respect to each dimension independently of other dimensions (Gore & Judy 1981; Orth & Maughan 1982; Shirvell & Dungey 1983; Mathur et al. 1985). The development of new habitat suitability functions which do not treat depth and velocity preferences as independent functions has occurred (Bovee 1986; Gore & Nestler 1988) but these new criteria do not yet appear to have been incorporated into the IFIM procedure.

Further criticism of the weighted usable area concept has focused on whether large areas of sub-optimal habitat are equivalent to smaller areas of optimal habitat. In addition, if a reach is determined to lack suitable habitat (ie. has low weighted usable area), then it is assumed that the target species will be absent. This assumption is again based on the notion of habitat

preference curves being equivalent to probability of occurrence. Scott and Shirvel (1987) list studies which have shown this assumption to be invalid.

By far the greatest concern with the IFIM process concerns the relationship between weighted usable area and fish biomass or abundance (Gore & Nestler 1988). In the early years of development of the IFIM, weighted usable area and biomass were treated as positively linked (Bovee & Milhous 1978). Scott and Shirvell (1987) tabled the results of 444 analyses of the relationship between weighted usable area and biomass and found that few revealed any positive relationship. In fact, some significant negative relationships were reported. Scott and Shirvell (1987) suggested that the failure to demonstrate a positive relationship between weighted usable area may have arisen because of the problem of non-independent habitat preferences and a failure to reconcile the differences between large areas of sub-optimal habitat and small areas of optimal habitat. Orth (1987) suggested many commercially important species may be regulated by exploitation rather than by habitat availability, but it is perhaps significant that most of the positive relationships between weighted usable area and biomass reported by Scott and Shirvell (1987) were for brown trout. The biomass of this species, at least, does seem to be regulated by velocity, depth and substrate.

The critical assumption inherent in acceptance of a relationship between weighted usable area and biomass or abundance is that populations are regulated by the availability of suitable habitat. Some authors (Jowett 1982; Orth 1987) suggest that weighted usable area may not determine fish biomass or abundance but may set the limits to local population size. This is likely to occur only when stream habitat and fish communities are in equilibrium and fish are utilising their habitat optima (Gorman & Karr 1978). Scott and Shirvell (1987) point out that the strongest positive relationships detected in their study occurred in those systems where biomass was maintained at the system's carrying capacity and the relationship appeared to be strongest when space was limiting and the populations were dominated by older age classes. However, other factors may also come into play when fishes are at or near carrying capacity (ie. predation, competition, disease), which may exert influence on habitat use.

Much has been made of the variability of stream flow in Australia, and Pusey and Arthington (1991) suggested that the assumption that habitat is the limiting resource may not be valid for many populations of Australian freshwater fishes. It is clear, however, that aspects of physical habitat structure are in some instances correlated with fish assemblage structure (Pusey et al. 1993, 1995; Pusey & Kennard 1996) but the extent to which they are causally linked remains unknown. Sheldon and Meffe (1995) revealed, by path analysis, strong correlative links between stream-related variables such as depth and velocity, and fish abundance and biomass in streams of the south-east United States. In a similar analysis for stream fishes of the Wet Tropics region (which has very predictable streamflows), average water velocity and depth are very poor predictors of fish abundance and biomass, individually accounting for less than 20% of the observed variance (Pusey, unpublished data). Poff and Ward (1989) analysed streamflow records for much of continental North America and suggested that the processes that structure aquatic assemblages will vary depending on aspects of the prevailing flow regime. Grossman et al. (1998) found that resource limitation does not play a strong role in the maintenance of fish assemblage structure in streams with variable streamflow. In such streams, habitat and trophic generalism tend to predominate (Poff & Allen 1995). Pusey et al. (1993) suggested that the distributions of many fish species of northern Australia may, in part, be related to pronounced habitat generalism. Variable and unpredictable habitat structure in streams with variable flow regimes may favour generalist species.

Environmental flow assessments which rely heavily on methods focused on maintaining certain amounts of habitat may not be appropriate in many Australian river systems unless particular microhabitat types are demonstrably important (eg. macrophytes beds in the Esk River as reported by Davies and Humphries (1995)).

Research focused on examining the influence of discharge variability on such functional characteristics of fish assemblages as trophic and habitat specialisation is warranted in Australia, with a focus on historical and phylogenetic constraints on the development of resource specialism.

Other aspects of Australian fluvial systems may reduce the potential for application of the IFIM in this country. Although the methodology has been applied in a variety of climatological and landscape settings (Tharme 1996), it was originally developed for small simple coldwater streams with a snow-melt hydrology. Gan and McMahon (1990b) indicated that its applicability in ephemeral streams may be limited. In addition, the simulation models were found to perform poorly at low flows. Fluvial systems which are

characterised by long periods of no or low flow (ie. many Australian river systems) may therefore not be appropriate systems in which to apply the IFIM. Moreover, flood flows tend to be turbulent rather than gradually varying, thus making them difficult to model hydraulically. Rapid scour and deposition during floods and changing levels of channel hydraulic roughness due to varying amounts of suspended material may also decrease the ability of the model to simulate changes in habitat at high flows in a meaningful way.

Many applications of the IFIM rely on the identification of critical points in the discharge–weighted usable area relationship. These are most frequently described as inflection points at which the rate of change in weighted usable area with changing discharge changes abruptly. A hypothetical example is given in Figure 4 (see below) and in this case the critical discharge for species A occurs at 2 ML sec^{-1}. Below this value the predicted amount of habitat declines rapidly, whereas above it there is little change in the amount of habitat occurring at greater discharges. This point of inflection is therefore the critical value for species A. Presumably, if habitat availability is important for the continued persistence of species A, then a modified flow regime would have to include flows equal to or greater than the critical flow.

Problems may arise, however, when more than one species is considered and identified inflection points differ considerably. For example, species B in Figure 4 has a weighted usable area–discharge curve for which the critical value or inflection point occurs at a much higher discharge compared to species A. Species C, in contrast, shows no such inflection point. Given such circumstances, and where all target species are considered equally important, there arises the problem of dealing with multiple and potentially competing demands. The problem of the identification and treatment of fish assemblage needs (rather than species' needs) is not treated in any of the supporting literature associated with the IFIM process (King & Tharme 1994).

This problem was encountered in a study of the environmental flow needs of fish in Barker-Barambah Creek, Queensland, wherein several different responses to changing habitat were identified (Arthington et al. 1992a). It was not possible in this study to identify a single discharge value above which the habitat of all species was maintained at or near optimum. To accommodate these differences, Arthington et al. (1992a) recommended a band of flows rather than a single flow. The inflection point for changes in suitable habitat for 'food producing area' (analogous to rearing habitat included in the multiple transect methods discussed above) was also contained in this band of flow. Arthington et al. (1992a) reasoned that maintenance of food production was probably more important than minor deviations away from optimal habitat for individual species. Davies and Humphries (1995) also recognised this problem but dealt with it in a novel and more structured manner involving a final component of risk analysis (see Table 5, page 80).

Figure 4: *Changes in weighted usable area with discharge for three hypothetical species (A, B & C)*
(Asterisks indicate inflection points or critical discharge values.)

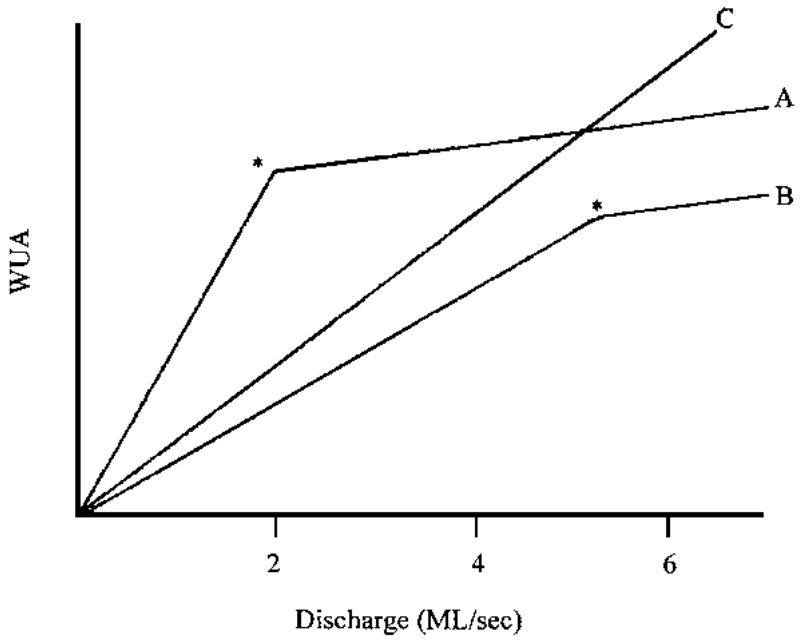


Table 5: *Criteria for assigning risk levels for different values of changes in habitat (ΔHA) relative to the reference flow (Q_{mp}) for key ecological variables*

Risk category Variables	I No risk or beneficial	II Moderate Risk	III High Risk	IV Very high Risk
ΔHA for stream bed, mussels, invertebrate species-richness and abundance, trout and blackfish	>85%	60–85%	30–60%	<30%
ΔHA for macrophyte beds and snag piles	<25% sites with <75% wetted area cf Q_{mp}	≥25% sites with <75% wetted area cf Q_{mp}	≥50% sites with 75% wetted area & 25% sites with <50% wetted area cf Q_{mp}	≥25% with <25% wetted area cf Q_{mp}
ΔHA for individual invertebrate taxa	<10% of taxa with <75% WUA cf Q_{mp}	≥10% of taxa with <75% WUA cf Q_{mp}	≥25% of taxa with <75% WUA & ≥10% of taxa with <50% WUA cf Q_{mp}	≥50% of taxa with <25% WUA cf Q_{mp}

Source: Davies & Humphries (1995).
Note: Q_{mp} = the median flow prior to irrigation phase.

From this table it can be seen that various levels of risk can be assigned to different flow levels on the basis of the amount of habitat loss that occurs for a proportion of all target taxa.

The problem of maintenance of differing levels of habitat maintenance at the same discharge is a critical one. If the objective of an environmental flow assessment is to maintain species diversity, as was one of the objectives of Arthington et al. (1992a), then conceivably one flow may favour one species to the detriment of another. Prewitt and Carlson (1980) compared the environmental flows recommended by four different methods, including the IFIM, and found that three of the methods resulted in recommended flows that conferred a competitive advantage of one species over another. The IFIM simulation of habitat revealed that the recommended flow provided optimum habitat for one species but critically low habitat for the other. This example suggests that the habitat simulation process provided by the IFIM is a valuable exercise for assessing assemblage level changes due to flow modification, even if it is not the sole basis for defining environmental flows.

Difficulties other than the problem of reconciling individual species' needs were identified by Arthington et al. (1992a). In their study of the flow needs of Barker-Barambah Creek, several species did not show a relationship between weighted usable area and discharge that contained an inflection point or which became asymptotic at higher discharges. This raises the problem of how to identify the optimum habitat for such species. At least 7 of the putative 14 riffle or run dwelling species considered by Arthington et al. (1992a) showed a response wherein weighted usable area increased with increasing discharge and showed no sign of becoming asymptotic over the range of flows simulated.

The IFIM package does contain a procedure that incorporates historical flow data into the assessment of discharge–weighted usable area changes, but it appears to have been used rarely (Tharme 1996). In essence, this procedure can produce a 'habitat duration curve'. From this, different habitat levels (ie. that which occurs for greater than 20% of the time) may be determined and used as criteria for species for which the relationship between weighted usable area and discharge is positive and linear.

Second, some species show different responses in different so-called representative reaches and the difficulty arises of identifying critical discharges. This

problem is not unique to the IFIM and was identified by Gippel et al. (1992) as being problematic in many of the environmental flow studies that have been undertaken in Victoria using the multiple transect method.

Third, some species may show different responses of weighted usable area to flow for different life history stages. If juveniles and adults co-occur, and do so for extensive periods of time, then the difficulty arises as to which life history stage is to be favoured. This was especially evident in the Barker-Barambah Creek study of Arthington et al. (1992a) for juveniles and adults of the long finned eel *(Anguilla reinhardtii)*. Juveniles showed a dome-shaped relationship of weighted usable area with discharge peaking at a flow of 0.6 m^3sec^{-1} over the three sites examined, whereas the relationship for adult eels was a strong positive and linear response which showed no evidence of becoming asymptotic over the range of flows simulated. The dilemma here is whether to maintain flows which maximise recruitment of juveniles but which are sub-optimal for adults, or whether to favour adults.

Finally, some species included in the simulations of Arthington et al. (1992a) showed no response of weighted usable area to changing discharge. These species, which included species of recreational importance (golden perch and silver perch), and a species of considerable conservation significance (the Queensland lungfish), were not likely to occur in the types of habitats included in the simulations. These species were more typical of deep pool habitats with slowly moving currents. These habitats are not well accommodated by the PHABSIM II or the RHYHABSIM models. Thus two of the study objectives of Arthington et al. (1992a), the maintenance of rare species (lungfish) and the maintenance of freshwater angling species (silver and golden perch), could not be addressed properly by use of the IFIM.

The IFIM is a potentially powerful tool for the examination of flows necessary to enable fish passage, providing critical river reaches can be identified. No assumptions concerning weighted usable area and biomass or abundance are necessary and there should be little confusion as to whether suitability indices represent suitability, preference or probability of use, as the functions would presumably be defined by laboratory experiments and be based on actual measurements of the ability to negotiate certain depths and velocities.

Richardson (1986) used PHABSIM to model changes in suitability of critical reaches of the Tweed River for passage by Australian bass. Suitability criteria were determined empirically in the laboratory for juvenile and adult bass and used in simulations for five apparently different critical reaches. A predetermined lower limit of 25% of habitat area being suitable for passage was set prior to simulation. Richardson (1986) found that passage for juvenile bass was limited by high water velocities at discharges greater than 37 MLd^{-1}, whereas adult bass were limited by insufficient depth at flows less than 120 MLd^{-1}. The IFIM was also applied to an examination of fish passage by Arthington et al. (1992a). The study area consisted of a large shallow riffle and causeway located near the junction of Barker-Barambah Creek and the Burnett River. Fish assemblages in Barker-Barambah Creek were found to differ substantially up and downstream of this putative barrier. RHYHABSIM simulations indicated that passage across the causeway was likely to be limited over the entire range of simulated flows because water depth remained below minimum passage limits gleaned from the literature for a range of species.

4.2.4 Expert Panel, Scientific Panel and Holistic Approaches

The many drawbacks associated with the methods described above (eg. expense, transferability, defensibility and ecological relevance) have stimulated the development of alternative approaches to the formulation of environmental flow guidelines. Foremost amongst these are the Expert Panel Assessment Method developed by New South Wales Fisheries and formally described by Swales and Harris (1995), the Scientific Panel Assessment Method described by Thoms et al. (1996) and developed for an assessment of the Barwon-Darling River, the Building Block Methodology developed in South Africa and described in King and Tharme (1994) and the Holistic Approach, developed as a result of a meeting of South African and Australia scientists and first described in Arthington et al. (1992b). Tharme (1996) referred to these methods as alternative or holistic methodologies.

4.2.4.1 The Expert Panel Assessment Method

Swales and Harris (1995) stress that a reliable method for assessing environmental flow needs should be: (i) widely applicable, (ii) inexpensive and (iii) not require extensive field measurements. The Expert Panel Assessment Method was developed to meet these

perceived needs and comprised two expert panels each consisting of an expert on each of the fields of fish ecology, invertebrate ecology and geomorphology. In its original form, the Expert Panel Assessment Method was applied only in the situation where desired quantities of water were released from an upstream storage and the suitability or desirability of each flow in downstream reaches was assessed independently by each panel. The primary criterion upon which the suitability of each flow as an environmental flow was assessed related solely to its suitability for the survival and abundance of native fishes. Swales and Harris (1995) state that this restrictive view was based on the premise that fish are a good indicator of overall environmental quality. The criteria used to determine the suitability of an individual flow release related to fish survival and abundance, adult spawning requirements, fish passage, juvenile recruitment, feeding and growth.

In the most comprehensive account of the Expert Panel Assessment Method (Swales & Harris 1995), two panels were formed and asked to rank the suitability of four separate release volumes corresponding to 80, 50, 30 and 10 percentile flows. In this study, congruence between the recommendations of the two separate panels was assumed to represent a validation of the method. However, panel rankings of the various flows varied considerably and this has been downplayed considerably by the authors. Visual inspection of the resultant scores derived for 'non-seasonal' flows indicates that perhaps only two of the six comparisons can be considered as being remotely similar. Bishop (1996) applied a statistical test (the details of which are, unfortunately, not presented) to determine the degree of congruence between the scores derived from the individual panels and found that only 1 out of 18 of the comparisons (non-seasonal and seasonal comparison combined) showed a significant association at the $p<0.05$ level. Clearly, the two expert panels had differing expert opinions on the same flows.

Bishop (1996) further examined the recommendations provided by the Expert Panel Assessment Method reported in Swales and Harris (1995) and suggests that variation in panel scores may arise from variation in the specialist's knowledge base, from the subjective manner in which flows are scored, from the difficulty in assessing stream habitat from the stream bank and, lastly, from conflicts between the direct experience of each expert and supplied hydrological data. Bishop (1996) lists several other potential areas of concern with the Expert Panel Assessment Method, particularly with respect to its application in determining environmental flow needs of the Snowy River (Snowy River Expert Panel 1996).

Cooksey (1996) provided a critique of the Expert Panel Assessment Method from the perspective of behavioural psychology based on similarities between the methodology and other group techniques. One area of concern raised by Cooksey (1996) was the role of interpersonal dynamics in the assessment process and the potential for a single dominant personality to influence assessments made by other panel members. In addition, consensus in judgement may represent 'collective bias' rather than agreement upon fact. Group dynamics play a fundamentally important role in collective decision-making when anonymity is not guaranteed.

Cooksey (1996) also criticised the use of a rank-based system, particularly when the suitability of a set flow is determined 'on-site'. Such a system, especially when rankings are produced rapidly, tends to result in rankings which are derived intuitively rather than rationally. Intuitive assessments generally occur 'covertly' and their basis is difficult to publicly retrace. Abstract rating scales tend to reinforce this intuitive process. Interestingly, Bishop (1996) presents an example where expert experience and intuition were overridden by the provision of erroneous hydrological data. Other criticisms of the Expert Panel Assessment Method offered by Cooksey (1996) include the choice of experts, the value systems of the supposed experts and the mechanisms by which consensus is achieved.

Significant drawbacks of the Expert Panel Assessment Method as described in Swales and Harris (1995) are that it can be applied only in the situation where upstream storage facilities can control downstream discharges, and that there is little supporting information allowing subsequent examination of the resulting advice. Although Swales and Harris (1995) suggest that techniques for determining environmental flows need to be inexpensive and not require extensive field measurements, this latter point illustrates a significant drawback of the method. A review of the application of the Expert Panel Assessment Method in the Snowy River (CWPR 1996) frequently drew attention to this point. Nonetheless, many of the participants in the Centre for Water Policy Research review drew attention to its benefits, which include:

- direct communication of specialist knowledge from recognised experts;
- ensures incorporation of interdisciplinary judgements;

- relatively inexpensive and rapid; and
- provides direct links between scientists and managers.

The Scientific Panel Assessment Method of Thoms et al. (1996) is similar to the Expert Panel Assessment Method approach but differs considerably in some key aspects. Foremost among these differences is that the Scientific Panel Assessment Method, as applied in the Barwon-Darling River, is not a visual assessment of trial releases. Rather, it incorporates visual inspection of key sites with the collection and interpretation of field data and background information gathered from prior empirical studies and the theoretical literature. In essence, it is a more refined and transparent version of the Expert Panel Assessment Method.

The Scientific Panel Assessment Method study of the Barwon-Darling River is notable for a number of reasons. First, it had very well-defined objectives, which related not only to the provision of interim flow rules but also included assessment of why particular flows were necessary. (Not all of the studies reviewed in this work actually included an explicit statement of the desired objectives although this would seem to be an absolutely necessary first step.) Second, the Scientific Panel Assessment Method sought to recommend strategic future research relating to the flow needs of this river. Third, it recognised the existence of a very incomplete understanding of the relationships between ecosystem function and flow and, importantly, it recognised that even when viewed against this incomplete knowledge base, ecosystem–flow dependencies in the Barwon-Darling River may be atypical, given the high degree of flow variability within this river. Fourth, the study recognised that any interim flow guidelines must be acceptable to primary stakeholders and that the study must consider a variety of impacts. In this aspect, the Scientific Panel Assessment Method assessment of the Barwon-Darling attempted to take an holistic view in that it used key ecosystem–hydrology features and attempted to surmise flow–ecosystem interactions. In many respects the Barwon-Darling River study echoed the philosophical underpinning of the Holistic Approach espoused by Arthington et al. (1992b).

As a result of taking this holistic view, freshwater fishes do not feature as the primary target taxa in the Barwon-Darling River study (Thoms et al. 1996) but rather are considered as just another, albeit important, ecosystem component. Of primary concern in this study were ecosystem responses to three major system attributes: flow regime, flood hydrograph and physical structure. Thoms et al. (1996) note that in the past environmental flow studies have focused too narrowly on the provision of minimum flows and suggest that this is an inappropriate focus in dryland river systems, given their high degree of flow variability. Accordingly, they considered many aspects of the flow regime including, but not limited to, total discharge, floods of various return periods and magnitude, drought frequency, seasonality and many aspects of the flood hydrograph. Potential interactions between these various flow attributes and aspects of the resident fish populations such as breeding, migration, species distributions, gene flow, trophic responses and larval recruitment were all considered. Importantly, this study considered such fundamental aspects of ecosystem function as the movement of energy and carbon between the terrestrial and aquatic environment and the bases for the various food webs existing within the river and their relationship to flow. This represents a considerable advance on earlier work, which was much more narrowly focused on the maintenance of areas in which fish feed or which are suitable for the production of aquatic invertebrates upon which fish feed. Similarly, the study of Thoms et al. (1996) was also concerned with the role of flow events in maintaining habitat diversity within an extended spatial hierarchy (ie. macro, meso or reach, and micro-scales). Again, this represents a considerable advance on studies concerned with flow determinations made at a few perceived critical reaches.

This focus on the relationship between ecosystem processes and flow within an extended spatial and temporal hierarchy is a defining feature of holistic methodologies. Two other holistic methodologies have been applied in Australia to address environmental flow needs: the Building Block Methodology (King & Tharme 1994) and the Holistic Approach (Arthington et al. 1992b), although final documentation of their use has not yet occurred. A fuller account of their application will be presented elsewhere in this review, but a summary account will be included here in order for the reader to place them in context with other methods detailed above.

4.2.4.2 The Building Block Methodology

The Building Block Methodology (King & Tharme 1994) was developed in South Africa as a rapid technique for addressing the urgent environmental flow problems that existed at the time of its conception. There are three major assumptions underlying the methodology.

1. The riverine biota can cope with naturally occurring baseflow conditions but may be reliant on other higher flow conditions in order to fulfil important life history needs.
2. The identification and incorporation of these important flow characteristics will help to maintain the river's natural biota and processes.
3. Certain flows influence channel morphology more than others and their incorporation into a modified flow regime will aid maintenance of natural channel structure and the diversity of the physical biotopes within the river (King & Tharme 1994; Tharme 1996).

A key element of the Building Block Methodology is the development of a desired future state at the beginning of the process and it against this desired future state that all subsequent deliberations are made. The Building Block Methodology, is stated to be relatively rapid but does require the collection of substantial data on the integrity of the study river's catchments and riparian vegetation, geomorphology and hydraulic characteristics of key sites, compilation of historical and present-day flow records, compilation of ecological information pertaining to that river, and a statement on the river's economic, conservation and cultural significance. These data are then considered within a highly structured workshop wherein explicit recommendations are made by individual expert participants.

Tharme (1996) lists several advantages of the Building Block Methodology including its strong links to natural hydrology, simplicity, rapidity, structured approach, transparency of the process of arriving at recommendations, and holisticity. However, some disadvantages are also listed by Tharme (1996). Foremost amongst these is that the Building Block Methodology is highly reliant on the provision of good quality flow data (preferably daily flows) and the reliability of hydraulic data gathered for individual test sites. The methodology is also reliant on professional judgement and specialist experience. It must be said, however, that the rigorous and explicit nature of the workshop component of the Building Block Methodology tends to make obvious the processes and route by which a flow recommendation is ultimately reached. Some, if not all, of these criticisms could be levelled at most environmental flow methods and are not necessarily peculiar to this methodology.

The Building Block Methodology has been applied in the Logan River of south-eastern Queensland (Arthington & Long 1997; Arthington & Lloyd 1998) and is discussed elsewhere in this review.

Certain ecosystem components such as waterbirds, herpetofauna, semi-aquatic mammals and other wildlife are presently omitted from the Building Block Methodology process or are collectively grouped (eg. water quality and macroinvertebrates) (Tharme 1996). Besides the constraints of finance, time and expertise, there is little reason to exclude them from the Building Block Methodology. In fact, their inclusion is highly warranted given that the methodology is intended to be holistic in outlook.

4.2.4.3 The Holistic Approach

The Holistic Approach proposed by Arthington et al. (1992b) is just that, a philosophical approach to defining environmental flow needs. In essence, it satisfies Tharme's (1996) definition of a methodology as being a collection of methods, although it does not yet prescribe a rigorous set of well-defined methods. Growns and Kotlash (1994) considered the flexibility of the Holistic Approach to be one of its main advantages.

There are three major assumptions underlying the Holistic Approach (Arthington et al. 1992b).

1. Water belongs to the environment and therefore other users of that water can only be accommodated from that quantity not required by the river.
2. There is more water in riverine systems than is strictly needed for maintenance of the riverine ecosystem.
3. If the essential features of the natural flow regime can be identified and adequately incorporated into a modified flow regime, then the extant biota and functional integrity of the ecosystem should be maintained.

It is questionable whether the first assumption (that water belongs to the environment) is an assumption or an underlying premise. Though resolution of this question is essentially trivial, it remains as the most important and fundamental component of the Holistic Approach. It firmly sets as a starting point what the rights of the environment are in the dialectic process between scientists and resource managers. It could also be said that this premise also establishes the 'bottom line' beyond which any deviation can be said

to be likely to result in ecological damage and unsustainable development.

The primary feature of the Holistic Approach is the hydrological analysis of historical unregulated flow records for the river in question. These data are used to set boundary conditions for any modified flow regime. A proposed flow regime will only be ecologically acceptable if it does not contain flow events which are outside the historical pattern. For example, if a particular modified flow regime contains elements (sequences of days of set discharge) which have never occurred in the historical record, then that modified flow regime as it stands is ecologically unacceptable. In a recent application of the Holistic Approach in Australia, the interaction between flow and community metabolism received considerable attention (S.E. Bunn and P. Davies, pers. comm.) and will probably become an essential component of the approach as this process develops and technological advances ensure that measurements of community metabolism become more routinely and easily undertaken.

The Holistic Approach has many aspects in common with the Building Block Methodology (Tharme 1996). Both are still in the development phase and, as yet, are essentially untested. Final reports concerning the application of either method were not available at the time of writing. A fuller discussion of both methods will appear elsewhere in this review.

It should be emphasised that both the Building Block Methodology and Holistic Approach are essentially based on expert opinion, except that the processes by which those opinions are incorporated into a flow strategy are better documented and based (preferably) on sound quantitative data. It should also be emphasised that the Holistic Approach is, in itself, not a set of prescribed rigid and well-defined methods but rather a philosophical framework capable of incorporating a range of methods.

4.2.5 Flushing flows and fish passage

Although the intended purpose of this chapter is to review the different methodologies and basis of application of each different method used in assessments of the environmental flow needs of Australian freshwater fishes, consideration of the role of flushing flows requires a broader perspective. As a generic term, flushing flows can be considered as large supplementary flow releases intended to achieve some predetermined environmental response. There appears to be considerable diversity in the Australian literature concerning the terminology, nature and purpose of flushing flows. This is evident in Table 6 (page 86) which lists the main intended function of such a supplementary flow, in a range of environmental studies as well as the term used to describe the flow. Also given is the method by which the volume, timing and duration of the flow were determined. It must be emphasised that the studies from which this table was constructed included environmental flow studies focused heavily upon freshwater fish as well as studies of broader application. Note also that this table contains information on flushing flows other than those flows required for the initiation of spawning or enabling passage of freshwater fishes.

Several main points are illustrated by Table 6. First, high flows are obviously needed to maintain several different aspects of ecosystem integrity, such as substrate renewal, channel maintenance and water quality maintenance. Second, although there are several terms used in the literature (ie. shear flow, high flow, channel maintaining flow), the most commonly used term is 'flushing flow'. Where other terms are used, the authors have usually been very specific about that flow's intended function (eg. the shear flows recommended in Davies et al. (1996) were intended to mobilise fine sediment and litter from the surface of very highly productive algal mats). In other cases, no specific function other than the broad function of channel maintenance or substrate renewal is given. There is some danger in this situation as a flushing flow designed to achieve one specific function may also be seen as providing benefits in other areas. For example, if a flow is designed to achieve channel maintenance, is this flow also appropriate for substrate renewal or water quality maintenance? In this case the answer may be yes, but in the case of flows designed to maintain water quality, it is unlikely that such flows will necessarily achieve channel maintenance. Importantly, flushing flows may cease to be beneficial if released at inappropriate times, such as during low flow periods when fish spawn.

Table 6: *Flushing flows, their intended purpose and derivation in studies of the environmental flow requirements of Australian rivers*

Intended function	Methods used for characterisation of release	Term used	Comments
1. Substrate renewal			
Tunbridge (1980)	empirical observations of flow rate necessary to maintain one riffle free of silt	flushing flows	no suggested protocol concerning pattern or magnitude other than referring to Tennant (1976) flushing flow of 200% daily average
Tunbridge & Glenane (1988)	apparently based on Stalnaker & Arnette's (1976) recommendation of twice average monthly flows	flushing flow	little justification apparent for choice of magnitude, duration and timing
Anderson & Morison (1989)	not listed	flushing flows	
Arthington et al. (1992a)	natural high flows beyond storage capacity assumed to be sufficient	flushing flows	suggested that flows greater than the 80th percentile necessary
Grose (1993)	rates of rise and fall determined from natural hydrograph, duration not to exceed 90th percentile	high flows	primarily concerned with maximising the benefit and minimising detriment of inter-storage transfers
Swales (1994)	difficult to determine method used except to say that flow is stated as being sufficiently large to exceed threshold for motion of stabilised sediment	flood flows	flood timed to occur between late autumn and mid-spring but no data on exact timing; release to mimic natural hydrograph
Davies et al. (1996)	based on hydraulic principles and analysis of natural flow record to determine frequency and duration	shear flows	considered maintenance of productive algal mats free from silt and debris as being important from a system perspective
Kelly (1996)	not listed except for amount	flushing flows	recommends release to coincide with fish breeding and migration
2. Channel maintenance			
Hall & Harrington (1991)	no actual amount specified, recommended that flush needed		difficult to determine channel maintenance in Tambo River due to historic influences
Arthington et al. (1992a)	natural high flows beyond storage capacity assumed to be sufficient	flushing flows	
Gippel et al. (1992)	flood magnitude based on principles of hydraulic geometry and flood frequency and duration by reference to natural flow record	channel maintenance flood	rules for timing and release strategies given and based on occurrence of natural floods and natural in-flows to storage
Swales (1994)	Expert panel approach suggested to be the most effective	flushing flow	notes that there are no standard methods in Australia but suggests that most successful approach likely to involve reference to natural hydrograph

continued

Table 6: *Flushing flows, their intended purpose and derivation in studies of the environmental flow requirements of Australian rivers – continued*

Intended function	Methods used for characterisation of release	Term used	Comments
2. Channel maintenance *continued*			
Arthington et al. (1994)	hydraulic geometry	channel maintenance	this report was not intended to include a detailed environmental flow schedule but was intended to list potential impacts of flow regulation, given that the original report remains confidential
Swales (1994)	no information given	flood flow	flood to resemble natural flood hydrograph
Davies et al. (1996)	hydraulic geometry and reference to natural hydrograph	channel maintenance	
3. Water quality maintenance			
Tunbridge (1988)	observations on flow needed to achieve flushing of saline water from Lake Coonewarre	flushing flows	strong focus on the requirements of fish suitable for angling
Tunbridge & Glenane (1988)	suggested area of further research and to open sand bars	flushing flow	needed to maintain estuarine salinity levels appropriate for recreational fisheries
Anderson & Morison (1989)	not given		details included in report volume not available to the author at time of writing; however, Wimmera River experiences high salinity and low oxygen levels during low flow periods
Arthington et al. (1992a)	empirical relationship between flow and salinity established, flows to be released on an *ad hoc* basis when irrigation demand high and salinity above 1000 $\mu S.cm^{-1}$	flushing flows	strict guidelines on releases not given but notes that flows should not exceed rates of rise and fall for each month derived from records
Denham & McAuliffe (1994)	not listed	flushing flow	annual allowance of 9 gL for salinity, referred to as flushing flow in as much as allowance released as a series of 'flushes'
Swales (1994)	not listed	flushing flows	may need high flows to maintain suitable levels of dissolved oxygen and water temperature
Kelly (1996)	not listed	flushing flows	recognise problem of rising saline groundwater and that environmental flows may need to remain higher than historic levels and that flushing flows may cause some disturbance
4. Wetland inundation			
Anderson & Morison (1989)	none given	no specific term used	flows required to reach two terminal lakes in an endorheic system
Swales (1994)	Expert panel approach suggested to be the most effective	no specific term used	
Cooney (1993)	hydraulic geometry and satellite imagery	no specific name given	

continued

Table 6: *Flushing flows, their intended purpose and derivation in studies of the environmental flow requirements of Australian rivers – continued*

Intended function	Methods used for characterisation of release	Term used	Comments
5. Control of nuisance plants and fish			
Arthington et al. (1992a)	based on natural high flows which have removed floating rafts of water hyacinth	flushing flows	flows required to destabilise and move floating rafts of water hyacinth
Denham and McAuliffe (1994)	not clear	flushing flow	6 gL allowance allocated for the suppression of bluegreen alga blooms – state that such use is a last resort response and that prevention of high nutrient loads preferred
Davies et al. (1996)	based on hydraulic geometry and analysis of natural flow regime	no specific term used	suggest that natural high winter flows may be necessary to depress population size of *Gambusia holbrooki*
6. Synchronisation of ecological processes			
Gippel et al. (1992)	based on an examination of the return period, timing and duration of the first flood of the year following Arthington et al. (1992b)	first flood and flushing flow	first flood of the year suggested by Arthington et al. (1992b) to be ecologically important although there is little confirmation of this
Arthington et al. (1992b)	based on an examination of the return period, timing and duration of the first flood of the year	first flood and flushing flow	suggested necessary for 'resetting ecological processes' and should be large enough to achieve other functions listed above

Another general characteristic revealed in Table 6 is that the methods used to determine the magnitude, duration and timing of high flows are often poorly described. In some cases, discharge levels recommended are based on very few empirical data or based on rules derived from elsewhere in the world. For example, Tennant (1976) suggested that flows equivalent to 200% of the average daily flow be used to achieve a flushing flow and this has been followed in Australian studies (eg. Tunbridge 1980). In variable systems such as occur in many parts of Australia, a 200% variation in flow may, however, be a frequent and minor occurrence. For example, monthly instantaneous maximum flows in Barker-Barambah Creek during the wet season may be over 10,000 times greater than monthly minimum flows (Arthington et al. 1992a).

Several studies (Gippel et al. 1992; Cooney 1993; Arthington et al. 1994; Davies et al. 1996) use the principles of hydraulic geometry and analysis of flow records to determine the size and magnitude of events that are intended to achieve specific functions. The natural flow record can provide powerful information on the nature of high flow events, such as the frequency and timing of events of known magnitude and the shape of their hydrographs, and thus provide the operational rules for such events in any modified flow regime. Close inspection of the natural flow record and its use in providing the operational parameters in modified flow regimes is one of the central tenets of the Holistic Approach first enunciated by Arthington et al. (1992b). Gippel et al. (1992) acknowledged that in-stream flow management must be holistic and used such data to define release strategies for the Thomson River.

4.3 Biases in the selection of target taxa

In most of environmental flow investigations conducted in Australia there has been a consistent bias in choice of target species upon which to base flow recommendations, and that bias is most frequently towards species of recreational fishing value, even when such species are exotic. In studies conducted in southern Australia, trout (eg. Tunbridge 1980; Tunbridge 1988; Hall 1989; Davies & Humphries 1995) is often the

target taxon. In many cases there appears to be no attempt to consider the degree of detriment to other native species that may occur when environmental flows are maintained to favour a particular exotic species. Indeed, one study (Tunbridge 1988) included both juvenile trout and native galaxid minnows in a consideration of the habitat requirements of a single category of small fishes labelled "juvenile" fishes. There is abundant evidence that these species compete and that galaxid abundance is negatively correlated with that of trout (see McDowall & Fulton 1996). Moreover, in this study (Tunbridge 1988, p. 99), relatively high flows were recommended for the summer months, apparently to maximise suitability for trout, although such flows may be inimical to native fishes at this time.

Other evidence of this bias is also evident. Arthington et al. (1992a) list "important angling species" as one of the target taxa considered in an assessment of environmental flow needs in Barker-Barambah Creek, although maintenance of fish species-richness and of rare species was also considered. Anderson and Morison (1989) specifically address "fisheries" benefits of a modified flow regime in the Wimmera River, rather than focusing on addressing benefits that may accrue to individual species or to the ecosystem as a whole.

In many cases it is assumed that by addressing the in-stream flow needs of target taxa of recreational importance, the needs of other species will also be met. For example, Tunbridge (1980) states that it is assumed that the passage requirements of blackfish are covered by trout requirements, despite the inclusion of a subsequent discussion of the differences in burst swimming capabilities of the two species. Similarly, Kelly (1996) stated (following Tunbridge 1997) that habitat conditions suitable for golden perch are considered adequate for other biota.

A focus on angling species within the family Percichthyidae is apparent in many studies, even for those studies that took place outside of the natural range of species within this family. The reasons for this may include the conspicuousness of the family, given that many of them are large, their culinary value or because the habitat requirements, movement patterns and reproductive biology of several species are apparently well known (ie. golden perch, blackfish, Murray cod and Australian bass). Nonetheless, there are still substantial gaps in knowledge for these species that deserve further study (eg. juvenile versus adult movement patterns of golden perch). In one study (Hall 1989), the spawning requirements of *Galaxias maculatus* were highlighted (ie. one flush to initiate spawning in inundated riparian vegetation and a subsequent flush to initiate hatching) yet it is unclear how these requirements were accommodated within the requirements of the major target taxon - blackfish. Species with high conservation significance (but without recreational significance) were directly considered in relatively few studies (Hall & Harrington 1991; Arthington et al. 1992a; Davies & Humphries 1995).

4.4 Geographical bias in selection of review material

It may appear that the author has been overly critical of environmental flow studies originating from south-eastern Australia, but this is primarily because more such studies have been undertaken in this region over a longer period. Only one environmental flow study from Western Australia (Davies et al. 1996) was available for review at the time of writing, but was incomplete and in draft form only. Few studies from Queensland were available for review although several environmental flow studies are currently being undertaken. However, in many cases the supporting documentation was incomplete, restricted in content or not available. The report by Arthington et al. (1992a) on the environmental impacts of the impoundment of the Barker-Barambah Creek was the only complete study available. An assessment of the flow requirements of the Logan River using the Building Block Methodology and an assessment of the requirements of the Brisbane River using the Holistic Approach were both incomplete at the time of writing. Two environmental flow studies have been undertaken in northern Queensland in the last decade. The first was for the Tully-Millstream Hydroelectric Scheme (Arthington et al. 1994) and the second addressed increased water harvesting from Behana Creek, a tributary of the Mulgrave River near Cairns. The final report dealing with the Tully-Millstream Hydroelectric Scheme is a confidential document and has not been released to the public. As a consequence, it could not be reviewed, although Arthington et al. (1994) contains some information on this scheme. There was no available written material concerning the Behana Creek development despite substantial investigation of the freshwater fishes of this system by the Queensland Department of Primary Industries. Several Water Allocation and Management

Plans are currently being drafted for other rivers in Queensland, but have not yet been finalised and released.

4.5 Recommendations for further R&D

The development of the philosophy of environmental flow management appears to be towards a more holistic consideration of the interactions between landscape, hydrology and the riverine biota. It seems unlikely that an environmental flow study could, at present, focus entirely on freshwater fishes to the exclusion of other taxa, as has been the case in the past. This is not to say that freshwater fishes are unimportant components of the riverine ecosystem, but only that they are part of an integrated whole. Nonetheless, freshwater fishes do have 'flagship' status with the general community and will probably continue to have significant importance in environmental flow decisions. Unfortunately, there is still an enormous absence of quantitative data concerning the interaction between hydrology and fish biology. The recommendations listed below are made in light of this data vacuum, but also acknowledge that some progress in the field is being made by researchers throughout Australia.

This review has highlighted some of the deficiencies associated with the methods used to define environmental flows in Australia and recommendations for future research will be made in light of these deficiencies. The recommendations listed below are also made in the context of the author's personal research experience in the fields of environmental flow management and fish ecology.

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

1. An understanding of the habitat requirements of many species of fishes.
2. An understanding of basic life history and its relationship to hydrology for many 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 fishes 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 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. Each of these seven points will be dealt with below.

All of the in-stream flow methodologies described in the preceding sections 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. Koehn and O'Connor (1990), in an excellent treatment of the biological information necessary for the management of Victoria's freshwater fishes, attempted to detail the general habitat requirements of 42 species. Of these, however, habitat requirements for 29 species were for the adult stage only. Where larval habitat was included the description was generally cursory, reflecting the substantial lack of investigation in this area. Koehn and O'Connor (1990, p. 105) state that the data were generally descriptive and that quantitative data on preferred depths, water velocity and cover types are not available for many species, despite such data being needed for such management processes as the definition of in-stream flow needs.

The New South Wales Fisheries study of freshwater fishes (Harris & Gehrke 1997) is certainly the largest such coordinated endeavour in this field and this continent yet undertaken. However, little specific habitat information can be gleaned from this report other than very general statements about whether a species is a riffle or pool dwelling species. Admittedly, collection and analysis of such data were not listed as one of the objectives of the study. Fortunately, data concerning habitat structure (eg. flow, depth, width substrate, vegetation, cover) were collected at the time of sampling and will be of considerable benefit if they are analysed and made available. Such data may also be of benefit in explaining some, if not much, of the variation observed in the distribution and abundance of fishes in

rivers of separate regions of New South Wales reported by Schiller et al. (1997) and Gehrke (1997). Moreover, as management moves towards more rapid means for assessing the ecological integrity of riverine systems, a better understanding of the relationship between habitat structure and diversity and fish species-richness is a necessary step in developing boundary conditions within natural ecosystems.

Harris and Silveira (1997) discuss the development of an Index of Biological Integrity (*sensu* Karr 1981) for use in New South Wales and applied it to the results of the New South Wales Fish Survey. A significant component of the index is the comparison of structural and functional attributes of fish assemblages at test sites against some predetermined ranked criteria. These attributes include the number of native species, dwelling benthic species, pool dwelling benthic species and pool dwelling pelagic species, and the proportion of individuals within a sample in each of a number of trophic categories. Notwithstanding the fact that functional attributes such as trophic structure will be influenced by habitat structure (Pusey et al. 1995a), position in the catchment (Pusey et al. 1995a), the evolutionary history of the assemblage (Pusey & Kennard 1995) and the degree of in-stream production (Pusey & Kennard 1995), many of the metrics used by Harris and Silveira (1997) are sensitive to variation in habitat structure over relatively small spatial scales (Pusey et al. 1993, 1995a, unpublished information). Consideration of habitat diversity in ways other than the inclusion of catchment area as its surrogate may aid in interpreting much of the variation in Index of Biological Integrity scores for individual sites reported by Harris and Silveira (1997) and lead to a more robust and widely applicable version of this procedure.

The description of the habitat requirements of individual fish species in such general terms as riffle or pool dwelling is of little benefit in studies concerned with estimating the impact of changes to a river's flow regime, except in the case where such macrohabitat features disappear altogether as a result. Of far greater benefit are data concerning a species' flow, depth, substrate and cover requirements expressed in a quantitative manner. Such data are not easily collected, analysed or expressed and there is a danger that once this has been done for a species in one location, the information will be used in other situations or localities for which it is inappropriate. This was one of the criticisms of the IFIM approach early in its development (Moyle & Baltz 1985). These authors warned that habitat use does not necessarily reflect preference and, moreover, that preference may be influenced by many factors, including predation and competition. Transportation of such data outside of the reach in which they were gathered may therefore be problematic. Current research undertaken by the Centre for Catchment and In-Stream Research, Griffith University, is focused on defining the macrohabitat and microhabitat requirements of about 60 species of freshwater fishes from electrofishing catch data for many thousands of individual 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). Uncritical application of these habitat data outside of the areas from which they were collected, and particularly in computer simulations such as in the IFIM, is explicitly not recommended (Pusey et al., in prep.).

The IFIM process (primarily the habitat modelling component), despite its many potential drawbacks, has been used in Australia (see above) and will probably increase in usage. One reason for this is that the method is attractive to engineers and non-biologists, given its strong quantitative basis (personal observation). For it to be useful, however, further investigation of its applicability is warranted. For example, it needs to be established over a range of river and hydrological types, whether there is any congruence between a reach's modelled suitability and the actual biomass or density of fish. Moreover, the modelling process may be better applied in the consideration of the availability of certain critical habitat elements such as woody debris or macrophyte beds. Davies and Humphries (1995) cogently argued that the preservation of a single habitat element (macrophyte beds) was sufficient to ensure the maintenance of one fish species of high conservation value. Other studies have also shown that substantial amounts of the spatial variance in fish assemblage structure observed in some rivers can be explained by critical habitat elements not related to flow, depth and substrate (Pusey et al. 1993, 1995b; Pusey & Kennard 1996) or that substantial temporal variation in assemblage structure within a site may also be explained by temporal variation of such elements (Pusey et al. 1993, unpublished data). Identification of such critical elements and subsequent incorporation into the modelling process may prove fruitful.

It was briefly mentioned in the discussion of the IFIM that there is the potential for using this process to generate habitat duration curves for individual species at a site. Further development of this aspect warrants examination. Such an application may be more ecologically relevant than the identification of critical discharge values below which habitat suitability declines rapidly, or for those species which exhibit relationships between discharge and habitat suitability which are not asymptotic. 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 IFIM.

If the IFIM, specifically the habitat modelling component, is to be used to any extent in Australia, thought should be given to the development of methods that allow for the consideration of multi-species assemblages rather than for individual species. The risk assessment approach used by Davies and Humphries (1995) warrants further development.

Many methods used in Australia, such as the IFIM or 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). Research undertaken in Queensland by the Centre for Catchment and In-Stream Research indicates that the fish fauna of this state (and probably elsewhere also) contains few obligate riffle dwelling species and that richness of such a component is highest in those areas for which discharge tends towards constancy and high predictability (ie. many of the rivers of the Wet Tropics region). Riffles in such areas tend to be reliably available habitats throughout the year and, consequently, have a more well-defined and exclusive fauna. Elsewhere in Queensland the riffle fauna is less well-defined and made up of more widely distributed (within habitat types) species. Therefore, a focus on riffle areas may be appropriate in some areas but not others. Information is needed to allow an assessment of such a fundamental problem.

The problems of choosing appropriate landscape units for examination or consideration, spatial variation in habitat fidelity and the development of habitat use data all raise the question of how plastic is the habitat use exhibited by individual species. Several studies on aquatic communities (Horwitz 1978; Poff & Ward 1989; Poff & Allen 1990) suggest the degree of habitat specialisation exhibited by a species will be influenced by the degree of flow variability in which it is found. This notion has been used, in part, to explain the widespread nature of many of Australia's freshwater fishes (Pusey et al. 1993; Harris & Gehrke 1994; McDowall 1996) and why freshwater fish diversity is higher in some areas than others (Pusey et al. 1995; Pusey & Kennard 1996). It is of considerable importance that the relationship between discharge variability and habitat fidelity or plasticity be determined empirically. A major advance in this area would be a national examination of regional variation in discharge variability in order to identify river systems in which special attention may be necessary to ensure that habitat conditions remain unchanged in any modified discharge scenario. Experimental examination of changes in habitat use under conditions of differing discharge variability has not occurred in Australia or elsewhere. Elegant and complex habitat modelling may prove totally inappropriate if it cannot be shown that fishes do indeed respond to changes in habitat structure.

Similarly, if rapid desktop versions of environmental flow methods (such as the Montana method) become an important part of the process for defining environmental flows, then they need to be validated in this country. The preceding discussion of such methods has emphasised how practitioners viewed these methods as being impractical when transferred to the Australian situation. Tennant (1976) based his classification of habitat quality into such categories as excellent or good on an enormous amount of quantitative data. This has not occurred in Australia. A continent-wide, coordinated approach to developing the empirical basis for such a classification may prove fruitful, particularly for identifying those regions where the use of such desktop methods is entirely inappropriate due to marked seasonality or markedly unpredictable flow regimes.

An intense focus on the depth, flow and substrate needs of freshwater fishes may prove to provide little advancement in our ability to effectively manage freshwater fish populations. Appreciation of what constitutes the habitat of a fish species needs to be expanded. The example described by Grossman et al. (1995) and Petty and Grossman (1996), where the density and distribution of one species was better predicted by a knowledge of the habitat requirements of their invertebrate prey, despite fairly narrow habitat preferences exhibited by the predator, illustrates this problem well. There is very little Australian information relating attributes of fish assemblages with those of their food base.

Both Davies and Humphries (1995) and Thoms et al. (1996) considered fish habitat in a broader sense than just depth, flow and substrate. In the case of Davies and Humphries (1995), macrophyte beds were considered as critical habitat elements for pygmy perch. Thoms et al. (1996) viewed habitat over a much broader spatial hierarchy in order to consider the inundation of floodplain waterbodies as critical habitat. In each case, a critical habitat component exists which is not covered by the depth, flow and substrate requirements of adult fishes. Identification of the critical habitat requirements of individual species is necessary in order for sustainable management of freshwater fishes to develop.

The definition of critical habitat needs is virtually impossible without detailed life history information. It seems, to the author at least, that funding agencies and tertiary institutions view life history studies as not being particularly worthy of investigation or support. This is a dangerous situation. 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. 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 (Centre for Catchment and In-Stream Research and Cooperative Research Centre for Freshwater Ecology).

The investigation of larval fish biology of freshwater fishes is still in its infancy in Australia. For example, the recent publication of a guide to the identification of temperate Australian fishes (Neira et al. 1998) contains data on only 10 species of freshwater fish from six families. Similarly, only one paper delivered at the International Larval Fish conference held in Sydney in 1995 was concerned with an Australian freshwater fish species. Recent research in the Murray-Darling River system has revealed that flow conditions are a vital factor in the survivorship of larval and juvenile fishes (P. Humphries, pers. comm.). 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. Some species (eg. neosilurid catfishes) evidently need flood conditions for successful spawning (Orr & Milward 1984) while others spawn during periods which may contain floods but are not dependent on floods as a stimulus to spawn (Pusey et al. 1998). 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. The need for a better understanding of the interaction between streamflow and recruitment in order to facilitate better stock management has been highlighted previously (Harris & Gerhke 1994).

This point also raises the need for further research into patterns of fish movement. 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 above. However, much of this research is limited in taxonomic extent (Section 4.3 above) 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 (eg. Mallen-Cooper & Edwards 1991; Mallen-Cooper & Thorncraft 1992; Harris et al. 1992; Mallen-Cooper 1996). 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, such as those of Mallen-Cooper (1992, 1994) 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 (Bishop et al. 1995; A. Hogan, pers. comm.) but, with the exception of 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. Moreover, Stuart (1997) 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.

A very significant knowledge gap related to the issue of fish movements is the degree to which the dynamics of riverine processes contribute to downstream estuaries and vice versa. Loneragan and Bunn (1997) showed that the magnitude of commercial fishing catches in the estuarine reaches of the Logan River of south-eastern Queensland was tightly associated with the magnitude of summer discharge, explaining between 69% and 80% of the annual variation in catch of such species as mud crabs, flathead and king and tiger prawns. Newton (1996) observed that temporal variations in ichthyoplankton densities were correlated with zooplankton densities following flooding, and postulated that increased flows resulted in increased nutrient concentrations which fuelled increases in phytoplankton blooms, the effect of which was transmitted up the food chain. Freshwater discharge into estuaries is a major determinant of estuarine production (Loneragan & Potter 1990) and, given that about one-third of Australia's fisheries catches are derived from estuarine-dependent species (Lenanton & Potter 1987), is of considerable economic importance. Using a 13-year data set concerning fish assemblage structure, density and dietary data, Livingston (1997) demonstrated that streamflow was the most important factor influencing estuarine fish production and food web structure in a Florida estuary. Such studies are limited in extent and number in Australia, with the exception of the research undertaken in Western Australia by Murdoch University researchers. In some areas of Australia, estuarine fishes are an important component of the fishes occurring in fresh waters. For example, over one-third of the species occurring in the ichthyologically diverse Wet Tropics region spend at least some part of their life history in estuarine waters (Pusey & Kennard 1996), yet little is known about the importance of such species to riverine processes.

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 examined fish trophic ecology from a community ecology perspective. This approach is needed for a number of reasons. Poff and Allen (1990) compared the trophic structure of fish assemblages in rivers of varying streamflow variability and reported that trophic specialism was more developed in predictable rivers, supporting the hypotheses of Horwitz (1978) and Poff and Ward (1989). 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.

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 attendant water bodies, will prove a useful aid in defining environmental flow strategies, especially 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.). In addition, 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.

As well as the substantial knowledge gaps highlighted above, there is an additional problem of the translation of recommended environmental flow strategies into day-to-day operating rules for water managers. This problem needs to be addressed urgently to foster better understanding between scientists and managers and better adoption of recommended flows. Of significant regard in this matter is the absence of mechanisms by which flow variability can be factored into water release strategies. The author suspects that the current situation is one where the flow requirements are stated in such terms as "high flows need to be included once every three years and extreme low flow periods need to be incorporated once every five years if they do not occur naturally in the intervening period", but without any mechanism that allows the storage operator to decide whether a flood follows a drought or precedes it. 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, then the establishment of flow conditions within individual rivers must be shown to be correlated with indices such as the Southern Oscillation Index. This may have little relevance to areas other than eastern Australia.

Better use of existing storages as experimental facilities to test hypotheses about the relationship between flow and fish biology could also undoubtedly occur and should be encouraged. Moreover, there seems to be a reluctance to assess whether suggested environmental flow strategies are actually achieving their stated objectives. Only one study (Saddlier & Doeg 1997) was available for review, which was concerned with the establishment of a monitoring program to determine the success of a post-impoundment release strategy. Interim recommendations apparently have the habit of becoming final recommendations. Release strategies should be viewed as both experiments and as a process that may need fine tuning as more sophisticated techniques and methods and a better understanding of the relationship between flow and biota develops (see Arthington et al. 1992b).

Most methods for the determination of environmental flows have been developed in North America which has a long history of the study of stream fish ecology, commencing with the initial faunal surveys undertaken in the late 1700s and early 1800s (Heins & Matthews 1987). General ecological information and more quantitative information on stream fish ecology began to appear by the late 1800s (eg. Forbes 1880, 1883; Jordan 1891) and information on the relationships between fish biology and hydrology appeared as early as 1902 (Forbes 1902) and especially after 1950 (eg. Starrett 1951; Larimore 1959). Studies devoted to examining the interrelationships between species and the regulation of entire communities dominated the study of stream fish biology in the 1970s and 1980s (see references in Heins & Matthews (1987) and Grossman et al. (1990)), culminating in experimental studies testing hypotheses generated by much of this earlier research. The cumulative knowledge gained from this long and fruitful research provides a very stable and wide base upon which management decisions may be made.

In contrast, studies of Australian freshwater fishes have a very short history and the fauna was "very poorly known until recent decades" (McDowall 1996). Exploratory and taxonomic research, with a few notable exceptions (eg. Lake 1971), only commenced in earnest in the early 1970s. Life history research has been undertaken during this period but the main focus has been a traditional one of describing fecundity, larval development and growth curves. Few studies have addressed the interaction between hydrology and life history (eg. Beumer 1979; Milton & Arthington 1983, 1984, 1985; Harris 1986, 1987, 1988) and fewer studies have quantitatively addressed the habitat requirements of individual species (Davies 1989; Koehn et al. 1994; Humphries 1995). A synthesis of the ecology of Australia's freshwater fishes is lacking, although regional variations on this theme have been produced (Koehn & O'Connor 1990). The most recent general publication concerning Australia's freshwater fishes (McDowall 1996) is also regionally oriented and its stated main objective is to enable species identification. Even in the most densely populated region of Australia, there still remains a patchy and incomplete coverage of the biology and ecology of freshwater fishes (McDowall 1996). This problem is even more pronounced in much of northern Australia, for which relatively little is known about distributions, migration, reproductive and trophic ecology, let alone how these factors are related to hydrology (but also see Bishop et al. 1995). Such deficiencies appear very serious in the light of projected increases in demand on the nation's water resources, especially in areas for which regional development is strongly predicated on the need to provide certainty of water supply for irrigation (eg. Queensland, Anon. (1997)).

4.6 Conclusions

Knights and Fitzgerald (1994) make a number of interesting comments in their discussion of a more pragmatic approach to environmental flow management. Among these is the suggestion that the issue of environmental flow management is one of resource management and not science. This observation may explain why most environmental flow provisions in Australia are based on decisions which are "…arbitrary, hasty and politically driven". (Knights & Fitzgerald 1994). They also suggest that the "...only factor concerning any environmental flow determination that we can be sure about is that it will be wrong". Taken together, these comments suggest that one of the problems facing practitioners of environmental flow management is the lack of science, or perhaps more specifically, lack of relevant information.

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.

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 have studies been undertaken to determine for how long ecosystems can be maintained at set criteria (ie. 20th percentile flow) without detriment. Thus their use cannot be strongly defended. However, that is not to say 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) are undoubtedly 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 above 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 knowledge gap highlighted above.

Expert panel and holistic methodologies vary greatly in the time and expense required for their conduct. 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 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 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. In addition, the consideration of habitat in a broad sense, such that it incorporates such off-stream features as floodplains rather than habitat at a few supposedly representative critical reaches, is an advantage of this method.

Holistic methodologies such as the Building Block Methodology and the Holistic Approach 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 recommendations are achieved by the participants. Both methods are relatively time and labour expensive, however. A significant advantage of these approaches is

that they allow for the incorporation of a range of methodologies but, importantly, are not constrained to accept the recommendations offered by any 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 their defensibility. Riverine ecosystems are not just a series of 'critical' reaches but are composed of an extended spatial hierarchy (Frissell et al. 1986) and, therefore, environmental flow assessments need to be made within this extended hierarchy also. Critical habitats or reaches may indeed exist but may not necessarily be those identified at the beginning of a study.

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 away from this protocol represented a significant increase in risk to the biota (Tunbridge 1997).

In conclusion, all of the methodologies or approaches discussed above 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. Statzner et al. (1997) reported that almost 40% of the current worldwide investment in freshwater resource management is devoted to restorative measures, whereas freshwater research accounted for only 0.1%. Clearly, cost-effectiveness needs to be assessed with respect to the long term rather than the short term. One of the stated objectives of this review was to assist in the development of a best practice framework for the application of techniques to environmental flow assessment. At present, a best practice framework must: (i) include a more holistic appreciation of the riverine environment; (ii) recognise that some methodologies are at best questionable and potentially damaging; (iii) be undertaken with an extremely high degree of scientific rigour; (iv) recognise that each river is different and is likely to have its own economic, social and ecological peculiarities; and (v) recognise the deficiencies in the knowledge base available. As such, Tunbridge's (1997) recommendation of a "full environmental study", possibly within a structured workshop format proposed by the Building Block Method and Holistic Approach, seems the most appropriate approach in the future.

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5. The influence of river flows on coastal fisheries

Stuart E. Bunn, Neil R. Loneragan and Miles Yeates

5.1 Introduction

There is a growing awareness of the influence that river discharge can have on the physical, chemical and biological characteristics of estuarine and coastal areas. Much of the public attention has focused on the negative effect of flood flows and associated export of sediment, nutrients and other contaminants. For example, the degradation of coral reefs (Mitchell et al. 1996), the die-off of seagrass and dugongs (Preen et al. 1995), and the eutrophication of coastal estuaries (eg. McComb & Humphries 1992; Dennison et al. 1993) are linked to high exports of sediment and/or nutrients from catchment disturbance.

However, many positive linkages between river discharge and the dynamics of coastal ecosystems are also recognised. For example, seasonal or inter-annual variation in discharge can determine whether the mouth of an estuary is open or closed and whether marine species are able to recruit into them. Flow-driven changes in salinity and turbidity are important factors influencing the distribution and abundance of fish and crustaceans (eg. Whitfield 1996). Furthermore, nutrients exported from rivers to coastal areas may stimulate the production of microalgae, which are thought to be important primary sources of energy to coastal food webs (eg. Fry & Wainwright 1991; Mallin et al. 1992).

Despite these positive links between river discharge and coastal ecosystems, there is a common perception that "water going to sea is wasted" (Whitfield & Wooldridge 1994; Rosenberg et al. 1995) and that the flow of rivers should be captured by dams and weirs and put to better use. Over 375 large dams have been built in Australia, mainly in the south-east of the continent (Zann 1996). These have reduced the magnitude of downstream discharges, particularly flood peaks, and changed seasonal patterns of flow. The impacts of such flow regulation on coastal ecosystems and, in particular, coastal fisheries remain unknown. This is astounding given that a significant proportion of Australia's total fisheries harvest is derived from estuarine and inshore waters (eg. Lenanton & Potter 1987). The ecological needs of downstream estuaries and coastal zones have rarely been considered in allocating environmental flows in Australia (Zann 1996). This is not the case in South Africa, where demands for potable water are so great that recent projections suggest that the country will be using all of its freshwater resources by 2020 (Schlacher & Wooldridge 1996).

The objectives of this chapter are as follows.

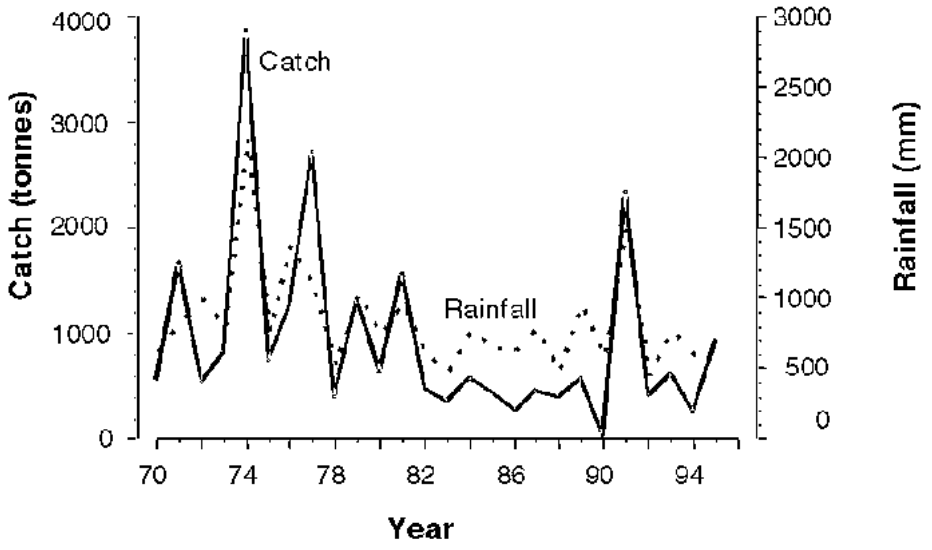
1. Review the available evidence for linkages between river flow and estuarine/coastal fisheries, drawing where possible from Australian examples, and discuss likely causal mechanisms of observed relationships.
2. Recommend a 'best practice' framework for the application of techniques to environmental flow assessment.
3. Outline priority areas for future research and development.

5.2 Evidence of links between coastal fisheries and river discharge

5.2.1 Penaeid prawns

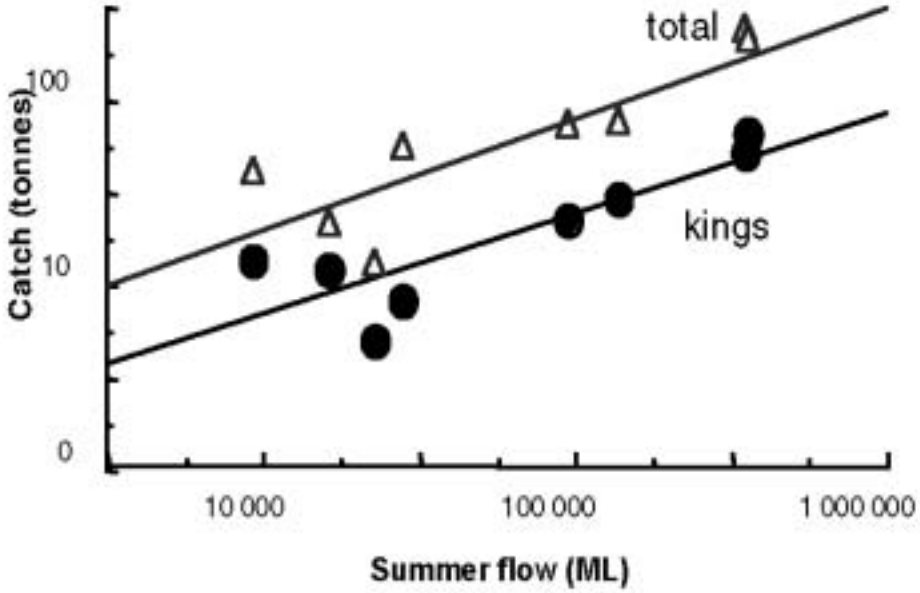
For many coastal fisheries in Australia, inter-annual variation in commercial catches or landings appears to be correlated with variation in river discharge. For example, catches of school prawns (*Metapenaeus macleayi*) in New South Wales are enhanced in years with high river discharge (Ruello 1973; Glaister 1978). Similarly, catches of banana prawns (*Penaeus merguiensis*) in the south-eastern region of the Gulf of Carpentaria are highly correlated with annual rainfall (see Figure 5, p. 107). Catches over a 25-year period ranged from only 30 t during a year of low rainfall to 2,300 t the following year when exceptionally high levels of rainfall were recorded. Similar relationships between flow and catches of eastern king prawns (*P. plebejus*) have been observed for the Fitzroy River (Platten 1996).

Figure 5: *Catch of banana prawns (*Penaeus merguiensis*, solid line) and rainfall (dashed line) in the south-eastern Gulf of Carpentaria*



Note: Most of the annual rainfall occurs during the summer wet season and is highly correlated with run-off.
Source: Loneragan & Bunn, in press.

Figure 6: *Relationship between summer flow and annual commercial catch of prawns (total and king) from four fishing blocks in the mouth of the Logan River*



Note: Data for catch and flow are both on $\log_{10}$ axes. Lines are the least square regression lines.
Source: Loneragan & Bunn, in press.

Relationships between flow and prawn catches (five species) have been quantified for the Logan River, in south-east Queensland (Loneragan & Bunn, in press). The Logan River has unregulated flow, with the exception of a single small dam in the headwaters of Burnett Creek in the southern part of its catchment. The river is one of four systems in south-eastern Queensland in which commercial fishers are licensed to catch prawns using beam trawls. The main fishing season extends from about September until April, with the timing of the season varying between each river system and the species of prawns being caught.

An important finding of the Logan study was that the strongest positive correlations were observed between prawn catches and summer discharge: most correlations with spring, autumn and winter flows were negative (though not significant). Variation in summer flow in the Logan River accounted for about 80% of the variation in catch of king and tiger prawns, and 74% of the variation in total prawn catches (see Figure 6, p. 107; Loneragan & Bunn, in press).

The relationships between prawn catches and wet season flow volume observed in the above studies can be generally described by the equation:

Prawn catch $\propto Q_{wet}^{0.65}$

where Q_{wet} is the total flow volume from January – April (DNR 1998a).

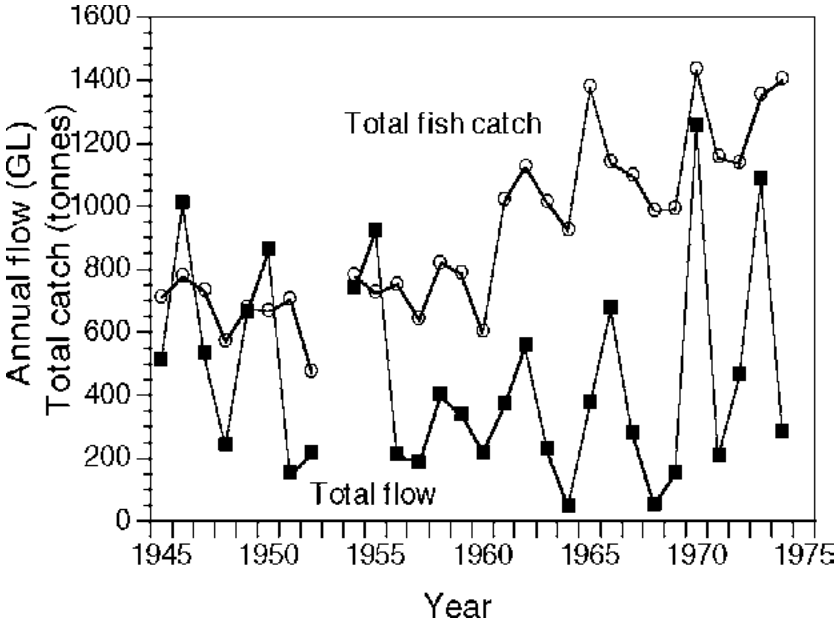
5.2.2 Fish and crabs

There is also growing evidence of similar relationships between river discharge and longer lived species of crustaceans and fish. For example, historical data on commercial landings of fish in Moreton Bay from 1945–1975 mirror the inter-annual variation in discharge from the Logan River (see Figure 7 below) (Loneragan & Bunn, in press) and Brisbane River (Bunn & Loneragan 1998).

More recent data on commercial catches from the mouth of the Logan River indicated that summer discharge explained about 80% of the variation in catch of mud crabs (*Scylla serrata*) and 69% of the variation in flathead (*Platycephalus* spp.) (Loneragan & Bunn, in press). Positive (and some negative) correlations were also observed between fish catches in Moreton Bay and total flows from the Brisbane River (but not summer flows) (Bunn & Loneragan 1998).

There is similar evidence of a significant relationship between flows in the Fitzroy and Burdekin Rivers of central Queensland and both recreational and commercial fish catches in the area (Platten 1996). Increases in the catches of coral trout (*Plectropomus* spp.), cod (Serranidae), pearl perch (*Glaucosoma scapulare*), hussar (*Lutjanus adetii*), snapper (*Pagrus auratus*), red throat emperor (*Lethrinus* spp.) and Moreton Bay bugs (*Thenus orientalis*) were all correlated with increases in river outflow. The spatial scales at which such correlations were manifested are remarkable, with significant patterns observed in reef areas up to 70 km from the coast (Capricorn Bunker Group) (Platten 1996). The commercial catch of barramundi in the Gulf of Carpentaria also exhibits a close link to rainfall, and good catches of adult barramundi are often linked to strong freshwater flows in the years the fish were spawned (QDPI Fisheries, unpublished data).

Figure 7: *Total annual flow in the Logan River and total annual fish catch from three landing ports in Moreton Bay, for the period between 1945 and 1975*



Note: The overall trend of an increase in fish catch over time most likely represents increased fishing effort (not measured).
Source: (Loneragan & Bunn in press).

5.3 Likely causes of patterns

It is evident from the above analyses that there are strong links between the timing and magnitude of river flows and commercial (and recreational) catches of fish and crustaceans in coastal waters. However, the exact nature of the causal mechanisms for the observed relationships between river discharge and catches of fish and crustaceans is unknown.

5.3.1 Changes in catchability

Changes in physical and chemical conditions (eg. turbidity/light and salinity) of coastal waters brought about by the influence of river flows can have an immediate effect on catchability of fish and crustaceans, through:

- reducing the area of suitable habitat and restricting the distribution of populations, making them easier to catch in specific locations (eg. stenohaline marine species will be strongly influenced by salinity gradients);
- stimulating movement of species (eg. as a cue to migrate); or
- improving sampling efficiency of fishing equipment (eg. lower visibility may improve efficiency of nets).

As a consequence, increased catches may not necessarily reflect increased population sizes that may occur through enhanced recruitment or survivorship of juveniles (see below).

It is quite likely that some of the observed relationships between flow and catch of long-lived species of fish and crustaceans (noted above) are simply the result of improved catchability at high flows. For example, mud crabs and flathead do not contribute to the commercial fishery until they are at least 12 to 24 months of age. Similarly, many of the reef species off the central Queensland coast (see Platten 1996) may take longer than 24 months to enter a fishery. The immediate response to flows cannot be attributed to enhanced recruitment or survivorship of juveniles, which would result in a lagged response (see below). High catches of banana prawns in the Gulf of Carpentaria have been linked to a secondary effect of rainfall, which includes a lowering of salinity and increased riverine discharge. These changes are thought to act as a stimulus for emigration of juvenile banana prawns from their nursery habitats in mangrove-lined creeks and rivers to coastal waters (Vance et al. 1985; Staples & Vance 1986; Staples et al. 1995). Common peaks in mean monthly oceanic production of prawns off the Clarence, Evans and Richmond Rivers in New South Wales suggest a common enhancement of the seasonal emigration of *M. macleayi* from the three estuaries in November due to increased river discharge (Glaister 1978). The positive relationships between riverine flow and prawn catch in the Logan River may also arise from increased summer run-off stimulating the emigration of juveniles into the lower estuary and Moreton Bay (Loneragan & Bunn, in press).

High river flows also stimulate the downstream movement of mud crabs (Hill et al. 1982) and this could increase their catchability in waters of the lower estuaries and bays. It is worth noting that high river flows are known to stimulate the migration of golden perch (*Macquaria ambigua*) in the Murray-Darling River system (Cadwallader & Lawrence 1990), and may also be important to the production of similar river-based fisheries.

5.3.2 Recruitment

Variations in river flow may also lead to changes in catches of fish and crustaceans through changes in spawning activity (eg. lowered salinity may trigger spawning activity) or through changes in available habitat for spawning adults or for juveniles (eg. if juveniles use floodplain wetlands). This should produce a lagged effect in the observed response to flow (ie. response will only be evident once the cohort has entered the fishery).

Such a lagged effect has been noted between annual run-off and barramundi catch in the Gulf of Carpentaria (QDPI, unpublished data). High river flows may lead to a greater expanse of inundated floodplain habitat used by juvenile barramundi and, ultimately, to higher numbers of adults entering the fishery in subsequent years. Bunn and Loneragan (1998) also noted significant correlations between catches of some fish and crustaceans in Moreton Bay and lagged flows (ie. from one or two years previous). This could also indicate an underlying recruitment-driven process or the result of flow-driven changes in productivity (see below).

5.3.3 Productivity

Many studies have postulated that terrestrial material flushed by rivers into estuaries provides a significant input to estuarine food webs. For example, carbon from saltmarshes and mangroves was thought to provide an 'outwelling' of material that made a significant contribution to secondary production (eg. Lee 1995).

However, recent studies using stable isotopes have shown that the contribution of terrestrial carbon to estuarine and coastal food webs is in fact limited (eg. Haines & Montague 1979; Peterson & Howarth 1987; Newell et al. 1995; Loneragan et al. 1997). Nutrients exported from river systems, however, are known to have a significant influence on the productivity of estuarine and coastal ecosystems (eg. Newton 1996; Livingston 1997). Seasonal exports of nutrients stimulate phytoplankton and benthic microalgal production, which are important primary sources in coastal food webs (Fry & Wainwright 1991; Mallin et al. 1992; Newell et al. 1995; Loneragan et al. 1997).

Increased algal productivity (particularly of palatable forms), stimulated by high river discharge, may lead to increased secondary production and, ultimately, the production of higher order consumers (including species targeted for commercial and recreational fishing). Some commercial species such as prawns are short-lived and are caught in Australian fisheries at an age of about six months (Dall et al. 1990). For these species, nutrients transported downstream from catchments during high summer flows could stimulate primary productivity in estuaries and ultimately lead to increased production through high survivorship and/or growth of the juvenile stages. This may translate into increased catches later in the same year. For longer lived species, which do not enter the fishery until two or more years, a lag effect would be expected, similar to that described.

5.3.4 Additive effects

It is conceivable that one or more of these causal mechanisms may be operating at the same time. The effects of catchability and recruitment could be additive (or multiplicative) and may obscure the detection of simple relationships between fisheries production and flow. For example, low wet season flows may result in reduced catchability of a fish species and dampen the outcome of stimulated recruitment from a flow event several years previous. The fact that strong correlations have been observed between catches of some long-lived species and flows from the same year suggest that catchability may mask lagged responses due to changes in recruitment or productivity.

5.4 Best practice for assessing links between river flows and coastal fisheries

Irrespective of the potential causal mechanisms, there is no doubt that river regulation has the potential to affect coastal ecosystems, and assessment of the likely impacts on these 'receiving' waters should form an integral component of environmental flow studies. Existing databases on recreational and commercial catches of marine fish and crustaceans are a major source of biological information that can be used to assess flow-driven responses. However, not all may be suitable for the kinds of explorative investigations outlined here and the following recommendations are made as a guide for further studies.

5.4.1 Selection of target species

There may be several reasons for choosing particular 'target' or indicator species, including:

- commercial or recreational importance;
- conservation or scientific interest;
- high functional importance ('keystoneness', Hurlbert 1997); and/or
- representative of particular functional groups or life history strategies.

Inclusion of data on species of commercial or recreational importance provides an opportunity to estimate the potential economic impacts of flow diversion (DNR 1998b). Ultimately, the choice of species will be constrained by the availability of high quality data but it is worth selecting taxa that meet at least some of the above criteria.

5.4.2 Data quality and quantity

The quality (and, to a lesser extent, quantity) of available fisheries data remains one of the major constraints in the search for predictive relationships between flow and catch. Ideally, the fisheries data should include:

- catches caught from a known grid area (rather than landings at a fish market from unknown locations);
- catch data per month or quarter (rather than annual catches);
- catch effort (eg. number of boat days fished per unit time); and

- separation of data by species (rather than by common name groups).

Flow data should be obtained from the closest gauging station to the river mouth or simulated from known records of contributing tributary streams and rivers. At the very least, monthly total flows are required for the same period as the fisheries data and for several years previous (to enable investigation of lagged effects). Other features of the flow regime may also be considered (eg. maximum or minimum daily flows for each month or season). In the case of larger embayments or coastal regions with more than one contributing river, attributes of the combined flow data (summed for all rivers) can also be considered.

It is difficult to be prescriptive about the amount of data (ie. number of years) required to develop strong predictive relationships. Clearly, models generated from only a few years of data (ie. only a few data points) are unlikely to be robust. Ideally, the time period chosen for analysis should include years with a broad range of flows.

5.4.3 Life history attributes

The life history attributes of the target species must be considered when looking for potential relationships with flow. For example, what time of the year (season) is likely to be associated with spawning or migration of juveniles? How long do the species spend in various life stages (eg. as larvae or juveniles)? Flow records for these particular time periods should be chosen specifically to look for potential lag effects in catches.

5.4.4 Simple explorative analyses

As a first cut, simple (linear) relationships between flow attributes and catches of target species should be investigated (using appropriate transformations of the data where needed) (eg. Figure 6, p. 107). This may enable the development of predictive models which can then be used to quantify likely changes in catch (and potential economic costs) associated with changing flow regimes (see DNR 1998b). For long-lived species, relationships derived from catches and flows from the same year are likely to be due to variations in catchability. Time-lagged analyses (where flow data from previous years are analysed with catch data of the cohort as it enters the fishery) should also be undertaken to investigate potential effects of flow on recruitment or productivity. The latter should be targeted at key stages in the life history of the target species.

5.4.5 Multivariate analyses

As indicated, the effects of catchability and recruitment/productivity may be additive (or multiplicative) and obscure simple relationships. Multiple regression analysis or other multivariate modelling of catches and multiple flow attributes may also be required.

5.4.6 Cohort analyses and aging of surveyed populations

An additional approach, not illustrated in the above examples, is to make use of available size(age)-frequency data for long-lived target species of fish and crustaceans. Such data may be available from commercial catch records or specific research studies. Analysis of the size-frequency distribution may show that a specific year-class has either failed or, alternatively, has a disproportionately high abundance. These discrepancies in the age-frequency distribution may be traced back to the flow conditions at the time (eg. a year-class may be missing or under-represented because of unusually low wet season flows). This approach may help to identify potential flow-driven links in recruitment.

5.5 Priority areas for future R&D

It is apparent from this review 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 on 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, to improve the knowledge base upon which coastal fisheries are managed.

5.5.1 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; and
- 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-eastern 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.

5.5.2 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.

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6. Methods addressing the flow requirements of aquatic invertebrates

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6.1 Introduction

A large number of methods or methodologies has been developed to determine in-stream or environmental flows that aim to rehabilitate ecosystems in regulated streams and rivers. Tharme (1996) provides the most recent and comprehensive critical review of environmental assessment methods that have been developed worldwide. Other reviews specifically carried out for Australian rivers include Kinhill (1988) and Growns and Kotlash (1994).

Historically, studies of environmental flow methods have rarely been applied to invertebrate species or communities. This is possibly because invertebrates are not seen to be of significant commercial value. In-stream flow assessments have generally only been conducted for fish species.

The aims of this review are as follows.

1. Review techniques for assessing the flow requirements of aquatic invertebrates, so that water managers have the information necessary to decide which techniques are suitable for their situation, their limitations, advantages and cost-effectiveness.
2. Assist in the selection of a 'best practice' framework for the application of techniques for 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.

This chapter reviews the ability of different types of methods to be adapted for the purposes of use with aquatic invertebrates. Where specific methods have been used to determine the flow requirements of invertebrates in Australia, these are discussed in more detail. In addition, this chapter describes several current research projects and identifies how they address the research needs.

6.2 Methods based on the use of historical flows

The majority of methods based on historical flow records are poorly documented, possibly because they were developed in an impromptu manner in the beginning of the development of environmental flow allocation methods (Tharme 1996). Historical flow methods (also called fixed percentage or threshold methods) are often used to set 'minimum flows' to limit the off-stream use of water during periods of low flow via the analysis of flow duration curves. The most commonly used method based on historical flows is the Montana Method, which is also called the Tennant Method (Tennant 1976).

Historical flow methods are most appropriate during water resource development for identifying the amount of water that may be required as an environmental allocation. These methods can normally be used to develop a flow allocation in a short amount of time, they are simple and only require historical flow records from unregulated rivers. The main disadvantages of these types of methods are that there is no direct use of biological or ecological data, and a single value is often applied year round while minimum flows should probably be set on a month-by-month basis (Stalnaker 1981). The application of the Montana Method in Australia is difficult to justify because the flow patterns, biota and climatic conditions differ from those where the method was originally developed (Richardson 1986; Arthington & Pusey 1993; Tharme 1996). That little biological information is used in these types of methods means that their specific use for assessing the needs of invertebrates is questionable.

Other aspects of the unregulated historical flow record of a river may be applicable for the development of different flow allocation methods. This is because the historical record informs water managers and researchers of the type of hydrological regime that was present in the river before regulation, abstraction or future development. Historical flow records are now used in several methodologies that have been developed lately in Australia and South Africa, for example the Holistic Approach (Arthington et al. 1992), the Building Block

Methodology (King & Tharme 1993) and the Expert Panel Assessment Method (Swales & Harris 1995).

6.3 Methods based on relationships between physical habitat and discharge

Tharme (1996) suggested that the largest group of in-stream flow methods is that which utilises the relationship between simple measures of physical habitat and discharge. These methods are designed to assess various conditions of physical microhabitat at different levels of discharge. The most commonly used method of this type is the wetted perimeter method (Collings 1974, cited in Stalnaker & Arnette 1976). Methods based on wetted perimeter rely on the relationship between the wetted perimeter of a stream and discharge determined from transect-based measurements. Physical habitat and discharge methods do not appear to have been used in Australia for determining environmental flow allocations for invertebrates.

Tharme (1996) lists a series of advantages and disadvantages of these types of methods. The advantages include the following.

- They can be applied to any type of river providing that the requirements of the target species for depth, velocity, cover and so on are known.
- One of the principal types of approach, planimetric mapping, has the potential to produce the highest resolution results and is readily adaptable for application in the assessment of stream flows for a variety of purposes.

The disadvantages include the following.

- Wetted perimeter methods rely on information collected from a single cross-section. The transferability of results to other cross-sections along a stream may be limited.
- They produce a rather simplified picture of the in-stream flow requirements of aquatic biota.
- A major assumption is that a single hydraulic or other environmental variable can act as a surrogate for the flow requirements of various species at all stages in their life cycle. A particular environmental flow developed through using a method that focuses on a single requirement of one species may be detrimental to other life stages of that or other species.
- The suitability assessments of species requirements are highly dependent on the adequacy of the species-specific criteria that are used.
- These methods were originally developed for use with coldwater salmonid species (eg. trout) and the necessary information for their use with other species is scant.
- The degree of precision of the criteria employed in habitat-discharge methods decreases when data are extrapolated across a number of species and differing catchment conditions.

The disadvantages of the simple habitat-discharge methods for determining environmental flows outweigh the advantages. The two main disadvantages that would limit the use of these methods for use with invertebrates in Australia are that the information about the depth, velocity and cover requirements of invertebrate species is scant, and the flawed assumption that a single hydraulic variable can act as a surrogate for the flow requirements of various species at all stages in their life cycle.

6.4 The In-stream Flow Incremental Methodology

The In-stream Flow Incremental Methodology (IFIM) was developed in the United States and was designed to allow a complete evaluation of the effects of incremental changes in flow on a stream environment. During its development in the 1970s and 1980s, this methodology attempted to integrate planning concepts of water supply, analytical models from hydraulic and water quality engineering, and derived habitat versus flow functions (Stalnaker et al. 1995). The methodology produced simulations of the quantity and quality of 'potential habitat' resulting from proposed water development. Over the last 15 years, the IFIM has developed into a river network analysis that incorporates fish habitat, recreational opportunity, and woody vegetation response to alternative water management schemes.

The IFIM is meant to be implemented in five sequential phases: problem identification, study planning, study implementation, alternatives analysis, and problem resolution. However, the main component of the methodology, the Physical Habitat Simulation System (or PHABSIM), is used during the study implementation stage and is based primarily on specific field measurements that quantify changes in available

habitat as a function of increases or decreases in streamflow. The standard output from a PHABSIM analysis is a plot of available flow-related habitat, termed weighted usable area, versus discharge. It is the plot of weighted usable area versus discharge that is used by water managers to negotiate water use for regulated rivers.

PHABSIM is applied to specific study sites within a river. At the selected study sites a range of physical measurements, including water depth, water velocity and substrate, are made over a range of discharges. Measurements of these physical characteristics are made in a grid pattern along several transects placed over a study site. PHABSIM combines the information from the physical measurements and information on the habitat preferences of the target species to produce a suitability value for each grid cell throughout the study site. This procedure is repeated for a range of discharges to generate the plot of weighted usable area versus discharge. The results of a standard PHABSIM analysis are confined to the study sites where the physical measurements were made. However, extrapolation of the PHABSIM analysis can be made to an entire river using the IFIM.

6.4.1 Applying the IFIM to invertebrates

The IFIM has been recommended as the most promising modelling technique that could be used in Victoria to assess environmental flows (Kinhill 1988). The review by Campbell (1992) was carried out to provide information on the feasibility of using invertebrates to assess the environmental flow requirements. The aims of the review were:

- to conduct a literature search to identify freshwater invertebrates from Victorian streams likely to be closely dependent on current; and
- to develop a theoretical evaluation protocol that can be used to determine the suitability of species for use in environmental flow models and for obtaining model data.

The information Campbell presented on flow requirements of Australian invertebrates is scant. In 1992, water velocity preferences were only available for two groups of animals, simuliids (blackfly larvae) and sphenids (water pennies). Clear differences between the water velocity preferences of two species of simuliids were presented based on work by Horne and Bennison (1987) and Horne et al. (1992). The work involving water pennies (Smith & Dartnall 1980) showed some behavioural patterns of two species of *Sclerocyphon,* but the work did not investigate if there were differences between the species. Similarly, a review by Growns and Chessman (1995a) on the flow requirements of macroinvertebrate taxa living in the Hawkesbury-Nepean River system found scant information. Of the approximately 800 taxa known to occur in the river, Growns and Chessman (1995a) found information for the flow preferences of only 12 macroinvertebrate taxa, mainly blackfly larvae and chironomid (non-biting midge) larvae.

Since Campbell's review was published, there have been a number of other studies on the relationships between water currents and macroinvertebrates in Australia (eg. Barmuta 1994; Growns & Davis 1994; Growns & Chessman 1995b; Davies & Humphries 1995). A review or re-analysis of this information could produce a database of the flow preferences of many invertebrate taxa. If the IFIM was to be adopted in Australia as a method of determining environmental flows, it would be useful to compile all information available about the habitat preferences of various taxa in a central database.

Campbell (1992) suggested that IFIM models can be easily and usefully applied to stream invertebrates without any modification. However, he indicated that any invertebrate taxa that were to be used for an IFIM study should be sensitive to flow conditions and velocity, substratum type and depth. These taxa could be selected in two ways.

1. Select those taxa in a locality which have the strongest flow preferences.
2. Select taxa *a priori* by checking the ecology of invertebrate taxa known to occur at a site against a list of characteristics that would be desirable in an indicator taxon. The desirable characteristics would include flow dependence, wide geographical spread, easy identification and easy detection in the field.

Campbell acknowledged that it would be valuable to have water flow requirements for stream species that rely directly on currents to feed (obligate rheophiles, Ambuhl 1959), or the obligate flow exposure group (Growns & Davis 1994). However, Campbell also indicated that information about other taxa that are not so obviously current-dependent would also be valuable.

Campbell also discussed the use of stream hydraulic variables in environmental flow determinations. Campbell suggested that while it is clear that the distribution of invertebrates in streams is related to

environmental variables such as substratum type, stream currents and water depth, it is not these characteristics that invertebrates are responding to but to the types of hydraulic environments that occur near the stream bed. The hydraulic environment near the stream bed can be characterised by environmental variables such as shear stress and velocity, turbulence, Reynolds number and Froude number. These variables are related to and incorporate measures of depth, velocity and substratum characteristics. Campbell advocated the use of the hydraulic descriptors in predictive models such as the IFIM in a similar fashion as was originally suggested by Gore (1989). Growns and Davis (1994) demonstrated that near-bed hydraulic variables are better than the traditional IFIM variables (eg. depth or current velocity) in explaining the distribution and abundances of macroinvertebrates in streams in Western Australia. Growns and Chessman (1995b) demonstrated that near-bed hydraulic variables could be more efficient than traditional environmental variables for predicting flow preferences of aquatic invertebrates. These findings suggest that the incorporation of near-bed hydraulic variables may improve the usefulness of the IFIM.

Campbell (1992) concluded that stream invertebrates could be potentially used for monitoring the effects of changes in streamflow patterns and as a basis for constructing predictive models of these effects using the IFIM. The data that would have been necessary to use macroinvertebrates in a predictive model were not generally available in 1992. Campbell (1992) suggested that three areas of research needed to be addressed in order to use IFIM approaches for defining environmental flows in Victoria.

1. Examining the relationship between hydrological classifications of streams in Victoria and the invertebrate fauna.

   Campbell suggested that if different invertebrate communities exist in different hydrologically distinct streams, then the indicator groups might be useful for selecting taxa to use in IFIM studies. Marchant et al. (1994) classified the macroinvertebrate communities of eight river systems in Victoria. The main finding was that altitude was the main environmental variable associated with changes in macroinvertebrate communities, rather than river type. The inclusion of other river types in a classification of macroinvertebrate communities may discern different patterns. The information needed for this type of analysis may be available through the Monitoring River Health Program, where reference sites have been sampled throughout Victoria. An Australian-wide assessment of the relationship between hydrologically distinct rivers and macroinvertebrate communities could also be conducted using the data from the Monitoring River Health Program.

2. Defining which environmental variables are the best predictors of invertebrate distributions and how they can be measured simply.

   Although considerable amounts of information have been gathered since the review by Campbell (1992) on the benefits of using near-bed hydraulic descriptors to predict invertebrate distributions (eg. Gore 1989; Growns & Davis 1994), there has been less information on how hydraulic conditions can be measured simply. Barmuta (1994) recommended that in order to identify the influence of local flow phenomena, smaller than conventional benthic sampling devices need to be used. Barmuta (1994) found that there was no simple, empirical relationship between mean velocity of water flow and the maximum velocity found between bricks arranged in a geometric pattern in a stream. This means it would be even more difficult to predict local velocities from the average flow between rocks (in a normal stream) that are not arranged randomly and have different sizes and shapes. Accurate measurement of local currents (eg. flow travelling through a 1 mm^2 area) around objects in a flow is possible in laboratory flumes using either laser or acoustic doppler velocimeters. However, these instruments are not designed to be used in the field on a routine basis. Velocity meters that are capable of being used routinely in the field and of measuring the velocity of water in small volumes (through approximately 1 cm^2) are becoming more readily available. However, it remains to be determined if these small meters can still be used to accurately determine flow phenomena at a scale to which invertebrates may respond.

3. Obtaining the flow environment, water velocity and substratum requirements and preferences of stream invertebrates.

   At the time Campbell (1992) conducted his review there was little quantitative data available on flow

requirements of Australian stream invertebrates. As noted earlier, such information is now available on the flow requirements of a variety of invertebrate taxa. This information would need to be compiled into a standard format to be useful for use in IFIM studies. However, it remains to be determined if the information on the flow preferences of single taxa is site-specific, that is, if the flow preferences determined for one site can be used at other locations. One of the aims of a LWRRDC-funded project (see Section 6.9.2) seeks to address this concern.

Despite Campbell's conclusion that invertebrates can be used in an IFIM approach, he considered that there was a need to understand the issue of how to provide environmental flows at different ecological scales. Campbell (1992) considered that the question of scale arises because PHABSIM defines in-stream habitats that are large relative to the scale of processes to which invertebrates are likely to react, and small relative to whole catchments. Campbell defined four scales at which environmental flows need to be considered.

1. Regional scales to allow for different regional hydrological patterns, which could be addressed by developing a broader decision-making system that incorporates the IFIM.
2. Catchment scales to ensure that the reaches that are selected for study represent the stream types that are affected. Campbell suggested that this is a sampling problem and could be evaluated by comparing the results from several test sampling occasions. The IFIM overcomes this problem with the concept of 'representative reach', which defines the method for selection of study sites.
3. The reach scale, which is the scale at which the present IFIM methods are aimed and is most appropriate for fish.
4. The patch scale (in the order of m^2) which would include estimates of bed roughness and water velocity appropriate to the scale of invertebrates. Campbell suggested that this scale might require the incorporation of new parameters into existing models and comparing the results with those obtained when more conventional environmental variables are used.

6.4.2 The use of the IFIM in South Africa

In 1987, two major workshops were held in South Africa to assess the water requirements of the country's rivers. From one of those workshops, a study was commissioned on the Olifants River to initiate the establishment of one or more scientifically acceptable methods for the assessment of in-stream flow requirements in South Africa (King & Tharme 1994). The report had a variety of aims but those that relate directly to the IFIM include:

- to develop local expertise on the methodology through a research program of field work and computer training;
- to test and assess the methodology, present possible solutions to problems encountered, and suggest further research;
- to use the methodology to establish the in-stream flow requirements of the Olifants River; and
- to compare the results of the methodology investigations and a historical flow record approach and discuss their ecological and management implications.

This study was probably the first attempt to apply the IFIM in its entirety inside or outside the United States. King and Tharme (1994) applied the main component of the IFIM, PHABSIM, to three major zones of the Olifants River. They selected four fish and three invertebrate species to construct suitability index (SI) curves and weighted usable area graphs. The invertebrate species were chosen to so that they were present at all sites. They included the larvae of *Peloriolus granulosus* (Elmidae), *Rheotanytarsus* sp. (Chironomidae) and *Polypedilum ?articola* (Chironomidae). Based on the results of the PHABSIM analysis, King and Tharme (1994) recommended that discharges along the Olifants River should not fall below 1.0 $m^3 s^{-1}$ because this was the value at which the majority of the weighted usable area curves for different taxa began to decrease sharply with decreasing discharge. In contrast to the minimum flow requirement, King and Tharme (1994) identified that the use of the IFIM provided little information that could help determine the highest acceptable discharge. This was mainly because the different relationships of weighted usable area versus discharge varied in a way that did not appear to be related to channel shape or bankfull level.

King and Tharme (1994) identified 15 steps to implement the IFIM in a river system. They divided the 15 steps into 5 broad categories:

1. Steps 1–3: Introduction to the study river, and identification of study objectives, target species and study sites.
2. Step 4: Macrohabitat assessment.
3. Steps 5–8: Establishment of PHABSIM microhabitat study sites and collection of calibration data.
4. Steps 9–11: Collection and analysis of data on target species.
5. Steps 12–15: Running PHABSIM.

Based upon their experiences, King and Tharme (1994) identified the advantages and disadvantages of the use of the IFIM (see Table 7, page 121). The advantages mainly related to the way the methodology provides a structured and objective way of quantifying the response of biota to flow-related conditions in rivers. In addition, they considered that the methodology provided a scientific and logical framework for collecting the data required to quantify the responses of biota to stream discharge. However, King and Tharme (1994) suggested that the disadvantages of the IFIM outweigh the advantages. The disadvantages centre on the lack of description on how various components of the methodology should be interpreted and the difficulty in using the methodology software.

King and Tharme (1994) concluded that the IFIM could not provide a complete in-stream flow assessment in a way that was required in South Africa. The methodology was not designed to give a comprehensive recommendation on a modified flow regime that should be released from a dam for maintenance of the river downstream in some predetermined state. In addition, there are limited structural links between the methodology and the hydrological record of a river, and the historical flow records are not used to aid the final flow recommendation. The traditional use of the IFIM is to provide a description of the loss and gain of physical microhabitat with changes in discharge for one or more aquatic species. King and Tharme (1994) indicated that the methodology should be seen as one of many methods, not mutually exclusive, that could be used to determine the in-stream flow requirements of a river.

6.4.3 The use of the IFIM in Tasmania

The first published study to use the IFIM in Australia with macroinvertebrates as the target species was that of Davies and Humphries (1995). This was a three-year project conducted in the South Esk River basin in the north of Tasmania. The aims of the project as follows.

1. Delineate the environmental quality objectives for the Macquarie, South Esk and Meander Rivers that could be fully or partially managed by flow manipulation.
2. Obtain data on variables that could relate the potential for achieving these objectives to discharge at selected representative locations within the main river channels.
3. Provide a framework for assessing the risk of failure to achieve objectives at different discharges to be used in making trade-offs between environmental values and uses and abstractive water uses.
4. Make initial recommendations on irrigation season discharges for each river that would result in low or moderate risk of failing to achieve the proposed environmental quality objectives.

The study was not a strict use of the IFIM to recommend environmental flows. Rather, the IFIM was used to provide data for assessing the risk of failure to achieve specified environmental quality objectives at different discharges during the irrigation season. However, for the purposes of the study, the IFIM approach was used to conduct a full PHABSIM analysis that comprised:

- obtaining habitat use (depth, velocity and substratum) information for target fauna from field data;
- obtaining 'available habitat' data at representative study reaches at selected discharges;
- generating habitat preference curves for target fauna.
- using the field-derived 'available habitat' data in hydraulic simulations to extrapolate 'available habitat' data to discharges not measured in the field; and
- combining the measured and simulated habitat data with the habitat preference information to generate usable habitat area–discharge curves for selected taxa.

Table 7: *Advantages and disadvantages of the 15 steps required to use the IFIM, as identified by King and Tharme (1994)*

Category	Advantages	Disadvantages/Criticisms
Steps 1–3	The selection criteria are based upon sound scientific principles	Little practical guidance given on identifying the study area or defining the objectives. No information is provided on ways to design a study to assess flow requirements of invertebrates rather than fish. No information is provided on ways to combine information on individual indicator species to provide community level flow requirements. Limited information is provided on how to assess in-stream flows for a whole river system. The information needed for the criteria to select sites is impossible to obtain or obtainable only at high cost.
Step 4		Although this component is identified as a vitally important part of IFIM, it is not adequately explained and approaches for its implementation are mostly theoretical, with few practical guidelines. This component is not regularly applied elsewhere in the world and combining the PHABSIM results with macrohabitat variables to give a representation of the total habitat in a river is not performed. In addition, at present, given some of the difficulties, the justification and method for a link between the macrohabitat and microhabitat seem inadequate. This component appears to be introduced principally to safeguard the validity of the PHABSIM results because these are dependent on an assumed persistence in the channel morphology. The results from this component are limited unless information on the tolerance ranges of the target species is available.
Steps 5–8	This is the most straightforward and intuitively understandable component within IFIM. The methods used in IFIM to describe channel morphology and flow patterns are as good a means as any presently available to acquire the data for a small-scale ecological study.	The services of a river ecologist, a fluvial geomorphologist, an hydraulic engineer/modeller and surveyor are required to place the river transects required to gather calibration data.

continued

Table 7: *Advantages and disadvantages of the 15 steps required to use the IFIM, as identified by King and Tharme (1994) – continued*

Category	Advantages	Disadvantages/Criticisms
Steps 9–11	The development of selectivity index curves provides a structured and objective way of quantifying the response of biotato flow-related conditionsin rivers.	The difference between preference and utilisation curves can be vastly different when used with invertebrates because the small sampling errors can cause major differences between the two types of curves. This problem is more likely with invertebrates than fish because the larger number of data points can result in outliers that can bias the results. The information from this component cannot provide all the information needed to develop a comprehensive in-stream flow recommendation for an entire riverine ecosystem. Information generated for this component (SI curves) appears to have limited transferability between sites and over time. This means that to provide information for the requirements of a species over a year is demanding in terms of time and data requirements.
Steps 12–15		The hydraulic programs in the IFIM software are difficult to master and use well, even for an experienced modeller. There appears to be no text explaining the theoretical concepts incorporated into the models. The manual for PHABSIM is large and repetitious. The models have many redundant or invalid routines. The software does not allow metric units of measurement.

The ecological values that were included in the environmental quality objectives were:

- the maintenance and/or improvement of habitat quality (both physical and chemical) and habitat diversity for riverine fauna and flora;
- the maintenance and/or improvement of near-natural communities of native fauna and flora; and
- the maintenance of viable populations of flora and fauna known to be endemic to the rivers of the South Esk River basin or to have significant populations of high conservation value in that river.

Sixteen invertebrate taxa were chosen to be included in the biological variables derived for the risk assessment, so that their abundances and distribution were maximised among study sites. These taxa included *Atalophlebia australis* (a mayfly), *Tasmanocoenis* sp. (a mayfly), Baetidae (a mayfly), two species of Hydroptilidae (micro-caddisflies), one species of Hydrobiosidae (a caddisfly), *Taschorema asmanum* (a caddisfly), Velesunio *mortonicus* (a bivalve mollusc), *Rivisessor gunnii* (a gastropod mollusc), Chironomidae larvae, Elmidae adults and larvae (riffle beetles), Hirudinea (leeches), Amphipoda (scuds) and Hydracarina (water mites). Weighted usable area–discharge curves were generated for these taxa at the sites where they occurred within the South Esk basin.

Assessment criteria were established to judge the degree of risk of failure to comply with the ecological values in the environmental quality objectives. The change in habitat between a range of flows and the pre-irrigation median flow was calculated for a series of biological variables, which included the invertebrate information. The risk level was then ascertained for each variable at a range of discharges using professional judgement. A series of conclusions was then drawn about the level of risk to the environment associated with various flows during the irrigation season. For example, Davies and Humphries (1995) stated that sustained flows of less than 2 m^3 sec^{-1} in the South Esk River are thought to pose moderate to very high risks to a range of ecological and fishery values.

Davies and Humphries (1995) successfully used an IFIM approach to achieve the aims of their study. The PHABSIM analysis provided the information necessary to determine the risk of providing various modified flow regimes in three rivers. However, the study was labour-intensive, requiring a large field work component. A labour-intensive study is necessary using PHABSIM because of the amount of biological and hydraulic information necessary. Davies and Humphries (1995) conducted a full PHABSIM study at 6 sites for 16 invertebrate taxa and two fish species within 3 years. Environmental flow determinations for a single river based on a single target species would take less time providing that the hydraulic measurements required at a series of different discharges could be completed in a short period.

6.4.4 Difficulties in using the IFIM to assess the in-stream flow requirements of macroinvertebrates

Both King and Tharme (1994) and Davies and Humphries (1995) comment that the collection of invertebrate data for the IFIM is more expensive than for fish because more samples are required. The sorting and identification of macroinvertebrates also adds to the cost. In contrast, fish can normally be identified in the field. However, many invertebrate taxa will occur in one benthic sample, so that a series of samples collected from one site will provide enough information to develop SI curves for a number of species, effectively reducing the cost per species.

Another problem associated with the application of the IFIM to macroinvertebrates in Australia might be the lack of transferability of data between studies, for two reasons. Firstly, different taxonomic levels are often used between studies, for example, King and Tharme (1994) used species level identification whereas Davies and Humphries (1995) used different taxonomic levels for different taxa. Unless species level identifications are used consistently in every study carried out using the methodology, the data would not be transferable between studies. However, if it can be demonstrated that all species within a genus or family have the same habitat requirements, then data on common taxa could be transferred between studies. Secondly, the high degree of endemism of aquatic invertebrate species in Australia may mean that habitat selectivity curves must be established for individual species in many different rivers.

The use of family level identification of macroinvertebrates may assist in the ability to transfer water flow assessments from one study system to another. However, transferability will be limited because:

- currently available information suggests that different species within the one genus or between different genera in the same family are likely to have different flow preferences – in this case, the combining of data

from different taxa into a family level flow preference would effectively broaden the range of flow preferences; and

- different species in the same family are likely to occur in different rivers and because they may have different flow requirements, the use of family level data may lead to spurious results in the other river.

There are obvious advantages to using habitat preference curves established from previous studies to reduce costs of future studies. However, the use of SI curves derived from other sites is based on the assumption that the same species has the same water flow requirements in different streams. This assumption could be incorrect because a number of factors, such as food availability, competition or predation, may influence the flow requirements of a species at a site. If these factors and processes are not present in a different river then the flow preference of the species may change (James Gore, Colorado State University, pers. comm.). A LWRRDC research program is testing the similarity of invertebrate SI curves between sites in streams near Sydney (see Section 6.9.2).

The main aim of PHABSIM is to identify the available habitat of target species with increasing discharge. Campbell (1992) suggested that PHABSIM could be used with invertebrates if indicator species were chosen based on specific criteria. However, invertebrates are probably the most diverse biotic group occurring in fresh waters. The use of one species at a site to indicate the flow conditions that are required for all invertebrate species occurring at the same site, which may vary between 30 to 500 taxa depending on the river (Growns & Growns 1997), is questionable. If the water flow requirements of many species could be incorporated into a weighted usable area–discharge curve, the use of the IFIM and PHABSIM may be more amenable for invertebrates. King and Tharme (1994) suggested that one of the limitations of the IFIM was that information on different species could not be used to create a single weighted usable area curve. In addition, the use of multiple-species weighted usable area graphs may be limited because the large number of species at any site may mean that the weighted usable area is maximised over a large range of discharge levels.

6.5 Methods for flushing flows relevant to invertebrates

Flushing flows can be an important component of an environmental flow allocation for a regulated river (Reiser et al. 1989). Flushing flows could be important for a variety of reasons (Tharme 1996), but for macroinvertebrates the removal of fine sediment following a large flow event may be the most important. Fine sediment particles fill gaps between substratum elements. The filling of gaps in the substratum may reduce habitat heterogeneity for macroinvertebrates, reduce oxygen availability in the lower substratum, and isolate the hyporheic zone. Other important ecological aspects of flushing flows for invertebrates may include the rearrangement of substratum particles and ecological processes involved with the reconnection of floodplain habitats with the main river channel. However, the importance of flushing flows may alter with river type, depending on the natural hydrology and substratum characteristics.

There are currently no standard methods for determining appropriate magnitudes, timing, frequency and duration of flushing flows (Tharme 1996). The possible need for flushing or channel maintenance flows among different river types throughout Australia should be documented so that river management agencies can take into account these flow types in environmental flow allocations, if required.

6.6 Methods for migration/ movement requirements of invertebrates

In her review of environmental flow allocation methods, Tharme (1996) did not describe any flow types that may be relevant to the migration or movement requirements of plants or animals. This suggests that there are no techniques available to describe the flows appropriate for invertebrate movement. These types of flow may be applicable to invertebrates because, although some benthic invertebrates are relatively sessile, many invertebrates move considerable distances during their life through a phenomenon termed 'drift'. Drift is the downstream movement of benthic macroinvertebrates in the water column. Aquatic invertebrates may use drift as a method of dispersal, escape from predation, or as a way to locate better food sources (Brittain & Eikeland 1988). However, the actual role and importance of

invertebrate drift in the ecology of rivers and streams is unknown.

The relationship between drift and discharge is complex and other factors appear to alter the relationship. Increases in discharge or water velocity generally lead to increased drift, especially during spates (eg. Crisp & Robson 1979; Bird & Hynes 1981). However, a phenomenon termed 'catastrophic drift' can occur where very large numbers of animals enter the water column after a substantial decrease in discharge, such as after the stopping of flow in a regulated river (Minshall & Winger 1968; Pearson & Franklin 1968; Radford & Hartland-Rowe 1971).

The relationship between drift and discharge also appears to be different for individual species. Brittain and Eikeland (1988) suggested that certain taxa such as the mayfly *Baetis* sp. and the amphipod *Gammarus* sp. seek protection within the substratum during floods so that their numbers in the drift may decrease with increasing discharge. Statzner et al. (1984) showed that the drift of some taxa showed a positive relationship with flow, some a negative one and some no relationship to flow in a stream in Africa.

Other factors such as water temperature can alter the relationship of drift to discharge. Williams (1990) concluded that minimum water temperature was more influential than discharge in influencing the total amount of drift occurring in a stream in Ontario.

Allocating a certain flow for invertebrate movement is of questionable value, no matter what method is used to derive a particular allocation. This is mainly because the ecological role of drift remains uncertain. Flows could be provided for particular species, however, the role of drift would have to be considered in the overall population dynamics of that species.

6.7 Methods for addressing water quality issues relating to invertebrates

Tharme (1996) provided a critique of models and methods necessary for assessing in-stream flows for water quality purposes. Water quality modelling is generally the way that the water quality needs of streams and rivers are considered. The models mainly predict the effects of alterations in discharge on a range of water quality variables. However, the methods that are described by Tharme (1996) do not specifically relate to the water quality requirements of macroinvertebrates. In addition, none of the models or methods described by Tharme (1996) has been used in Australia for the specific purpose of maintaining invertebrate communities or populations.

Water quality is an important aspect for the maintenance of invertebrate populations in streams. Although the methods that Tharme (1996) described may be appropriate for setting levels of flows that would maintain invertebrate populations, the specific water quality objectives that would need to be achieved to maintain invertebrate communities are not currently clearly defined. The Australian and New Zealand Environment and Conservation Council (1992) provided water quality guidelines for fresh and marine waters. However, criteria for the protection of aquatic life are defined without specific reference to invertebrates. Different invertebrate taxa have different tolerances to the same pollutants (Chessman et al. 1997) and the information necessary to develop criteria (eg. toxicity levels) may be available only for particular species for some pollutants, for example, species used in toxicity testing. The provision of an environmental flow to achieve water quality criteria appropriate for one species may not provide conditions suitable for other invertebrate species.

There are many chemicals and nutrients involved in providing adequate water quality. High concentrations or levels of many environmental variables may cause deterioration of the water quality required for most invertebrates, but the level at which different chemicals become toxic will differ between species. The possible dilution effect of additional water in a river derived from a specific flow allocation may alter the toxic effects of only one of a series of chemicals.

The development of specific environmental flow methods to provide adequate water quality for invertebrates would be very complex. This is mainly because the provision of a flow allocation to provide adequate water quality for invertebrates is an indirect effect and the responses of invertebrates will be varied. However, if an environmental flow to a river is to be provided from an existing water source, such as a dam or sewage effluent, then the question of the quality of the water to be released arises. The offtakes of many of the dams in Australia are situated far below the water surface and the water can be colder, contain less oxygen than surface waters and possibly have high concentrations of particular metals. Sewage effluent is often treated for the removal of nutrients before it is released to a river, but the levels of water quality variables often exceed those of

the receiving water. An increase in the concentrations of certain chemicals (eg. metals or pesticides) through sewage effluent disposal can cause deterioration of the aquatic ecosystem. Water quality issues concerning invertebrates would be better addressed through water quality control programs, not through the provision of specific flow allocations.

6.8 Other methods

6.8.1 Expert Panel Assessment Method

The Expert Panel Assessment Method has been applied in seven circumstances in Australia since it was first developed by Swales et al. (1994). However, one of the final reports is still in a draft form and was not available for this review. Aquatic macroinvertebrates have been included in all the expert panel studies to date because of the interdisciplinary nature of this method. The inclusion of macroinvertebrates has also been based on the recognition that invertebrates act as ecological indicators of riverine health and many invertebrate species require suitable in-stream flows for the completion of their life cycles.

A detailed review of the Expert Panel Assessment Method has been undertaken by the Centre for Water Policy Research (CWPR 1996). This section details how invertebrates have been incorporated into the method and describes the assumptions used to draw conclusions about environmental flows. It also identifies differences and similarities between the invertebrate components in each application of Expert Panel Assessment Method. The expert panel assessments are presented in chronological order.

6.8.1.1 The original expert panel approach

The Expert Panel Assessment Method was initially tested by Swales et al. (1994) and described in full by Swales and Harris (1995). In order to test the method, Swales et al. (1994) compared the recommendations from an expert panel with those of two other methods for assessing in-stream flow requirements – the stream flow history analysis method and the physical habitat assessment method. The expert panel consisted of three river ecologists, a fish biologist, a stream invertebrate ecologist and a fluvial geomorphologist. A range of four streamflow releases representing the 80th, 50th, 30th and 10th flow exceedance percentiles were made from Chaffey Dam into the Peel River in New South Wales. One study site was situated five kilometres from the dam wall and the expert panel was asked to assess the suitability of each flow percentile as an environmental flow to maintain fish survival, recruitment and abundance. The panel member's assessments were made visually, based on experience in the field of specialisation and professional judgement. The use of invertebrates in this study was limited to a judgement of how they would assist the survival of fish in the river. Swales et al. (1994) considered that the most reliable estimate for an environmental flow was based on the streamflow history analysis method because it was based on natural streamflows. They suggested that the most valuable role for the expert panel process was in assessing and validating environmental flow regimes obtained using other in-stream flow methods.

6.8.1.2 Snowy River study

The Snowy River Expert Panel was commissioned by the Snowy-Genoa Catchment Management Committee to assess the environmental flow requirements of the Snowy River below Jindabyne Dam. The aquatic invertebrate expert was Dr Sam Lake (Cooperative Research Centre for Freshwater Ecology, Monash University).

The brief of this expert panel was as follows.

1. Identify the environmental parameters that are currently influencing the ecological functioning of the Snowy River.
2. Assess the changes to the river from catchment development and the consequences for the ecological functioning of the river.
3. Identify critical environmental thresholds with the flow regime to address the ecological functioning of the Snowy River below the Snowy Mountains Scheme.
4. Develop a set of recommendations for flow management to maximise ecological benefit.
5. Recommend a strategic environmental flow research program.

Lake (1996) provided a description of the fauna present in the river based upon a brief sampling at five locations along the river. He suggested the possible effects of river regulation on the aquatic invertebrate fauna and identified the mechanisms that may have caused conditions that are favourable to the present fauna but were changed from the condition of the pre-regulated river. The mechanisms that were identified by Lake to cause a change in the fauna included:

- organic pollution created by discharge from Cobbin Creek, combined with low flows in the Snowy River;
- a shift in habitat from running water to standing water, causing a fauna normally associated with standing waters; the fauna appears to be a secondary one responding to conditions of severe flow regulation;
- a decrease in diversity of macroinvertebrates in riffles and runs caused by low flows and a large amount of unstable relatively featureless habitat; and
- the high variability in water temperature and oxygen availability, causing a shift in the fauna from a biota normally found in a large montane river.

From the identification of the mechanisms causing the shift in fauna normally expected in such a river, Lake (1996) suggested that the lack of water in the upper river reaches was the main cause of environmental disturbance and so an increase in the baseflow was needed to inundate suitable habitat, dampen water temperature extremes and dilute poor water quality inputs. He also suggested that major water events such as floods were required to create suitable habitat, and that in the lower river a sufficient baseflow was required to dampen temperature extremes.

The description of the effects of the dam on the fauna was based principally on habitat alteration and the main purpose of the recommended flows appears to be to re-create habitat within the river. Environmental flows were also recommended to improve water quality, in particular, water temperature.

Overall, the Expert Panel Committee provided four recommendations concerning changes in the present management of Jindabyne Dam. The recommended minimum daily, seasonal and high flows were based on the historical (pre-regulation) flow conditions.

Boulton (1996) provided a review of the methods and conclusions reported by Lake (1996). The main criticism given by Boulton (1996) that specifically related to the invertebrate component of the expert panel report was that insufficient detail was provided on how the invertebrates were sampled. The lack of detail on the sampling method used was criticised because without this information it was difficult to provide a better review and difficult to repeat the sampling if necessary. Boulton (1996) also criticised the level of identification of macroinvertebrates provided by Lake because the lack of taxonomic resolution in sections of the report would prevent a detailed assessment of water quality by readers of the report. However, Boulton (1996) agreed with the assessment of Lake of the likely causes of the altered invertebrate fauna and with the environmental flows recommended. Boulton also agreed with Lake's assessment that the loss of flow variation has adversely affected the life cycles of the aquatic fauna in the Snowy River, but indicated that such assessments should be supported by references to appropriate literature.

6.8.1.3 Barwon-Darling River study

The Department of Land and Water Conservation in New South Wales commissioned the Barwon-Darling River Expert Panel to determine environmental flow requirements in the Barwon-Darling River. Dr Fran Sheldon (University of Adelaide) and Dr Terry Hillman (Cooperative Research Centre for Freshwater Ecology, Murray-Darling Freshwater Research Centre) were included in the expert panel as invertebrate ecologists. The tasks given to the panel were as follows.

1. Make a qualitative assessment of the impact of consumptive water use and upstream flow regulation on the biological and physico-chemical components of the in-channel environment.
2. Identify the type and relative importance of relationships, whether casual or symptomatic, between specific aspects of the flow regime and changes in the biological and physico-chemical environment.
3. Make a determination of those aspects of the flow regime that are most critical to maintaining and or improving river 'health'.
4. In relation to 3, identify where water management actions are needed to:

- protect the critical elements of low flows (ie. < 2,000 ML d^{-1}) that are important for in-stream ecosystem health;
- protect the ecologically important elements of flows between 2,000 ML d^{-1} and 20,000 to 30,000 ML d^{-1}, but with an emphasis on less then 12,000 ML d^{-1}; and
- redress specific ecosystem damage.

5. Recommend a strategic environmental flow research program that will provide quantitative or semi-quantitative data for the development or refinement of flow management rules to aid in-channel environmental protection.

The invertebrate data used to assess environmental flows in the Darling River were collected in 1990 by Dr Fran Sheldon. Quantitative samples were taken at 14 sites along the length of the river. The survey of the invertebrates showed that the main habitats within the river, such as the main river channel, backwaters, billabongs and creeks, and the small habitats such as wood and aquatic plants had their own distinct invertebrate assemblage. Thoms et al. (1996) indicated that because each habitat type had a distinctive invertebrate assemblage, the diversity and range of habitat types present at each site could be used as indicators of the diversity of the overall invertebrate assemblage.

Macroinvertebrates were included in the expert panel assessment by judging which aspects of the river hydrology most affected the physical habitat features at different channel capacities. Similar assessments were also made for other ecosystem components, including fish, macrophytes and trees. The features of the natural hydrograph that were considered most important to ecosystem health were assessed by finding which hydrological features occurred most often among the assessments for individual ecosystem components. The expert panel then made recommendations for management options and environmental flows by assessing the changes in important hydrological features that have occurred through development (eg. water abstractions and diversions). Pre-development flows within the Barwon-Darling River were estimated using a flow simulation model.

6.8.1.4 Wollondilly River study

The Wollondilly River Expert Panel was organised by the Healthy Rivers Commission in New South Wales. The draft final report was not available for this review.

6.8.1.5 Murray River study

The Murray River Expert Panel was commissioned by the Murray-Darling Basin Commission, and Dr Phil Suter (Cooperative Research Centre for Freshwater Ecology, La Trobe University) acted as the invertebrate specialist. Only a draft final report was available for this review.

The overall aim of the expert panel was to identify changes in river operations for the Murray and Lower Darling Rivers that should result in general improvements in the environmental condition of these river reaches, while considering the current needs of existing water users.

The study had the following major and project tasks.

Major tasks

1. Identify the major characteristics of a flow regime which would maintain or restore ecological values.
2. Assess the impact of the current operating regime on biodiversity and ecological processes.
3. Identify changes in current management which should improve ecological values.
4. Set priorities on the possible management actions according to their predicted environmental benefits and a broad assessment of their ease of implementation.

Project tasks

1. Establish the current habitat types and the condition of these habitats, including documenting changes from the likely natural state.
2. Identify the major aspects of the flow regime which would maintain or restore ecological habitats and/or communities and thus set long-term flow objectives for each reach.
3. Identify current threats to each habitat type and/or community, including those related to flow and those related to other factors.
4. Identify management actions which could be taken to alleviate threats and improve ecological values.
5. Set priorities on management actions from an ecological perspective.
6. After discussion with river operators regarding the feasibility of the range of management actions, set overall priorities for management actions. This would include a range of short-term, medium-term and long-term objectives for the management of the river which would improve its ecological condition.

There appear to be no direct recommendations specifically related to macroinvertebrates made by the expert panel. Macroinvertebrates were only addressed in the report in relation to physical habitat within the river. The expert panel suggested that the invertebrate fauna could be returned to a more natural condition by increasing the variability of flows within the river. It suggested that the increased flow variability would increase bank stability, improve aquatic macrophyte growth and increase the types of biofilms occurring on

snags. The baseline information regarding invertebrates that was used to draw these conclusions was based on the monitoring program that has been taking place since 1980 (see Bennison & Suter 1990) and unpublished data from La Trobe University.

6.8.1.6 Campaspe River study

The Campaspe River Expert Panel was commissioned to provide ecological information for environmental input into the Bulk Entitlement Process in Victoria (Kelly 1996). The purpose of the environmental input was to ensure that the current environmental values of the river are maintained through the Bulk Entitlement Process (Kelly & Donald 1997). The final report from the expert panel is still in draft form.

Dr Richard Marchant (Cooperative Research Centre for Freshwater Ecology) was the invertebrate ecologist on this expert panel. Its aims were as follows.

1. Identify the major features within each reach that require protection from current and envisaged threats.

   This included an assessment of:

   - major biological habitat types/communities/ species, both in-stream and riparian;
   - condition of major habitat types;
   - major geomorphological influences;
   - stability of substrate; and
   - associated wetlands.

2. Identify the key factors and major characteristics of a flow regime required to maximise, or impact on, biodiversity and ecological processes. This included an assessment of low flow, regulated flow and flood flow requirements as well as consideration of the requirements of associated wetlands. The flow requirements of individual species were also examined.
3. Assess the impact of the current operating regime on biodiversity and ecological processes. The difference between the current and likely natural regime was examined in terms of the positive or negative changes that have occurred.
4. Identify changes in current management that would improve ecological values. A range of flow recommendations applicable to different time scales were formulated to include low flow, regulated flow and flood flow requirements, as well as wetland watering requirements.
5. Predict likely environmental benefits under a range of water management and allocation scenarios and set priorities for management actions. This included consideration of the impacts on other users and financial cost of any works required or changes to operating regime.
6. Make any recommendations on the integrated management of the river as a whole.

Two sites on the Coliban River, a tributary of the Campaspe River, and ten sites on the Campaspe River were examined by the expert panel. Invertebrate samples were taken at six of these sites. Samples were collected with a hand net but no details were provided of specific habitats sampled, that is, if all representative habitats were included. However, sampling of all habitats may have been difficult, given the limited amount of time spent at each site. Each sample was placed in a white tray and the animals were identified as far as possible with the aid of a 10x-hand lens.

For each of the six sites, a detailed list of taxa was given and potential threats were identified, for example, at one site on the Coliban river the presence of a slug of sand was identified as the result of anthropogenic disturbance with the potential to disrupt the current invertebrate community. A brief summary was provided of the major habitat types present in each reach and species of aquatic macrophytes were identified.

The presence of diverse communities at the first three sites was linked to the fact that suitable habitat was present at those sites and Marchant considered that this had a much greater influence on these communities than did differences in flow.

Marchant (1996) concluded that the macroinvertebrate communities at the five sites examined in detail (one site above Lake Eppalock and four below it) were similar to each other. He suggested that this observation was consistent with data collected by the Victorian Environmental Protection Authority between 1990 and 1993. Marchant stated that as the flow regimes are clearly different in the river sections that were examined, it is reasonable to conclude that the current discharge patterns in the Campaspe are not having a measurable impact on macroinvertebrate communities. Based upon his findings, he makes only one recommendation concerning the flows released from Lake Eppalock, that is, at the end of the irrigation

releases the flow should be reduced slowly, over days or weeks rather than hours.

6.8.1.7 Murrumbidgee River study

This study was commissioned by the New South Wales Environmental Protection Authority and was conducted as a preliminary study of the environmental flow needs of the upper Murrumbidgee River. The aim of the study was for the expert panel to provide a reasoned assessment of the current environmental flow requirements of the Murrumbidgee River and provide recommendations for further investigations.

The invertebrate component of the expert panel was based upon a brief (half-hour) examination of the invertebrate fauna at five sites on the Murrumbidgee River. Two habitat types were sampled (slow and fast) using a hand-held dip net. Invertebrates were placed in a white sorting tray and the animals identified as far as possible using a 10x-hand lens.

Based on the occurrence of the types of animals occurring at each of the five sites, Marchant (1997) concluded that the upper Murrumbidgee River was not severely degraded. Some of the sites within the river probably suffered intermittent disturbances such as erosion, nutrient addition or physical degradation, but Marchant suggested that these did not appear to have a long-term impact on the invertebrate communities. Marchant (1997) concluded that the current reduction in flow at these sites did not appear to have an obvious impact on the composition of the invertebrate fauna and that improved low flow regimes and flushing flows may improve habitat quality and habitat diversity for macroinvertebrates.

The recommendations generated by the expert panel did not directly use the information generated by the macroinvertebrate sampling. Three of the recommendations made by the panel were partly based on the assumption that they would increase the available habitat for invertebrates. These recommendations included that a minimum depth of flow should be maintained in certain parts of the river, that releases should be made to mimic natural flow variability, and that an annual fresh should be released in spring.

6.8.1.8 Common elements of expert panel assessments

The use of the Expert Panel Assessment Method has changed from that proposed by Swales and Harris (1995). The method was first used to assess the environmental flow requirements of fish, with separate assessments made for a range of release volumes from a specific dam. Since then, the expert panels have been used to provide water management authorities with preliminary assessments of the environmental flow requirements of particular river systems. This factor is common to all the expert panel assessments. However, the goals of each expert panel have varied according to the needs of the commissioning water management agency.

The inclusion of invertebrates in the expert panel process has been limited to using invertebrates to provide an indication of environmental health or to identify how the river ecosystem has changed due to flow regulation. At no time have assessments been made of the relationship between the abundances and/or diversity of invertebrates and different release strategies using an expert panel.

For each expert panel the assessment of invertebrates has been done using either minimal sampling at between 6 and 12 sites on a watercourse or using invertebrate information obtained from earlier studies. In most of the expert panel studies it is assumed that there is a positive relationship between habitat diversity and biological diversity at the study sites. Most invertebrate ecologists in the expert panels have commented that one effect of river regulation has been to decrease habitat diversity and that this would lead to a decrease in faunal diversity.

Professional judgement is made by the invertebrate ecologist on the state of the invertebrate community, the possible reasons for any changes to invertebrate communities from altered flow regimes, and the possible remedial benefits of environmental flows. The overall recommendation of the expert panel is then made by incorporating the recommendations of the invertebrate ecologist with the recommendations of other panel members from other scientific disciplines via a review of the information provided by the entire panel. The recommended flows provided by the expert panels are based on aspects of the natural hydrograph (or simulated natural hydrograph) of the particular river before regulation.

To summarise, the common elements of the expert panel applications are as follows.

1. The field assessments are done over several days.
2. Assessments of environmental flows are taken in conjunction with scientific disciplines other than invertebrate ecology.
3. Brief invertebrate sampling of sites is usually carried out at the river or data collected previously from the river are used.

4. The invertebrate information is used to assess the health of the regulated river.
5. It is often assumed that there is a positive relationship between habitat diversity and biological diversity at the study sites.
6. The final flows recommended by the expert panel are based on aspects of the natural hydrograph (or model thereof) of the particular river before regulation.

6.8.2 Correlation of hydrological parameters with macroinvertebrate community structure

Growns and Growns (1996) were commissioned by the Sydney Water Corporation to provide recommendations on experimental modification of flow regimes in the Hawkesbury-Nepean River system. The work was required because the Sydney Water Corporation needs, as part of its operating licence, to develop an environmental impact assessment for environmental flow regimes in the Hawkesbury-Nepean River, Woronora River and Shoalhaven River. A monitoring program was established to identify the effects of current water management and dams on the benthic diatom assemblages and the invertebrate fauna of the Hawkesbury-Nepean River (Growns 1997). The biological information from the monitoring program was related to the changed hydrology in the Hawkesbury-Nepean River system to provide information to the Sydney Water Corporation for an experimental environmental flow release. The aim of the study was to determine which aspects of the natural hydrographs had changed due to the operation of the water supply system, and relate these changes to changes in the river biota caused by regulation. An experimental flow regime was then designed to alter the flow regime at regulated sites in a manner that would restore aspects of the natural hydrograph that were important to the macroinvertebrate communities.

Growns and Growns (1996) examined the environmental flow requirements of three invertebrate communities (pool rocks, pool edge and riffle) and benthic diatoms in the Hawkesbury-Nepean River system. Macroinvertebrates and diatoms were sampled from 13 unregulated sites and 10 regulated sites in the Hawkesbury-Nepean River system in autumn and spring 1995 using rapid assessment sampling. The flow requirements of each macroinvertebrate community were examined by correlating 12 hydrological descriptors with the biological information using Mantel's tests (Manly 1987). The 12 hydrological variables were calculated from the four-year antecedent daily flow record at the majority of sites. The 12 hydrological variables included the maximum, median and minimum daily flows, the number of days with no discharge, flood frequency and duration, a baseflow index, coefficient of variation of daily discharge, a rate of change index, and the predictability, constancy and contingency indices described by Colwell (1974). The 12 hydrological descriptors were calculated for 2, 4, 6, 12, 24 and 48-month time periods before an autumn and spring sampling occasion.

Growns and Growns (1996) concluded that the relationships that were observed between the macroinvertebrate communities and the hydrological descriptors were complex and they varied between the different biotic assemblages. One clear result was that the biota were most strongly related to the hydrological descriptors calculated for relatively long antecedent time periods, from six months to four years. In addition, it was apparent that different types of biota responded to different aspects of the hydrograph. Thus no one overriding characteristic of the flow regime was identified as being of paramount importance to the biota.

Growns and Growns (1996) suggested that to modify a regulated flow regime, several hydrological characteristics would have to be addressed simultaneously for the biota to respond. The authors suggested that the most effective way that this could be achieved would be to release a certain percentage of the water that entered reservoirs in a natural pattern. This would have the advantage of mimicking the flows that were occurring in the unregulated streams. In addition, if flows were mimicked in a more natural pattern, the flow descriptors estimated at regulated sites would become more similar to the estimates of flow descriptors at unregulated sites.

The method of relating hydrological conditions to the invertebrate communities used by Growns and Growns (1996) is valuable because it can relate the effects of changed river flow on a whole community occupying a habitat, not just on an individual species. However, the technique could be modified to examine individual species. It does not rely on subjective opinions but provides detailed relationships between the biota and hydrological conditions in a single river system.

6.9 Studies in progress

6.9.1 The Campaspe project

This project aims to determine the effects of manipulation of flows from Lake Eppalock to provide an environmental flow for the Campaspe River in Victoria. Excess water is released from Lake Eppalock or it spills in most years. The Cooperative Centre for Freshwater Ecology has negotiated the manipulation of the dam's operation so that 25% of in-flow to the dam is released during the non-irrigation period of May to October (Humphries & Lake 1996). However, the experimental release will only be done provided the dam is 64% full (Dr Jane Growns, Cooperative Research Centre for Freshwater Ecology, Murray-Darling Freshwater Research Centre, pers. comm.). The invertebrate component of the study relies on a BACI (Before-After-Control-Impact) type design with invertebrates sampled for one or two years before the change in dam operation and three years after. The invertebrate study is in its first year and the recommended flow releases are proposed to begin in 1999.

Two components of the macroinvertebrate community are being examined (Jane Growns, pers comm.). The main hard substrate in the Campaspe River is coarse woody debris or snags, mainly from river redgum trees (*Eucalyptus camaldulensis*). The invertebrate snag community is being quantitatively sampled at two sites in each of three river sections at varying distances from the dam as described by Humphries and Lake (1996). Snag communities are also being sampled at three sites in the nearby Broken River to enable a comparison to be made of the results from the Campaspe River.

In addition to the snag communities of these two rivers, the shrimp community (decapods of the genera *Macrobrachium, Paratya* and *Caradina*) is being sampled at each of the nine sites in the two rivers to examine possible beneficial aspects of an environmental flow on its life histories.

6.9.2 LWRRDC environmental flow projects

Fourteen environmental flow R&D projects were commissioned by LWRRDC under the Environmental Flows Management Initiative of the National River Health Program. They covered a range of themes including techniques, storage management, flow impacts on biota, flows and nuisance algae, and fish and wetland flow requirements. Three of the projects examine environmental flows in relation to invertebrates.

6.9.2.1 Impact of critical flow events on biota in regulated streams

Andrew Livingston and Helen Lacher of the Tasmanian HydroElectric Commission are managing this project. The aims of the project are as follows.

1. To examine the effects on invertebrate abundance, community structure and richness of short-term flow events of varying magnitudes resulting from hydro operations.
2. To determine changes in stream hydraulics with flow fluctuations.
3. To examine responses of invertebrate communities to flow events of differing types: repeated diurnal fluctuations (hydropeaking); step changes in flow of differing periodicity and magnitudes; single 'pulse' events (releases/spills or dewatering).
4. To monitor recovery of the biota following single 'pulse' flow events (low or high flow).
5. To compare the responses of the regulated stream fauna to imposed flow events with those of unregulated stream invertebrates to natural flood or low flow events of similar magnitude.
6. To compare responses with predictions made using the In-stream Flow Incremental Methodology (IFIM) to assess 'limiting' habitat availability.
7. To assess the sensitivity and resilience of macroinvertebrate communities to flow events characteristic of hydro-regulation, and the validity of the IFIM approach in predicting responses to events.

6.9.2.2 Impact of hydrological disturbance on stream communities

This project is being conducted by Dr Sam Lake and Shane Brooks of Monash University. The aims of the project are as follows.

1. Assess how artificially imposed flow variation structures invertebrate communities that have evolved under different natural disturbance regimes.
2. Test the hypothesis that interactions between the hydrological regime and substratum stability determine the impacts of hydrological disturbance on stream communities.

3. Construct an empirical model that predicts the resistance of stream communities to disturbance by increased and decreased discharge based on hydrological and geomorphological variables. This model will then be independently tested to assess its value as a tool for water resource managers and water authorities at a national level.
4. Identify taxa that are sensitive to flow variation for potential use as bio-indicators of hydrologically disturbed systems.

6.9.2.3 Application of the IFIM to stream macroinvertebrates

The principal investigator for this project is Dr Ivor Growns of Australian Water Technologies.

The aims of the project are as follows.

1. Derive habitat preference curves for key macroinvertebrate species in unregulated streams of eastern New South Wales.
2. Use the IFIM to predict usable habitat areas for these species under different flow regimes.
3. Test the IFIM predictions on regulated streams in the same region.
4. Compare the IFIM with simpler (rapid assessment) methods of setting in-stream flow requirements.

6.9.3 Application of a habitat-based method in Tasmania

Although this method does not use invertebrates to assess or provide information for an environmental flow allocation, it does attempt to establish the relationship between habitat diversity and invertebrate biodiversity in rivers. The project aims to develop a habitat-based approach for estimating environmental flow requirements of a broad range of Tasmanian rivers (Nelson 1997). The advantage of establishing the habitat-based technique over other methods is that it is designed to evaluate community level requirements rather than target individual species. The aim of the method is then to provide an environmental flow for the entire ecosystem rather than specific target fauna.

The method broadly assumes that a significant relationship between habitat diversity and faunal diversity exists in any river and therefore habitat analysis could provide an alternative to faunal analysis. The paramount concern of the study to evaluate the method is to determine if the available habitat under current low flow conditions can be correlated with biodiversity (Nelson 1997).

The final method to evaluate environmental flows is intended to:

1. provide rapid estimates of environmental flow requirements;
2. develop a fast, effective predictive technique that can be tested on other rivers;
3. supply an acceptable degree of accuracy with a minimum of field work; and
4. determine the relationship between faunal diversity and habitat area.

The method is based on measuring habitat components and faunal diversity using transects. However, the difference between the transect methods used for this environmental flow assessment and other traditional habitat-based studies is the divergence away from single reach measurements at each site, that is, using a number of transects consecutively arranged along one river reach encompassing several habitats. In the habitat evaluation method specific individual habitats are not necessarily continuous or consecutively arranged but are assessed within an entire reach that is representative of that section of the river.

The basic approach is to quantitatively assess the diversity of habitat available within a section of river in association with more intensive surveying methods across individual habitats. The former will provide an index of diversity and the latter an index of habitat area. Habitat transect measurements associated with discharge and river levels will be taken at three to five representative macrohabitat types. These measurements will be taken at a series of water levels following the initial transect survey. The project was due to finish in June 1998.

6.10 Comparison of methods and conclusions

The methods that have been reviewed in this chapter differ considerably in their aims and goals but they have all been developed in order to provide estimates of flows necessary to improve or maintain the ecological environment in regulated rivers. Historical flow methods simply use the antecedent discharge record of unregulated flows but have generally been used to set minimum flows. Habitat/discharge methods generally aim to set flows that assist species to complete certain

phases of their life cycle. The aim of PHABSIM is to provide an understanding of how the extent of the usable habitat of an animal changes with differing discharges. The correlation method of Growns and Growns (1997) aimed to identify which aspects of a natural hydrograph may cause beneficial changes to invertebrate communities in a regulated river. The Expert Panel Assessment Method aims to take a multidisciplinary approach to provide recommended environmental flows.

Four of the eight types of methods for assessing environmental flows are recommended for potential use with macroinvertebrates. The historical flows method is not recommended because it does not incorporate any biological information. The habitat/discharge methods are of limited use because the information necessary to use them is scant and they are biologically simplistic. The information necessary to develop methods for movement of macroinvertebrates is also scant. In addition, the ecological role of drift remains uncertain. Methods that set flows to provide adequate water quality for macroinvertebrates could be adapted for use in Australia. However, because of the indirect nature of the effect of providing such a flow, their effectiveness is doubtful. Water quality issues for macroinvertebrates would be better addressed through adequate water quality control programs.

The amount of information, the complexity and the relative cost differ between each of the recommended methods (see Table 8, page 135). The differences mainly relate various aims and goals of the methods. The cost of all of the approaches is directly related to the amount of data collected and therefore its complexity. The amount of information required for the invertebrate components in the IFIM or correlation approaches is considerably more than for the Expert Panel Assessment Method. The differences in information necessarily mean that the correlation and IFIM approaches use more resources than the Expert Panel Assessment Method and therefore would cost more to implement (see Table 8, page 135). Because more information is used in the correlation and IFIM methods compared to the Expert Panel Assessment Method, the estimates of environmental flows produced with the correlation and IFIM methods will be more defensible in trade-off situations in water allocation decisions.

Any decision to use one particular method to estimate environmental flows over any other method by a water management agency will be partly judged on the cost-effectiveness of the available approaches. However, the cost-efficiency estimate of any method can only be readily evaluated when both measures of cost and efficiency are available for each particular method. The relative costs for each method can be determined by judging the time taken to produce environmental flow estimates. However, efficiency of environmental flow allocation methods can only be determined by demonstrating that the target processes, communities or species actually respond to an environmental flow in the predicted manner. This information is not available for any of the methods described in this review. None of the methods described in this review has actually been shown to deliver a flow that improves or sustains river health or populations of target species or communities in the long term.

Such information can only be gained with adequate manipulative experiments and measurement of appropriate ecological indicators. Environmental flows are generally provided to large sections of rivers or streams. The manipulative experiments needed to test any particular method would require measurement of ecological indicators before and after the introduction of the environmental flow at sites spread over large sections of rivers. In addition, the length of time that any manipulative experiment is carried out should take into account the probable length of time that it may take for an ecological response.

The methods that have been used to relate flows to the requirements of invertebrates depend on the provision of suitable habitat within a stream for invertebrates. The main assumption implicit in the methods is that habitat is the limiting factor that determines invertebrate abundance and diversity in a river. Although the absence of a particular habitat will result in the absence of the fauna that normally exists in that habitat in a river, this does not mean that the provision of the habitat will result in that fauna being found in the river. This is because other factors such as poor water quality, predation or competition can influence the distribution and abundance of invertebrate populations and communities.

In addition, the relationship between biotic diversity, or the abundances of species and habitat diversity, may not hold because the diversity or abundances of animals may be determined by earlier flow events at critical developmental stages. Davies (1989) and Davies and Humphries (1995) provide an example in which the abundance of adult brown trout is determined by low flow events immediately after hatching of eggs and not by flows during adult life.

Table 8: *Summary of methods for assessing environmental flow allocations*

Method	Historical flows	Habitat/ discharge	IFIM	Methods for flushing flows	Methods for migration movement	Method for water quality	Correlation	Expert panels
Recommended for potential use for macroinvertebrates	No	No	Yes	Yes	No	No	Yes	Yes
Types of data	Historical flow records from unregulated river	Field measurements from transect. Biological information on the importance of certain flow types	Data from past or contemporary field surveys. Outputs from predictive models	Historical flow record	?	?	Biological data from field surveys and daily flow records	'Opinion' expressed without documentation. Data from brief surveys
Level of complexity	1	3	6	?	?	?	5	2
Cost in relation to time to:								
– collect, analyse and collate published, historic or field data	Low	Medium	High	?	?	?	High	Low
– produce/interpret outputs from predictive models	N/A	N/A	High	N/A	N/A	N/A	N/A	N/A
– develop each flow/issue relationship	Low	Low	Medium	?	?	?	Medium	Low
– prepare for and run group workshop/activity	Low	Low	Low	?	?	?	Low	High
Defensibility in trade-off situations	Low	Low	Moderate–High	?	?	?	Moderate–High	Indefensible–Moderate depending on how the environmental flow regime is determined

Paltridge (1997) showed that the severity of the dry season in the Northern Territory can influence the invertebrate recolonisation patterns seen in temporary streams and Boulton and Lake (1992) found that some invertebrate species did not recruit in an intermittent stream the year following a drought. The influence of low flow periods in affecting recruitment may also occur in perennial streams in Australia. The habitat-based assessment study that is currently being conducted in Tasmania (Section 6.9.3) may provide some valuable information to address the assumption of a direct relationship between faunal diversity and habitat diversity.

Freshwater macroinvertebrate communities are composed of a variety of taxonomic groups, including segmented and non-segmented worms, millipedes, snails, mites, crustaceans and insects. However, insects make up the vast majority of invertebrates occurring in fresh waters. The taxonomic diversity shown by invertebrates means that there is a great diversity in their breeding cycles and ecological requirements. Because of their diverse nature, the relationships between the water flow regime and the aquatic invertebrate biota will be complex (eg. Growns & Growns 1997). This may make suggestions for specific environmental flow releases difficult, unless only one type of biota is targeted for an environmental flow allocation. Environmental flow allocations generally have been made specifically for one species, mainly fish species such as trout (Bovee 1982). However, if the aim of an environmental flow regime is to improve river health, then all biotic components of an ecosystem should be considered. The ability to incorporate more than one ecosystem component into an environmental flow assessment has only been developed in the last decade through the Building Block Methodology (King & Tharme 1994), the Holistic Approach (Arthington et al. 1992) and the Expert Panel Assessment Method (Swales et al. 1994). The further development of such methodologies is necessary because of the complexity of the relationships between hydrology and aquatic biota in river systems. The use of environmental flow allocation methods that take into account the entire riverine ecosystem would fit into the best practice framework for macroinvertebrates.

6.11 Summary of research needs

The research issues and needs identified in this review are summarised in Table 9 (page 137). 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 IFIM. 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 9: *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 5 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 ✓

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