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

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Arthington, A.H., Brizga, S.O. and Kennard, M.J. (1998) *Comparative Evaluation of Environmental Flow Assessment Techniques: Best Practice Framework.* LWRRDC Occasional Paper 25/98. ISBN 0 642 26744 8.

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List of abbreviations

ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
DNR	Department of Natural Resources, Queensland
EPA	Environmental Protection Authority
IFR	In-stream flow requirement
LWRRDC	Land and Water Resources Research and Development Corporation
WAMP	Water Allocation and Management Planning

1. Introduction

This report is one of four arising from the project 'Comparative Evaluation of Environmental Flow Assessment Techniques' funded by Environment Australia, the Land and Water Resources Research and Development Corporation (LWRRDC) and the National Landcare Program. An introduction to the project is provided in LWRRDC Occasional Paper 27/98 *Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Methods* (Arthington & Zalucki 1998a).

The objectives of the project are as follows.

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

Reports arising from the project are:

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

This report contains a review of the major methodological frameworks (*sensu* Tharme 1996) for environmental flow assessment developed or applied in Australia.

2. Methodologies for assessing environmental flows

The narrow focus on single issues (eg. the flow requirements of fish) and the many drawbacks associated with the flow assessment methods reviewed in Arthington and Zalucki (1998a) have stimulated the development of alternative approaches to the formulation of environmental flow guidelines.

In this review, these alternative approaches are termed 'holistic methodologies' (after Tharme 1996) and they are distinguished from single purpose methods by the common feature that they aim to assess the flow requirements of the many interacting components of river systems. Although the spatial scale of holistic assessments varies widely, the overall objective is to address the needs of the entire 'riverine ecosystem' (Arthington et al. 1992a). An holistic ecosystems approach to environmental flow assessment and river management has been advocated by river ecologists for over a decade (eg. Ward & Stanford 1987; Petts 1989) but the formulation and application of holistic methodologies is a relatively recent development originating largely in Australia and South Africa.

Holistic methodologies reviewed in this report are 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 a 'benchmarking' process recently added to this method (DNR 1998a, 1998b; Vanderbyl 1998), and the Flow Restoration Methodology (Arthington 1998a; Arthington & Zalucki 1998b).

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

3. The Holistic Approach

3.1 Origins of the Holistic Approach

The Holistic Approach to environmental flow assessments was formulated in late 1991 at a Brisbane workshop involving Australian and South African water scientists. The conceptual basis of the approach emerged from South Africa's first in-stream flow workshops (King & O'Keeffe 1989; Bruwer 1991) and Australian research on in-stream flows (Pusey & Arthington 1991; Arthington et al. 1992b). The main concepts of the approach were presented as a joint paper (Arthington et al. 1992a) to the 1991 International Seminar and Workshop on Environmental Flows (Pigram & Hooper 1992) hosted by the Centre for Water Policy Research at the University of New England, Armidale.

The Holistic Approach aims to assess the water requirements of the complete ecosystem, including such components as the source area, river channel, riparian zone, floodplain, groundwater, wetlands and estuary, as well as any particularly important features such as rare and endangered species. To capture this all-inclusive concept of rivers, Arthington et al. (1992a) used the term 'riverine ecosystem'. The approach is based on theoretical concepts and understanding of the processes governing river ecosystems and their floodplains, wetlands and estuaries (eg. Vannote et al. 1980; Junk et al. 1989; Ward 1989) and on disturbance theory (Resh et al. 1988). 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 off-shore systems affected by river flows, that is, the riverine ecosystem in its entirety. It then argues 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 characteristic of the river should persist and much of the 'functional integrity' of the riverine ecosystem should be maintained.

The term 'functional integrity' includes genetic and species diversity, community structure and ecosystem processes (eg. nutrient dynamics and energy flow). Defining the concept of the 'essential features' of a river's natural (unregulated) flow regime is more difficult. It can be argued that all of a river's flow characteristics are essential to maintenance of its biota and function at some spatial and temporal scale. The Holistic Approach suggests that some features of river flow regimes are more important than others, and should be maintained in the regulated regime, or changed as little as possible from natural quantities and patterns. Examples of essential features include perenniality or intermittency of the river system, the seasonal distribution of flows, periods of no flow, and the variability of flows at daily to monthly, seasonal and inter-annual time scales.

The main idea of the approach is to identify the essential features of the natural hydrological regime, define their influence on key geomorphological and ecological characteristics of the riverine ecosystem, estimate each flow attribute and progressively sum and combine them to construct a modified flow regime. The basic hydrological features suggested initially for inclusion in a modified flow regime were low flows, wet season flows (including the first major flood of the wet season, various medium-sized floods and some very large floods) and any other special-purpose flows of particular importance for the river in question (Arthington et al. 1992a). The modified flow regime is constructed month by month (or on a shorter time scale where relevant) and flow element by flow element, each flow element representing a well-defined feature of the flow regime understood or believed to achieve particular ecological, geomorphological or water quality objectives in the modified river system. The annual water needs of the riverine ecosystem are the sum of the low flow requirements throughout the year plus the additional wet-season flows, ranging from small freshes to floods. To this sum might be added the requirements for flushing flows or any other special-purpose flows to achieve particular objectives which are not likely to be achieved by the other flow provisions. It is assumed in the methodology that very large floods would not be restrained by dams or other infrastructure and so would occur more or less naturally as a component of the modified flow regime (Arthington et al. 1992a).

The total water requirements of the riverine ecosystem would ultimately be defined in terms of monthly flow allocations (or on a shorter time scale where relevant), and monthly maximum and minimum flows, desirable levels of flow variability and the timing, frequency, duration and hydrograph shapes of floods and flushing flows (Arthington et al. 1992a). It is implicit in the methodology that these attributes of the modified flow regime must lie within the range of values characterising the historical pattern, on the assumption that if a particular modified flow regime contains elements (eg. sequences of days of set discharge) which have never occurred in the historical record, then that modified flow regime is ecologically unacceptable (Pusey 1998).

Arthington et al. (1992a) suggested that initially, unless detailed knowledge of ecological requirements and responses to flow is available, the water allocation for the river should be regarded as a first estimate of the water to be provided annually and manipulated monthly within certain limits. The approach was intended to be iterative, and refinement of this first estimate would need to be made over time as the effects of the initial recommendations were monitored and/or special issues researched.

The philosophical position underlying the Holistic Approach is that water belongs to the environment and that other users should be accommodated, where practicable, from the 'excess' production of this resource. Blühdorn and Arthington (1994a) subsequently introduced the 'sustainable harvest concept', that is, the amount of water available for distribution to consumers at any particular time/place once the spatial and temporal requirements of the environment have been estimated. In a paper to the 1995 Cooma seminar on 'Techniques for Environmental Flow Assessment', Arthington et al. (1995) suggested that the aim of holistic flow assessments should be to avoid crossing critical thresholds of change in the flow regime that shift the river ecosystem from one state of dynamic equilibrium (approximating the pre-disturbance regime) to a less desirable equilibrium state (see also Sparks 1992). From this perspective, defining these critical thresholds in river flow regimes and translating them into ecological outcomes for the river can be regarded as the core of the approach. The final challenge is to decide how much change in the natural system is acceptable.

3.2 Applications of the Holistic Approach

The first use of the Holistic Approach to build a modified flow regime coincided with its formulation at the end of Stage 1 of the Barker-Barambah Study (Arthington et al. 1992b), initiated and funded by the Queensland Water Resources Commission. This study laid out a wide-ranging set of criteria for stream ecosystem maintenance, and a preliminary flow allocation strategy was recommended based on the concepts of the Holistic Approach (Arthington 1994). Monthly flows expressed as percentiles bracketed the flows required to maintain fish habitat and food resources (aquatic invertebrates), and reproductive processes, and to achieve fish passage in shallow reaches. Various desirable wet season flows were estimated, including flows to dilute saline water in the irrigation area downstream from the impoundment, and short bursts of high flows in the naturally wet months (December to March) to flush the substrates, provide cues for fish migration and to remove water hyacinth (*Eichhornia crassipes*) from the system. It was assumed that these high flows, if provided at the appropriate time of year, would also perform other functions such as channel and wetland maintenance. Recommendations were made on the daily, monthly, seasonal and inter-annual variability of flows and how these might be achieved in the modified flow regime (Arthington 1994).

This study discussed the need for a flexible water allocation strategy accommodating very dry and very wet years, and the extent to which water releases from a dam and an unregulated tributary stream would contribute to the recommended environmental flows. The flow management strategy advised that unnaturally high flow releases from the impoundment for irrigation purposes during the dry season could impact on the habitats used for fish spawning, and recommended that the variability of water levels at such times should match those of the natural flow regime, using coefficients of variation of daily flow as a guide (see Hall 1991).

Stage 2 of the Barker-Barambah study monitored the impact of the regulated flow regime on water quality and biota to test some of the Stage 1 hypotheses about desirable environmental flows (Blühdorn & Arthington 1994b). At least one species of fish failed to breed in the regulated section of Barambah Creek, where large pulses of water were released to downstream irrigators during periods that usually have low flows. Stage 2 of the study proposed methods to define flow patterns and biotically relevant flow events, and guidelines for management of dissolved oxygen levels and salinity (Blühdorn & Arthington 1995) were also developed.

This project introduced the concept of 'scheme transparency', a term now fairly widely used in discussing environmental flow management below dams, along with the term 'scheme translucency'. To achieve scheme transparency, Blühdorn and Arthington (1994b) proposed the use of a simple model to estimate, from dam in-flows and unregulated tributary flows, the monthly flow releases required to achieve particular target flows for ecological purposes at a point downstream from the main irrigation area on Barambah Creek. This approach of managing all natural and regulated sources of water to a particular river reach in a conjunctive fashion to maximise the achievement of environmental and consumptive water requirements has been adopted in the Queensland Water Allocation and Management Planning (WAMP) initiative (Burgess & Thoms 1997).

A third phase of research in the Barker-Barambah catchment was undertaken jointly with the Centre for Water Policy Research, University of New England, Armidale. It represents an additional stage in the holistic process, that is, providing a methodology for actually delivering desirable environmental flows on a daily basis, and evaluating the implications of environmental flows for other water users. The aim of this LWRRDC project was to develop a combination of simulation and stochastic dynamic programming techniques to derive the best water management decisions through time for ecological purposes whilst at the same time attempting to maximise net revenue from irrigated cropping systems in a highly variable environment (Arthington et al. 1998a; Dudley et al. 1998; Scott 1998; Scott et al. 1998). This study modelled alternative scenarios for sharing reservoir capacity, natural in-flows to the storage, and tributary flows for maximum benefit to the environment and to water users (irrigators). The ecological objective was to maximise some measure of 'environmental effectiveness' (Dudley et al. 1998), where environmental effectiveness equates to the degree of achievement of a particular target flow regime (either the natural flow regime or a modified flow regime produced using the Holistic Approach).

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

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

The use of hydrological indices as measures of specific environmental targets in a modified flow regime has been incorporated into Queensland methodologies for assessing environmental flows as part of the WAMP initiative (Burgess & Thoms 1997; Vanderbyl 1998). These methods are discussed in Section 7 below.

3.3 Uptake of the Holistic Approach

The concept of an holistic approach to environmental flow assessments to protect riverine ecosystems is widely accepted in Australia. Several frameworks as well as specific studies have adopted this approach and contributed to its development.

3.3.1 Western Australia

The Water and Rivers Commission, Western Australia, has commenced a program to apply the Holistic Approach as the standard methodology for developing environmental flow requirements and allocations. A trial application of the approach has been undertaken in the Canning and North Dandalup Rivers (Davies et al. 1996) and a final report from this study is expected during 1998. Key aspects of the natural physical environment of streams in south-west Western Australia are the strong seasonality and predictability of the flow regime (*sensu* Colwell 1974), the importance of flows for maintenance of channel and in-stream habitat structure, the influence of zero flows and flow permanence on the aquatic fauna and benthic community metabolism, and the role of flow in providing fish habitat, spawning and passage requirements. Various quantitative methods were used to determine the discharge required to maintain these structural and functional aspects of streams (Davies et al. 1996). For example, estimates of shear flows required to mobilise sandy sediments colonised by benthic microbial mats and algae were based on measurements of near bed velocity and water depth.

This study developed guidelines on the temporal aspects of each essential quantity of flow by examining historical flow records. The method used originated from the Tully-Millstream environmental flow study (Arthington et al. 1994). For each of the environmentally critical flow quantities, the mean number of flow events, mean number of days and the mean duration of each event were determined (with standard errors) for each month from the natural daily flow record (1951–1993). From this analysis, a monthly matrix of critical flow categories was developed, starting with the lowest flows and building up to the highest flows required for ecological and channel maintenance purposes. In some months, no ecological allocation could be determined from existing data and knowledge of processes in the system, so the total monthly flows were adjusted in accordance with the known seasonal pattern, based on the proportion of the median annual flow in each month (Davies et al. 1996). A somewhat similar process of iteration between months takes place within the Building Block Methodology when there is insufficient data to recommend a particular flow in some months (see Arthington & Lloyd 1998; King & Louw 1998).

The process of building a modified flow regime applied in the North Dandalup system produced monthly flow allocations for typical wet and dry years. The variability in these monthly patterns from year to year was determined using the coefficients of variation of flow for each month and the overall ‘Predictability’ (P) and ‘Seasonality’ (M) of the natural flow regime (after Colwell 1974). The study also recommended that variation in daily flows (ie. within months) should be determined by examination of the historical flow sequences and used to guide the operation of daily water releases so that they assume a reasonable approximation of historical daily flow variability and hydrograph shape (Davies et al. 1996). This was also the methodology recommended in the Barker-Barambah and Tully-Millstream studies.

3.3.2 New South Wales

Several approaches to environmental flow assessment have been developed and applied in New South Wales. The earliest was the Expert Panel Assessment Method (Swales & Harris 1995). This method is reviewed in Section 5. Swales and Harris (1995) envisage the Expert Panel Assessment Method “as a tool in new approaches to environmental flow assessment, such as the holistic model described by Arthington et al. (1992)”. The Scientific Panel Assessment Method is a more sophisticated and transparent version of the Expert Panel Assessment Method, which Thoms et al. (1996) acknowledge as having many features in common with the philosophy and methodology of the Holistic Approach. Dunbar et al. (1998) regarded the application of the Scientific Panel Assessment Method to the Barwon-Darling system as an application of the Holistic Approach. The Barwon-Darling study is reviewed in Section 6.

Growns and Growns (1997) applied the Holistic Approach to an assessment of the environmental flow requirements of invertebrates in the Hawkesbury-Nepean River system. This application determined the relationships between invertebrate communities and various hydrological descriptors, and then developed recommendations on flow release patterns from various impoundments based on the principle of mimicking the pattern and timing of flows in reference streams.

New South Wales has developed interim environmental objectives for inland and coastal rivers (EPA 1997). Through a process of consultation around Australia, critical river flow issues have been identified, and the principle of mimicking natural flows has been adopted to “improve and protect entire ecosystems and thus, the health of the rivers, rather than merely recommending flows for a single species or specific purpose” (EPA 1997). River flow objectives include protecting natural low flows, freshes and floods, mimicking the natural frequency, duration and seasonal nature of drying periods, maintaining natural flow variability and the rise and fall of river heights within natural bounds, as well as maintaining groundwaters and variability critical to surface flows or ecosystems. Interim environmental objectives are now being set for each catchment (EPA 1997). The methodologies for assessing environmental flows on a catchment by catchment basis through the Stressed Rivers Program appear to vary, but are essentially applying the principles and procedures of the Holistic Approach (Wayne Erskine, pers. comm., 1998).

3.3.3 Queensland

The Queensland Department of Natural Resources has developed an expert panel approach for environmental flow assessment derived from the panel approach developed in New South Wales. In Queensland, an expert panel applies the Habitat Analysis Method, incorporating the philosophy and basic methodology of the Holistic Approach (Walter et al. 1994; Burgess & Vanderbyl 1996) but using habitat as a 'surrogate' for assessing the flow requirements of aquatic biota. This method assumes that maintaining the full range of habitats in a healthy state will maintain the physical, biological and functional features of the riverine ecosystem (Walter et al. 1994). In providing flows to maintain all major types of habitat, the aim is to mimic the spatial and temporal characteristics of the natural flow regime as far as possible (Burgess & Vanderbyl 1996; Burgess & Thoms 1997, 1998).

Various innovations focused on statistical indicators of critical flow events, hydrological modelling and assessment of alternative environmental flow scenarios have been added recently to the expert panel process and use of the Habitat Analysis Method (Burgess & Thoms 1997; DNR 1998a, 1998b; Vanderbyl 1998). The entire methodology is used primarily as a planning tool for assessing existing and future options for water resource development at the scale of whole catchments. At this level, The Queensland Department of Natural Resources considers that the focus on maintaining habitat is sufficient, but recognises that more detailed assessment of the flow requirements of species and communities will be needed when environmental flows are estimated for individual river reaches in relation to particular infrastructure arrangements (T. Vanderbyl, DNR, pers. comm.). The Habitat Analysis Method is reviewed in Section 7.

Other developments of the Holistic Approach have occurred in Queensland. The fundamental approach was considered from the outset to be applicable to both new water management projects at the planning stage (where the essential features represent flow quantities and patterns to be maintained in the modified flow regime) and river flow restoration projects. In the latter context, the essential features are those flows which must be built back into the modified flow regime to shift the regulated system in the direction of the pre-regulation state (Arthington et al. 1995). To highlight this type of application of the Holistic Approach and distinguish it from other derivative methodologies, a new framework termed the Flow Restoration Methodology has been developed (Arthington 1998a; Arthington & Zalucki 1998b). There appear to be many parallels between the approach taken in the Flow Restoration Methodology and methods applied in New South Wales and Victoria to restore flow regimes in regulated rivers. The Flow Restoration Methodology is reviewed in Section 8.

3.3.4 Other areas

Elements of the Holistic Approach are increasingly being incorporated into environmental flow management strategies in other areas of Australia. Gippel et al. (1994) applied the approach in a re-analysis of the in-stream flow recommendations for the Thomson River in Victoria, incorporating many biological issues but paying particular attention to seasonal flows and special releases to maintain channel structure below the impoundment. Gippel et al. (1994) called this "an holistic approach". Boyd (1994) laid out an agenda for defining in-stream flows based on an holistic approach. Cross et al. (1994) summarised the flow-related needs of river ecosystems based on the stepwise construction of a modified flow regime from low to high flow elements as proposed in the Holistic Approach. The idea of sharing regulated and unregulated catchment flows as a means of ensuring seasonal flood flows to wetlands was derived from this approach (McCosker & Duggin 1993; R. McCosker, pers. comm.).

Holistic/building block approaches are advocated in the United States (Sparks 1992; Richter et al. 1996) and the United Kingdom. In a recent international review of methodologies, Dunbar et al. (1998) recommended the holistic/building block approach (which they regarded as much the same process) for use in England and Wales. In Australia and elsewhere, there does not appear to be any competing paradigm for environmental flow assessment and management within the context of sustaining water-dependent environmental systems. However, Jowett (1997) interpreted the Holistic Approach as precluding the possibility that a riverine ecosystem can be enhanced by other than a natural flow regime. This point is revisited below.

3.4 Strengths and limitations of the Holistic Approach

3.4.1 Strengths

The following summary of strengths and limitations is based on published assessments of the Holistic Approach and the opinions expressed by authors of the methods chapters in this review.

1. The Holistic Approach may be seen as a philosophical 'umbrella' (Young et al. 1995) or framework defining the overall objective of environmental flow assessments, that is, that the needs of the environment must be assessed and satisfied before humans can take water. It can be seen as setting a new philosophical position for water for the environment (Young et al. 1995).
2. The Holistic Approach takes the philosophical position that water belongs to the environment and only the 'excess' or 'sustainable harvest' in a river system can be allocated to human uses. This articulation of the inherent philosophy is consistent with the accepted ideas of sustainable harvest theory, that is,. setting some 'minimum leave-behind level' (Young et al. 1995).
3. The Holistic Approach addresses the importance of considering water for the environment in the context of the natural regime and the whole catchment, including conservation of biodiversity and natural systems (Reeves 1994). The approach is holistic in that a wide range of aquatic and catchment geographic/topographic components are included in the modified aquatic ecosystem (Young et al. 1995). The approach is comprehensive, making extensive use of an hydrologist, hydrogeologist, geomorphologist, plus an aquatic entomologist and botanist, and a fish biologist (Dunbar et al. 1998).
4. Using the natural flow regime as a guide to the flow requirement of the system is consistent with the principle of 'designing with nature' (Reeves 1994). Including natural features such as seasonal patterns of flow, low flows, periods of no flow and flood flows is the most appropriate approach given Australian climatic and hydrological conditions (Karim et al. 1995; Jowett 1997). It is consistent with the 'natural flows paradigm' (Richter et al. 1997).
5. Jowett (1977) regarded the Holistic Approach as an 'historic flow method' which is easier to use than habitat methods because it incorporates its own goals and objectives for levels of stream protection (ie. in Jowett's view, the aim is to maintain the system as close to natural as possible, or to maintain its 'essential features').
6. Reference to long-term daily hydrological records is seen as ideal because they provide comprehensive information on the timing, magnitude, frequency and duration of flow conditions that occur often in the river and to which biota have adapted (Young et al. 1995; Tharme 1996).
7. It is implicit in the approach that the attributes of a modified flow regime must lie within the range of values characterising the historical pattern, on the assumption that if a particular modified flow regime contains elements (eg. sequences of days of set discharge) which have never occurred in the historical record, then that modified flow regime is ecologically unacceptable (Pusey 1998). Richter et al. (1997) have also adopted this principle in the Range of Variability Approach to environmental flow assessment.
8. The Holistic Approach is a philosophical framework capable of incorporating a range of methods and techniques to determine the flow requirements of individual components of the riverine ecosystem (Young et al. 1995; Tharme 1996; Pusey 1998). The approach could incorporate In-stream Flow Incremental Methodology type analysis for key target species (Dunbar et al. 1998), and the use of tools such as the Expert Panel Assessment Method (Swales & Harris 1995). However, the Holistic Approach differs from the Expert Panel Assessment Method by commissioning quantitative advice relevant to in-stream flow management, rather than drawing on opinions (McCosker 1998a, 1998b).
9. The approach is a field and office method including both biological and hydrological data in flow assessments. It is flexible, has moderate requirements in terms of cost and time, and has various output formats (Growns & Kotlash 1994).
10. The Holistic Approach allows negotiation relative to consumptive water demands (Growns & Kotlash 1994; Growns & Growns 1997). The idea is to specify the needs of the river as a basis for

negotiation over what is 'practical' in each circumstance (Young et al. 1995).

11. The approach recognises that detailed ecological understanding is not available for many Australian rivers, nor the species within them, and it recommends an iterative process after the first estimations of flow requirements to overcome uncertainty and refine later allocations based on ongoing experience and further research (Young et al. 1995; Dunbar et al. 1998). Thus the current lack of detailed ecological knowledge should not postpone (water) allocation strategies (Young et al. 1995).

12. The adaptive management element of the Holistic Approach, whereby the ecological significance of various flow characteristics is explored through monitoring and research, holds great promise for advancing understanding of natural flow variability within different types of riverine ecosystems (Richter et al. 1997). An adaptive management approach closely resembling that of the Holistic Approach is fundamental to successful application of the Range of Variability Approach (Richter et al. 1997).

13. Many of the advantages of the Holistic Approach are similar to those of the Building Block Methodology (Tharme 1996; McCosker 1998a, 1998b).

14. Many elements of the Holistic Approach could be usefully applied in England and Wales (Dunbar et al. 1998). Of particular relevance is the consideration of the whole river ecosystem, the ability to act reasonably quickly to provide interim recommendations, and the inclusion of a monitoring phase which may well include more detailed assessments of the needs of target species (Dunbar et al. 1998).

3.4.2 Limitations

1. The Holistic Approach has gathered the usual amount of criticism that novel proposals tend to attract (Young et al. 1995). The first objection is whether it is just hydrologic rather than holistic, since the tools to integrate biology fully do not exist now, a criticism that is "just as true for most other environmental flow techniques" (Young et al. 1995). Jowett (1997) classified the Holistic Approach as an "historic flow method", believing it to have no explicit biological objectives other than maintaining an aquatic ecosystem close to its existing state.

2. The Holistic Approach does not explicitly indicate the biological implications of flow decisions, although it would be possible to determine these links by assessing case studies (Young et al. 1995).

3. The approach is limited by the status of research into factors such as the extent to which changes in flow characteristics impact on the river system, and how long such changes can be endured before the system shifts to a new state (Tharme 1996; Bunn 1998).

4. The approach is strongly reliant on 'professional judgement' (Tharme 1996).

5. The Holistic/Building Block Approach incrementally builds up the flows for specific purposes to produce a particular modified flow regime. There will always be some uncertainty as to whether or not something important has been left out in this 'bottom-up' process (Bunn 1998).

6. The approach has not developed into a standard set of procedures and, hence, is not at the stage where routine applications are possible to provide reproducible results. The output is loosely defined at present rather than a standard set of results (Tharme 1996).

7. The Holistic Approach is a 'low risk' approach aimed at maintaining an ecosystem in its existing state and precludes the possibility that a riverine ecosystem can be enhanced by a flow regime that is not 'natural' (Jowett 1997).

8. Many Australian rivers could not be altered to mimic natural regimes because they are fully or over-committed at present; however, one could argue that the Holistic Approach seeks to transcend such limitations by invoking a new 'philosophical position' (Young et al. 1995).

9. The concept that there is 'excess' water or a 'sustainable harvest' in a river system requires close examination and testing, where possible. It also begs the question of what is a 'natural flow regime' and how to decide on that state, especially given various climate change scenarios (Young et al. 1995).

10. The assumption that the extant biota and functional integrity of a river system will be maintained by a modified flow regime incorporating essential features of the natural regime is a concern. Many other factors influencing a river are changing simultaneously (Young et al. 1995); for example, many factors other than flow affect the condition of riparian vegetation (McCosker (1998a,1998b).
11. The approach requires analysis of daily flow records, either from gauges on natural streams or simulations, but the modified flow regime is largely expressed as monthly or seasonal flows (Young et al. 1995).
12. Some of the problems inherent in the approach are similar to those encountered with the Building Block Methodology (Tharme 1996).
13. There does not appear to be a clearly defined identity for this approach, and it is often confused with, or considered the same as, the Building Block Methodology (Tharme 1996; McCosker 1998a, 1998b).

3.5 Recent developments of the Holistic Approach

Several recent developments have addressed a number of the points raised above, whereas other objections to the Holistic Approach are of a philosophical nature.

Some critics feel that the Holistic Approach is primarily hydrological (Jowett 1997) because the tools to integrate biology fully do not exist now, and the method "does not explicitly indicate the biological implications of flow decisions" (Young et al. 1995). This objection misses the fundamental intent of the approach, that is, that each characteristic of the natural flow regime is included in the modified flow regime because it is known or believed to achieve an explicit geomorphological or ecological outcome (for examples see Arthington et al. 1992a). Whereas many recommendations must be based on opinion or 'best scientific information' in poorly studied systems, links between flow and outcomes for the aquatic ecosystem have been quantified in recent applications of the approach (see Davies et al. 1996). The scope for using a wide array of quantitative methods and tools under the umbrella of the holistic framework is obvious, and widely accepted (Swales & Harris 1995; Young et al. 1995; Tharme 1996; Bunn 1998; Dunbar et al. 1998).

Nevertheless, it is a fact that the full geomorphological and biological implications of any modified flow regime cannot be predicted at present in any river system. The 'benchmarking' process (Vanderbyl 1998) used in Queensland's WAMP initiative provides a novel methodology for addressing this difficulty (Section 7).

Young et al. (1995) queried the concept of the 'natural' flow regime and how to decide on that state, especially given various scenarios of climate change. These are legitimate concerns and they affect all holistic approaches which rely upon use of historical flow data to define the features to be retained in a modified flow regime. Several methodologies (Habitat Analysis Method, Flow Restoration Methodology) incorporate the development of an hydrological model with a daily time step representing the entire catchment as an integral and essential part of environmental flow assessment. Despite the obvious advantages of access to such models, ecologists are concerned about their accuracy, especially at very low and very high flows. Other concerns are that the effects of such factors as deforestation, changes in land use, and presence of off-stream storages on the flow regime are generally not accommodated in the models, and that the lengths of record used to simulate extended historical flow sequences may not be long enough to capture cyclic and episodic flow patterns and events. The effects of climate change have not been incorporated into these models thus far. Focused R&D may be needed to improve these features of catchment hydrological models.

Young et al. (1995) suggested that there is a mismatch between the analysis of the natural flow regime using daily flow records and description of the modified flow regime largely expressed as monthly or seasonal flows. In fact, the Holistic Approach specifically recommends various ways of incorporating daily flow variability within the monthly structure of the modified flow regime (see above, also Arthington 1994; Arthington et al. 1994; Davies et al. 1996). Recent developments using a combination of simulation and stochastic dynamic programming techniques provide a methodology for delivering environmental flows on a daily basis in a highly variable environment (Arthington et al. 1998a; Dudley et al. 1998; Scott 1998; Scott et al. 1998). The Flow Restoration Methodology also aims to deliver water for environmental purposes on a daily basis (Arthington 1998a).

The assumption that the extant biota and functional integrity of a river system will be maintained by a modified flow regime similar to the natural regime has worried some critics (Young et al. 1995) because many other factors influence river condition (for example, catchment land use, riparian zone management, water pollution). The North Dandalup study (Davies et al. 1996) and the Brisbane River trial of the Flow Restoration Methodology (Arthington 1998a; Arthington & Zalucki 1998b) included a process for identifying these other factors, and suggested remedial actions as part of the framework of river management. In general, however, the integration of flow management with other aspects of catchment and river management requires much more attention, and is addressed in the R&D component of this project (Arthington et al. 1998b).

Jowett (1997) has objected that the Holistic Approach precludes the possibility that a riverine ecosystem can be enhanced by other than a natural flow regime. This viewpoint merits consideration and debate within the broader agenda for the provision of water for the environment. One perspective is that enhancing aquatic habitat for a particular purpose or species (eg. a recreational fish species) is likely to modify the conditions required for other species, or new and unforeseen problems may develop (Petts 1989; Sparks 1992). The opportunity to sustain water-dependent ecological systems in the longer term may be sacrificed for the sake of short-term gains.

Young et al. (1995) concluded that the Holistic Approach can be seen as setting a new philosophical position for water for the environment, one that recognises the rights of the environment before consumptive water requirements are met. They suggested that this might not be universally acceptable, nor possible in over-committed river basins.

Nevertheless, the (ARMCANZ & ANZECC 1996) National Principles for the Provision of Water for Ecosystems are founded on this new philosophical position of water rights for the environment, even in developed and over-committed river basins.

Their goal is:

> *to sustain and where necessary restore ecological processes and biodiversity of water dependent ecosystems* (ARMCANZ & ANZECC, 1996, p. 5).

Principle 4 states:

> *In systems where there are existing users, provision of water for ecosystems should go as far as possible to meet the water regime necessary to sustain the ecological values of aquatic ecosystems whilst recognising the existing rights of other water users.* (ARMCANZ & ANZECC 1996, p. 8).

Principle 5 states:

> *Where environmental water requirements cannot be met due to existing uses, action (including reallocation) should be taken to meet environmental needs.* (ARMCANZ & ANZECC 1996, p. 9).

Principle 6 states:

> *Further allocation of water for any use should only be on the basis that natural ecological processes and biodiversity are sustained (ie. ecological values are sustained).* (ARMCANZ & ANZECC 1996, p. 9).

Australia is committed to the philosophical position underlying the Holistic Approach and is engaged in a national effort to put this philosophy and the national principles built upon it into practice.

4. The Building Block Methodology

4.1 Origins of the Building Block Methodology

The Building Block Methodology has been developed over the past decade by South African water scientists (eg. King & Tharme 1994; King & Louw 1998). It arose from the need to produce rapid advice on the in-stream flow requirements (IFRs) of South African rivers using limited amounts of data. The Building Block Methodology originated in two major workshops on in-stream flow assessments (King & O'Keeffe 1989; Bruwer 1991) and was advanced through an exchange of ideas with Australian ecologists, leading to joint description of a conceptual framework termed the Holistic Approach (Arthington et al. 1992a). Further separate development in South Africa produced a structured methodology for assessing the flow requirements of whole river systems, distinguished from the Australian approach by the name of the Building Block Methodology. A full description of the methodology can be found in King & Tharme (1994) and King & Louw (1998).

The Building Block Methodology makes the following assumptions.

1. The biota associated with a river can cope with low flow conditions that naturally occur often, and may be reliant on higher flow conditions that naturally occur at certain times, for example, specific floods.
2. Identification of the most important characteristics of the natural low flows and floods, and combining them as the modified flow regime, will facilitate maintenance of the river's natural biota and processes.
3. 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 objective of the Building Block Methodology is to determine ecologically acceptable, modified flow regimes for impounded rivers and other situations where flows are regulated. Application of the methodology provides advice on the IFR of a river through a systematic sequence of activities involving three main phases.

1. A comprehensive information gathering phase undertaken by experts in their fields (fluvial geomorphology, hydraulic modelling, aquatic ecology, aquatic chemistry, hydrology, water engineering, social and recreational aspects). Coordination of activities is achieved early in the process through an IFR planning meeting, and this phase of the Building Block Methodology culminates in the production of a comprehensive 'Starter Document' provided to all participants prior to a structured IFR workshop.

   Pre-workshop activities also involve the selection of IFR sites throughout the catchment under investigation, and most of the data gathering and subsequent simulation activities are focused around these critical river sites. They are selected to capture and represent spatial geomorphological and biological variation along the river and its major tributaries. The Starter Document is sent to workshop participants about three weeks before the IFR workshop and serves to achieve three objectives: it informs all participants about the river; it encourages the experts to focus on the river's flow requirements; and it remains as a lasting synthesis of knowledge on a specific river at a specific time (King & Tharme 1994).

2. The IFR workshop generally involves about 20 people, with those present representing agency water managers and engineers, the consulting engineers appointed for the specific development, and the disciplinary experts. The workshop commences with a rapid overview of the Starter Document and, usually, a field visit to each in-stream flow site along the river. These activities help to put the whole study and the background information into context for workshop members. A chairperson and facilitator then guide the workshop participants through the various steps of the Building Block Methodology to reach a consensus on a recommended modified flow regime for the river. This is based on monthly flows and special-purpose flows over shorter time spans, each component of flow being specified in terms of magnitude, time of year, duration, and rate of rise

and fall of flood flows. Flow regimes are developed for river maintenance and for drought conditions.

A 'motivation' is provided for each specified flow by its proponent, and these are recorded in the workshop report. The recommendations are designed to achieve a particular 'desired future state' for the river along each reach, given its existing ecological condition and the importance of the reach and river in the broader context of riverine conservation and social uses of the river (King & Louw 1998). The concept of desired future state is elaborated below in relation to the Logan River trial of the Building Block Methodology. The construction of the flow regime is quantitative in that conversion of much of the ecological knowledge about the river into recommended environmental flows depends upon accurate river cross-sections and stage-discharge rating curves, while recommendations for certain high flows depend on accurate hydrological data (King & Tharme 1994).

Each workshop takes two to four days, depending upon the size of the catchment, its geomorphological and ecological heterogeneity, and the number and location of proposed water developments. A technical report is produced after the workshop, recording the processes used, the inputs of experts, and the outcomes in terms of in-stream flow recommendations.

3. The third phase of the Building Block Methodology occurs after the IFR workshop. It constitutes a series of activities that link the environmental flow considerations to the engineering activities taking place in the catchment. Hydrological yield analysis (Hughes et al., in press), assessment of conflicts with potential consumptive users, and a coarse flow-related assessment of the implications of IFR recommendations for the complete river system are combined to produce a description of the 'working guide desired state', with its IFR (King & Louw 1998). Two or three other possible states which would require more or less water than the IFR are also described, each linked to its probable physical, ecological, social and economic consequences. Outcomes from these assessments are then linked to a public participation process, ending with a decision on whether or not the project will proceed and the IFR will be met. If the project proceeds with agreement to meet the IFR, planners use the IFR tables to reserve water for the river (King & Louw 1998).

4.2 Applications of the Building Block Methodology

4.2.1 Applications in South Africa

Since 1991, the Building Block Methodology has been applied systematically to major water resource projects in 14 rivers throughout South Africa (King & Louw 1998). The experience gained has had many spin-offs apart from routine use of the methodology by national and provincial conservation institutions during negotiations leading to water allocations for the environment. Applications across South Africa have identified many shortfalls in knowledge of riverine ecology and triggered a number of focused medium and long-term research projects specifically designed to help improve both the methodology and its information output (King and Louw 1998). In this respect, there are parallels with the Holistic Approach, which has been particularly beneficial in focusing river research in Queensland.

The Building Block Methodology is formally endorsed by the South African Department of Water Affairs and Forestry, and is institutionally accepted by other water management and conservation organisations. The methodology has been adopted as the standard approach for environmental flow assessment under the new Water Law for South Africa.

4.2.2 The Logan River trial of the Building Block Methodology

A 1996 trial of the Building Block Methodology in the Logan River in south-east Queensland was the first application of the methodology to be undertaken outside of South Africa. It formed part of a research project funded by LWRRDC and the Queensland Department of Natural Resources, with substantial in-kind and intellectual property contributions from South African water agencies and the scientists who have been foremost in developing the Building Block Methodology in that country. The outcomes from the Logan River trial will be used in a broader departmental initiative aimed at developing a Water Allocation and Management Plan (WAMP) for the catchment.

Two reports have been published describing the Logan River study, the background data collection activities and methods of analysis (Arthington & Long 1997) and the workshop process and its outcomes (Arthington & Lloyd 1998). The strengths and limitations of the Building Block Methodology have been assessed in the final report to LWRRDC on the Logan River project (Arthington 1998b).

A brief summary of this study is provided here to illustrate key features of the methodology and some new developments during the Logan River trial.

Selection of in-stream flow requirement sites

The Building Block Methodology produces a detailed assessment of the river's IFRs at specific sites called IFR sites (see phase 1, above). In the Logan River catchment, four IFR sites were selected, each located downstream of an existing or proposed flow regulation structure. IFR Site 1 on the Logan River at Rathdowney is a riffle site affected by Maroon Dam releases and natural flows from the Upper Logan River and Palen Creek catchments. It was considered likely to show critical responses to flow regulation by Maroon Dam. This site is used below as the focus for discussion of the Logan Building Block Methodology study.

Desired future state

The Building Block Methodology determines the flow requirements of a river based on the attainment of a desired future state at various locations within the catchment. When the methodology is applied in South Africa, a realistic desired future state is determined by a mixed group, usually including people living in the catchment, management agencies, and the scientists participating in the study. Workshop participants then estimate the IFR which will achieve the agreed desired future state. In the Logan River study, a draft desired future state based on South African models was presented at the workshop and revised by the group to produce the following statement:

> *The Desired Future State for the Logan River and its estuary is a riverine ecosystem characterised as far as possible by natural geomorphological and ecological processes, natural biodiversity and ecological and cultural values. Water resources of the river are presently used for irrigation, industrial and domestic consumption. The DFS includes the sustainable utilisation of these resources. The degraded condition of the channel and riparian vegetation in the lower Logan River catchment is recognised and the In-stream Flow Requirements (IFR) should be designed to promote a return to natural processes of erosion, deposition and channel maintenance, water of high quality, diverse riparian and aquatic communities, and natural ecological processes* (Arthington & Lloyd 1998).

Workshop participants also agreed on the desired future state for each IFR site, using a new process developed for the Logan River study by Dr Jackie King. Each specialist was asked to classify the four IFR sites according to their disciplinary perspective, using a predetermined set of river condition categories. For example, each specialist ranked IFR Site 1 at Rathdowney in terms of its current conservation status and the desired future state as follows.

Table 1: *Desired future state for IFR Site 1, Logan River at Rathdowney*

Specialist	Current conservation status	Desired future state
Geomorphology	High	High
Riparian vegetation	Moderate	High
Aquatic macrophytes	High	High
Invertebrates	High	Very high
Fish	High	High
Water quality	Very high	Very high
Overall condition	High	High

The workshop agreed that the desired future state should maintain the reach in its present condition, with perennial flow and natural flow variability, but with improved diversity and density of native riparian vegetation. The assumption was that improvements in the condition of the vegetated riparian zone would assist in maintaining bank stability and help to prevent increased erosion and sedimentation downstream; enhance in-stream habitat and biological diversity; and assist in maintaining downstream water quality.

Methodology of the Building Block Methodology

Development of flow recommendations is a dynamic, interactive process requiring that each workshop participant draws upon the information resources of their specialist chapter in the Background Papers, and their understanding of the ecological or geomorphological processes governed by the flow conditions at the particular IFR site. The Building Block Methodology uses detailed cross-sections and stage-discharge data at IFR sites to determine water levels which will inundate shallow riffle areas, stream banks, riparian vegetation, backwater areas and floodplains, or stimulate important biological responses. The flows required to maintain natural geomorphological processes and channel morphology, water quality, and water-dependent wildlife (frogs, reptiles, mammals and birds) are also considered.

The Logan River study used quantitative methods wherever possible to develop flow recommendations. For example, biological data gathered as part of the Queensland Monitoring River Health Initiative and data from two LWRRDC research projects were analysed using various multivariate statistical techniques to relate flow and physical habitat characteristics to fish, macrophyte and invertebrate distributions (see Choy & Marshall 1997; Kennard 1997; Mackay 1997, respectively). Mackay (1997) applied a novel multivariate procedure using Andrews' functions (Andrews 1972; see also Nathan & McMahon 1990) to match habitat use against habitat availability. In addition to quantifying habitat requirements, ecologists provided flow recommendations based on published information describing the reproductive biology and timing of recruitment of plants and fish species occurring in the catchment (see Kennard 1997; Mackay 1997; McCosker 1997).

Compilation of the IFR for each river site followed a standard procedure. After general agreement had been reached on the kind of flow regime that would facilitate maintenance of the desired future state, the specific flows required were identified month by month, starting with the low flows. Each specialist proposed the low flow needed to achieve particular habitat and other conditions (eg. depths that will inundate riffles and support invertebrate communities; depths and velocities suitable for certain fish species).

The hydraulic modeller then interpreted the implications of the flows described in terms of depth, wetted perimeter, velocity, or areas inundated, using the surveyed cross-sections and plots of various hydraulic relationships (Long 1997). After agreement had been reached by all workshop members, details of the low flows were added one by one to a blank IFR table of discharge (rows) versus calendar months (columns) (see Table 1, page 14). At this stage, capping flows (the recommended upper limits to the flows which may be passed through a river reach in a naturally low flow month; King and Louw 1998) may be recommended.

The next step is to define small freshes and flood flows, with each of the latter being described in terms of five criteria: magnitude, timing, frequency, duration and hydrograph shape. Workshop participants used flow sequences and hydrograph shapes drawn from the hydrological data on the river's natural flow regime to define these five characteristics of freshes and floods.

The IFR table was filled out initially to quantify the IFR for normal river maintenance, with the desired future state as the target for the flow recommendations. The next step in the Building Block Methodology is to define a range of flows to be maintained during drought conditions. These 'drought' flows are required to ensure continued existence of aquatic species, but would not be expected to sustain reproduction and recruitment of most species, although some hardy species might be able to breed under drought conditions. Thus drought flows are intended to maintain the resilience of the aquatic ecosystem under conditions of extreme stress.

Droughts are regarded as natural events, linked to regional climate and rainfall/run-off characteristics of the catchment. In the Building Block Methodology, it is understood that environmental flows would be allowed to fall to the recommended drought levels only during natural drought events, and not as a consequence of water abstraction or river regulation. As a general rule, the timing of flows during drought conditions is tied in with natural flow events in the river system.

Every flow recommendation made by participants at the Logan River workshop was verbally justified, recorded by the individual and the workshop scribe, and later incorporated into the Workshop Report. A summary of the flow recommendations for IFR Site 1 at Rathdowney is presented in Table 2 (page 18). The Workshop Report (Arthington & Lloyd 1998) describes how the requests from different workshop participants were integrated and gives the detailed justification for each of these flows.

After the completion of the IFR tables for three sites, a flow matching exercise was undertaken by workshop members. The matching exercise compared the flow requirements recommended for the different IFR sites to check that there were no major discrepancies between sites, or between the IFR recommendations and the simulated virgin flow regime. The natural low flow characteristics of the Logan River were subsequently analysed in more detail and compared with the IFR recommendations to determine the need for provision of zero flows as part of the advice on in-stream flows (Brizga 1998a).

Flow recommendations for the Logan River

One possible perception from the Logan River trial of the Building Block Methodology is that relatively little water was requested to achieve high levels of desired future state in freshwater reaches of the river. At Rathdowney, the total environmental flow recommended by the Building Block Methodology was less than 50% of the mean and median virgin annual flow. An analysis of virgin and present flow regimes at the IFR sites in relation to the natural occurrence of low and zero flows (Brizga 1998a) showed that the IFR recommendations developed at Rathdowney contained more prolonged unbroken spells of low flows than occur in the virgin flow regime, and that the drought IFR in Table 2 (see page 18) resembles the 1 in 100 year low flow event, based on spell duration and low flow frequency analysis. The low flow analysis also suggested that the flow requirements of the Logan River at Paynes Bridge may have been underestimated (Brizga 1998a).

Several explanatory points can be made about the methodology and these particular outcomes of its application in the Logan catchment. Firstly, the Building Block Methodology assumes that the water resources of a catchment will be developed and used for consumptive purposes, and therefore sets out to identify the *absolute minimum quantities* of water (and timing, duration and return periods of these quantities) needed for river maintenance and during natural droughts. It is understood in the methodology that more water will always be desirable, and is expected to be available unless there is very substantial development of the catchment.

Secondly, the Building Block Methodology is designed to make a 'block booking' of water for the river at the planning stage of new developments (King & Louw 1998). It is not intended to provide a rigid recommendation on the river's future flow regime. A series of activities after the workshop (hydrological yield analysis, assessment of conflicts with potential consumptive users, a coarse flow-related assessment of the implications of IFR recommendations for the complete river system) are combined to produce a description of the 'working guide desired state', with its flow requirements (King & Louw 1998). Two or three other possible states which would require more or less water than the working guide IFR are also described, each linked to its probable physical, biological, social and economic consequences. Outcomes from these assessments are then linked to a public participation process, ending with a decision as to whether or not the project (eg. dam, weir) will proceed and the IFR will be met. If the project proceeds with agreement to meet the IFR, planners use the IFR tables to reserve water for the river. The modified flow regime that finally characterises the regulated river will be influenced by planned water releases from dams in the catchment, by stream flow derived from unregulated tributaries and local run-off, and by very large flows which would occur during spills from dams.

These features of the methodology must be taken into consideration when interpreting the outcomes from the Logan River study. A first point is that the environmental flows recommended at each IFR site in the freshwater river should be regarded as the *minimum flows* for river maintenance and during droughts, if there are to be substantially increased water demands or proposals for major new water infrastructure in the catchment in the future. If the Logan is not to be so developed, or not for some time, then alternative desired river states and modified flow regimes could be developed based on the workshop IFR recommendations, using a process similar to the scenario phase of the Building Block Methodology.

A second factor influencing the Logan River flow recommendations was that the study was focused mainly on the freshwater river. This was because the Building Block Methodology does not include a process for developing flows to maintain downstream estuarine and coastal processes, although South African estuarine scientists have since developed a parallel procedure for this. The Logan workshop included a special session to discuss how the flow requirements of the estuary might be addressed (see Arthington & Lloyd 1998) and, as part of this, examined the possible significance of linkages between river flows and estuarine fisheries. Using a few relatively simple statistical analyses linking river flows and fish catches, Loneragan & Bunn (1997) showed that the closer the total summer flow entering the estuary to pre-regulation discharges, the higher the fish catch in the Logan estuary and southern Moreton Bay. This quantitative assessment, and other flow-related issues affecting the geomorphology and water quality of the estuary (see Arthington & Lloyd 1998), are being addressed in the catchment-wide WAMP. They provide a sound basis for increasing the high flows through the Lower Logan River at Paynes Bridge, just upstream from the estuary.

A similar approach is taken in South African studies on coastal rivers, where any discrepancy in the flow requirements of a mature lower river and its estuary is accommodated by adopting the larger, estuarine flow requirement for planning purposes (J. King, pers. comm., 1998).

4.3 Strengths and limitations of the Building Block Methodology

4.3.1 Strengths

1. The Building Block Methodology is relatively simple and rapid to apply (Tharme 1996), usually taking less than one year from initiation of background studies to provision of the workshop recommendations, depending upon the amount of information available for the study catchment (Arthington & Lloyd 1998).
2. The methodology is pragmatic and designed to cope with environmental flow assessment in South Africa, where time, finances, available data and expertise are often real constraints (Tharme 1996).
3. The methodology involves a consistent, structured approach, employing a rigorous and explicit workshop process for development of flow recommendations based on the best scientific data available (Tharme 1996; Arthington & Lloyd 1998).
4. There are strong clear links with the natural long-term hydrological record of the study river (Arthington & Lloyd 1998). The methodology ensures that the modified flow regime of the regulated river will be characterised by the flow events having most influence on its fundamental character, even though part of the flow will be used for consumptive purposes (Arthington & Lloyd 1998; McCosker 1998a, 1998b).
5. The use of daily flow data renders the methodology more sensitive than those based on monthly data (Tharme 1996). Hydrological models enable a reasonable proportion of the natural spatial and temporal flow variability characteristic of a catchment to be captured, even though a substantial part of the river's flow may be diverted for consumptive use (Arthington & Lloyd 1998). Flows are recommended for both maintenance and drought years (ie. the Building Block Methodology is responsive to crisis management) (Tharme 1996).
6. An important feature of the Building Block Methodology is its holistic approach and the flexibility to incorporate all available physical and biological information about the river into the environmental flow assessment (Arthington & Lloyd 1998; Choy 1998; McCosker 1998a, 1998b). The range of environmental flow objectives addressed is increasing with every new application in South Africa (Tharme 1996). It can also address flows for recreational and aesthetic purposes (Tharme 1996).
7. The Building Block Methodology is firmly linked to a parallel process for estimating the environmental flow requirements of estuaries (Tharme 1996).
8. Rigorous reporting is a strong feature of the Building Block Methodology. It results in production of a Starter Document (or Background Papers) as a permanent record of the state of the river at the time of the flow assessment, as well as a Workshop Report recording site-specific flow recommendations and the basis for them. Outcomes from the IFR workshop are reported in a consistent fashion in IFR tables structured to facilitate the communication of quantitative flow recommendations to engineers and planners (Tharme 1996; Arthington & Lloyd 1998).

Table 2: *In-stream flow recommendations for IFR Site 1, Logan River at Rathdowney*

(Discharges in $m^3 s^{-1}$, flood duration expression in days, volumes in million m^3, depths in m.)

SITE: IFR1 – Rathdowney **MAF (virgin):** 103 $10^6 m^3$ **MAF (present):** 98 $10^6 m^3$ **MED (virgin):** 83 $10^6 m^3$ **MED (present):** 77 $10^6 m^3$

	IFR BUILDING BLOCKS Capping		**OCT see text**	**NOV see text**	**DEC see text**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP see text**	**VOL**	**MAR**	**MED**
IFR FOR MAINTENANCE	LOW	**flow $m^3 s^{-1}$**	0.13	0.21	.37[a]	0.41	0.5	0.68[a]	0.64	0.46	0.42	0.27	0.16	0.09[a]	11.4	11	13.7
	FLOW	**depth m**	0.13	0.16	0.2	0.21	0.24	0.3	0.28	0.23	0.21	0.17	0.14	0.11	GL	%	%
		fdc% v.	70`	62	60	70	74	71	63	60	61	69	73	75			
		p.	99.7	92	54	63	67	61	54	50	54	66	95	100			
	FLOODS																
	Magnitude[b]																
	Depth, duration[d]				<===== 103 $m^3 s^{-1}$ 1:2 yrs[c] =====>						<=====5 $m^3 s^{-1}$ ======>				26.7	26	32
						Depth 6 m, 6 days[cd]					Depth 1 m (min) 4 days				GL	%	%
				(in 1st month when occur naturally)							(in 1st month when occur naturally)				IFR Maintenance		
	Magnitude[b]				$m^3 s^{-1}$	10 $m^3 s^{-1}$	25 $m^3 s^{-1}$	8 $m^3 s^{-1}$							38	37	45.7
	Duration[d]				5d	5d	7d	5d							GL	%	%
IFR FOR DROUGHT[e]	LOW	**flow $m^3 s^{-1}$**	0.05	0.05	0.05	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.05	0.05			
	FLOW	**depth m**	0.084	0.084	0.084	0.118	0.118	0.118	0.118	0.118	0.118	0.118	0.084	0.084			
		fdc% v.															
		p.															
	FLOODS																
	Magnitude[b]				2	2	2	2									
	Depth (m)				0.60	0.60	0.60	0.60									
	Duration[d]				5–7	5–7	5–7	5–7									

a. Low flow levels were determined via ecological/geomorphological motivations for these months (see text).
b. Magnitude refers to the flow at the flood peak.
c. All flood flows should match the natural return period for events of specified magnitude.
d. All floods should be provided to match the natural hydrograph shape for events of specified magnitude.
e. Drought flows should *not* be used in design calculations or without prior consultation with a river ecologist.

9. Consistency in the methods used to estimate and report environmental flow recommendations has permitted comparisons of outcomes across many South African river systems (Tharme 1996; J. King, pers. comm., 1998).

10. The IFR workshop is followed by a scenario phase when alternative (higher or lower) desired future states of the river are considered, each linked to its probable social and economic consequences. These assessments feed into a public participation process, ending with a decision on whether or not the project will proceed and the workshop IFR, or some lower or higher IFR, will be met. Thus wide-ranging consultations influence the final decision about the type of river desired and the environmental flows needed to achieve it (Tharme 1996; Arthington & Lloyd 1998).

11. The Building Block Methodology incorporates a monitoring program to assess the benefits of the environmental flows, so that adjustments may be made to the IFR as more knowledge of the river's requirements becomes available from monitoring and research (Tharme 1996). The whole methodology can sit comfortably within a framework of adaptive environmental management (Arthington & Lloyd 1998).

12. The entire methodology can be applied to part of a river system or to the whole catchment, and to regulated rivers as well as those where flows are modified by incremental development (Arthington & Lloyd 1998). It is sufficiently robust to be applied to any river.

13. The Building Block Methodology is applicable to individual rivers on a case-by-case basis, but also allows extrapolation from regional generalisations to rivers for which there is very little information (Tharme 1996).

14. The methodology is formally endorsed by the South African Department of Water Affairs and Forestry, and is institutionally accepted by other water management and conservation organisations. It has been written into the new Water Law for South Africa.

4.3.2 Limitations

1. The concept of the desired future state is difficult, and is not sufficiently precise as a target for the construction of a modified flow regime. Stating specific objectives for each component of the flow regime would facilitate the assessment of different scenarios and probable outcomes for the river if the full IFR cannot be provided. Clear objectives are also required to establish relevant components in the monitoring program and to assess how well it achieves the desired future state for the river (Arthington & Lloyd 1998).

2. An alternative approach would be for the workshop to develop several flow regimes, each designed to meet the specified objectives that would go towards maintenance of different levels of the desired future state (Arthington 1998b; Arthington & Lloyd 1998).

3. The Building Block Methodology is intended to be a rapid process which does not allow for long-term data collection or intensive use of quantitative methods. It is therefore highly reliant on professional judgement and experience of the study river system or similar systems elsewhere. It would benefit from collection of biological data over a longer period and more use of quantitative methods, habitat simulation models, and so on (Arthington & Lloyd 1998).

4. The Building Block Methodology is holistic, but issues such as water quality and the flow requirements of water-dependent wildlife require more development and stronger linkages into the methodology (Bunn 1998; Pusey 1998).

5. Additional formats for presentation of flow data (eg. fewer large tables and more graphics such as, monthly flow duration curves, flow spell analysis, flood frequency analysis; flood hydrographs; Colwell's indices) would facilitate discussion about the natural hydrology of the river before building a modified flow regime (Arthington & Lloyd 1998).

6. Electronic access to flow data would allow workshop members to undertake analyses relating their site-specific geomorphological, biological or water quality data to features of the flow regime. This would undoubtedly strengthen the recommendations for various quantities, timing and duration of particular flows, and should also foster

the development of better methods to link flow and geomorphological or ecological processes (Arthington & Lloyd 1998).

7. When each component of the IFR table is agreed upon at the workshop, it should be analysed immediately to determine the match against the natural flow regime at the particular IFR site. This would identify any serious shortcomings in the recommendations and, if necessary, rectify them before progressing any further (Arthington & Lloyd 1998).

8. The condition of a river system may be influenced by many factors and disturbances that are not flow-related (eg. land management practices, clearing of riparian vegetation, discharge of pollutants). The Building Block Methodology needs to be linked to a framework for addressing these issues in a parallel fashion (Arthington & Zalucki 1998b; McCosker 1998a, 1998b).

4.4 Recent developments of the Building Block Methodology

King and Louw (1998) acknowledge the limitations of the process related to desired future state, and cite two initiatives addressing these concerns: the formation of catchment forums to advise on objectives for rivers; and research to develop a process whereby an objectives hierarchy can be developed by consensus to guide the management of any river. New developments and improved processes (eg. an element of risk analysis to assess alternative flow scenarios) are also emerging from the application of the Building Block Methodology to the Lesotho Highlands project in South Africa (J. King, pers. comm., 1998).

The use of more quantitative methods to assess environmental flows using the Building Block Methodology is developing rapidly in recent South African applications. The Lesotho Highlands project will involve extended spatial hydraulic and biological data collection over a period of almost one year, and various quantitative methods will be used to develop linkages between river flow characteristics and ecological processes. Methods addressing water quality and the needs of water-dependent vertebrates are also being developed.

Australian and South African scientists continue to exchange ideas and share experiences as the holistic methodologies evolving in both countries develop and improve with each new application. The Logan River trial of the Building Block Methodology was an important step in this process, and played a large part in the development of the Flow Restoration Methodology described below. The Logan study also contributed some important concepts to the recent WAMP study in the Fitzroy Basin, wherein a similar building block approach was used by the Technical Advisory Panel to construct alternative environmental flow scenarios.

5. The Expert Panel Assessment Method

5.1 Origins of the Expert Panel Assessment Method

The Expert Panel Assessment Method (Swales & Harris 1995) was the first multidisciplinary team approach to environmental flow assessment developed in Australia. It emerged from the early work of Richardson (1986) and others on the flows required to protect freshwater fisheries. The method was proposed by New South Wales Fisheries as a suitable reconnaissance planning technique for initial assessment of proposed developments and was intended to be "widely applicable, inexpensive and not require[ing] extensive field measurements" (Swales & Harris 1995, p. 127). The suitability of stream flows for the survival and abundance of native fish was taken as the primary criterion of the suitability of the discharge as an environmental flow, because "fish communities are generally acknowledged to be a good indicator of overall environmental quality or river 'Health', and respond to direct and indirect stresses of the entire aquatic ecosystem" (Swales & Harris 1995, p. 127).

In the first test of the Expert Panel Assessment Method, flows were manipulated experimentally below six headwater water storages on tributaries of the Murray-Darling River in eastern New South Wales. Arrangements were made in the winter of 1992 for four different flow releases to be made from the storages, "representing the 80%, 50%, 30% and 10% flow percentiles" determined from flow duration curves for each river (Swales & Harris 1995). The suitability of selected flows for maintaining habitat quality, fish and invertebrates (as food for fish) was assessed visually during a field inspection and scored by two independent expert panels comprising specialists in fish biology, invertebrate ecology and fluvial geomorphology. The panels were asked to asses the suitability of flows on a seasonal and non-seasonal basis.

The most significant outcome of this trial was the consistent recommendation by panel members that the natural seasonal patterns of river flows should be restored (lowest flows in summer, intermediate in spring and autumn and highest in winter months). These recommendations appeared to represent a reversal of the extant regulated flow regime and, in effect, a denial of the water requirements of irrigators. Other issues were considered, such as the impact of regulated flows on channel morphology and the need to incorporate flows to restore in-stream habitat.

In this trial of the Expert Panel Assessment Method, congruence between the recommendations of the two separate panels was assumed to represent a validation of the method (Swales & Harris 1995). However, panel rankings of the various flows varied considerably and this has been downplayed 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 not presented) to determine the degree of congruence between the scores derived from the individual panels and found that only one 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 (Pusey 1998).

Bishop (1996) further examined the recommendations provided by the Expert Panel Assessment Method reported in Swales and Harris (1995) and suggested 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 the hydrological data supplied to the team. Bishop (1996) listed 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).

Two forms of testing of the suitability of environmental flows produced by the Expert Panel Assessment Method were recommended by Swales and Harris (1995). Firstly, assessments of biotic community responses to flow alterations and comparisons with the predicted changes; and, secondly, the use of several different methods to assess the in-stream flow needs of biota and comparison of the results.

The latter approach has been applied to the Peel River below Chaffey Dam (Swales et al. 1994), where it was found that the flow allocation derived using the Expert Panel Assessment Method was similar to that produced by flow duration curve analysis; both were considered superior because they incorporated seasonal flow variability and were "oriented towards maintaining the river ecosystem". The outcome from a fairly detailed field assessment of fish habitat requirements was considered less useful since it was focused on target fish species. The actual methodology used to integrate information on fish habitat requirements derived from field studies was not described in the paper by Swales et al. (1994) but appears to represent an application of the basic transect methods described above.

5.2 Strengths and limitations of the Expert Panel Assessment Method

5.2.1 Strengths

Swales and Harris (1995) concluded that the Expert Panel Assessment Method has certain advantages over other methods for assessing environmental flows. Participants in the University of New England Centre for Water Policy Research review of the Expert Panel Assessment Method (Centre for Water Policy Research 1996) also drew attention to these benefits. The main advantages of the method are as follows.

1. The Expert Panel Assessment Method ensures direct communication of specialist knowledge from recognised experts in the fields of fish biology, river ecology and fluvial geomorphology into river management recommendations (Swales & Harris 1995).
2. It ensures incorporation of interdisciplinary judgements into river management recommendations (Swales & Harris 1995).
3. It does not require extensive field measurements so is rapid and inexpensive to apply (Swales & Harris 1995).
4. It is likely to be most useful as a site-specific method for recommending environmental flows in particular regulated rivers, rather than as a general methodology to determine 'standard' in-stream flows in regulated rivers over a wide geographical area (Swales & Harris 1995).
5. It is likely to be useful "as a tool in new approaches to environmental flow assessment, such as the holistic model described by Arthington et al. (1992)" (Swales & Harris 1995).
6. It can be used in an experimental context to trial different flow release strategies and monitor their suitability.

5.2.2 Limitations

1. Cooksey (1996) provided a critique of the Expert Panel Assessment Method from the perspective of behavioural psychology, based on similarities between the method and other group techniques. One area of concern 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 (Pusey 1998).
2. 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 (Pusey 1998).
3. 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.
4. Bishop (1996) 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 the hydrological data supplied to the team.

5. Significant drawbacks of the Expert Panel Assessment Method 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 (Swales & Harris 1995).
6. Although Swales and Harris (1995) suggest that techniques for determining environmental flows need to be inexpensive and not requiring extensive field measurements, this latter point illustrates a significant weakness of the method. A review of the application of the Expert Panel Assessment Method in the Snowy River (Centre for Water Policy Research 1996) frequently drew attention to this point.

5.3 Recent developments of the Expert Panel Assessment Method

The Scientific Panel Assessment Method (Thoms et al. 1996) appears to be a more sophisticated development of the Expert Panel Assessment Method, but differs considerably in some key aspects. It is therefore treated as a separate methodology and reviewed below.

6. The Scientific Panel Assessment Method

6.1 Origins of the Scientific Panel Assessment Method

The Scientific Panel Assessment Method (Thoms et al. 1996) is a derivative of the Expert Panel Assessment Method, but differs from it in that "key ecosystem/hydrology features and (surmised) interactions were used as a basis for assessment, rather than visual assessment and interpretation of trial releases from storage" (Thoms et al. 1996). The method involved visual inspection of many sites along the whole reach of the Barwon-Darling River, as opposed to the alternative Expert Panel Assessment Method approach in regulated rivers where multiple flow assessments are made at one or a few sites. The Scientific Panel Assessment Method integrates 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. Thoms et al. (1996) also distinguish the Scientific Panel Assessment Method from the Habitat Assessment Method of Walter et al. (1994).

The Barwon-Darling study attempted to take an holistic view of the system by considering key ecosystem components (fish, trees, macrophytes, invertebrates and geomorphology) and their responses to three 'habitat elements': flow regime, flood hydrograph and physical structure. Thoms et al. (1996) noted that, in the past, environmental flow studies have focused too narrowly on the provision of minimum flows and suggested that this is an inappropriate focus in dryland river systems given their high degree of flow variability. Accordingly, the Scientific Panel Assessment Method 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. Each of these attributes of the flow regime was related to the needs of fish, trees, macrophytes, invertebrates and geomorphology in a useful cross-tabulation. For example, the potential interactions between the 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.

The Barwon-Darling 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 under the Expert Panel Assessment Method, 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 (Pusey 1998).

The Barwon-Darling study also considered 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 critical reaches within defined geomorphological zones. A focus on the relationship between ecosystem processes and flow within an extended spatial and temporal hierarchy is a defining feature of holistic methodologies (Pusey 1998).

Thoms et al. (1996) acknowledged the similarity of the Scientific Panel Assessment Method to the Holistic Approach (Arthington et al. 1992a) and the Building Block Methodology. Dunbar et al. (1998) regarded the application of the method to the Barwon-Darling system as an application of the holistic/building block approach.

6.2 Strengths and limitations of the Scientific Panel Assessment Method

6.2.1 Strengths

1. The scientific panel study of the Barwon-Darling River (Thoms et al. 1996) is notable for its 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 (Pusey 1998).

2. The Scientific Panel Assessment Method provides a rapid interim environmental flow assessment by integrating 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 (Pusey 1998).
3. This expert method takes an holistic view of the system by considering key ecosystem components (fish, trees, macrophytes, invertebrates and geomorphology) and their responses to three ‘habitat elements’: flow regime, flood hydrograph and physical structure (Pusey 1998). In this respect, it has the same advantages as the Holistic Approach and the Building Block Methodology.
4. The Scientific Panel Assessment Method considers the role of flow events in maintaining habitat diversity within an extended spatial hierarchy (ie. macro, meso or reach, and micro scales). This represents a considerable advance on studies concerned with flow determinations made at a few critical reaches within defined geomorphological zones (Pusey 1998).
5. The Scientific Panel Assessment Method considers many aspects of the flow regime, including total discharge, floods of various return periods and magnitude, drought frequency, seasonality and many aspects of the flood hydrograph. In this respect, it has the same advantages as the Holistic Approach and the Building Block Methodology.
6. The methodology estimates acceptable percentage reductions in various flow parameters of importance to ecosystem function. This is similar to the Water Allocation and Management Planning (WAMP) benchmarking process (Vanderbyl 1998) and in the Flow Restoration Methodology (Arthington 1998a), but is less sophisticated in the Scientific Panel Assessment Method.
7. Recommendations are provided on land use impacts on the river and suggestions are made on the management of out-of-channel processes.
8. The methodology recommends future strategic research relating to the flow needs of the river (Pusey 1998).
9. The methodology recognises that any interim flow guidelines must be acceptable to primary stakeholders (Pusey 1998).

6.2.2 Limitations

1. This expert panel methodology has the same inherent weaknesses as all holistic methodologies. It is highly dependent on knowledge of the quantitative relationships between flow and geomorphological/ecological response. It can only develop interim guidelines for provision of environmental flows, because detailed field studies are not a part of the methodology.
2. Although the methodology states the reasons for provision of certain flows, it does not provide the same level of quantitative supporting evidence as the Building Block Methodology or the Holistic Approach (Pusey 1998). In the Barwon-Darling study, various levels of flow percentiles were related descriptively to physical features affecting each ecosystem component.
3. The methodology estimates percentage reductions in various flow parameters which would be ‘acceptable’ (Thoms et al. 1996), but does not provide any scientific basis for the magnitude of the proposed reductions, apart from an emphasis on the importance of in-channel flow heights (Brizga 1998b). No scientific basis is given for recommendations to maintain geomorphological processes (Brizga 1998b).

6.3 Recent developments of the Scientific Panel Assessment Method

There do not appear to be any recent developments of this methodology in print.

7. The Habitat Analysis Method

7.1 Origins of the Habitat Analysis Method

The Habitat Analysis Method was developed by the former Queensland Department of Primary Industries, Water Resources, to determine environmental flow requirements as part of the Water Allocation and Management Planning (WAMP) initiative (Burgess & Vanderbyl 1996). The originators of the Habitat Analysis Method regard it as an extension of the 'panel of experts' approach developed in New South Wales (Walter et al. 1994). The method employs a Technical Advisory Panel with disciplinary and/or local knowledge of each catchment to determine the flows required to sustain the 'riverine system'.

The centrepiece of the method is a Technical Advisory Panel workshop run 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 habitat; (iii) development of bypass flow strategies to meet those requirements; and (iv) development of a monitoring strategy to check the effectiveness of flow strategies.

Several basic assumptions from the Holistic Approach have been built into the Habitat Analysis Method, as cited below by Walter et al. (1994) and Burgess and Vanderbyl (1996).

1. Environmental flows and river management should attempt to mimic the natural flow regime (Arthington et al. 1992a; Arthington & Pusey 1993)
2. The need to consider the aquatic biota in terms of sustainable and resilient populations (Blühdorn & Arthington 1994b).
3. Flows which maintain habitats in good condition provide a 'surrogate' means of determining environmental flows for riverine biota.
4. Water can be described in terms of flow: water levels, flow velocity, timing of flows (seasonal, diurnal), rates of change of flow and volume.
5. Water can be described in terms of quality: suspended solids, turbidity, salinity, nutrient levels, temperature, pH and other chemical properties.
6. In some cases, flows released for consumptive use may satisfy environmental requirements en route through the natural watercourse.

The Technical Advisory Panel workshop is preceded by a data collection phase when the following information is collated:

- catchment and watercourse maps;
- locations of water infrastructure and management nodes
- longitudinal sections of major streams
- streamflow data at management points within the catchment highlighting key features of catchment flow regimes such as seasonality;
- history of infrastructure development;
- current water management rules;
- State of the Rivers reports and water quality reports;
- overview of river morphology and bank stability
- broad survey of fish populations in catchment;
- list of important riverine habitat;
- list of rare and endangered species; and
- a summary of relevant government policies and plans for wetland and river management.

Slides of representative habitats and satellite imagery of river reaches are also assembled before the workshop.

The workshop process produces a matrix of habitat types (waterholes, riffles, impoundments, backwaters, wetlands, brackish zone, estuarine zone, mangroves) *versus* critical environmental flow requirements (eg. critical water levels, acceptable ranges, timing and duration of flows). Bypass flow strategies are then proposed to meet the flow requirements of each habitat, initially by identifying broad management responses (eg. minimising temperature variation, maintaining specific water depths, mimicking natural flow events). The objective at this point is "to develop flow provisions which are not too complex, so that all panel members can see the links back to the critical flow requirements" of habitats (Burgess & Vanderbyl 1996).

The outcomes of these processes would typically include environmental flow provisions for waterhole, riffle zone and wetland management, inclusion of part of the first major flow of the season, based on the suggestion that the first major flood of the wet season may be important as a source of suspended solids, nutrients and carbon, as well as providing cues for fish migration and spawning (see Arthington et al. 1992a). Channel maintenance flows are also recommended. At this point, any rare and endangered species are considered to determine the implications of the proposed environmental flow options for maintenance of species of special status. Burgess and Vanderbyl (1996) emphasise that it is important to exclude rare and endangered species from the initial workshop discussions so as not to consciously develop provisions specifically for them. This is in keeping with the key principles of the method, namely, to provide for the needs of the 'riverine ecosystem' using habitat as the 'indicator' for estimating environmental flow requirements, rather than focusing on the needs of individual species or communities.

After the workshop a number of activities commence before the environmental flow provisions are presented to a community consultative group. Each environmental flow provision identified at the workshop is quantified in terms of quantity of water, flow rate, duration and seasonal timing. Burgess and Vanderbyl (1996) state that: "Whilst most provisions will relate to natural flow events, some could be in the form of constraints such as maximum flows through a regulated section during dry times" (cf Arthington et al. 1992a; and the concept of the 'capping flow' in the Building Block Methodology). The impact of providing each environmental flow option is then assessed by considering its effectiveness in meeting critical environmental requirements (ie. 'sensitivity'), water resource entitlements (ie. 'yield and reliability') and the capacity of infrastructure outlet works ('physical limitations and costs') (Burgess & Vanderbyl 1996). These impact assessments allow for rational debate of the issues during the community consultation phase, which is followed by fine tuning of the environmental flow provisions (Burgess & Vanderbyl 1996).

The final step is to present options for the specified environmental flow provisions back to the expert panel members, to verify that they are consistent with the original intentions of the workshop, and to quantify sensitivity levels associated with effectiveness in meeting critical environmental flow requirements (Burgess & Vanderbyl 1996). This feedback loop is achieved either by reconvening the workshop or by circulating a report and seeking comments from the panel members. At this point the environmental flow provisions and options regarding these provisions are presented to a formal stakeholder consultation process designed to assist in determining an acceptable balance between all water uses. The outcomes from this final phase are formal specifications of the environmental flow provisions to be included in any water management plan (Burgess & Vanderbyl 1996).

7.2 Recent developments in the Technical Advisory Panel workshop process

The workshop approach to assessment of environmental flows developed as part of the WAMP initiative has advanced considerably since the first expert panel workshops were held in the Fitzroy Basin. Technical Advisory Panels have now adopted a more explicit ecosystems approach to environmental flow assessments, drawing upon principles and methods embodied in the holistic/building block approach and the Scientific Panel Assessment Method of Thoms et al. (1996). This ecosystem framework appears to have superseded the simple dependence of the process on an assessment of the water requirements of habitats, and the Habitat Analysis Method is no longer referred to in writings about the WAMP initiative (eg. Burgess & Thoms 1997, 1998; Vanderbyl 1998). Although the process is still highly dependent upon the use of habitat as an indicator of ecosystem health, there is a more explicit recognition of the flow requirements of selected aquatic species or communities; for example, 'trigger flows' are recommended to stimulate fish movement, migration and spawning (DNR 1998a, 1998b).

The method of constructing a flow regime to maintain the whole riverine ecosystem mimics that of other holistic and building block approaches, which divide the river into discrete geomorphological zones with different hydrological and habitat characteristics, and then identify critical flow thresholds and ranges of flow to achieve defined geomorphological and ecological objectives. For example, the recent Condamine-Balonne study (Burgess & Thoms 1997, 1998) recommended the following critical flow thresholds in the upland river zone:

- low flow depth over riffles to ensure an upper limit for benthic invertebrate habitat (developed using a wetted perimeter method);

- flows to initiate motion of the surface sediment, which is important for maintenance of in-channel morphology and disturbance of benthic invertebrate habitat;
- flows to inundate gravel bars, which are a major morphologic feature of this zone and an important refuge area for fish once inundated;
- flows to inundate the riparian zone deemed important for bankside vegetation; and
- flows to inundate the floodplain and so to maintain links between the channel and floodplain, especially in terms of the transfer of carbon and nutrients.

Once the critical thresholds (ie. water levels within the channel and various levels of inundation on the floodplain) have been determined, they are converted to discharge using a stage-discharge rating table pegged to the nearest gauging station. The Technical Advisory Panel's major task is then completed and the process goes into a modelling phase run by the Department of Natural Resources.

The development of a hydrological model with a daily time step representing the entire catchment is an integral part of the WAMP process, and is essential to environmental flow assessments. Models are developed using the Integrated Quantity Quality Modelling platform, which originated in New South Wales. An Integrated Quantity Quality Model is essential to generate extended historical flow sequences representing the pre-regulation state of the river, and to quantify and assess changes in flow regimes brought about by particular regulation structures and practices (Burgess & Thoms 1997, 1998). The model also provides the flow sequences used in development of alternative environmental flow scenarios, and permits assessment of their implications for consumptive uses of river water. Finally, the model is used to develop real time flow management rules for the entire catchment, employing an 'environmental flow node' within the Integrated Quantity Quality Model (Burgess & Thoms 1997, 1998).

The environmental flow management rules aim to achieve two important outcomes for the environment. Firstly, they aim to maintain the critical flow thresholds identified by the Technical Advisory Panel to ensure that water is provided to key aquatic and floodplain habitats. Secondly, they aim to mimic the natural timing, frequency, rate of flood recession and overall variability associated with each critical discharge. Using these rules, the next step is to run a series of simulations involving an extended historical flow sequence (up to 100 years), each simulation representing a different scenario of water management to meet consumptive needs, plus the relevant environmental flow requirements specified by the Technical Advisory Panel. Scenarios might include, for example, the existing level of development, or that level plus a new dam, or increased water allocations without the construction of a dam. The power of the models is such that any number of water management scenarios can be constructed and run to determine how well they achieve the required environmental flows at key points or nodes throughout the catchment.

Alternative management scenarios are run through the Integrated Quantity Quality Model to produce a series of key descriptive statistics, each statistic describing the quantitative and temporal dimensions of the critical flow thresholds specified by the workshop. For example, the key descriptive statistic for maintenance of healthy riparian and floodplain systems in the Fitzroy Basin is the frequency of riparian and floodplain inundation (DNR 1998b). Each key statistic is compared with the value for the natural, unregulated flow regime, and the percentage change from natural is calculated. The final step is to interpret the ecological significance of these proportional changes in key flow statistics, which serve as 'indicators' of important geomorphological or ecological processes in the river basin (Vanderbyl 1998).

A process of 'benchmarking' was developed during the Fitzroy Basin WAMP study to guide the assessment of impacts due to flow regulation (DNR 1998a, 1998b; Vanderbyl 1998). The idea of benchmarking is simple. If changes in key flow statistics can be related to degrees of degradation, then 'benchmarks' are available for assessing the potential impacts of modified flow regimes. In the Fitzroy WAMP, flow statistics for a number of other river systems within Australia with known or documented flow-related ecological or physical impacts were calculated and normalised against the natural statistics in those catchments. The percentage changes in statistics in the Fitzroy Basin were then compared against the percentage changes in these other catchments demonstrating significant to severe levels of impact, and plotted in three colour bands: green (little change from natural river health), yellow (significantly degraded) and red (seriously degraded). The results are presented in 'traffic light diagrams' (Vanderbyl 1998).

It was found that some of the key flow statistics used in the Fitzroy WAMP benchmarking study do not have to change very much to produce potentially severe levels of impact on the river system (Bunn 1998). By taking an overall view of about 12 statistics describing key features of the flow regime that Technical Advisory Panels agree are important, the benchmarking process can be used to rate each water management scenario in terms of its potential impact on the river ecosystem. Scenarios are then presented to the Community Panel and eventually the preferred scenarios are selected to become part of the WAMP strategy for the catchment (Vanderbyl 1998).

7.3 Strengths and limitations of the Habitat Analysis Method and benchmarking

7.3.1 Strengths

1. Environmental flow strategies are based on the best available scientific understanding of riverine ecology (Walter et al. 1994; Burgess & Vanderbyl 1996).
2. Environmental flow provisions are relatively simple to specify and so are in a form which is suitable for both management and resource allocation (Walter et al. 1994; Burgess & Vanderbyl 1996).
3. The Habitat Analysis Method is relatively quick and inexpensive to apply as the riverine experts are only required for the workshop and feedback stages (Walter et al. 1994; Burgess & Vanderbyl 1996).
4. The most important characteristics of the natural flow regime are maintained to some degree in the modified flow regime. In this respect, it has the same advantages as the Holistic Approach, the Building Block Methodology and the Scientific Panel Assessment Method.
5. In the benchmarking process, important characteristics of the natural flow regime are described statistically, using measures of flow quantity and temporal attributes that best represent the ecological benefits conferred (eg. a floodplain flow or a fish trigger flow) (Bunn 1998). Flow variability is also addressed and incorporated into the environmental flow rules.
6. Changes in flow regime due to proposed water developments are assessed in ecological terms using key flow statistics and benchmarking in degraded catchments. This is a novel 'top-down' approach (Brizga 1998b, 1998c; Bunn 1998).
7. The WAMP expert panel method is a catchment-wide process, designed to assess water availability, existing infrastructure and water allocations, future demands and development options, and to give a preliminary assessment of important environmental flow requirements at key points throughout the catchment (Brizga 1998b, 1998c; Bunn 1998).
8. Methods used in WAMPs permit a wide range of possible scenarios to be modelled and evaluated in terms of their potential impact on ecological systems in a situation of limited data on flow-related geomorphological and ecological processes (Bunn 1998).
9. The benchmarking process produces a first cut ranking of alternative water development and management scenarios in terms of their potential environmental impact throughout a catchment (Bunn 1998). It is the only process being used at present in Australia to predict the possible impacts of future flow regulation in poorly studied systems.
10. The green, yellow and red 'traffic light' diagrams are a novel way of communicating this ranking of impacts to the community, and help all involved to make the final decisions about acceptable and unacceptable scenarios of water resource development and management.
11. The methodology as a whole educates the community about all relevant issues affecting a river ecosystem rather than emphasising the flow requirements of a few species of 'charismatic megafauna' (Burgess & Vanderbyl 1996).

7.3.2 Limitations

1. In the WAMP process, environmental flow strategies are based largely on the maintenance of river and floodplain/wetland habitats in a healthy condition rather than on the specific flow requirements of ecosystem components (eg. channel structure; invertebrates, fish, riparian vegetation, key ecosystem processes) (Brizga 1998b, 1998c; Choy 1998; McCosker 1998a, 1998b; Moffatt 1998).

2. The WAMP process of specifying particular low flows and a few 'trigger flows' and floods from the 'bottom up' is based on limited technical knowledge of the river system and is vulnerable to leaving out some critical flow component or process driving the riverine ecosystem (Bunn 1998). Some scientists have expressed their discomfort with the lack of opportunity to collect their own field data, as is done in the Building Block Methodology and the Flow Restoration Methodology (Brizga 1998b, 1998c; Choy 1998; McCosker 1998a, 1998b; Moffatt 1998).
3. The benchmarking process is new and very useful at the basin-wide scale of WAMP assessments (Bunn 1998) but it requires critical examination and research to address such questions as the validity of using another river with a similar type of flow regime as a benchmark for assessing the potential impacts of flow regulation. Benchmarks need to be set soon so that the effectiveness of WAMP flow strategies can be assessed (Choy 1998).
4. The WAMP process gives some consideration to the ecological benefits of restoring elements of regulated flow regimes but lacks a comprehensive process equivalent to the Flow Restoration Methodology for reducing the impacts of historical and existing flow regulation (Arthington 1998a).

8. The Flow Restoration Methodology

8.1 Origins of the Flow Restoration Methodology

8.1.1 The Brisbane River study

There is presently no comprehensive scientific framework and set of methods for assessing environmental flow requirements and developing options for their implementation in rivers with a history of flow regulation by large dams. Expert panel methods (Swales & Harris 1995; Thoms et al. 1996) have addressed this problem in rivers such as the Snowy and Barwon-Darling, with varying levels of technical input and scientific rigour. Current Queensland Water Allocation and Management Planning (WAMP) projects are concerned primarily with catchments proposed for major new water infrastructure development, and in taking a basin-wide approach to water allocation. They have not yet investigated in detail how best to mitigate the effects of historical flow regulation.

A study of the environmental flow requirements of the Brisbane River downstream from Wivenhoe Dam commissioned by the South East Queensland Water Board provided an opportunity to trial a new methodology for assessing environmental flow requirements in a system with a long history of flow regulation. For simplicity, the methodology is termed the Flow Restoration Methodology to distinguish it from other holistic methodologies and frameworks currently applied in Australia. The Holistic Approach proposed by Arthington et al. (1992a) provided the theoretical framework for the Flow Restoration Methodology, and several key features of the Building Block Methodology were adapted into the methodology. It is clearly a hybrid of these earlier formulations.

The Flow Restoration Methodology is applied in two major stages (Arthington 1998a, Arthington & Zalucki 1998b). Stage 1 is an information gathering and review phase designed to determine what is known about the catchment or study area, so that knowledge gaps and data requirements for the environmental flow assessment can be identified. A report is prepared at the end of Stage 1 and Terms of Reference are developed for the detailed Stage 2 studies. In the Brisbane River study, Stage 2 involved the following seven main activities.

1. Development of a daily time step simulation model (Integrated Quantity Quality Model) of the river's unregulated flow regime and use of the model to determine the characteristics of the regulated flow regime under different water management and environmental flow scenarios.
2. Field and other forms of research to determine any environmental impacts of past and present flow regulation in the Brisbane River downstream from Wivenhoe Dam, and a desktop assessment of the potential impacts of using flows released from the dam to generate electricity. This step resulted in the preparation of a technical report by each member of a study team drawn from the disciplines of geomorphology, stream hydrology and hydraulics, water quality, and several areas of aquatic ecology.
3. A workshop process to define options for provision of environmental flows downstream from Wivenhoe Dam.
4. Development of alternative environmental flow scenarios and modelling of scenarios using the Integrated Quantity Quality Model. This was followed by an assessment of the implications of each scenario for the historical no-failure yield of the system.
5. Review of options for provision of environmental flows given existing and future constraints on the system, and consideration of alternative approaches and infrastructure arrangements to assist with providing environmental flows.
6. Development of a monitoring strategy to determine the ecological benefits of the environmental flow recommendations, and to advise on adjustments to flow management strategies, if necessary.
7. Identification of factors and processes other than flow regulation which may influence the condition of the river, and consideration of remedial actions.

8.1.2 Impacts of flow regulation

The first steps in the Flow Restoration Methodology are to describe the hydrology of the regulated river and then to determine the impacts of particular aspects of the regulated flow regime on the physical and biological characteristics of the river system. This work was focused on the river downstream from Wivenhoe Dam, using Savages Crossing as a major reference point. Changes in the flow regime of the Brisbane River were assessed by comparing historical flow phases before and after dam construction as well as flow data generated by modelling of unregulated and regulated regimes using the (Brizga 1998d). Key impacts of flow regulation in the Brisbane River are:

- elevated base flow;
- decreased variability in monthly and daily flows;
- loss of spells of low flow;
- decreased flood magnitudes; and
- altered flood hydrographs with increased durations and regulated drawdown rates.

Various methods were used to assess the ecological impacts of flow regulation:

- review of historical photographs, maps, site plans and rating curves;
- field surveys of riparian vegetation along river transect;
- upstream/downstream comparisons of habitat and biological community structure;
- comparisons between the Brisbane, Albert, Logan and Mary Rivers;
- correlation of river flows and fish/crustacea catches in Moreton Bay; and
- predictive modelling of biological community structure (using the RIVPACS approach; Wright 1995).

A brief summary of the main effects of flow regulation in the Brisbane River downstream from Wivenhoe Dam is presented in Arthington (1998a).

8.1.3 Developing environmental flow recommendations

Environmental flow recommendations were developed during an Environmental Flow Workshop using an eight-step process of analysis as a guide (see Table 3, page 33). During the workshop, hydrological, geomorphological and ecological information drawn from the disciplinary field studies was used to identify important characteristics of the unregulated flow regime which might be restored in part, or fully, to achieve specific environmental objectives. These objectives were established for each disciplinary area, and for the river as an ecosystem, as part of Stage 1. For example, the objectives for the fish ecologist were to maintain fish species diversity and abundance, community structure, migration patterns and life history processes, and to reduce exotic species.

After the workshop, flow recommendations were collated and developed into a series of environmental flow scenarios, each designed to achieve particular objectives. The first scenario aimed to reinstate most characteristics of the unregulated flow regime, starting with the natural low flows needed to maintain the physical distinctiveness of riffle, run and pool habitats and their distinctive biological communities. Various quantities of flow were added to this low flow requirement to make up the full scenario. Each quantity of flow built into the flow scenario was specified in terms of its temporal attributes, as follows:

- the time of year of particular flows;
- the annual frequency and return periods of freshes and floods;
- the shapes of flood hydrographs (rise and recession rates, peak discharge, duration); and
- the overall temporal patterns of the flow regime (flow variability).

When the Brisbane River study was conducted there was no established methodology for incorporating all of these quantitative and temporal characteristics of a flow regime into 'rules' that can be simulated using a daily flow model, and also implemented in real time by water managers. The Fitzroy WAMP project was in progress and eventually produced some relatively simple flow management rules in a similar fashion to the holistic/ building block approach, with the aim of keeping close to the natural flow regime if possible (Burgess & Thoms 1997, 1998; Vanderbyl 1998). In the WAMP process, these rules are simulated as real time flow management rules using the 'environmental flow node' which has been developed within the framework of the Integrated Quantity Quality Model.

The environmental flow node was not available at the time of the Brisbane River study. Instead, a different approach was developed, one which aims to capture

Table 3: *Steps in the development of environmental flows using the Flow Restoration Methodology in the Brisbane River system*

Step 1: Review changes to river's flow regime	
	Describe annual flows, monthly flows, daily flows; flow spells, high flow events, flood hydrographs
Step 2: Define low flow characteristics for 1996 scenario	
	Summary of changes in low flows
	Effects of elevated low flows on riffle/run/pool habitat
	Rationale for restoring low flows in relation to:
	Channel morphology and habitat structure; riparian vegetation; aquatic macrophytes
	Invertebrates; fish; platypus; other vertebrates; water quality
	Potential for restoring low flows
	Definition of capping flows in low flow months
	Low flow sequences and hydrographs; flow variability in low flow months
	Rationale for restoring flow variability; potential for restoring flow variability
Step 3: Determine implications of low flow recommendations for fish passage	
	Fishway efficiency; passage in other reaches
Step 4: Summarise 1996 scenario environmental flow recommendations, August–November	
Step 5: Outline alternative infrastructure arrangements to achieve environmental objectives	
Step 6: Define medium–high flow characteristics of river for 1996 scenario	
	Summary of procedures for management of floods
	Summary of changes in medium–high flows
	Potential for restoration of medium–high flows
	Estimation of medium–high flows in relation to issues listed under Step 2
	Define high flows to estuary
Step 7: Summarise 1996 environmental flow recommendations, December–July	
Step 8: Define environmental flow recommendations under future (2031+) scenario	
	Implications of future scenario
	Environmental flow recommendations, August–November
	Environmental flow recommendations, December–July

much more of the natural quantitative and temporal characteristics of the unregulated flow regime in both the short and long term. To construct various alternative environmental flow scenarios, a series of critical flow thresholds was identified, each threshold and band of flows between thresholds meeting specified geomorphological, ecological or water quality objectives. These thresholds and the rationale for each are listed in Table 4 (see page 35). Similar issues would be relevant in many river systems, although there would also be site-specific concerns to be addressed.

For the first set of flow scenarios, all flow events greater than the selected threshold discharge were included as the environmental flow (Ruffini et al. 1998). This amounted to giving the river most of the natural flow regime as its environmental flow, a starting point only for assessment of other possibilities. Different scenarios were then devised by varying the critical flow thresholds, or by varying the return periods of flows above each threshold. The second set of scenarios included only the first flow event in each month above each of the given threshold flows. Other scenarios were based on this second set, but whether a monthly flow event was included or not also depended on the occurrence of a similar event in that month in the preceding two, three or four years.

These procedures automatically captured all, or part, of the temporal characteristics and variability of the natural flow regime for a given threshold discharge. Operationally, this would be equivalent to allowing all (or only some) of the natural in-flows into Lake Somerset that are greater than the threshold discharge to be passed through Lake Wivenhoe and then downstream to the Brisbane River estuary. By gradually reducing the number of flows which exceeded each threshold, it was possible to refine each scenario down to a few 'essential' flow elements, and then to see what effect this would have on the overall flow regime, its seasonal patterns, flood characteristics and variability, and so on.

It was also recognised that other sources of flow would contribute to the overall pattern of variability in the flow regime downstream from Wivenhoe Dam. These sources might include rainfall and run-off in local catchments, in-flows from Lockyer and other creeks, periodic groundwater in-flows, variability in the delivery of water from Wivenhoe Dam in response to water orders, and variability in water abstraction rates along the river.

8.1.4 Modelling and assessing environmental flow scenarios

Environmental flows were simulated in the Brisbane River daily flow model (Integrated Quantity Quality Model) by drawing the flows above each threshold discharge through the system as additional water demands below Mt Crosby Weir. The flow sequences used to draw water for the environment through the system were obtained from the unregulated flow sequence at Savages Crossing. To define each environmental flow sequence, the Savages Crossing flows were run through a computer program to extract the flows required above each threshold. The aim was to duplicate the natural features of the simulated unregulated flows which would have occurred at Savages Crossing in the absence of Somerset Dam and Wivenhoe Dam (Ruffini et al. 1998).

The Brisbane River Integrated Quantity Quality Model was used to simulate a range of environmental flow scenarios over an historical time frame of 100 years. The effects of various environmental flow scenarios on the historical no-failure yield of the system were then modelled, using the water demands forecast for the year 2031 and assuming 100% utilisation of residual in-flows below Wivenhoe Dam. This analysis was used to identify the flow scenarios of most benefit to the environment and least impact on system yield, as well as flow scenarios which can only be achieved under new infrastructure arrangements.

The flow sequences simulated for Savages Crossing (and Mt Crosby) under each of the environmental flow scenarios were summarised using statistics describing key flow events. Statistical comparisons of the flow regime achieved under each scenario with the unregulated case gave an insight into how well each scenario would achieve the specified environmental flow objectives. A similar process of flow analysis and comparison is employed in WAMP projects (Vanderbyl 1998).

8.1.5 Implementing and monitoring environmental flows

The study considered a number of alternative infrastructure arrangements which could be considered as a means of maintaining a more natural range of low flows from Wivenhoe Dam to Mt Crosby, and from there downstream to the tidal reach. The study also recommended investigation of options to achieve more natural hydrograph shapes when flood waters are released from Wivenhoe Dam.

An essential component of the Flow Restoration Methodology is the development of a monitoring strategy to determine the benefits and effectiveness of environmental flows. Each participant in the Brisbane River study recommended a monitoring strategy relevant to their subject area, and these recommendations were discussed at the workshop to identify common themes and areas of overlap. Details are provided in Arthington and Zalucki (1998b).

The presence of large dams and flow regulation are not the only factors affecting the condition of the Brisbane River system. Other factors and processes unrelated to or only indirectly affected by regulation impinge on this river. These were identified and remedial actions were outlined.

8.2 Strengths and limitations of the Flow Restoration Methodology

8.2.1 Strengths

1. The Flow Restoration Methodology is a hybrid methodology drawing upon the theoretical concepts embodied in the Holistic Approach and the Building Block Methodology and has the advantages of these methodologies (Arthington 1998a).
2. It differs from expert panel methods in requiring a more rigorous scientific approach involving original field or desktop research before alternative flow scenarios are developed and modelled, and practical constraints can be addressed (Brizga 1998b, 1998c; Choy 1998; McCosker 1998a, 1998b).

Table 4: ***Brisbane River threshold flows and the rationale for each threshold***

RANGE		RATIONALE
MLd^{-1}	m^3sec^{-1}	
>500 – 1,000	5.17 – 11.57	• to provide flows as low and variable as possible given water demands at Mt Crosby • to maintain the physical distinctiveness of riffle, run and pool habitats • to maintain a variety of in-stream habitats for aquatic macrophytes, invertebrates and fish • to provide invertebrate food resources for platypus and other vertebrates • to provide low flow conditions required for fish spawning and larval development
>1,000 – 5,000	11.57 – 57.87	• to retard macrophyte growth at riffles/runs • to limit development of permanent emergent and riparian vegetation, and maintain diversity • to provide flow events to stimulate upstream dispersal of fish (and possibly invertebrates)
>5,000 – 8,000	57.87 – 93	• to entrain gravel substrates at North of Kholo • to scour particular aquatic macrophytes at North of Kholo, and maintain diversity • to maintain in-stream habitat for invertebrates and fish dependent upon macrophyte cover
>8,000 – 10,000	93 – 115.74	• to flood low level benches, flood runners and wetlands • to maintain lateral habitat for plants, invertebrates, fish and other vertebrates • to flush water hyacinth from backwater areas
>10,000 – 30,000	115.74 – 347.22	• to flood mid-level benches
		• to maintain lateral habitat for plants, invertebrates, fish and other vertebrates • to stimulate fish/crustacean catches and recruitment in estuary • to maintain water quality in river by mixing processes
>30,000 – 40,000	347.22 – 462.96	• to inundate floodplain and backwater areas • to maintain recruitment of riparian and wetland vegetation • to provide floodplain habitat for fish foraging, spawning and larval development • to stimulate fish/crustacean catches and recruitment in estuary and river mouth • to maintain water quality in river and estuary by flushing processes
>40,000 – 100,000	462.96 – 1,157.4	• to stimulate downstream migration of Australian bass • to stimulate fish/crustacean catches and recruitment in river mouth and Moreton Bay • to maintain water quality in the estuary and Moreton Bay dependent upon large flow events
>100,000	1,157.4	• to entrain gravel substrates at Savages Crossing
		• to retard macrophyte growth at Savages and similar riffles/runs • to provide habitat suitable for recruitment of riparian vegetation at higher channel elevations • to maintain ongoing geomorphological processes and channel structure • to maintain water quality in Moreton Bay dependent upon major freshwater plumes

Note: See Arthington and Zalucki 1998b for details.

3. The Flow Restoration Methodology uses a wide range of methods to assess the impacts of flow regulation (Workshop Comment, AWWA Forum on Environmental Flows, Arthington & Zalucki 1998c).
4. The use of a daily flow model for the river to generate extended historical flow sequences delivers a refined assessment of changes in flow regimes brought about by particular regulation structures and practices (Ruffini et al. 1998).
5. The flow model is essential to provide the flow sequences used in development of alternative environmental flow scenarios, and permits the assessment of their implications for consumptive uses of river water (Ruffini et al. 1998).
6. In, different flow scenarios are devised by varying various critical threshold flows and the return periods of flow events greater than each threshold. This approach has great flexibility, and captures more of the flow variability of the system than other methods currently in use (Ruffini et al. 1998).
7. Comparing each flow scenario statistically with the unregulated flow sequence helps to determine how well it would achieve key environmental objectives (Ruffini et al. 1998). 'Top-down' processes coupled with 'bottom-up' construction of a modified flow regime is the most rigorous approach to environmental flow assessment (Brizga 1998b, 1998c).
8. The methodology of modelling the effects of environmental flow scenarios on system yield provides water managers with valuable information as they attempt to rationalise competing water demands (Ruffini et al. 1998).
9. Identification of alternative infrastructure and water management arrangements provides additional advice on how environmental flows might be achieved in systems where there are real constraints on restoring historical flows (Workshop Comment, AWWA Forum on Environmental Flows, Arthington & Zalucki 1998c).
10. The inclusion of a monitoring program and a phase of further research on specific issues is a strong feature of the methodology (Workshop Comment, AWWA Forum on Environmental Flows, Arthington & Zalucki 1998c; Bunn 1998).
11. The Flow Restoration Methodology can be applied in a whole-of-system assessment involving large and small regulation structures, as well as in rivers where incremental water demands have modified the natural flow regime. Both types of flow modification must be addressed under the Council of Australian Governments' agenda (Brizga 1998b, 1998c).
12. This methodology of restoring key features of the flow regime is an ideal approach to the development of environmental flow recommendations in modified and regulated river systems, and one that is needed (Bunn 1998).

8.2.2 Limitations

1. Lack of data on river ecosystem structure and key ecological processes related to flow from before dams were constructed and flows regulated or otherwise modified constrains the assessment of the impacts of flow regulation, and demands the use of innovative methods (Bunn 1998). Further research is also required to evaluate the impacts of historical flow regulation (Brizga 1998b, 1998c).
2. As in the holistic/building block approach, there will always be some uncertainty as to whether or not something important has been left out in the process of constructing a flow regime in a step-wise manner; issues such as water quality and the flow requirements of water-dependent wildlife require more development and stronger linkages into this and other methodologies (Bunn 1998).
3. The dependence of all holistic/building block approaches and expert panels on the natural flow regime as a guide to desirable flows is vulnerable to the limitations/accuracy of daily flow models. These need to address the effects of land use change and other factors on stream hydrology and may require more rigorous calibration (Workshop Comment, AWWA Forum on Environmental Flows, Arthington & Zalucki 1998c).
4. The Flow Restoration Methodology must be trialled more widely to assess its strengths and limitations (Workshop Comment, AWWA Forum on Environmental Flows, see Arthington & Zalucki 1998c).

9. The Environmental Flows Decision Support System

This review of holistic methodologies is required to review the degree to which water management agencies involved in water allocation for environmental purposes would benefit from an Environmental Flows Decision Support System of the type being developed by the Murray-Darling Basin Commission and the National River Health Program. To this end, the concept and structure of the Environmental Flows Decision Support System are briefly outlined and related to other frameworks for environmental flow assessment and water allocation used in Australia. Potential similarities and differences are noted in so far as possible without having seen a final version of the Environmental Flows Decision Support System.

The main features of the Environmental Flows Decision Support System are described in a report by Young et al. (1995). The objectives of the project are to provide support to the Sustainable Rivers Program of the Murray-Darling Basin Commission by developing tools to help determine the environmental impacts of changes in river flow regimes, and to facilitate an informed trade-off process between environmental flow allocations and consumptive uses of water (Young et al. 1995). The Environmental Flows Decision Support System proposes to use the RAISON software platform developed in Canada. This incorporates a spreadsheet, internal database, a mapping and graphics system and an expert system shell. RAISON can also import data from many common databases, spreadsheets and geographic information systems. A Windows version will probably be used. RAISON also has the advantage that it can be linked to a number of FORTRAN flow models.

The basic approach to the analysis of a river to be employed using the Environmental Flows Decision Support System is, firstly, to divide the study river into a series of longitudinal river management zones, each with different geomorphological, hydrological and ecological characteristics, and also taking into consideration the management possibilities in different reaches and zones of a river system. This duplicates the processes employed in all holistic methodologies. The next step is to undertake a spatial disaggregation of the riverine environment using the lateral zones of in-stream, riparian, near floodplain and far floodplain, similar to the process employed by Thoms et al. (1996) in the Barwon-Darling study. This longitudinal and lateral spatial disaggregation is intended to provide relatively homogenous types of riverine environment (Young et al. 1995).

Proposed ecological indicators of river health will then be developed to give specific information relevant to each longitudinal and lateral zone. The essential concept of the Environmental Flows Decision Support System is to develop relationships between important hydrological parameters and the ecological indicators, which might be based on species, communities or on trophic structure. This approach duplicates the Holistic Approach/Building Block Methodology and the Scientific Panel Assessment Method, wherein key features of the natural flow regime are identified and related to known geomorphological and ecological characteristics of the riverine ecosystem. The challenge for the Environmental Flows Decision Support System will be to identify these relationships and to quantify them for the river systems of the Murray-Darling Basin.

The intention of the Environmental Flows Decision Support System project is to develop a series of simple models which will assist users of the system to identify how changes in a river's flow regime will affect the various ecological indices. Models are to be developed to show effects of hydrological change on such features as fish populations, riparian vegetation and algal blooms. Underpinning the development of models is the Ecology-Flows Handbook, which will summarise all that is known about these relationships in the basin. The Environmental Flows Decision Support System ecological models and the knowledge accumulated in the handbook will be updated periodically to capture the latest understanding of processes driven by flow regimes in basin river systems.

There are significant parallels between the concept of hydrology-ecology models within the Environmental Flows Decision Support System and the procedures now employed in the Queensland Water Allocation and Management Planning (WAMP) process and benchmarking system, and the Flow Restoration Methodology. Both methodologies use various hydrological indices and measures to summarise key features of natural and regulated river flow regimes and both attempt to relate changes in these hydrological indices to geomorphological and ecological outcomes.

Developing an understanding of how certain levels of change in key hydrological characteristics and indices affect a river system is a difficult process, given the lack of pre-impact monitoring in most regulated rivers. In the WAMP process, the linkages between indicators and ecological outcomes are developed using a Technical Advisory Panel and workshop process based on the existing knowledge base, and benchmarking against regulated and degraded catchments. Benchmarking relies on information derived from other regulated river systems to rank the ecological impacts of change in key hydrological indices. Three ranks of impact are identified: low, significant and severe (DNR 1998a, 1998b). These benchmarks guide the assessment of various water development and infrastructure scenarios and help to determine how well each would meet the recommended environmental flows.

The Flow Restoration Methodology uses original field and desktop studies to quantify the effects of past and present flow regulation on river channel morphology and aquatic habitat structure. It then identifies the responses of various biological components of the ecosystem to changes in discharge, velocity, substrate characteristics, habitat diversity, and so on, and such features as sources of food (energy), potential for migration, lateral connectivity with the riparian zones and backwater areas, and longitudinal connections with the downstream estuary (see Arthington & Zalucki 1998b). The Scientific Panel Assessment Method represents a somewhat less rigorous approach to the same problem of relating changes in flow in a modified river to ecological outcomes, but essentially does so without undertaking original field measurements or biological analysis, although it does attempt to use any available scientific information about the catchment.

Thus the Environmental Flows Decision Support System is proposing to employ an approach that is now in use in Queensland and elsewhere, and one that is accepted as a rational methodology. The advance that the Environmental Flows Decision Support System proposes to offer is the capacity to scrutinise these complex linkages and interactions between flow and river processes within the framework of a user-friendly, illustrated, geographic information system-based computer platform.

There are three dimensions to the potential utility of the Decision Support System. The first is how well it can capture and present to its users all of the relevant background information about a catchment or river basin, plus the relevant hydrological and ecological data which must be assembled to conduct an environmental flow assessment. Existing holistic methodologies have all developed ways to summarise and present such data to their study teams, and these data collation methods are constantly being changed and improved. A rigid framework for data collation and presentation may be premature; it certainly needs to be flexible. More consultation with other research groups and state agencies would avoid repetitious research and guide the Environmental Flows Decision Support System towards the best approaches and formats for data presentation. This is particularly relevant to the summation and analysis of flow data, which underpin every holistic assessment of environmental flow requirements.

The second issue is the predictive modelling component of the Decision Support System. If it can develop predictive models of the many processes which should be considered in any environmental flow assessment, the Environmental Flows Decision Support System will be an extremely useful tool. However, there are likely to be many gaps in this modelling capacity, even in well-studied areas of the Murray-Darling Basin. A more open-ended, interactive process for incorporating the 'best scientific knowledge' and 'expert opinion' will be necessary in most environmental flow assessments for a long time to come. Too great a reliance on a rigid Decision Support System may actually discourage the complex discussions and dynamic interactions which must take place throughout every environmental flow study and/or workshop.

A major challenge for the Environmental Flows Decision Support System will be integration of the outputs from a range of flow-ecology models and discussions to produce an overall modified flow regime, and then the simulation of that flow regime on a daily basis, as is now done in WAMP projects, the Flow Restoration Methodology and the Building Block Methodology. Each of these is now using a slightly different methodology to compile a modified flow regime based on daily flow data and daily, monthly and seasonal time steps, as reviewed in the previous sections of this report. It is understood that the Environmental Flows Decision Support System does not intend to advocate any particular process for the assembly of alternative environmental flow scenarios, but rather to use whatever data and methods are considered appropriate by the user group.

One of the possible outcomes from use of the Environmental Flows Decision Support System in its early formulations is a relatively simplistic overview of alternative environmental flow scenarios for any river system simply because of the practical difficulties of getting all the relevant information, and models, into the Decision Support System, assuming that information is available. This would be rather unfortunate since relatively sophisticated holistic methodologies are already available in Australia which bring knowledgeable groups of people together and encourage them to the very limits of their capacity to give scientific advice in relatively constrained circumstances. Presenting the key outputs from such multidisciplinary team approaches based on the best available science to water managers and community groups (as in the Building Block Methodology, the WAMP benchmarking process, the Flow Restoration Methodology and the Scientific Panel Assessment Method) seems to offer a more comprehensive approach than using a highly mechanised computer-based process with limited capacity to address ecosystem complexity and a multitude of unforeseen circumstances and issues. The constrained nature of a Decision Support System, irrespective of the knowledge it captures, may be an impediment to creative, lateral thinking, a key element in the difficult process of constructing modified flow regimes to achieve defined ecological objectives.

Finally, it is not clear that the Environmental Flows Decision Support System will incorporate or advocate post-implementation monitoring to determine the ecological outcomes from the provision of environmental flows. All holistic methodologies recognise that environmental flow recommendations are hypotheses which must be tested through monitoring and further research.

If a flexible, robust and informative Environmental Flows Decision Support System can be produced, based on a sound scientific understanding of processes operating in the Murray-Darling Basin, and incorporating an holistic methodology for assembling alternative environmental flow strategies, it is likely to be immensely useful. An evaluation process should be put in place before any decision is made to extend the Environmental Flows Decision Support System to other major river basins.

10. Comparison of holistic methodologies

A comparison of the methodologies reviewed in this report is deferred to LWRRDC Occasional Paper Number 25/98 (Arthington et al. 1998a), where comparisons are presented in the context of proposing a best practice framework for applying flow assessment techniques and holistic methodologies.

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