Hydrological Analyses for Environmental Flow Assessment

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Abstract: Most of the standard statistical analysis tools used by hydrologists were developed in response to the traditional engineering problems of drought management, flood mitigation, or development of water supply systems. In contrast, environmental flow assessment uses established or hypothesised relationships between hydrological characteristics of a stream and ecological response, so that the regulated flow regime can be tailored to provide a basic level of ecosystem protection. This paper reviews hydrological analysis techniques that have been applied to the problem of assessing environmental flows. The most appropriate approach is grounded in the assumption that the hydrological time series (or regime) contains identifiable, recurring ecologically and/or geomorphologically relevant facets or events. These facets are then dissected from the record and their hydrological characteristics (with a focus on variability) determined separately.

Keywords: Environmental Flows; Hydrology; Expert Panel; Geomorphology; Flow Variability

1. INTRODUCTION

Environmental flow (or in-stream flow) is a term used to describe the hydrological component of aquatic ecosystems that is required to rehabilitate, or protect, biodiversity and ecological integrity. "Integrity" is usually taken to mean self-sustaining, but the details of the definition vary depending on project objectives, priorities, constraints and other site-specific factors. Environmental flows are prescribed for unregulated rivers, where limits on future demands must be set, and on regulated rivers where efforts are being made to improve ecosystem functioning. In the past, environmental flow regimes were fairly simple, some consisting only of a constant minimum flow that was presumed sufficient to maintain aquatic life.

This paper reviews the application of hydrological analysis techniques in environmental flow assessments. The emphasis is on ways of characterising flow variability, as this aspect of the flow regime has many facets, and is generally regarded as being crucial for sustaining aquatic life.

2. FLOW VARIABILITY

The traditional practice of releasing relatively constant flows from dams conflicts with the *natural flow regime paradigm*, which states that discharge variability is central to sustaining and conserving biodiversity and ecological integrity [Walker et al., 1995; Stanford et al., 1996; Poff et al., 1997; Richter et al., 1997; Environment Protection Authority, 1997; Puckridge et al., 1998; Tharme and King, 1998]. Some limited understanding of the links between biological processes and aspects of flow variability has been achieved, with most progress being made on species of high conservation or commercial value. However, given this currently limited understanding, and the improbability of ever being able to fully define the needs of the whole biological community, the conservative alternative is to assume that the natural flow regime is the best indicator of environmental needs. In Australia and South Africa, which are known for their highly variable rivers [Finalyson and McMahon, 1988], this concept has been quickly converted into environmental flow policy objectives. For example, the objective of mimicking natural flow variability appears in numerous publications in the environmental flow literature [e.g. Environment Protection Authority of NSW, 1997; Arthington, 1998; Tharme and King, 1998; Snowy Water Inquiry, 1998]. The natural flow regime paradigm has merit, but translating it into recommendations for environmental flows can be problematic. One problem is how to quantify hydrological variability.

Flow variability in rivers has been examined statistically by several authors. Puckridge et al. [1998] defined 23 measures of hydrological variability, but only five were independent. However, they collated evidence that eight of these variables were linked (not necessarily causally, and not universally) to features of fish biology. Jowett and Duncan [1990] classified New Zealand rivers according to 7 indices that described inter-annual flow variability, or the range of extremes in the records. All but one of the hydrological indices were highly inter-correlated. This study found strong associations between flow variability and periphyton communities [positive and negative correlations] and rainbow trout abundance [negative correlation], weak associations with benthic invertebrate communities, and no relationship between flow variability and water quality. Jowett and Duncan [1990] concluded that variability in water velocity (associated with discharge variability) was the most important factor influencing river ecology and geomorphology. The Range of Variability Approach (RVA) [Richter et al., 1997], which uses daily data, defines 32 parameters that are Indicators of Hydrologic Alteration (IHA). Poff's [1996] classification scheme used 12-15 parameters, of which 3 measured variability.

Of course, there is no limit to the number of hydrological parameters that can be contrived to describe variability [see Growns and Marsh, 2000]; the challenge is to find the key parameters that have strong ecological and geomorphological associations and which can be translated into recommendations for environmental flows.

Many of the measures of Puckridge et al. [1998] are quite complex, and would be difficult to use as criteria for flow regime design. Jowett and Duncan's [1990] indices do not describe seasonal discharge or flood event variability. The RVA identifies annual river management targets based on a range of variation (e.g. ±1 standard deviation from the mean, or 25th to 75th percentile range) in each of the 32 parameters. The method prescribes that environmental flow regime characteristics should lie within the targets for the same percentage of time as they did prior to regulation. However, the natural level of inter-annual variability will be achieved only if river managers decide to vary flow characteristics within the target range. Without appropriate rules, managers of highly controllable rivers could maintain constant flow characteristics (near the upper or lower limits of the target range) over a series of years. Application of RVA does not necessarily preserve natural flow variability (e.g. see Figure 1).

The challenge of determining environmental flows is to design a regulated flow regime that will protect ecological integrity, but which uses a proportion of the natural discharge (usually less, but in rivers receiving inter-basin transfers it is more). Flow variability can be defined over the time scales of minutes, days, months and years. The only way to mimic (i.e. to copy or closely resemble) the full range of natural flow variability in the regulated flow regime is to adjust river flows *instantaneously* as a proportion of the natural inflows (i.e. the purest expression of the "translucent dam" principle). Apart from the impracticality of implementing such a scheme, the regulated flow would still fail to mimic natural flow variability at the scale of habitat hydraulics (temporal and spatial distribution of depth and velocity), unless channel geometry was similarly scaled down (i.e. the channel would have to be made smaller).

In practice, the process of determining environmental flows does not involve attempting to devise a regulated flow regime that has a statistically defined variability (across all time scales) identical to that of the natural flow regime. For example, all of the recent environmental flow projects listed by Poff et al. [1997] involved only partial restoration of the natural flow regime. Under conditions of limited water resources, competing demands, and constraints on flow control imposed by river structures, some flow variability targets will be low priority, and others will be impossible to implement.

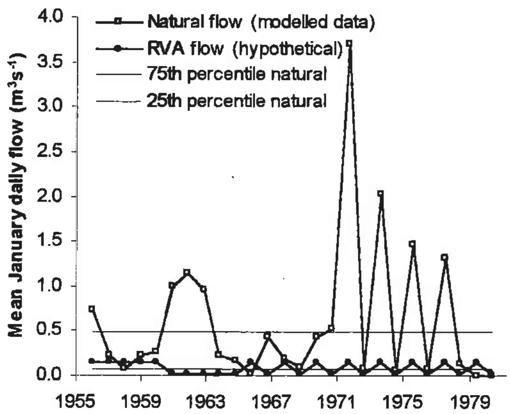

Figure 1. Natural [unregulated] mean January daily flow in the Fish River, NSW Australia (inter-annual C_v = 2.2), Range of Variability Approach (RVA) targets, and a hypothetical regulated flow regime that satisfies the RVA targets (inter-annual C_v = 0.9) (source: unpublished data, C. Gippel).

3. ENVIRONMENTAL FLOW METHODS

There are many techniques and methods being applied to the problem of environmental flow assessment, and they have been reviewed in detail elsewhere [O'Keefe et al., 1989; Jowett, 1997; Dunbar et al., 1998; Arthington and Zalucki, 1998; Arthington, 1998]. The methods can be classified into three basic approaches:

Rule-of-thumb or historic flow approaches use simple rules based on flow-duration or mean discharge to scale down the natural flow regime. The rules are usually based on empirical research into local flow-geomorphology-biota relationships [e.g. Tennant, 1976], and are thus region-specific.

Transect based hydraulic habitat analysis combines measured and/or modelled hydraulic data with knowledge of the hydraulic habitat preferences of the biota [usually key fish species] to provide desired habitat conditions throughout the year. Examples are PHABSIM which is a component of Instream Flow Incremental Methodology [IFIM] [Bovee and Milhouse, 1978], and simpler transect-based approaches [e.g. Gippel and Stewardson, 1998]. Tennant's [1976] historic flow method was based on surveys of this type.

Holistic or expert panel approaches cover a wide range of methodologies: the Expert Panel Assessment Method [Swales and Harris, 1995], the Scientific Panel Assessment Method [Thoms et al., 2000], the Building Block Methodology [Tharme and King, 1998], the Holistic Approach [Arthington et al., 1992], and the Flow Restoration Methodology [Arthington, 1998]. Central to these approaches is the idea of assembling a team of specialists from various disciplines to combine their expert knowledge to recommend a flow regime that satisfies objectives for the particular site. At one or more stages in the process, the experts are drawn together in a workshop situation with the aim of expediting an outcome. Apart from procedural differences, the main factor that differentiates the way individual expert panels operate is the level of effort applied to obtain information about relations between flow and habitat, geomorphology, water quality and biota. A common feature of these approaches is their objective to design an environmental flow regime that is the minimum required to achieve ecological integrity of the system (as defined within each project).

A central philosophy of the expert panel approach is that the flow regime can be dissected into various facets, some of which are thought to be more important than others for maintaining ecological integrity. Facets are hydrological features, indicators, events or conditions, definable in terms of magnitude, duration, frequency and seasonality, that recur in the discharge record. Such facets are equivalent to the events characterised in the Flow Events Method [Stewardson et al., 2001]. Sometimes the biological significance of these events is known, while often it is considered a hypothesis that might be tested through monitoring or further research. Although the expert panel approach may utilise elements of the hydraulic habitat and rule-of-thumb approaches, it is grounded in a more holistic philosophy that emerged from the weaknesses and limitations of the other approaches [Arthington, 1998].

The outcomes of the three broad approaches to environmental flow assessment can be quite different. The habitat-discharge models used in the hydraulic habitat approach result in flow regimes that theoretically provide ideal or pre-regulation habitat conditions, but which do not necessarily resemble the pre-regulation or natural regime in terms of intra- or inter-annual flow variability [e.g. Gippel and Stewardson, 1996]. The rule-of-thumb approaches essentially provide a scaled-down version of the natural regime, usually based on monthly flow statistics, such that the seasonal pattern of monthly discharge is retained. The RVA is a sophisticated rule-of-thumb method that incorporates elements of the expert panel approach.

Expert panels do not begin their deliberations on the basis of explicit numerical models that relate discharge to aspects of the river's geomorphology, water quality or ecology. Such models may be available, or even developed through the course of the investigation, but they are usually used as an aid to decision making, rather than as a numerical solution to the problem of defining a suitable regulated flow regime.

Flow variability is defined in various ways. In some studies the emphasis is on maintaining seasonality or timing of certain events [Tharme and King, 1998], and in others the emphasis is on maintaining inter-annual variability [Poff et al., 1997]. The all-inclusive objective to "mimic the natural flow regime" is absurd, because it is not possible to create a modified flow regime that has statistically defined flow variability close to that of the natural regime across all temporal scales.

The success of the expert panel approach is highly dependent on the level of relevant knowledge held by the invited experts, the relevance and quality of information regarding the system being investigated that is tabled, and the effectiveness of communication between the experts. The role of the hydrologist on the panel is to undertake statistical analyses in order to characterise the natural and current hydrology of the stream. If the river is ungauged, or has a patchy record, the first step will be generation of a synthetic flow record using modelling techniques.

Most of the standard statistical analysis tools used by hydrologists were developed in response to the traditional engineering problems of drought management, flood mitigation, or development of water supply systems. The emphasis has been on developing techniques of extrapolating beyond the gauged record, describing runoff in terms of its availability for human use, and calculating the hydrological risk posed to humans and their activities and assets [Gordon et al., 1992, pp. 346-402]. In contrast, environmental flow assessment uses established or hypothesised relationships between hydrological characteristics of a stream and ecological response. Standard methods of hydrological analysis were not specifically devised to describe flows in terms of their ability to sustain aquatic life. Some standard indices may be appropriate, but it is also necessary to describe discharge records in other ways that relate well to ecological and geomorphological processes.

4. HYDROLOGICAL TECHNIQUES

4.1 Standard Hydrological Methods

Methods of characterising flow regimes appear in numerous hydrology texts. However, Gustard [1992] and Gordon et al. [1992] described methods of flow regime analysis within texts that focussed on the application of hydrological principles to ecological issues. Despite this focus, the methods were presented primarily as being useful for evaluation of water resources, and regionalisation or classification of hydrological regimes. No indication of how these methods might be used to assist environmental flow assessment was given.

The inter-annual coefficient of variation of annual runoff (C_v) is a fundamental variable in hydrological analysis concerned with evaluation of available water resources, determining hydrological change through time, and comparing the regime of different rivers. Monthly discharge bar charts are commonly used to display intra-annual distribution of flows. The flow duration curve is one of the most commonly used ways of displaying the distribution of discharges, but its weakness is that it does not convey information about the sequencing of flows [Gustard, 1992]. Flow duration surface curves plot discharge on the vertical axis and month on the horizontal axis with the flow duration as a parameter. A series of flow duration surface curves characterises the seasonal variability of the full range of flows. The low flow frequency curve shows the proportion of years when a flow is exceeded, or equivalently, the average interval in years that the discharge falls below a threshold value [Gustard, 1992]. The flood frequency curve estimates the return period of floods of various peak magnitudes. The partial series is plotted using discharges above a threshold value, and is preferred when the events of interest have a recurrence interval less than 1:10 years ARI (average recurrence interval) [Gordon et al., 1992, p. 371].

4.2 Building Block Methodology Techniques

The most explicit and comprehensive guidance regarding hydrological techniques appropriate for environmental flow assessment is given in reports on the Building Block Methodology by Tharme and King [1998, pp. 61-88] and Hughes [2000]. In this methodology, 14 categories of hydrological information are produced on the basis of modelled or recorded daily flow data. Some of these categories are simply the same data presented in different forms. Periods of consistently dry or wet years are revealed by a plot of cumulative deviation of total annual runoff about the mean for all years of record.

The mean monthly flow for each month are plotted on a separate graph, to allow a "...quick understanding of seasonal distribution of flow", but this lumping of data can be misleading in highly variable systems. The analysis to determine the differences between natural and regulated regimes is simplistic, requiring comparison of monthly flows using box and whisker plots, or visual comparison of selected hydrographs. Indices of flow variability (coeffcient of variation and Colwell's predictability index) are recommended, even though Tharme and King [1998] admit that their usefulness in this context is unknown.

Cease-to-flow conditions were recognized as important, but methods for presenting this information were not provided. The original recommended flood series analysis appears to have been based on the annual series. This deficiency has since been pointed out by a geomorphologist (Dr K. Rowntree, Rhodes University) [Tharme and King, 1998, p. 84]. Typical flood hydrograph rates of rise and recession, duration, and volume are determined by visual examination of a range of flood hydrographs.

4.3 Spell Analysis

A spell is a period of consecutive days where the discharge remains either entirely above or below a given threshold. It has long been the practice in environmental flow studies to seek out and apply relationships between important ecological or geomorphological processes and threshold discharges [e.g. King and O'Keefe, 1989]. Donald et al. [1999] developed a computer program to characterise spells for given discharge thresholds.

4.4 Techniques Used in Australia

Snowy Water Inquiry [1998] characterised river hydrology on the basis of the monthly discharge bar chart, flow duration curve and monthly flow time series. The Snowy Genoa Catchment Management Committee [1996] also presented plots of river stage height against discharge and mean velocity at gauging stations [rating curves], daily times series plots, individual hydrograph plots, low flows expressed by 95th percentile exceedance flows, plots of flood frequency by month separated into classes according to flood peak, and mean flood duration. NSW Environment Protection Authority [1997] plotted cumulative frequency of events according to peak magnitude and cumulative frequency of events according to event duration.

Anderson and Morison [1989] plotted the intra-annual distribution of above bankfull events (>1:3.2 year ARI), and also smaller events of 4-day duration. A biologically significant low flow event was arbitrarily designated as having a magnitude <6 ML/d and a duration of >60 days. The frequency and duration of these events were tabulated. Plots of flow duration and flow duration surfaces were used to show the difference in flow regime between sites along the river, and the intra-annual distribution of flows.

Cooney [1994] plotted habitat availability as a function of discharge to determine thresholds that would inundate 50% of wetlands. The Holistic Approach study of Arthington et al. [1992] used flow duration calculated by month to define boundary conditions for seasonal flows, and characterised flood event duration and magnitude to define ad hoc special purpose floods.

4.5 Weaknesses of Current Techniques

Hydrological analyses have two purposes in expert panel studies. One is to inform the workshop participants regarding the hydrology of the river in question. This provides a common language to facilitate discussion about the problem. Ultimately however, the hydrological analysis must produce information that can be readily translated into recommended flows. The analytical techniques recommended by Tharme and King [1998], apart from the flood series analysis, use lumped high and low flow data. This seems counter to the fundamental Building Block process, which involves establishing a stable low flow as the first building block, small freshes as the second building block, and higher spawning, migration or geomorphic floods as the third building block.

The spell analysis program of Donald et al. [1999] offers strong potential for informing expert panels about some relevant characteristics of stream hydrology. However the program does not calculate statistics on the volumes of water associated with spells. Also, it does not analyse flood event hydrographs, so that rate of rise and fall cannot be computed. The analysis lumps all data either above or below the specified threshold, preventing the characterisation of events that lie *between* certain thresholds.

A common weakness of current hydrological analysis tools is that many of the calculations are performed on data sets that contain both baseflow and high flow data, when the environmental flow assessment involves assembling a regime from various hydrological events (baseflows and various high flow events) that are meant to mimic the characteristics of those events as they exist in the natural system. Further, spells analysis and flow duration (flow exceedance) analysis do not distinguish flood events as independent entities, as does partial flood series analysis. The partial series is constructed by nominating a period of time between discharge peaks that identifies them as being independent of each other (i.e. belonging to a different storm event). Without this distinction, large multi-peaked events can be interpreted as numerous independent floods of short duration. The implication of this is that flood event frequencies can be over-estimated, and flood event durations underestimated.

Environmental flow regimes are usually specified as monthly values, so disaggregation of the time series by month is a minimum requirement when characterising natural flow regimes. Baseflows and flood flows are usually specified independently, so these aspects of the natural flow regime should be analysed independently. Environmental flow studies are often concerned with seasonality of flows, as many biological processes are strongly seasonal. This suggests that the time series should be disaggregated by season, and the cease-to-flow, baseflow, and flood flow characteristics of these seasons characterised separately.

5. DISSECTING DISCHARGE RECORDS

An important first step in any environmental flow study is to characterise the natural (or pre-regulation) flow regime. It is usually assumed that the natural flow regime is the ecological ideal (all other things being equal). The ecologically and geomorphologically critical facets of the natural regime can be identified and used as a basis on which to model the environmental flow regime. In rivers that are already regulated, it is necessary to characterise the existing flow regime, as some of the identified critical facets of the natural regime may have been adequately preserved in the post-regulation regime, and need not be specified in the environmental flow regime. Alternatively, the regulated regime may contain (artificial) hydrological conditions that are known to be ecologically deleterious, and which require removal or modification.

For the purpose of discussing flows of environmental significance within the multi-disciplinary forum of an expert panel, it is useful to simplify the flow regime by reducing it to a number of facets or events that have particular significance for the river's ecology, geomorphology or water quality. These fall into five broad categories:

- Cease-to-flow
- Baseflow
- Flows important for maintenance of water quality
- Small, medium and large flow events of biological significance
- Small, medium and large flow events of geomorphological significance

Initially, the magnitude of the selected events may not be expressed by members of the expert panel in terms of a flow rate, but rather in such terms as "flow that overtops the banks", "flow that inundates the channel bed", "flow that allows fish passage through riffles", "flow that disturbs surface sediment", "flow that will de-stratify pools", or "flow that will mobilise bed material". The hydrological questions that arise regarding these events are usually: What is their magnitude? How frequently do they occur? What is their duration? When do they occur? What is the rate of change? (These are the equivalent to the five critical flow regime "components" referred to by Poff et al. [1997] when describing stream hydrology as the "master variable" that regulates ecological integrity) and, What volume of water do they require? These are the primary characteristics because they translate directly to specifications for an environmental flow regime, and they allow estimation of the volume of water required for allocation to the environment.

This review suggests that dissecting discharge records into important flow events [see Stewardson et al., 2001] is the most appropriate approach to hydrological analysis for environmental flow assessment, especially when using one of the expert panel or holistic-type approaches. This approach is grounded in the assumption that the hydrological time series (or regime) contains identifiable, recurring ecologically and/or geomorphologically relevant facets or events. These events are then dissected from the record and their hydrological characteristics determined separately. Given the hypothesised importance of hydrological variability, the emphasis is on characterising the extremes of the distributions. The statistical outcomes of this characterisation should be expressed in terms that can be translated into recommended environmental flows. The output of the analysis should be presented in a clear, graphical and tabular style that can be interpreted from ecological and geomorphological perspectives.

This paper does not recommend a prescriptive set of analytical steps that can be applied routinely in every case. How the events are defined, and what characteristics are most important, are matters for collective determination by the expert panel, not by the hydrologist working in isolation. The process may involve several iterations. For example, in hydrologically variable systems, the initial notion of what constitutes important events may be little more than a set of educated guesses. Hydrological characterisation of these events will inform the other specialists about the nature of the river's hydrology, who may then refine their definitions and request further analysis. Also, the results of any data gathering exercise that proceeds as part of the expert panel investigation, such as biological sampling, or hydraulic habitat measurements, may demand a reassessment of what constitutes important hydrological events. This procedure acknowledges the high level of uncertainty surrounding cause and effect in hydrologically variable aquatic systems.

5. DISCUSSION AND CONCLUSION

Many Australian rivers have naturally highly variable hydrology; different periods in the flow record can have markedly different hydrological characteristics, going through wet and dry phases of various lengths. The ecology of Australian rivers would be expected to have some tolerance for low levels of regulation, at least for a period of time. It may be possible then to achieve an acceptably healthy aquatic ecosystem in regulated rivers where the magnitude and/or frequency of some or all of the defined flow events deviates from natural conditions. The acceptable level of deviation is a question for the panel of experts to provide a tentative answer, while a more confident judgement awaits more information as adaptive management proceeds. The role of the hydrologist is to properly characterise these events so that the panel can make informed decisions.

The Flow Events Method [Stewardson et al., 2001] represents a development in environmental flows methodology, because it begins by seeking to define the ecologically important aspects of the flow regime, rather than relying on traditional hydrological statistics, narrow views of what constitutes ideal hydraulic habitat [Woo, 1999], or deliberations over arbitrarily or subjectively selected flow options [e.g. Snowy Water Inquiry, 1998]. One possible limitation of the Flow Events Method is that systems that are poorly understood from an ecological perspective would seem to demand little analysis. In these cases, an assumption of the importance of flow variability would be a reasonable starting point. Mimicking the natural flow regime may be a useful principle, but it cannot be achieved in practice.

Hydrologists should not feel constrained by the tradition of lumping low flow and high flow data, and concentrating on the characteristics of extreme floods and droughts. Although organisms respond to the flow regime in its entirely, this paper has argued that, for the purpose of assessing environmental flows, there is merit in dissecting the flow regime into facets or events that occur across a wide range of time-scales. This aids in understanding the system from an ecological perspective, and provides tools for crafting an interim flow regime that will help maintain or rehabilitate ecological integrity.

Practitioners are warned that designing an environmental flow regime solely on the basis of hydrological characterisation of the natural regime is a flawed approach if the river morphology has changed from its natural state. In these cases, an environmental flow regime may well restore the hydrology, but the in-stream hydraulic conditions and substrate quality (i.e. habitat) may still limit ecological recovery.

6 REFERENCES

Anderson, J.R. and A.K. Morison, Environmental flow studies for the Wimmera River, Victoria. Part A. Technical Report Series No. 73, Arthur Rylah Institute for Environmental Research, Kaiela Fisheries Research Station, Fisheries Division, Shepparton, Victoria. 1989.

Arthington, A.H., J.M. King, J.H. O'Keefe, S.E. Bunn, J.A. Day, B.J. Pusey, D.R. Bludhorn, and R. Tharme, Development of an holistic approach for assessing environmental flow requirements of riverine ecosystems, In: Pigram, J.J. and B.P. Hooper, (eds) Water Allocation for the Environment, Proceedings of an International Seminar and Workshop, Centre for Water Policy Research, University of new England Armidale, pp. 69-76, 1992.

Arthington, A.H. and J.M. Zalucki (eds), Comparative evaluation of environmental flow assessment techniques: review of methods, Occasional Paper No 27/98, Land and Water Resources Research & Development Corporation, pp. 66-105, 1998.

Arthington, A.H. Comparative Evaluation of Environmental Flow Assessment Techniques: Review of Holistic Methodologies, LWRRDC Occasional Paper 26/98. Land and Water Resources Research & Development Corporation, Canberra, 1998.

Bovee, K. D. and R. Milhous, Hydraulic simulation in instream flow studies: Theory and techniques, Instream Flow Information Paper 5, US Fish and Wildlife Service, Fort Collins, Colorado, USA, 1978.

Cooney, T. Barwon-Darling River riparian health report: wetland inundation, Technical Services Report No. TS 93.046, NSW Department of Water Resources, Environmental Studies Unit, Technical Services Division, 1994.

Donald, A., R. Nathan, and J. Reed, Use of spell analysis as a practical tool to link ecological needs with hydrological characteristics, Proc. 2nd Australian Stream Management Conference, 8-11 Feb, Adelaide, pp. 205-210, CRC for Catchment Hydrology, Monash University, Victoria, 1999.

Dunbar, M.J., A. Gustard, M. Acreman, and C.R.N. Elliot, Overseas approaches to setting River Flow Objectives, R&D Technical Report W6B(96)4, Institute of Hydrology, Environment Agency and NERC, Bristol, 1998.

Environment Protection Authority, Proposed Interim Environmental Objectives for NSW Waters – Inland Rivers, New South Wales EPA, Sydney, 1997.

Finlayson, B.L. and T.A. McMahon, Australia v the world: a comparative analysis of streamflow characteristics, In: Warner, R.F. (ed.) *Fluvial Geomorphology of Australia*, Academic Press, Sydney, pp. 17-40, 1998.

Gippel, C.J. and M.J. Stewardson, Use of wetted perimeter in defining minimum environmental flows, *Regulated Rivers: Research and Management*, 14, 53-67, 1998.

Gippel, C.J. and M.J. Stewardson, Development of an environmental flow management strategy for the Thompson River, Victoria, Australia, *Regulated River: Research and Management*, 10, 121-135, 1995.

Gordon, N.D., T.A. McMahon, and B.L. Finlayson, *Stream Hydrology: An Introduction for Ecologists*, John Wiley and Sons, Chichester, 1992.

Growns, J. and N. Marsh, Characterisation of flow in regulated and unregulated streams in eastern Australia, Cooperative Research Centre for Freshwater Ecology Technical Report 3/2000, Canberra, 2000.

Gustard, A. Analysis of river regimes, In: Calow, P. and G.E. Petts (eds), *The Rivers Handbook*, Blackwell Scientific Publications, Oxford, pp. 29-47, 1992.

Hughes, D. Hydrology, In King, J.M., R.E. Tharme, and M.S. de Villiers (eds), Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology. Freshwater Research Unit, University of Capetown, WRC Report No. TT 131/00, pp. 133-152, 2000.

Jowett, I.G. Instream flow methods: a comparison of approaches, *Regulated Rivers: Research and Management*, 13, 115-127, 1997.

Jowett, I.G. and M.J. Duncan, Flow variability in New Zealand rivers and its relationship to in-stream habitat and biota, *N.Z. J Marine and Freshwater Res.*, 24, 305-317, 1990.

King, J.M. and J.H. O'Keefe, Looking to the future – South Africa's requirements, In: Ferrar, A.A. (ed.), Ecological Flow Requirements for South African Rivers, S.A. National Scientific Programmes Report, No. 162, CSIR, Pretoria, pp. 110-116, 1989.

O'Keefe, J., J.M. King, J.A. Day, O. Rossouw, D.W. van der Zel, and R. Skoroszewski, General concepts and approaches to instream flow assessment, In Ferrar, A.A. (ed.), Ecological Flow Requirements for South African Rivers, S.A. National Scientific Programmes Report, No. 162, CSIR, Pretoria, pp. 41-56, 1989.

Poff, N.L. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors, *Freshwater Biology*, 36, 101-121, 1996.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg, The natural flow regime, a paradigm for river conservation and restoration, *BioScience*, 47, 769-784, 1997.

Puckridge, J.T., F. Sheldon, K.F. Walker, and A.J. Boulton, Flow variability and the ecology of large rivers, *Marine and Freshwater Research*, 49, 55-72, 1998.

Richter, B.D., J.V. Baumgartner, R. Wigington, and D.P. Braun, 1997, How much water does a river need?, *Freshwater Biology*, 37, 231-249, 1997.

Snowy Genoa Catchment Management Committee, Expert Panel Environmental Flow Assessment of the Snowy River Below Jindabyne Dam, Cooma, Australia, 1996.

Snowy Water Inquiry, Final Report, Snowy Water Inquiry, Sydney, Australia, 1998.

Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissell, R.N. Williams, J.A. Lichatowich and C.C. Coutant, A general protocol for restoration of regulated rivers, *Regulated Rivers: Research and Management*, 12, 391-413, 1996.

Stewardson, M., J. Fenton, and P. Cottingham, Applying the Flow Events Method in an environmental flow study of the Broken River, Proceedings MODSIM 2001 (this volume), 2001.

Swales, S. and J. Harris, The expert panel assessment method (EPAM): a new tool for determining environmental flows in regulated rivers, Chapter 10 in Harper, D.M. and A.J.D. Ferguson (eds), *The Ecological Basis for River Management*, Wiley, Chichester, pp. 125-134, 1995.

Tennant, D.L. Instream flow requirements for fish, wildlife, recreation, and related environmental resources, *Fisheries*, 1, 6-10, 1976.

Tharme, R.E. and J.M. King, Development of the Building Block Methodology for instream flow assessments and supporting research on the effects of different magnitude flows on riverine ecosystems, Freshwater Research Unity, University of Capetown, WRC Report No. 576/1/98, 1998.

Thoms, M. C., P. Suter, J. Roberts, J. Koehn, G. Jones, T. Hillman, and A. Close, Report of the River Murray Scientific Panel on Environmental Flows: River Murray - Dartmouth to Wellington and the Lower Darling River, River Murray Scientific Panel on Environmental Flows, Murray-Darling Basin Commission, Canberra, 2000.

Walker, K.F., F. Sheldon and J.T. Puckridge, A perspective on dryland river ecosystems, *Regulated Rivers: Research and Management*, 11, 85-104, 1995.

Woo, S. Habitat modeling not enough to save fish...or rivers, Stream Notes, Stream Systems Technology Center, Rocky Mountains Research Station, USDA Forest Service, April, pp. 5-7, 1999.