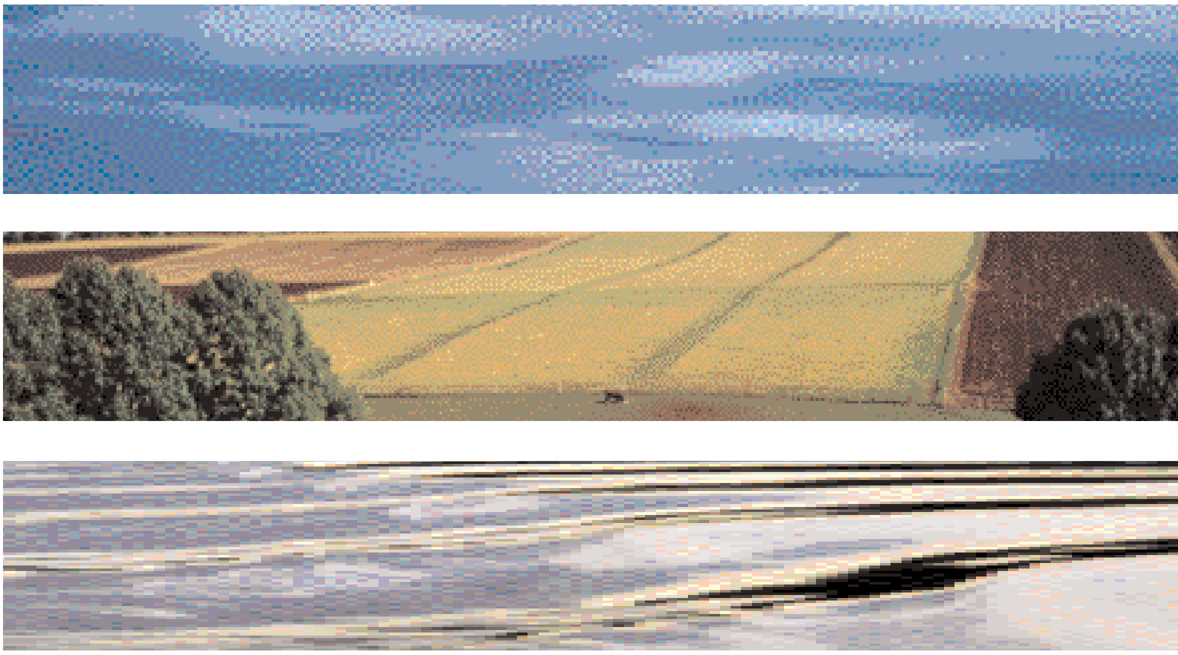
COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

ENVIRONMENTAL FLOW ANALYSIS

TECHNICAL REPORT
Report 05/13

JUNE 2005

Michael Stewardson



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Environmental Flow Analysis

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Preface

The report captures lessons learnt over more than a decade of involvement in the hydrological aspects of environmental flow projects. Whilst ecological aspects of environmental flows have received increasing attention through research and publications, the hydrological methods are often assumed to be well-established and reliable. In reality the opposite is sometimes true. There are an increasing number of hydrologists involved with environmental flow studies in Australia but few practical references to draw from. This report is intended to address this need. It does not deal with ecological issues in detail. It focuses on the hydrological and hydraulic methods. Please use it as a reference to support your work rather than a prescriptive method.

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Executive Summary

Most environmental flow studies include some evaluation of changes in flow regime associated with alternate water resource management options. This report provides an approach to this problem based developed through practical experience in designing environmental flow regimes for rivers in south east Australia. The concepts and techniques are generally applicable to the design of environmental floods, environmental flow requirements in estuaries and addressing the impacts of small-scale water resource developments. Many recent environmental flow studies adopt the natural flow paradigm by designing environmental flow regimes that mimic the natural variability in flows. This report describes a method for characterizing flow variability in an ecological meaningful way based on explicit consideration of the flow-ecology linkages. It also discusses the use of hydraulic analysis to develop rating curves of habitat parameters and characterization of habitat time-series. The report does not attempt to provide a prescriptive step-by-step approach since most states of Australia already have such procedures. Instead the techniques may be adapted to the needs of particular studies.

List of Figures

List of Tables

1. Introduction

1.1 Environmental Flow Analysis

A common element of all but the simplest environmental flow methods is the need to evaluate changes in flow regimes associated with alternate flow management options. This report provides an approach to this problem based on the Flow Events Method (Stewardson and Gippel 2003). The approach has been developed through practical experience in designing environmental flow regimes for rivers in south east Australia but is applicable more generally to rivers in other areas. The concepts and techniques are applicable to the design of environmental floods, environmental flow requirements in estuaries and addressing the impacts of small-scale water resource developments including effects of farm dams, private diversions and groundwater use.

Since changes to water resource allocations can have a direct economic effect on water users and their communities, environmental flow provisions must be based on a credible and transparent assessment of ecological benefits. The environmental flow method described in Chapter 2 provides a robust approach which has realistic information requirements and makes best use of knowledge generally available for Australian river systems. However available data and expertise will vary considerably between projects and this will influence the analytical methods that are appropriate for the study. The method presented in this report might be applied in its complete form or components of the method can be adapted to the needs and constraints of individual projects.

Over the last ten years, many environmental flow studies have been undertaken to underpin water allocation decisions across Australia. We have entered a phase when environmental flows are being delivered, albeit with environmental allocations heavily constrained by historic commitments to consumptive water users. In a few cases environmental flow regimes have been implemented for some time and will be soon due for review. These circumstances demand new techniques to optimise delivery of water allocated to the environment within the constraints imposed by the system's infrastructure and current allocations. Optimisation of system operation for consumptive water use will be increasingly combined with consideration of environmental flow outcomes. As part of this process we may need to clarify environmental flow targets to deliver environmental flow outcomes while allowing flexible system operation. Environmental flow targets based on frequency-magnitude relations (e.g. a desired distribution of low flow spell durations or peak flood magnitudes) can be environmentally desirable and allow operational flexibility. This is the basis of the flow events method further described in this report.

An environmental flow study can be a learning experience for all the participants in the project including the community affected by water management decisions, resource management agencies and the technical project team. In reality, the success of environmental flow studies is equally dependent on effective communication and establishing trust as it is on the details of the analysis. People come to a project with a personal model of how flow influences river ecosystems and what is needed to improve river health. A key role of the project is to build a shared view of the behaviour of the river ecosystem and water resource system, the nature of environmental problems and possible solutions. The analyses described in this report provide focus for this process and a systematic framework for structuring these deliberations.

1.2 Overview of Environmental Flow Methods

An environmental flow can be defined as water left in a river system, or released into it, for the specific purpose of managing the condition of that ecosystem (King *et al.,* 2003). In addition to maintaining minimum flows and flow pulses, environmental flow management can restrict augmentation of natural flows and maintain natural rates of change in flow.

Environmental flow methods are used to establish the response of river condition to different flow management options. This response can be represented conceptually by the functions shown in Figure 1. The "robust" response function shows limited impact of intermediate level of water use but greater water use results in a dramatic increase in environmental impact. The "fragile" response functions shows a system in which even a small level of water resource development will result in a large environmental impact.

The general form of the response function for river ecosystems has not been established and the reversibility of environmental impacts with reduced water use (i.e. enhanced environmental flows) is also not fully proven. Nevertheless, such response functions are required to make rational environmental flow management decisions and trade-off consumptive water use with ecological values associated with a natural flow regime.

A recent review identified more than 200 environmental flow methods available worldwide, of which 37 have been used in Australia (Tharme, 2003). Four distinct types of methods can be identified: (i) hydrological methods (ii) hydraulic rating methods (iii) habitat rating methods and (iv) holistic methods. Hydrological methods have been developed for broad-scale planning and make use of readily available streamflow data alone. Of these, the best known is the "Tennant method", developed in the USA, which identifies various levels of minimum flows based on specified proportions of the mean flow. More recently, the "Range of Variability Approach" (RVA) is a sophisticated hydrological method which evaluates flow regimes based on a comparison of 33 flow statistics for the regulated and natural flow regime (Richter *et al.,* 1996; Richter *et al.,* 1997; Richter *et al.,* 1998). A major disadvantage of hydrological methods is that the ecological significance of the hydrological statistics is often not clear.

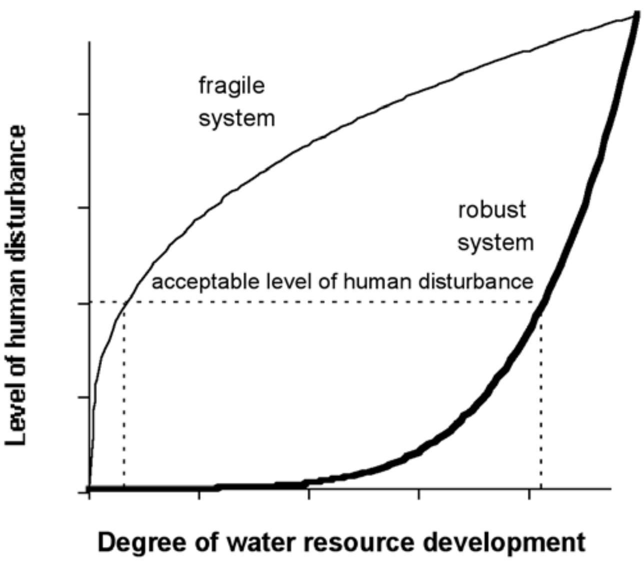


Figure 1. Conceptual Response Function Representing the Relationship Between Water Resource Development and Human Disturbance to the River Environment.

Hydraulic rating methods were developed to account for channel morphology in recommending environmental flows (often minimum flows). With these methods, a functional relationship is established between hydraulic parameters (often wetted perimeter) and discharge. With these methods it is often assumed that the hydraulic parameter is related to the availability of habitat.

If microhabitat characteristics of local species are well understood, habitat rating methods can be used instead. PHABSIM, the physical habitat simulation system used with the Instream Flow Incremental Methodology (Bovee and Milhous, 1978) is the most widely-used microhabitat model. A minimum flow is identified as the flow for which habitat is a maximum or the flow below which habitat is considered to decrease by an unacceptable amount (Gippel and Stewardson, 1998).

More recently, holistic methods have been widely adopted in Australia and South Africa. Holistic approaches were developed to provide environmental flow regimes to manage the condition of the major components of stream ecosystems. In contrast, earlier hydrological and rating methods focussed primarily on providing minimum flows for fish and sometimes invertebrates. Holistic methods can be used to specify minimum flows, maximum flows, flow pulses, flow variability and rates of change in flow. Generally a number of biophysical specialists are required to carry out the assessments in the holistic method. The Expert Panel Assessment Method (Swales and Harris, 1995), Flow Restoration Methodology (Arthington 1998), Scientific Panel Assessment Method (Thoms *et al.,* 1996) and FLOWS (SKM, 2002) are all examples of holistic methods developed for use in Australia.

A well-developed holistic method is DRIFT (Downstream Response to Imposed Flow Transformation) (King *et al.,* 2003). DRIFT is a structured process for combining data and knowledge from relevant disciplines to produce and evaluate flow scenarios for a water resource scheme. Hydrologic, hydraulic rating and habitat rating methods can be used for evaluating impacts of flow scenarios on different ecosystem components as part of the DRIFT method. One distinctive feature of the method is the assignment of severity ratings to different component responses for different flow management scenarios. The severity ratings provide a consistent quantitative basis for trading off consumptive water use and environmental flows and can be easily communicated to those involved with water allocation decisions. Although initially used for systems which are being developed from a largely unregulated state, King *et al.,* (2003) suggest that the same process can be used for evaluating environmental flow scenarios in rivers which have a history of regulation. In such cases, severity ratings need not be relative to natural conditions but may use some other reference point. The reversibility of environmental impacts caused by past flow regulation would need to be considered in the assignment of severity ratings for any proposed environmental flow releases in previously regulated rivers.

1.3 Natural Flow Paradigm

Increasing understanding of the ecological importance of flow variability has led to a concern that many regulated rivers lack the natural variations in flow required to maintain pre-regulation communities (discussed further in Chapter 5). It is felt that existing streamflow management practice overlooks the importance of natural streamflow variability in maintaining aquatic ecosystems (Poff *et al.,* 1997). As a consequence, some ecologists and managers are promoting the natural flow paradigm, which has been stated as

> "the full range of natural intra- and interannual variation of hydrological regimes, and associated characteristics of timing, duration, frequency and rate of change, are critical in sustaining the full native biodiversity and integrity of aquatic ecosystems" (Richter *et al.,* 1997).

Poff *et al.,* (1997) state that it is a

> "…fundamental scientific principle that the integrity of flowing water systems depends on their natural dynamic character".

Many recent environmental flow studies adopt this natural flow paradigm by designing environmental flow regimes that mimic the natural variability in flows.

Those applying the natural flow paradigm must ask the question "which aspect of flow variability should be maintained by the environmental flow?" It is not possible to maintain all aspects of variability (i.e. frequency, magnitude, duration of flow variations at all temporal scales) if there is to be some water resource development. Some trade-off is required.

The two 3-year hydrographs in Figure 2 are for unregulated rivers in Victoria; one is ephemeral, the other permanent. The hydrographs show flow variability at a range of temporal scales including:

- inter-annual variability in the volume of water yielded from the catchment and in the seasonality of flow pulses,
- strong seasonal variations in flow with higher flows in the winter-spring period,
- variability in the duration and timing of low flow periods,
- variability in the peak magnitude and duration of high flow pulses events, and
- patterns of variability in flow during flow pulses associated with rainfall patterns and the hydrological response of the catchment.

1.4 The Flow Events Method and River Analysis Package (RAP)

Clearly, environmental flow practitioners must ask "Which aspects of variability must be preserved in the regulated flow regime?" In response to this question, the CRC for Catchment Hydrology has developed the Flow Events Method (Stewardson and Gippel, 2003). This method provides a systematic approach to characterising the ecologically important components of flow regimes and is described in subsequent Chapters of this report. The Flow Events Method has been applied in several environmental flow studies in Victoria (Cottingham *et al.,* 2001a; Cottingham *et al.,* 2001b; Cottingham *et al.,* 2003a; Cottingham *et al.,* 2003b; LREFSP, 2002; Stewardson *et al.,* 2001; Stewardson and Cottingham, 2002; Stewardson and

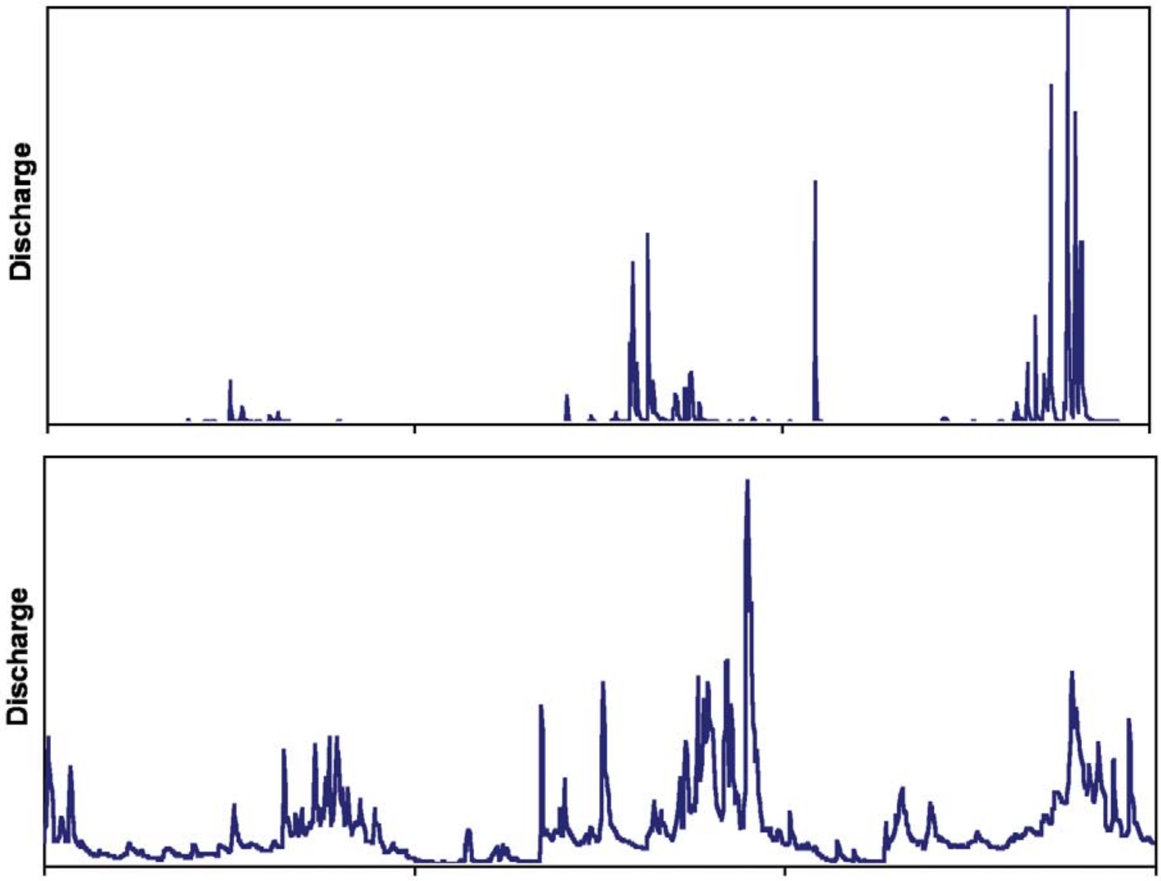


Figure 2. Three Years of Daily Discharge for Two Unregulated Rivers in Victoria; One Ephemeral and One Permanent.

Gippel, 2003). The CRC for Catchment Hydrology has now developed The River Analysis Package (RAP), a software program which can assist with the application of the Flow Events Method (Stewardson and Marsh, 2002). RAP can be downloaded from the web site: www.toolkit.net.au. Training in the use of RAP and its application to the Flow Events Method is available through the CRC for Catchment Hydrology (refer to the website for more information). For experienced hydrologists, it should be possible to apply the Flow Events Method using RAP with reference to this report and the user manual or Help System provided with RAP.

2. A Hybrid Method for Environmental Flow Assessment

The Flow Events Method has been developed by the CRC for Catchment Hydrology as an analytical procedure for use with a broad range of environmental flow methods. To date it has been used as part of the FLOWS method, the Victorian state-wide approach (SKM, 2002) and in Expert Panel studies (Swales and Harris, 1995). The Flow Events Method has similarities with the DRIFT (King *et al.,* 2003) environmental flow method (described in section 1.2). In particular both methods link a broad range of ecological responses to changes in flow statistics based on knowledge of river hydraulics and the relevant flow-ecology linkages. One of the distinctive features of DRIFT is that it provides a systematic protocol for evaluating ecological consequences of changes in the flow statistics based on severity ratings. DRIFT is a comprehensive environmental flow method. However DRIFT restricts the choice of flow statistics available for describing changes in the flow regime. This chapter describes a method which uses the severity rating system used in DRIFT with the Flow Events Method. The Flow Events Method provides a more flexible approach to defining environmental flow statistics for each particular flow-ecology linkage. The following chapters discuss aspects of this method in more detail including river channel surveys, hydrological analyses and the selection of environmental flow statistics. The following steps in this hybrid method are described below:

1. Preliminary Work
2. Identify Key Flow-Ecology Linkages
3. Define Environmental Flow Statistics
4. Model Hydraulic or Habitat Ratings
5. Evaluate Historic Changes in Flow Regime
6. Interpret Impacts and Specify Environmental Flow Targets

Central to the method is the identification of a set of flow-ecology linkages, the mechanisms by which flow regimes in a river influence stream ecosystems. By considering these mechanisms it is possible to focus on assessment of the key components of the flow regime. Flow rarely has a direct effect on aquatic communities; rather this effect is associated with some hydraulic attribute, which responds to variations in discharge. Some examples are:

- `mobilisation of bed material which is triggered by elevated bed shear stress of flow velocity,
- maintenance of aquatic vegetation along the river banks by inundation at higher flow stages, and
- disturbance to benthic fauna as a result of drying of the stream bed at low flows.

Using the Flow Events Method it is possible to transform a flow series into a time-series of the relevant habitat metric. To do this we use a habitat rating curve which expresses the relevant habitat metric as a function of discharge. This function is likely to be non-linear and sometimes discontinuous. The time-series of each habitat metric is analysed to account for the temporal-variability in the effect of each flow-ecology linkage. By using hydraulic parameters rather than discharge, it is possible to focus the analysis on the important part of the flow regime (i.e. high, medium or low flows) and express results using a meaningful habitat metric.

The hydraulic metric provides the magnitude of the events. For example the area of in-channel benches inundated during a flow pulse could be a measure of the magnitude of the event. The time-series analysis provides a frequency-magnitude relationship for the particular flow-ecology linkage being considered. The frequency-magnitude relationship is fundamental to the method. We evaluated changes in the flow regime based on changes in the frequency distribution of event magnitudes in the same way that we might consider changes in a flood-frequency curve. In some cases substantial shifts in the frequency distribution may be quite acceptable in some cases subtle shifts in the frequency-magnitude relations may have ecological consequences. In any case, the frequency-magnitude relations are the “language” used to describe flow impacts and specify environmental flow targets.

The CRC for Catchment Hydrology has developed a software program called RAP (the River Analysis Package) for environmental flow analysis. It is particularly useful for applying the Flow Events Method. The web site <www.toolkit.net.au> has more information on RAP and the facility to download a copy of the software.

The following sections provide a brief description of the environmental flow method. More detail on specific components of the method is available in subsequent chapters. The modelling section 2.4 and 2.5 may seem complex to those not familiar with the hydrological and hydraulic procedures used. Further details are provided in Chapter 5. Documentation for RAP available from <www.toolkit.net.au> provides an additional source of information.

2.1 Preliminary Work

The first task for an environmental flow study is to assemble the necessary hydrologic and hydraulic data and carry out some preliminary analyses. This will involve the following activities.

- Selecting river reaches for surveys (this is discussed in Chapter 3).
- Developing a one-dimensional hydraulic model for each river reach (this is also discussed in Chapter 3)
- Collating or modelling the flow time-series for the natural (or unregulated) situation and alternate flow management scenarios, including historic, current or future management regimes
- Carrying out a preliminary hydrological analysis (this is discussed in Chapter 4).

Environmental flow requirements are normally specified based on the physical attributes of particular river reaches, with the assumption that they are representative of the entire length of river being managed. The physical attributes are derived from channel surveys and hydraulic modelling. Our experience is with surveying the river channel but some studies may require surveys of floodplains or specific wetlands.

Hydraulic modelling is required to establish variations in hydraulic habitat metrics with discharge. The technical team for the project should prepare the specification of hydraulic model requirements. A clear need should be established before adopting more sophisticated hydraulic modelling options than a one-dimensional hydraulic model. In many cases, additional hydraulic detail (e.g. using two- or three-dimensional numerical models) will not greatly improve the environmental flow assessments because the reliability of assessments is more often limited by our understanding of ecological responses.

For environmental flow studies in Australian rivers subject to a relatively long history of modified flows, it is common to compare the historic modified flow regime with the natural (or unregulated) regime. If data are available, streamflow records for a period before and after the onset of flow regulation can be compared to indicate the hydrological change. However, it is quite possible that factors other than regulation have contributed to the differences in flow regime between these two periods. Ideally, a flow model would be used to simulate natural and regulated flow for the same time period (usually twenty years or more). This will minimise confounding influences of climate and land use changes. It is also possible to consider flow regimes modelled for alternate water management scenarios. These data must be provided for each reach considered in the project.

A preliminary hydrological analysis is carried out to provide a summary of how water resource developments have (or will) effect the flow regime at the representative reaches. The preliminary hydrological analysis should include a flow duration analysis, flood frequency analysis and median monthly flows. Analyses should use long-term records (e.g. an absolute minimum of 20 years) of streamflow data (normally daily). More details are provided in Chapter 3.

2.2 Identify Key Flow-Ecology Linkages

The technical team for a project should include expertise in relevant aspects of river ecology including aquatic fauna and flora, and fluvial geomorphology. This team should identify the likely mechanisms by which changes in flow regime will influence the condition of the river ecosystem. The focus should be on aspects of the river ecosystem which are recognised to have some environmental value. A field trip by the technical team along the river can assist in establishing the key flow-ecology linkages. Discussion across the disciplines is necessary to identify any complex responses associated with multiple components of the ecosystem. In particular, changes in fluvial geomorphology can have major implications for physical habitats and aquatic communities. This stage is discussed in more detail in Chapter 5.

In the projects we have undertaken so far, typically between six and fifteen flow-ecology linkages are identified for the river, but there is no restriction on the number. The following four flow-ecology linkages are examples from environmental flow projects in Victoria:

- Altered bench inundation regimes can affect bank vegetation and organic matter inputs to the stream,
- Changes in minimum flows will alter availability of deep water refuge habitats for fish,
- Increased flow velocities can have adverse effects on aquatic macrophytes, and
- Altered flood hydrology can modify ecological processes occurring in floodplain wetlands.

The selection of the flow-ecology linkages is the foundation of the final environmental flow recommendations. Selecting or omitting aspects of the river ecosystem at this stage can alter the results of the study. Some practitioners may be concerned that this introduces the possibility of bias into the assessment. However, environmental flow assessments are necessarily restricted by the limits of our knowledge of flow-ecology linkages. There are methods which don't require explicit statements regarding these linkages. Hydrological methods are an example of this (see previous Chapter). However, this does not mean that all aspects of the river ecosystem will be represented by these assessments. In fact it is more likely that such non-specific assessments will miss important or known flow-ecology links. The explicit statement of flow-ecology linkages provides a sound framework for the assessment and a stronger basis for communicating the relative merits of alternate flow scenarios.

2.3 Define Environmental Flow Statistics

In most cases, the impacts of flow modifications are assessed based on changes in relevant flow statistics calculated using flow and hydraulic data. Relevant flow statistics should be defined for each flow-ecology linkage (identified in the previous step). These flow statistics are defined with consideration of:

- hydraulic metrics,
- seasonality, and
- time-series analysis.

Discussions amongst the team regarding these statistics should be informed by the preliminary hydrological analysis and output from the hydraulic model. More details of this stage of the procedure are described in Chapter 5. The four examples in Table 1 illustrate how the environmental flow statistics can be defined. These examples correspond with the four flow ecology linkages used as examples in Section 2.2.

Table 1. Defining Environmental Flow Statistics

Flow-ecology linkage	Seasonal Aspects	Time series analysis	Hydraulic metric
Bench inundation	non-irrigation & irrigation season	percent time exceeded[1] (i.e. cumulative probability plot)	area of inundated channel with a lateral gradient <0.1
Deep water refuge habitat for fish	non-irrigation & irrigation season	event frequency (minimum magnitude)	area of channel with depth > 1.5 m
Aquatic macrophytes and velocity	growing season (Jan-April)	percent time exceeded[1] (i.e. cumulative probability plot)	reach mean velocity
Wetland inundation	all year	event frequency (peak magnitude and duration)	area of floodplain inundated (ha)

[1]This is similar to a flow duration curve except that the analysis uses the time series of a hydraulic metric rather than flow.

2.4 Model Hydraulic or Habitat Ratings

Most environmental flow statistics will draw on some hydraulic rating relationship. For example, availability of benthic habitat might be linked to the relation between wetted perimeter of the channel and discharge. These hydraulic ratings need to be derived from output of the hydraulic model. Figure 3 shows hydraulic ratings derived for two sites on the Goulburn River for the hydraulic metrics listed in the right hand column of Table 1. The sites are downstream of Lake Eildon on the mid-Goulburn River and downstream of the Murchison Bridge on the lower Goulburn River (shown later on Figure 11)

These hydraulic rating curves were modelled as part of an environmental flow study for the Goulburn River. For the case of wetland inundation, it was not possible to predict area of inundated wetlands (as proposed in Table 1) using the data and 1D hydraulic model available in the Goulburn River Study. To overcome this limitation, a functional relationship relating inundation to discharge was established from knowledge of the lowest flow at which wetlands begin to be inundated and the flow at which all wetlands are inundated. A linear increase in inundated wetland area was assumed for increasing discharge within this range. A more rigorous approach would require the development of a floodplain hydraulic model or use of satellite images during or soon after floods of different magnitudes to construct a more accurate form of this relationship. The added cost of floodplain hydraulic modelling could not be justified in the Goulburn River study. In some cases such a model might be available, such is the case with the Chowilla floodplain (Figure 4) and the Barmah Forest (Figure 5) both on the River Murray. Note that the Chowilla floodplain relationship is similar to the one assumed for the Goulburn River, while the Barmah Forest relationship is not linear.

2.5 Evaluate Historic Changes in Flow Regime

Natural and regulated flow series are obtained for the project sites in the preliminary stage of the project. In this stage, these time-series of discharge are transformed to a time-series of the hydraulic metrics associated with each flow-ecology linkages (Table 1) using the hydraulic ratings (Figure 3). The resulting time series of the hydraulic metrics are analysed using

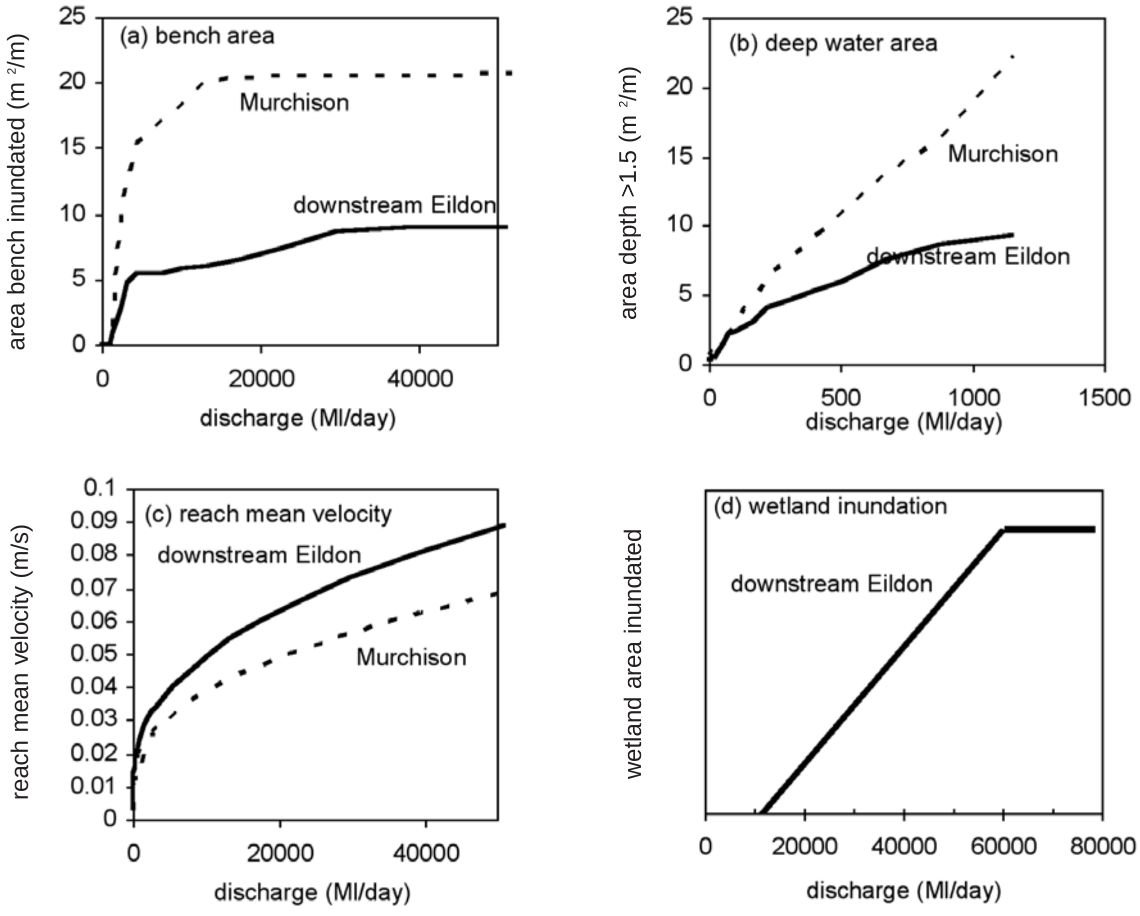


Figure 3. Examples of Hydraulic Ratings for Two Sites on the Goulburn River.

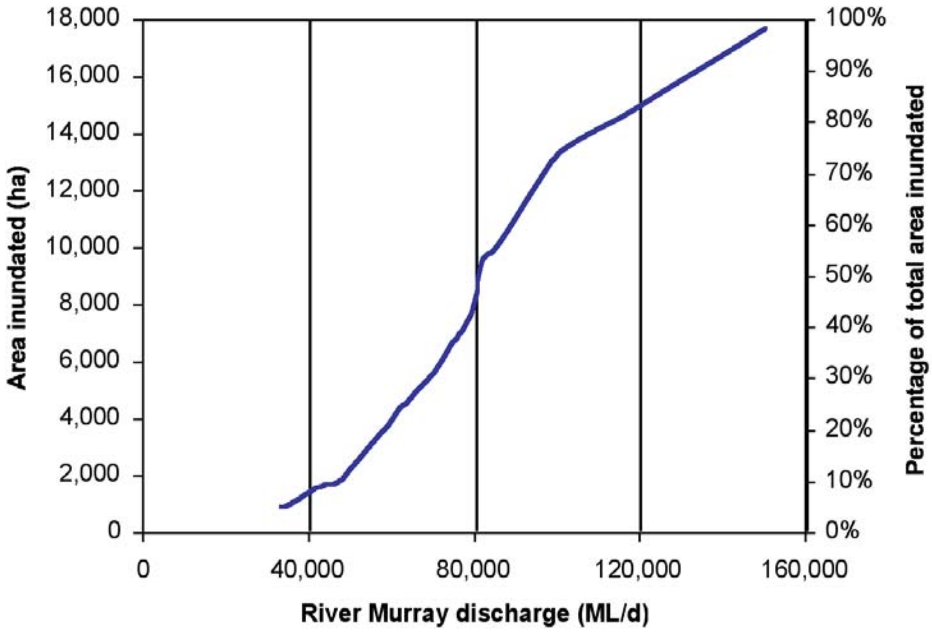


Figure 4. Area of the Chowilla Floodplain Inundated as a Function of River Murray Daily Discharge. Data source is Sharley and Huggan (1995). Figure provided by C. Gippel (Fluvial Systems)

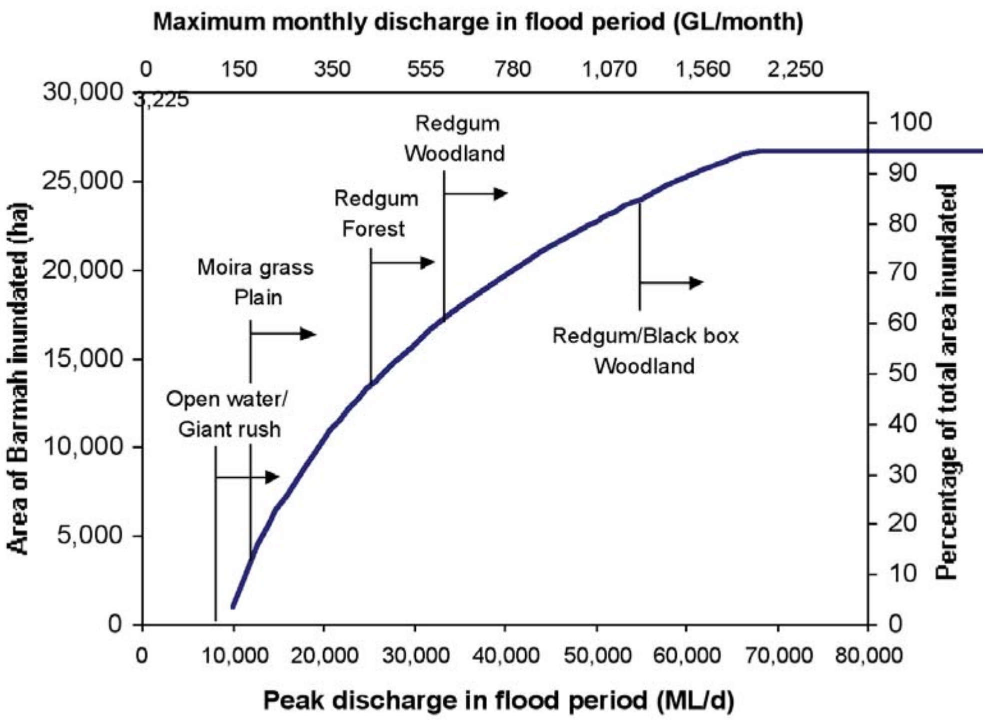


Figure 5. Area of Barmah Forest Inundated as a Function of River Murray Instantaneous Flood Peak and Monthly Peak Discharge at Tocumwal (for instantaneous peak discharge) and Yarrawonga (for monthly total discharge). 'Commence to flow' discharges of main vegetation associations are indicated. 'Effective flooding' (i.e. with a minimum required depth of water) of these communities occurs at higher discharges. Data sources are Bren *et al.,* (1988, p. 87) and Bren *et al.,* (1987). Figure provided by C. Gippel (Fluvial Systems).

the analysis and seasonality specified in Table 1 to generate environmental flow statistics. Results for the four flow-ecology linkages in Table 1 are shown in Figure 6 for a site downstream of Lake Eildon on the Goulburn River. Results are shown for each "season" listed in Table 1.

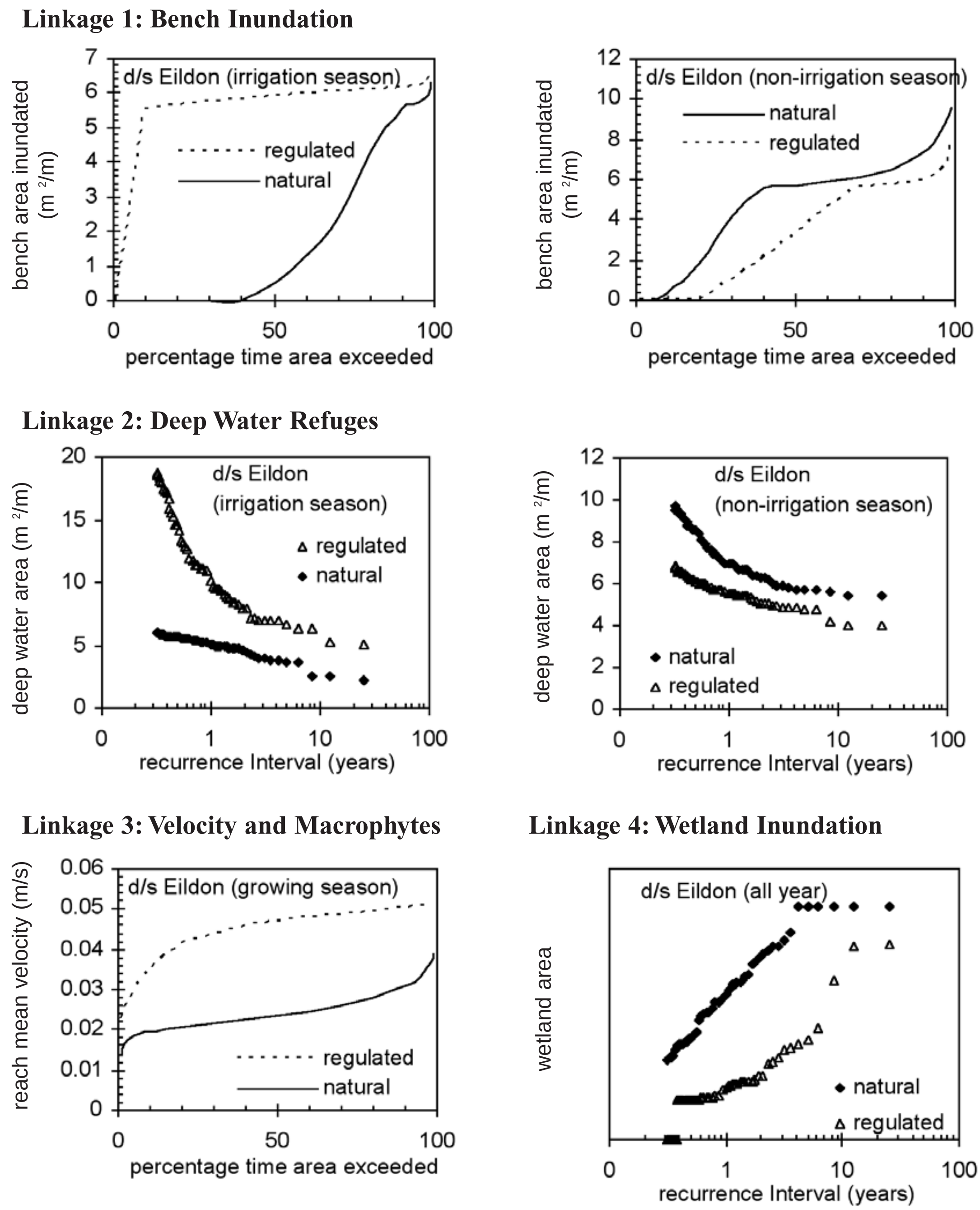


Figure 6. Results of Frequency Analysis for Environmental Flow Statistics at a Site Downstream of Lake Eildon on the Goulburn River.

2.6 Interpreting Impacts and Specifying Environmental Flow Targets

The results in Figure 6 are a description of how flow regulation has affected ecologically important aspects of the flow regime. The question now is to evaluate the seriousness of these impacts and recommend environmental flow targets to constrain impacts to acceptable levels. One effective and straightforward approach is to use the figures themselves (i.e. Figure 6). It should be possible to draw an envelope (or range) on the frequency-magnitude relations plotted for the natural regime within which conditions are maintained at acceptable level. Alternatively multiple envelopes could be drawn for increasing severity of impact (illustrated below). Drawing these envelopes directly on the figures may seem a rather crude approach to interpreting these impacts and specifying targets. However, we have found this to be a very satisfactory way of deciding on the correct interpretation amongst a technical team and communicating impacts to a wider audience. The resulting environmental flow targets are completely

Table 2. Severity Ratings.

Severity rating	Severity of change (from reference condition)	Equivalent loss of abundance (relative to reference)	Key for lines shown on Figure 7
0	None	No change	
1	Negligible	0%-20% reduction	
2	Low	20%-40% reduction	
3	Moderate	40%-60% reduction	
4	Severe	60%-80% reduction	
5	Critically severe	80%-100% reduction (includes local extinctions)	

clear for interpretation by water authorities and other agencies. Further, these "envelope" targets are based on frequency magnitude relations rather than a single magnitude event for a fixed frequency. Thus increasing the variability in the environmental flow regime whilst allowing flexibility of operation of the water resource system.

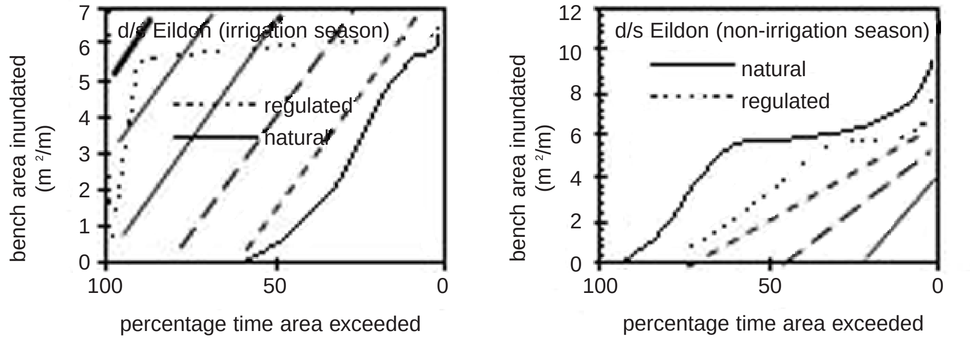
To illustrate this approach we consider the problem of interpreting the severity of impacts associated with the flow regulation using the envelope curves. In some cases, a single curve would be sufficient defining the boundary between acceptable and unacceptable impacts. The curve is effectively the environmental flow target. However, in the example we are simply concerned with assessing the severity of impacts on some fixed scale. To do this, we borrowed a technique from the DRIFT method (King *et al.,* 2003). Lines are drawn on these figures indicating thresholds past which further departures from the natural regime will lead to an increasingly severe environmental impact. Members of the project team with appropriate expertise should draw these lines. They are drawn with consideration of the ecological implications of shifting the frequency and magnitude of events. Severity ratings are listed in Table 2 and further explained by King *et al.,* (2003). Project teams may wish to modify the scales used in the severity rating system to reflect local knowledge and ecological concerns but an explicit scale is required with some basis for decision-makers to interpret the ratings. The drawing of these severity "envelopes" on the graphs is away of making explicit the thinking of an expert assessing these changes. They are subjective but open to independent scrutiny. This is a form of risk assessment, not a deterministic prediction of the ecological response.

The results of the assessment can be presented in a table showing the severity of impacts of past regulation for each flow-ecology linkage. For example, Table 3 shows severity ratings for the site downstream of Eildon on the Goulburn River (note that these results are hypothetical and used to illustrate the method).

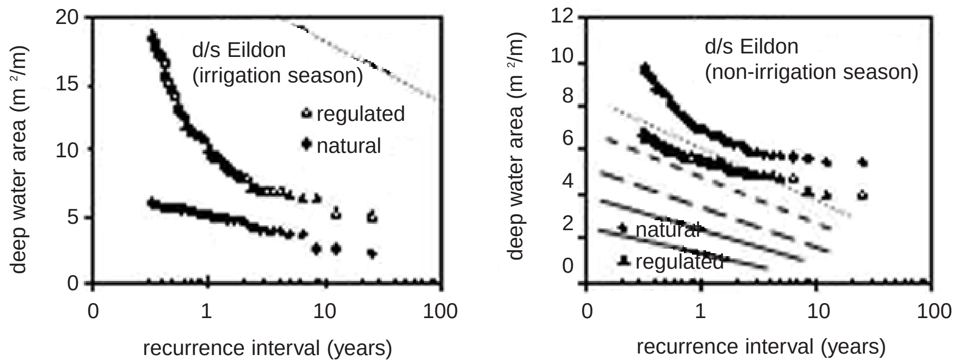
Table 3. Severity of Impact of Past Regulation on Ecological Components for the Goulburn River Downstream of Lake Eildon.

Ecological Factor	Rating	Severity
Bench inundation	4	Severe
Deep water refuge habitat for fish	1	None
Aquatic macrophytes and velocity	4	Severe
Wetland inundation	5	Critically Severe

Linkage 1: Bench Inundation



Linkage 2: Deep Water Refuges



Linkage 3: Velocity and Macrophytes

Linkage 4: Wetland Inundation

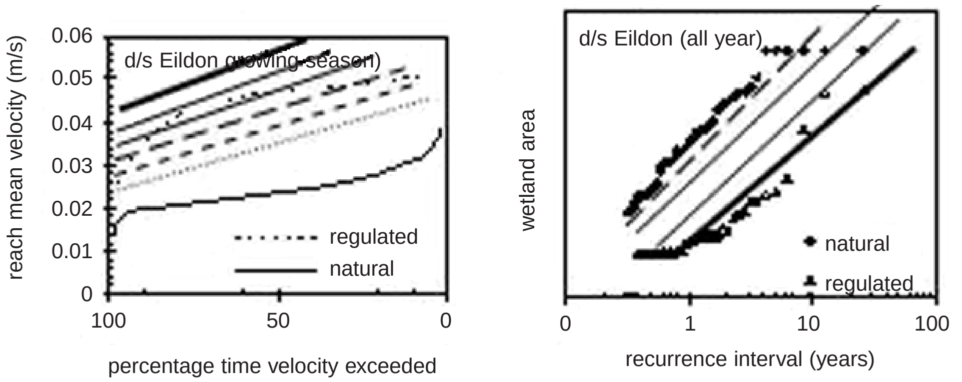


Figure 7. Results of Frequency Analysis for Environmental Flow Statistics at a Site Downstream of Lake Eildon on the Goulburn River showing Hypothetical Severity Ratings. A key for lines indicating severity ratings is given in Table 2.

3. River Channel Surveys

Environmental flow analyses often require knowledge of the hydraulic characteristics of river channels, which is typically derived from analysis of hydraulic survey data. These surveys usually consist of multiple channel cross-sections because these data can be easily converted for input to a one-dimensional hydraulic model. There is a need to balance survey costs and the adequacy of surveys for representing variability of the hydraulic environment when choosing the quantity and spatial arrangement of these cross-section surveys along a river.

Environmental flow studies generally require an assessment of channel conditions along large segments of a river, typically extending between major tributary junctions. It is recognised that for most of these investigations extensive mapping or sampling of long lengths of river is not cost effective. A common approach to evaluating river characteristics is to sample hydraulic conditions within one or more representative reaches. This "representative reach" approach requires two assumptions:

1. The hydraulic characteristics of the reach are representative of the entire length of river being considered, and
2. The surveyed cross-sections are an adequate sample of conditions along the representative reach.

To illustrate the representative reach concept, Figure 8 shows the three reaches used in an environmental flow study of the Broken River. The three reaches were located downstream of the three major points of regulation and each were about 1 km long. Reach 1 is a short distance downstream of a reservoir (Lake Nillahcootie), reach 2 is just downstream of a major diversion (Broken Weir) and reach 3 is downstream of another major diversion (Casey's Weir) and the release channel for a major off-stream storage (Lake Makoan). Each reach includes at least one meander wavelength and at least fifteen cross-sections were surveyed along the reaches. Cross-sections were evenly spaced with some additional cross-section located at riffle crests.

The CRC for Catchment Hydrology carried out an investigation of the representative reach concept based on detailed field surveys in three Victorian streams (Howes and Stewardson, 2002). The study provides evidence to support the use of representative reaches.

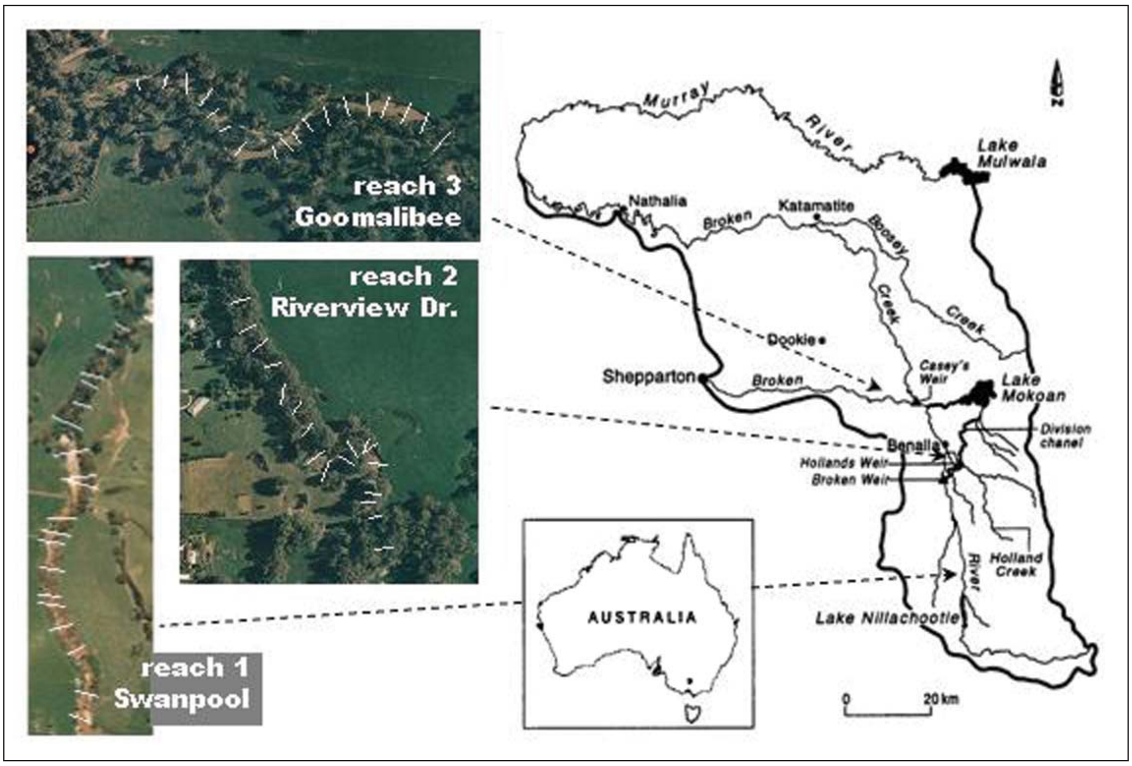


Figure 8. The Representative Reaches and Cross-sections Surveyed for an Environmental Flow Study of the Broken River, South East Australia.

Results suggested that the representative reach generally had similar mean hydraulic characteristics to a longer length of river. However the representative reach only provided results representative of stream variability if the environmental conditions were visibly homogeneous over the longer reach. In many streams there will be more variability in channel hydraulics over longer sections of river.

In another study, 150 cross-sections were surveyed along a 10 km stretch of the lower Loddon River in north-central Victoria (Figure 9a). We chose to look at variation in Froude number because it is generally the most variable hydraulic parameter along a river reach. High Froude number indicates riffle-type conditions and low Froude number indicates pool type conditions. The reach was divided into ten 1 km sub-reaches each with 15 cross-sections. We see that the mean Froude numbers for each sub-reach are similar (Figure 9b) but the standard deviation of Froude number varies substantially between the sub-reaches (Figure 9c). These results show that a 1 km sub-reach may be adequate for evaluating mean conditions but is unlikely to provide an adequate sample of the range of hydraulic conditions along this river.

The project team must decide on the number and length of representative reaches. Clearly more and longer survey reaches will provide a more representative sample of the river channel. Generally there is a survey cost associated with increasing the number of reaches as survey teams need time to access each site, carry out reconnaissance surveys and establish survey points. In practice we tend to limit the length of surveys so that they might be surveyed within one or two days but still include at least one complete meander wavelength. The number of reaches is generally constrained by the project budget but at least one reach should be located downstream of each major point of regulations (i.e. reservoirs or diversions) as in the Broken River example.

There is some disagreement regarding the best method for locating cross-sections within a reach. Two principle methods are (i) subjective and (ii) statistical sampling. The more popular approach is to choose the location of cross-sections to include the range of ‘microhabitats’ found along the reach. This is subjective sampling, and while there may be advantages in capturing the full range of conditions along the reach, there are some problems with this

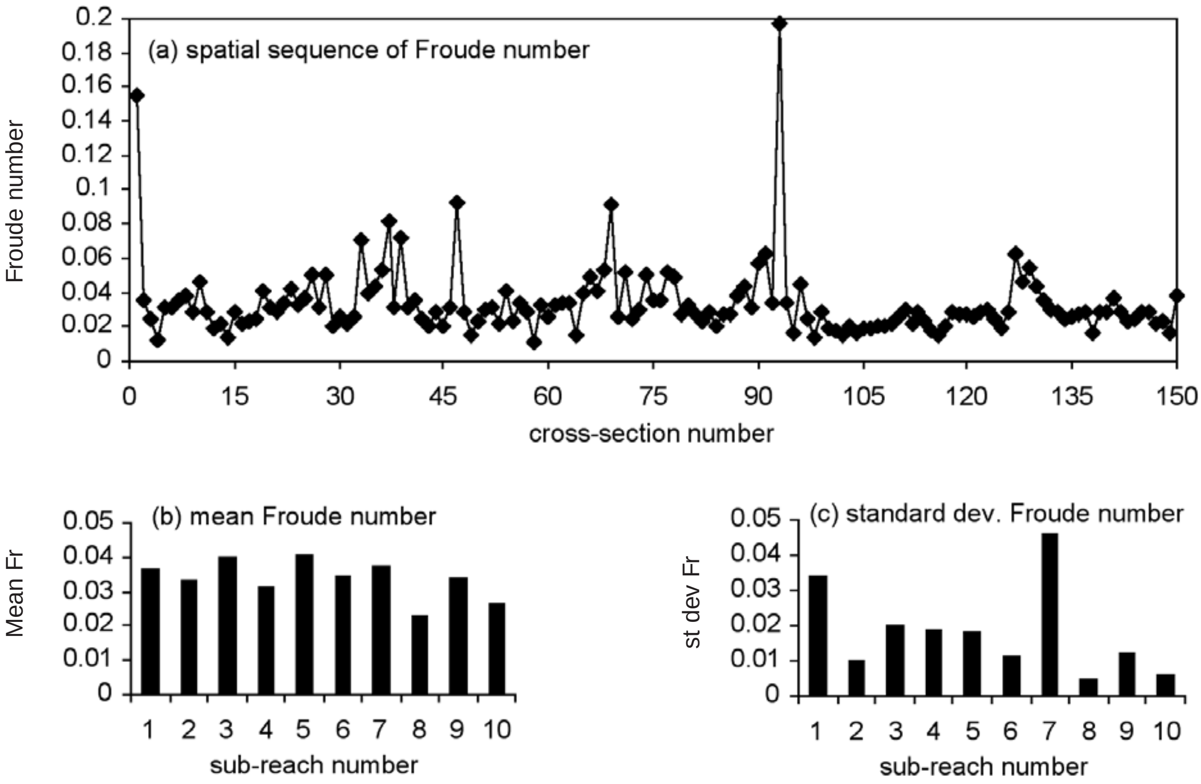


Figure 9(a). Cross-sectional Froude Number at 150 evenly Spaced Cross-sections along a 10 km Reach of the Lower Loddon River, North-Central Victoria. Figure 9(b) and (c) show the Mean and Standard Deviation of Cross-sectional Froude Number for Ten Discrete Sub-reaches, each with 15 Cross-sections (data provided by Elisa Howes, The University of Melbourne).

method. The distribution of microhabitats will change with discharge, which may result in the number and location of transects being a function of the flow at the time of survey. As a consequence different results may be obtained from sampling at different flows. Another drawback of subjective sampling is that the selection of samples based on consideration of their representative nature does not satisfy the requirements of statistical inference and prevents any systematic assessment of precision in channel parameters estimated from the survey.

The second sampling style is statistical, either completely random, or the systematic approach, where having selected a first location at random, the remaining sample units are taken at some fixed interval. Systematic sampling is often a simpler scheme to implement in streams as cross-sections can be spaced equidistantly along the thalweg of the stream section. Sampling via statistical methods has an advantage over subjective sampling, as it allows the data to be assessed through a variety of statistical tests, to establish the reliability of the sample to represent reach conditions. For these reasons statistical sampling is the method recommended in this report.

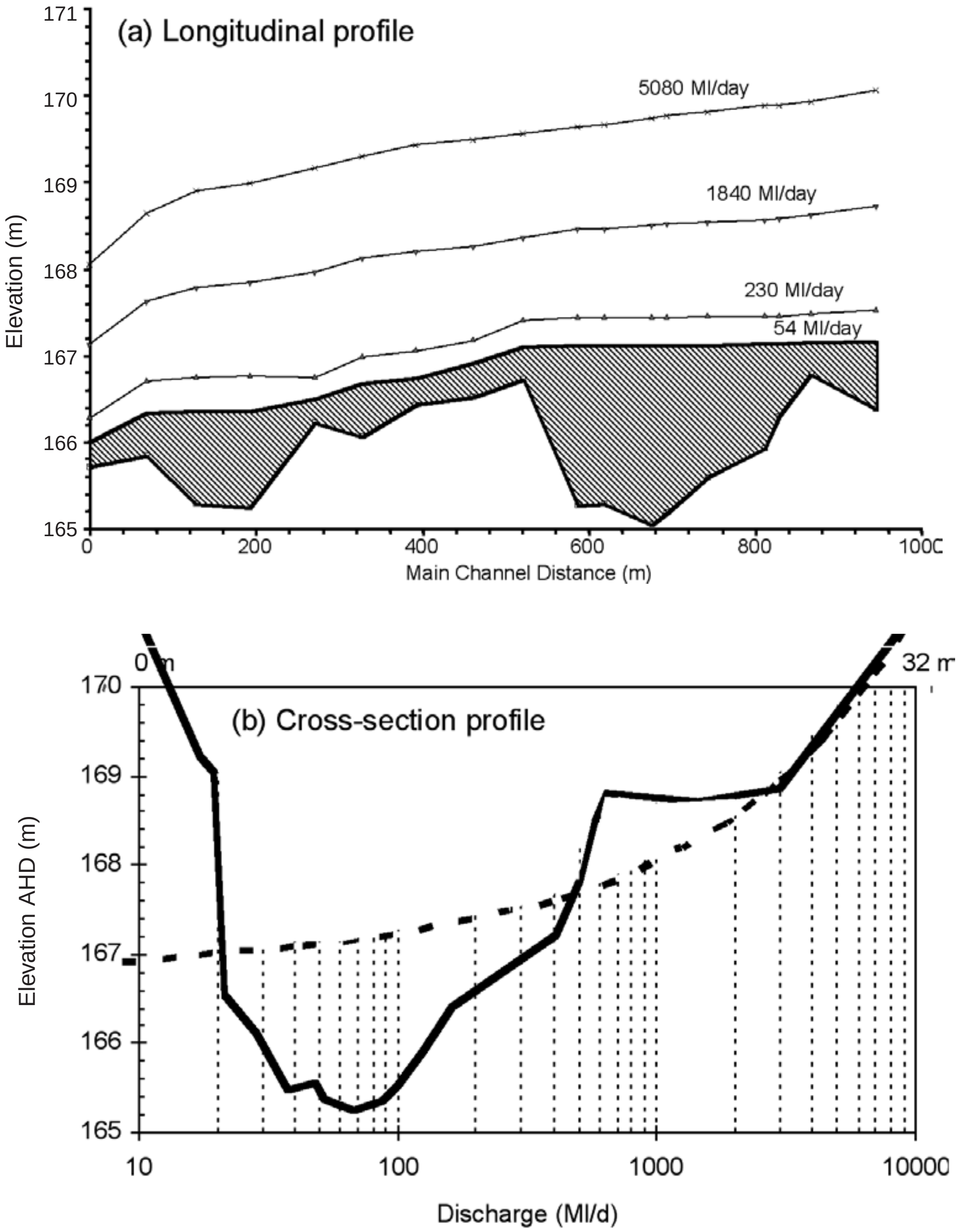


Figure 10. Water Surface Levels Modelled Using a One-dimensional Model (HEC RAS) Applied to a Reach of the Broken River with Results Presented as (a) Longitudinal Water Surface Profiles and (b) a Rating Curve and Channel Cross-section within a Pool (at a Distance of 580 m along the Reach)

Reach surveys for environmental flow studies typically use between 5 and 15 cross-sections. Analysis of sample error in hydraulic attributes estimated from these samples indicates that fifteen cross-sections will provide a sufficient sample in most cases. However, fewer cross-sections are required in less variable channels or where less confidence is required in the results of the hydraulic assessment. Generally more cross-sections are required to evaluate variability in hydraulic conditions (c.f. mean conditions) or to represent hydraulic conditions which are rare along the river.

Stewardson and Howes (2002) provide a simple procedure for estimating the number of cross-sections required to provide a representative sample of hydraulic conditions along a stream reach. The recommended procedure includes a rapid field survey, which should require two people no more than 2 hours to complete if the river can be waded. Use of this procedure will ensure that the reach is sampled representatively. However, in many cases, this pilot survey will not be cost effective and a conservative estimate of the number of cross-sections required is probably the best approach.

A one-dimensional hydraulic model is often used to model variation in water levels with discharge (Figure 10). The model uses data from cross-section surveys and is usually calibrated using a surveyed water surface profile at a known discharge. Cross-sections at particular locations are sometimes required for correct calibration of a one-dimensional hydraulic model. It is often suggested that “control points” must be surveyed to apply these models. Strictly, a hydraulic control is a cross-section along the channel where water levels are controlled by the cross-sections shape and not by downstream water levels. This situation is rare in natural channels. Nevertheless, model reliability is improved if cross-sections are located where there is a change in the energy gradient, normally identified as a change in the water surface slope, and in particular at riffle crests. It is also desirable for the downstream cross-section to be located at a hydraulic control point, riffle crest, where flow is close to uniform, or at a section where the relationship between stage (i.e. water level) and discharge is known (e.g. a streamflow gauge).

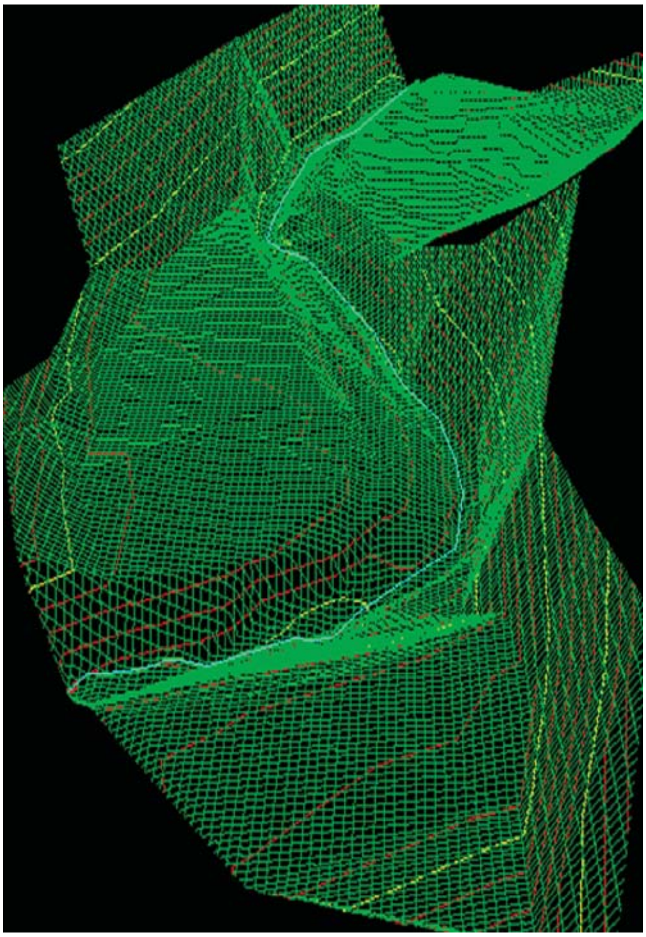


Figure 11. Digital Terrain model Fitted to Feature Survey of Lerderderg River, Central Victoria (image supplied by Geoff Vietz, EarthTech Pty Ltd)

Feature surveys are an alternative to cross-sectional surveying and have been used in some environmental flow studies. With this approach, survey points can be located anywhere along the reach and need not be constrained to particular cross-sections. More survey points can be located in areas of particular interest or needing greater detail to describe the channel boundary. Other features can also be surveyed including vegetation, physical and geomorphic features of interest. A digital terrain model is fitted to these survey points and used to generate cross-sections at desired locations for input to a one-dimensional hydraulic model (see Figure 11). This approach allows surveyors to select survey points within the line of site of surveying equipment possibly resulting in reduced survey times. The flexibility to generate cross-sections at any location along the survey reach or randomly if desired is the other advantage of feature surveys. The relative merit of feature surveys will depend on survey conditions, reach length and width and modelling requirements and should be assessed by the project hydraulic modeller and surveyors.

4. Preliminary Hydrological Analysis

Water resource schemes have a first-order impact on the downstream flow regime. The nature of this hydrological impact will largely determine the scheme's ecological impacts. For this reason, an assessment of the hydrological impacts provides the foundation for establishing issues that should be addressed during the design of an environmental flow regime. In particular, the preliminary hydrological analysis can inform the identification of flow-ecology linkages for the river.

For environmental flow studies in Australian rivers subject to a relatively long history of regulation, it is common to compare the historic modified flow regime with the natural (or unregulated) regime. If data are available, streamflow records for a period before and after the onset of flow regulation can be analysed to indicate the hydrological change. However, it is quite possible that differences in flow regime between these two periods are, in part, the result of factors other than flow regulation. Ideally, a flow model would be used to simulate natural and regulated flow for the same time period (usually twenty years or more). It is also possible to consider flow regimes modelled for alternate management scenarios or different historic periods distinguished by differences in the extent or nature of regulation.

The natural flow regime is widely used as the "reference point" for environmental flow studies and the environmental flow regime is designed to return components of the natural regime. In most cases, "natural" refers to flows that would have occurred in the absence of the water resource scheme and neglects the hydrological effects of catchment clearing. In some cases it could be argued that the long history of regulation and other changes in the river ecosystem such as riparian clearing, altered water quality or channel changes mean that the natural regime is not an appropriate reference point. However, methods of identifying such cases and establishing alternate reference regimes are not yet available and considerable expertise would be required to take an alternate approach.

The key characteristics of a water resource scheme that determine its effect on streamflow are:

- temporal pattern of natural streamflow,
- temporal pattern and location of water demand,
- volume of impoundments (if any),
- location of diversion points,
- location of turbine (for hydro-power generation),
- volume and management of off-stream storages, and
- environmental flow release rates.

A comprehensive knowledge of the water resource scheme and in particular the capacity and operation of storages, release valves, diversion structures and pumps is useful for interpreting the hydrological analysis. Further downstream of an impoundment, unregulated tributary inflows generally mitigate changes to the flow regime. There may be more than one impoundment or diversion in a river network and water may be transferred between neighboring catchments.

4.1 Standard Hydrological Analyses

In our experience, a preliminary hydrological analysis for an environmental flow study should include three core components:

- flow duration, monthly percentiles and flood frequency analyses are widely used and well described in texts such as Gordon *et al*. (1992).
- monthly median flows (with 10th and 90th percent exceedence flows for each month to indicate the range of flows), and
- flood frequency (using the partial duration series).

The results of a preliminary hydrological analysis carried out as part of an environmental flow study of the Goulburn River, north east Victoria (Figure 12) is used to illustrate these three analyses (Figure 13). Results are shown for two sites: (i) downstream of Lake Eildon, a large impoundment which releases water in summer for irrigation use and (ii) Murchison which is downstream of the major irrigation offtake point on the Goulburn River. The results show the different effects of regulation at these two sites. Downstream of Lake Eildon, operation of the reservoir has reduced the frequency of flows exceeding 10,000 ML/day per day but increased the frequency of flows less than this magnitude (Figure

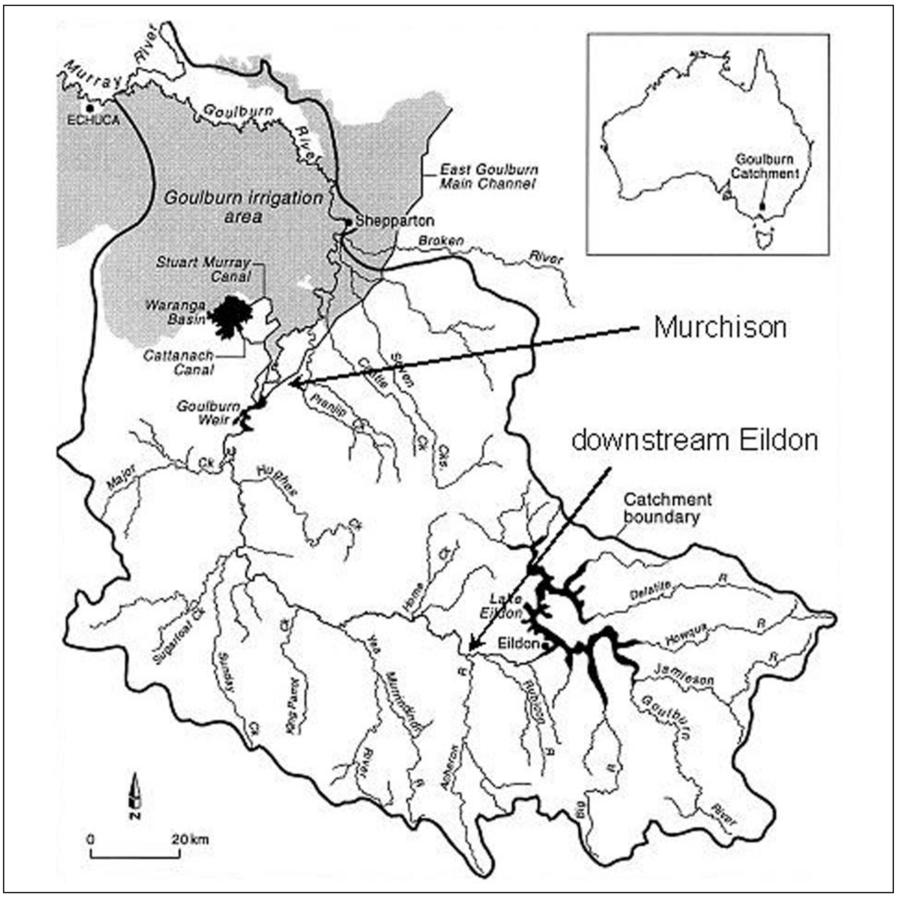


Figure 12. Goulburn River Catchment Map.

13a). This effect is typical of irrigation storages which make releases during the drier part of the year for diversion into irrigation districts further downstream.

In contrast, diversion of the summer releases from Eildon at Lake Nagambie, upstream of Murchison site, means that there is a reduced frequency of flows over the full range of magnitudes at this site (Figure 13d). The histograms of median monthly flows show changes in the seasonal distribution of water. Downstream of Eildon there is a seasonal reversal, with higher median flows in the drier part of the year as a consequence of regulation (Figure 13b). The 10th and 90th percentile flows (whisker-bars on this histogram) show a dramatic reduction in the range of flows in the winter months. The flood frequency analysis shows a major impact on the frequency of flooding at both sites particularly downstream of Lake Eildon. Flood magnitudes exceeding 35,000 Ml/day have a 1 year recurrence interval prior to regulation but a ten year recurrence interval in the regulated regime.

The purpose of the preliminary hydrological analyses is to identify the flow regime components affected by regulation. It is not expected that these analyses will be used directly to develop the environmental flow regime. A more detailed analysis of particular flow components relating to particular ecological factors is suggested in the following chapter for developing environmental flow recommendations.

Additional analyses that can also be considered in the preliminary analysis are:

- flow spell analysis (high flows or low flows), and
- rates of flow change.

Analyses of spells and rates of change of flow are described in the following sections.

4.2 Spell Analysis

Spell analysis is a common way to characterise the low or high flows periods in the hydrograph. Spells are defined by a threshold flow with high-flow spells having a lower threshold and low flow spells have an upper threshold below which the spells occur. The key to using spell analysis successfully is to select meaningful thresholds.

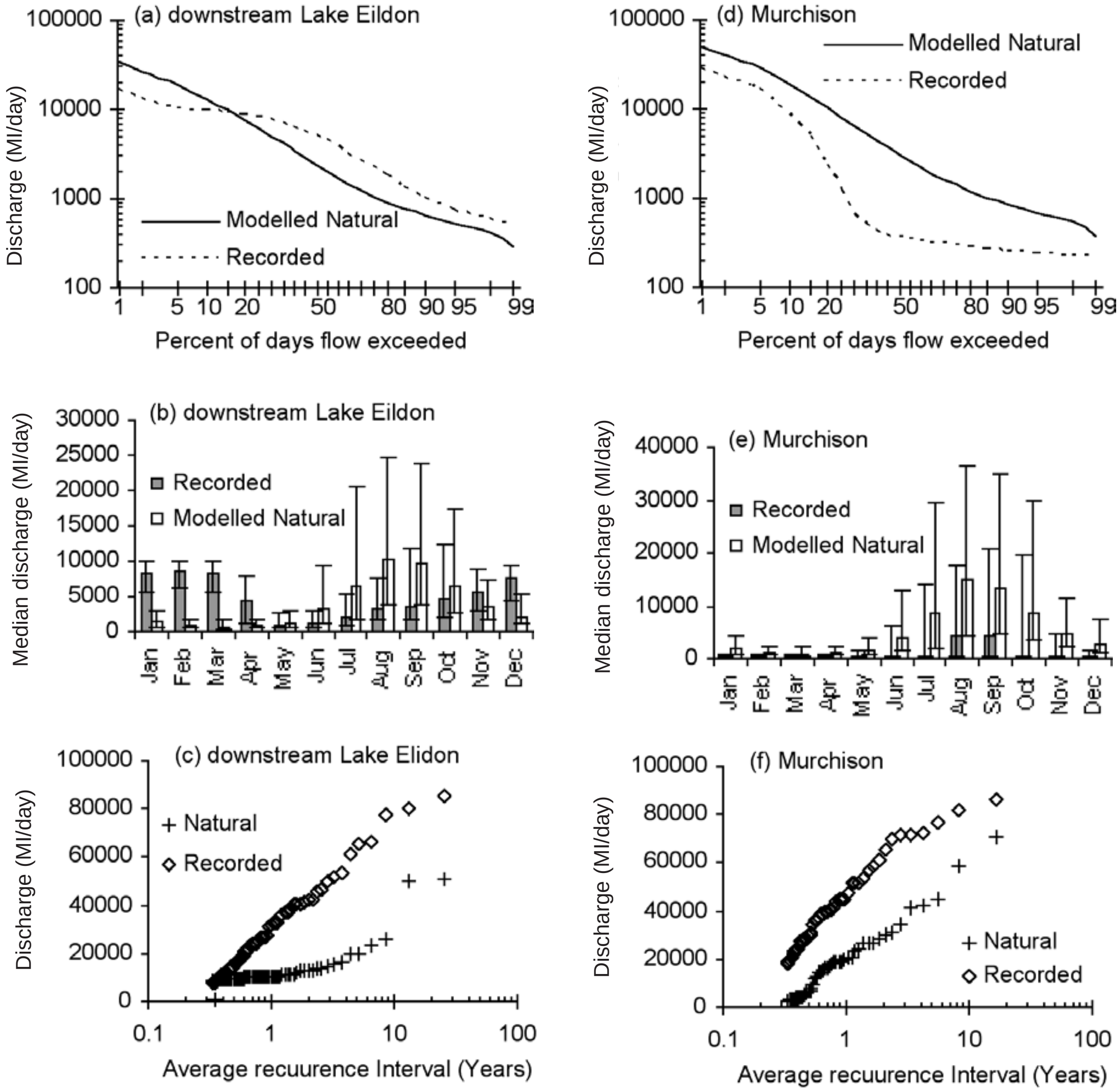


Figure 13. Results of a Preliminary Hydrological Analysis for Sites on the Goulburn River Downstream of Lake Eildon (an Irrigation Reservoir) and at Murchison (Downstream of the Major Irrigation Diversions). Comparison of Modelled Natural Flows and the Recorded (or Regulated) Flows is Based on Flow Duration Curves shown in (a) and (d), Median Monthly Flows in (b) and (e) and Flood Frequency Curves Based on the Partial Duration Series in (c) and (f). Whiskers on the Median Monthly Flows indicate the 10th and 90th Percentile Flows for each Month.

As with the identification of flood peaks for flood frequency analysis, the results of a spell analysis rely on how you choose to identify discrete spells. It could be that two spells occur only a few days apart; should these be considered as separate spells or part of the same spell? An independence criterion, expressed as the minimum number of days between spells, is often used to define separate events. If the period between the spells is less than the independence criteria then they are treated as a single spell. It is also possible to define the minimum spell duration with spells less than this duration being excluded from the analysis. The flow threshold, independence criteria and minimum duration all affect the results of the analysis and should be documented in any reports referring to spell analysis.

Flow spells are normally characterised by duration but it's also possible to use other spell characteristics such as the total or mean rate of flow during the spell. The chosen characteristic (normally duration) is calculated for all spells in the flow record. Spell analysis normally examines the duration of spells occurring in a hydrograph by providing either the mean duration or frequency of the spells. Alternatively the distribution of spell duration is presented as the duration plotted

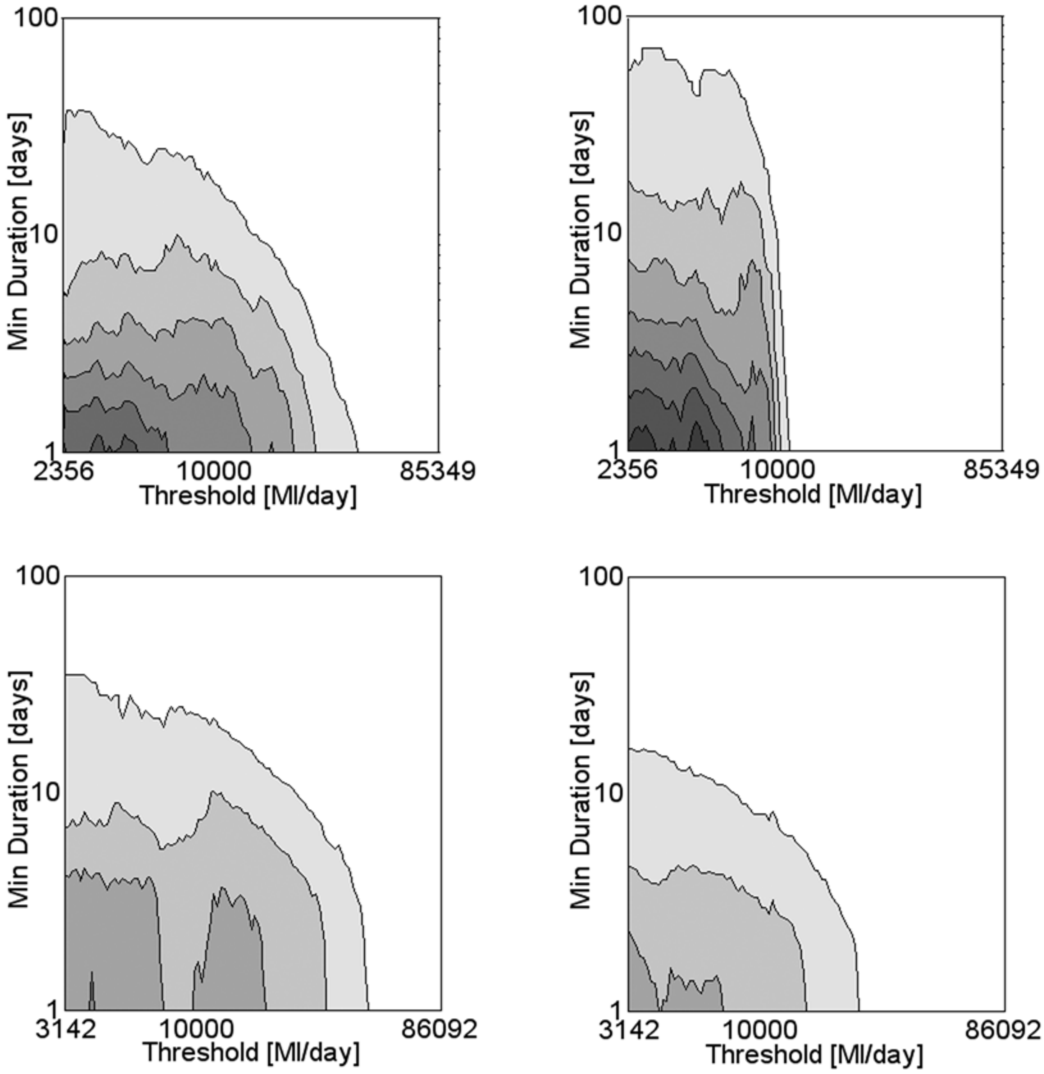


Figure 14. Natural and Regulated Frequency of Spells at Two Sites on the Goulburn River Based on High Flow Spell Analysis with Results Presented in the Event Domain. The Grey Scale Indicates Frequency with Darker Grey Indicating a Greater Frequency of Exceedence. (source: Ciaran Harman, The University of Melbourne).

against average recurrence interval for exceeding this duration (Figure 14). It is also possible to examine the number of spells each year as an annual series to evaluate the inter-annual variability in spell numbers. The details of the spell analysis must be selected to meet the needs of a particular application.

In ecology, flow spells analysis often assumes a fixed flow threshold. This allows us to focus on variations in flow duration. This is a contrast to flood-frequency analysis which considers variation in flow magnitude but normally ignores the duration of flood events. Flow spells are in fact multi-variate events. Each spell has both a magnitude and duration and flow spells which occur over a period of time will have a (bivariate) distribution of spell durations and magnitudes.

Ciaran Harman (The University of Melbourne) has recently developed a more general approach to spell analysis that avoids the need to select thresholds. Instead, the focus is on variability in spell duration and magnitude. In this approach, spell frequency is plotted in the "event domain" as a function of both threshold and minimum duration. This is likely to be a more useful approach for the preliminary analysis because there is no need to select arbitrary flow thresholds. This approach has considerable promise for use in environmental flow studies although some familiarity with the technique is required to interpret the results.

Figure 14 shows the results of a spell analysis in the event domain for two sites on the Goulburn River. Downstream of Lake Eildon, most spells exceeding

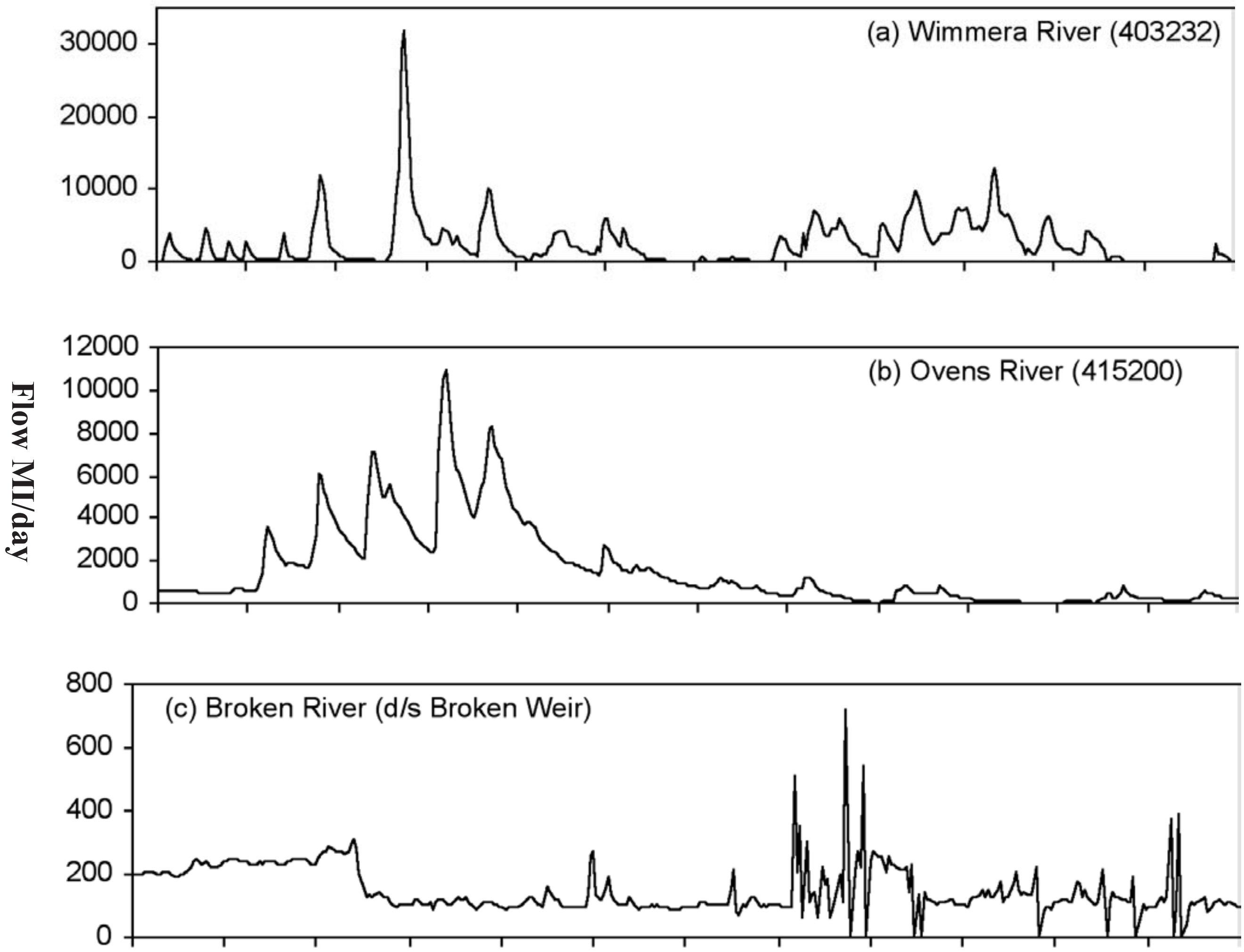


Figure 15. One Year Hydrographs for the Wimmera, Ovens and Broken Rivers.

10,000 Ml/day have been eliminated as a consequence of regulation and the duration of lower spells has increased substantially. At Murchison, downstream of the major irrigation off-take point, the frequency of all spell durations and thresholds has decreased.

4.3 Rates of Flow Change

In the absence of water resource developments, rates of rise and fall are largely controlled by catchment hydrology and hydraulics of the channel network. Rates of rise in response to storm events tend to be more rapid than rates of fall on the receding limb of the hydrograph. Operation of a water resource scheme can introduce more rapid fluctuation in flow than would normally occur.

There is no single method for characterising rates of change in flow to evaluate impacts of regulation. Some have examined rates as the difference in flow (increase or reduction) divided by the period of time over which the flow change occurs, either a time-step in the flow record or the entire rising or falling limb of a flow event. A disadvantage of this approach is that rates will generally increase with increasing flow. Changes in flow during low flow periods will tend to be hidden by much larger flow changes during periods of high flows. In many cases, stream organisms will be more sensitive to flow changes at lower flows, since this can lead to larger changes in flow velocity and stage. If this is the case, it is more sensible to characterise rates of change in flow by the ratio of flows at the start and end of a fixed time step. Using this approach we can compare the hydrographs shown in Figure 15.

We can plot the rates of change in flow over each one day time step as a cumulative distribution (Figure 16). The hydrograph of the ephemeral Wimmera River

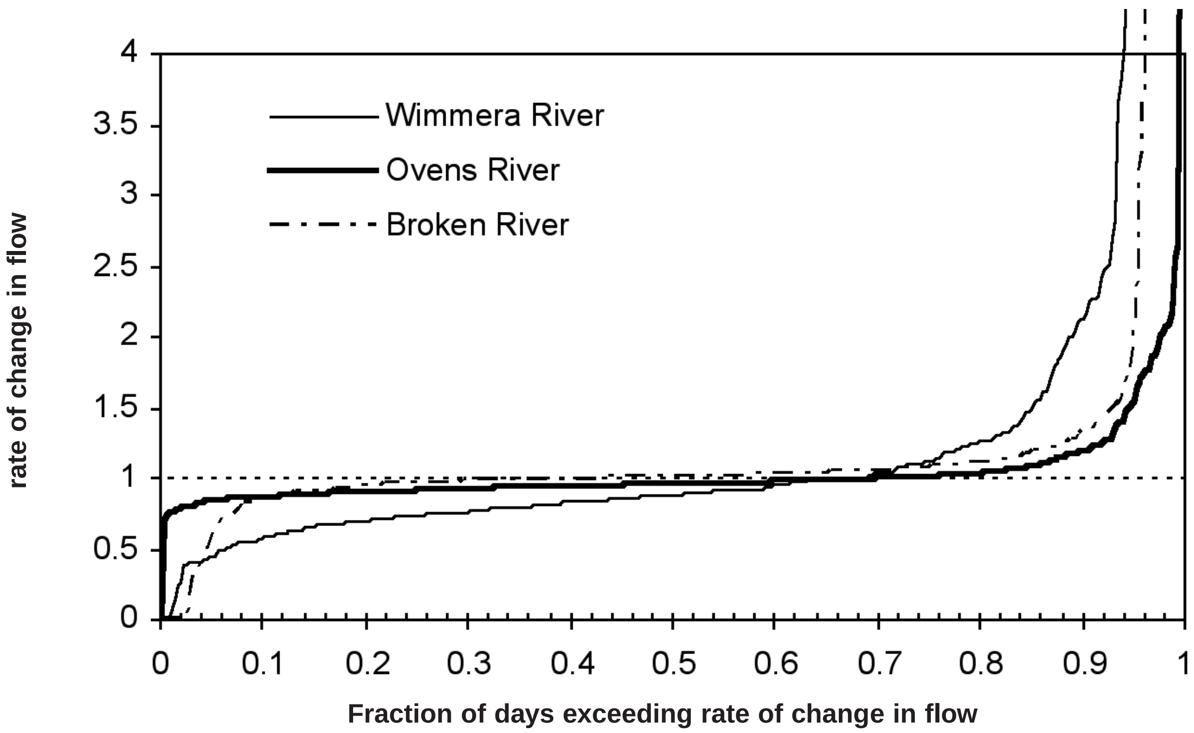


Figure 16. The Cumulative Distribution of Rates of Change in Flow for the Three Hydrographs shown in Figure 14.

shows much greater rates of rise and fall than the Ovens River. The Broken River has similar rates of rise and fall to the Ovens River with the exception of some extreme values which are much higher than the Ovens and more similar to the Wimmera River. These extreme values are introduced by operation of Broken Weir, upstream of the Broken River site. In the hydrographs, rates of rise for the larger events in the Ovens River seem greater than in the Wimmera River but small increases in flow during the lower flow period have much lower rates of rise. To examine the rates associated with larger flow pulses, we could introduce a lower threshold and only examine rates of change for period when flow exceeds this threshold.

5. Defining Environmental Flow Statistics

The most demanding component of the environmental flow method presented in Chapter two are the tasks outlined in section 2.2 and 2.3:

- identifying the key flow-ecology linkages, and
- defining environmental flow statistics.

The method prescribed for these tasks in Chapter 2 is called the Flow Events Method. In general terms, the Flow Events Method is a procedure for developing environmental flow statistics. In the environmental flow method (in Chapter 2), flow statistics are used for comparing alternate flow management scenarios for a river reach. They can also be useful in ecological research for characterising the hydraulic environment of river reaches. Previously, environmental flow studies used "off-the-shelf" flow statistics borrowed from engineering applications or proposed with little supporting justification for the methods used. A recent review found that over 170 flow statistics have been proposed for environmental studies (Olden and Poff, 2003) and in most cases the ecological relevance of these statistics is not clear. The Flow Events Method overcomes this problem by explicitly linking the flow statistics with an ecological response. This chapter provides a more detailed description of the Flow Events Method.

However, first some background is provided on the evolution of environmental flow analysis and flow-ecology research over the last 30 years. The Flow Events Method is a logical approach based on recent scientific developments in aquatic ecology and borrows from earlier approaches to flow assessment. This theoretical and historical context should help clarify some aspects of the Flow Events Method.

5.1 Background

Hynes' (1970) review of river ecology focused widespread attention on the role of water movement in aquatic ecosystems. Numerous studies have demonstrated that flow has an important influence on the distribution of stream species (Allan, 1995, Vogel, 1994). This background section describes how environmental flow management practice has developed with increasing knowledge of the relationship between flow and aquatic communities. Initially, research and management emphasised the importance of spatial variation in physical conditions in streams and neglected variability through time associated with flow regimes (Boulton and Brock, 1999). More recent research has drawn attention to the importance of environmental variability and disturbances associated with flow variations.

The ecological niche concept was first proposed by Hutchinson (1957) to provide a stronger basis for understanding biological community structure in ecosystems of all types (aquatic, terrestrial etc.). Niche theory predicts that communities will establish an equilibrium structure with microhabitat and resource boundaries determined by biological interactions. Community structure was believed to reflect the variable ability of species to dominate other species under variable environmental conditions and the distribution of resources. So in a river, species that can tolerate or make use of high flow velocities are expected to dominate other species in faster flowing sections of a river. Many early studies of the interaction between flow and stream organisms adopted this equilibrium model of niche theory and examined spatial patterns in flow and species distribution, (Gorman and Karr, 1978, Grossman and Freeman, 1987).

The ecological niche concept provided the basis for early methods of habitat assessment used by stream managers. Methods for developing environmental flow regimes focused on protecting physical habitat for particular species in the regulated flow regime. For example, the PHABSIM approach (widely adopted in its original or some modified form) specifies environmental flows to protect microhabitat availability for key species (Bovee and Milhous, 1978). Microhabitats are defined by functions of velocity, depth and other environmental variables. The microhabitat approach was justified by reference to two studies showing that competition between fish species was reduced by physical habitat isolation (Bovee and Milhous, 1978). PHABSIM and many similar approaches implicitly use the niche model by relating species distributions to spatial gradients in environmental (most commonly physical) conditions.

A limitation of the ecological niche concept is the lack of consideration given to dynamic aspects of the abiotic environment. Environmental conditions are rarely constant and there may not be time for a competitively dominant species to exclude a competitively inferior species (Townsend, 1991). Some suggest that equilibrium conditions, which form the basis of niche theory, may be rare in ecology (Wu and Loucks, 1995). Increasing attention has been given to the importance of temporal variability in environmental conditions and disturbances that force communities away from a static or near-equilibrium condition by creating gaps for colonisation by new organisms (Karr and Freemark, 1985, Levin and Paine, 1974).

Such disturbances are quite apparent in rivers with a variable flow regime and recent studies have shown that disturbances associated with floods and droughts influence stream community structure (Allan, 1995, Lake, 1995, Poff and Allan, 1995, Poff and Ward, 1989). The term "disturbance" is often used in river management practice to refer to disturbances caused by human activities. In this context it might seem strange to consider disturbances a natural part of healthy ecosystems. However, research indicates that aquatic communities respond to natural sequences of disturbances and that eliminating these disturbances by modifying the flow regime may have an impact on river ecosystems.

Increasing understanding of the ecological importance of environmental variation has led to a concern that many regulated rivers lack the natural variations in flow required to maintain pre-regulation communities. Furthermore, some consider that existing flow management practice overlooks the importance of natural flow variability in maintaining aquatic ecosystems (Poff *et al.,* 1997). As a consequence, many ecologists and managers are adopting the natural flow paradigm, which has been stated as

> "the full range of natural intra- and interannual variation of hydrological regimes, and associated characteristics of timing, duration, frequency and rate of change, are critical in sustaining the full native biodiversity and integrity of aquatic ecosystems" (Richter *et al.,* 1997).

Poff *et al.,* (1997) state that it is a

> "…fundamental scientific principle that the integrity of flowing water systems depends on their natural dynamic character".

Many recent environmental flow studies adopt this natural flow paradigm by designing environmental flow regimes that mimic the natural variability in flows.

The challenge for environmental flow practice is to select appropriate methods of characterising environmental conditions including habitat availability and temporal disturbances so that the impact of flow regulation can be evaluated. To date, there are no accepted standard characteristics which can be used to describe flow regimes in environmental flow studies. The selection of environmental flow statistics is undertaken as part of each environmental flow study depending on the specific attributes of the system being investigated.

Using the Flow Events Method environmental flow statistics are selected based on an understanding of the mechanisms by which flow variations might influence aquatic ecosystems. In some cases these mechanisms may relate to changes in the dominant flow conditions which lead to a shift in community structure (as predicted by niche theory), other mechanisms may be ecological disturbances associated with episodic events particularly those associated with high or low flow periods.

There is considerable effort being invested in flow-ecology research and each year brings new understanding of the role of flow regimes in aquatic ecosystems. The Flow Events Method is well founded on the current theory and is a sound approach for current environmental flow practice. However, history shows that environmental flow practice is evolving rapidly with advances in stream ecology and it is to be expected that new methods will be developed over the coming years to replace the Flow Events Method and other methods in current practice.

5.2 Identifying Flow-Ecology Linkages

This stage of an environmental flow study requires some expertise. Specialists are usually required to review available literature and data combined with a field inspection to identify the mechanisms by which flow regulation might modify aquatic communities. In this report we refer to these mechanisms as "flow-ecology linkages". Throughout the review phase, practitioners try to identify potential threats to the river ecosystem by considering fluvial geomorphology and various components of the aquatic community including instream and riparian flora and fauna. Each specialist will have their own methods and sources of information.

It would simplify application of the Flow Events Method if there was a generic list of flow-ecology linkages which can be used for all studies. Whilst it may be possible for a specialist team to identify a set of flow-ecology linkages for use throughout a region or for a particular river type, it is not possible to identify a generic list for the diversity of river types in Australia.

At a fundamental level, flow-ecology linkages are likely to be associated with one of the following flow-related phenomenon:

- drying, inundation and hydrological connections of habitats,
- light attenuation,
- mixing and advection of dissolved gases and solutes,
- transport of inorganic sediments and organic matter,
- direct effects on organisms including drag and abrasion, and
- indirect effects on habitat availability such as channel change due to altered erosion rates.

This list is a starting point for environmental flow studies but more specific information about the relevant ecological processes and species is required for the flow events method.

The linkages identified by the project team should relate to ecological processes or species that have value to stakeholders in the project and may be affected by flow regulation. In many cases, the linkages will be different in different sections of the river depending on its physical and ecological character and the local effects of flow regulation. The selection of flow-ecology linkages will guide the rest of the study so it should be done carefully and supporting evidence provided wherever possible through reference to previous studies and relevant data. It is also important to be as specific as possible regarding the aspects of the stream ecosystem that are effected, in particular the groups of species.

The preliminary hydrological analysis described in Chapter 3 is a useful input to this process. Observations in the field by the project team might be explained by aspects of the current flow regime. It is sometimes difficult for non-hydrologists to interpret these hydrological statistics and some effort is required to describe how regulation changes the flow regime. Key threshold high and low flows can help with this interpretation including the indicative bankfull flow and low flow at which the bed begins to be exposed.

It will commonly be necessary to arrange a dialogue between specialists from different disciplines to inform this stage of the project. For example it may be important for an ecologist considering benthic fauna to understand the nature of changes in bed sedimentation or for a plant ecologist to understand the distribution of wetlands along the river. This dialogue can be initiated in workshops but requires time for resolution. Sufficient time should be allowed for specialists to explore these issues.

The key to quantifying flow-ecology linkages is to elucidate mechanisms by which flow influences the stream organisms. If no mechanism can be identified, then it is unlikely that a strong enough argument can be mounted to support the provision of an environmental flow to address this issue. For example, in one project it was suggested that "summer freshes (or flow pulses) are important for maintaining stream health". On its own, this information is insufficient for developing a sound environmental flow analysis and recommendation. Without more information there is no basis for deciding how big the flow must be before a summer fresh can be declared and how far apart two freshes must be before they can be considered as separate freshes. The question must be asked… "What is it about the fresh that is important in this case?" Freshes may play a range of roles including wetting the stream banks to maintain aquatic vegetation, inundating benches to entrain leaf litter as organic matter input to the stream or to trigger fish migration or spawning.

This mechanistic approach can be quite challenging for ecologists working with scant information but it is important to be disciplined in this way to ensure the results of the analysis are credible. In many cases the mechanisms ecologists identify will be simply hypotheses based on limited field observations. The level of knowledge underpinning the importance of the mechanism should be made explicit in the project documentation. Environmental flow decisions arising from the study should reflect the variable confidence in different components of the recommended environmental flow regime. The explicit statement of the mechanisms will also encourage further research and improvements in the knowledge-base for undertaking future environmental flow studies.

There may be a concern that the selection of a limited set of flow-ecology linkages provides an opportunity to bias a study to particular components of the river ecosystem at the expense of other less well-understood components. Although valid, there is no way to avoid this problem. With methods which do not define a clear set of linkages, it is more difficult to identify which components have been neglected. However this does not mean that the method provides a comprehensive assessment, indeed it may miss known flow issues simply because of it unspecific nature. This problem applies to all environmental flow studies and reflects our limited understanding of flow-ecology relationships. It should be recognised that there is a possibility of neglecting important aspects of the flow regime and water allocation arrangements should allow for the possibility of review of environmental flow allocations as our understanding of flow-ecology relationships improves. However, explicit statement of flow-ecology linkages is required for use of available scientific knowledge concerning possible impacts of flow regulation. It also provides an assessment which is more informative than those involved in deciding the environmental flow regime.

5.3 Hydraulic Metric

Having determined the species or processes likely to be threatened by changes in flow, the next step is to develop a method to quantify these flow regime changes. Again this is usually done through consultation with specialists including the project's hydrologist. These discussions need to consider the important spatial and temporal characteristics of the river environment for each flow-ecology linkage.

Once the flow-ecology linkage has been established, it is possible to choose (a) hydraulic criteria defining the threshold flows at which the linkage is triggered or (b) hydraulic metrics relating to the strength of the effect of different flows have on the linkage. For example, these metrics and criteria can relate to:

- the inundation of particular zones in the river (bed, banks, benches, riffles, wetlands and the floodplain),
- availability of microhabitat for one or more species,
- the strength of hydrological connections along the channel or between the channel and the floodplain,
- mobilisation of fine or course material on the channel bed and banks and maintenance of channel form,
- drag forces operating directly on organisms, or
- stratification of pools.

The initial step of the analysis is to estimate how strongly the relevant phenomenon is affected by flow. In most cases this will mean developing a relation between discharge and some hydraulic metrics considered significant for the issue of concern. For example, if inundation of channel benches is considered important, then a relation between area of benches inundated and discharge can be calculated from channel survey data using a one-dimensional hydraulic model.

Some dialogue is required between the hydrologist preparing the environmental flow analysis and any experts who are providing advice on particular flow issues. It may take some iteration to arrive at a shared understanding of the critical hydraulic aspects of the flow for each flow-ecology link. Through this process, misconceptions of the experts regarding flow

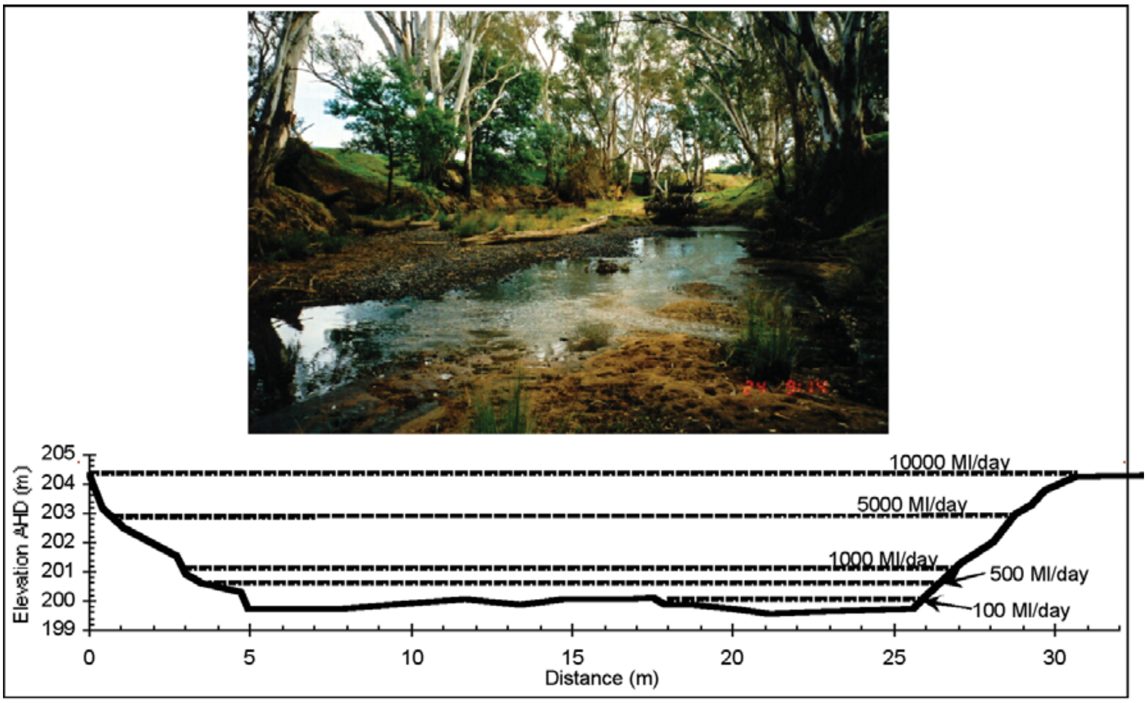


Figure 17. Cross-section Photo and Profile at Swanpool on the Broken River.

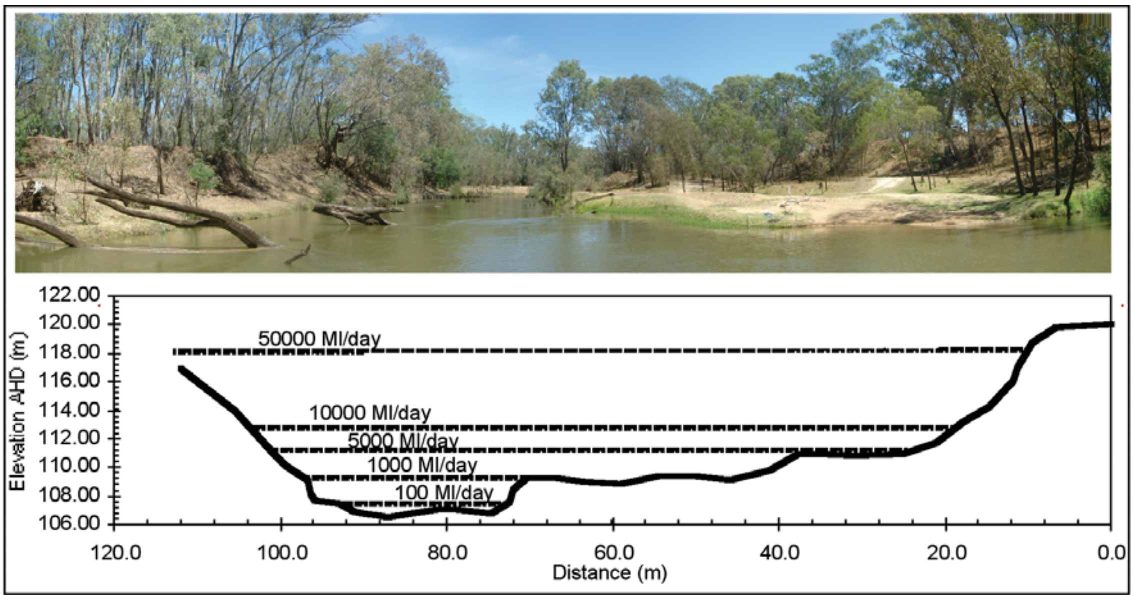


Figure 18. Cross-section Photo and Profile at Murchison on the Goulburn River.

conditions within the river can be addressed and the hydrologist can improve the relevance of the hydraulic criteria used for the analysis. Again, this process requires some time to reach a satisfactory resolution and may require a workshop and subsequent follow up discussions.

Discussions about suitable hydraulic metrics can be assisted by viewing plots of several channel cross-sections and water surface levels for different discharges (e.g. Figure 17 and Figure 18) although care is required to ensure distorted scales in these plots do not lead to false interpretations. Photos taken at the same location as the cross-sections can also provide useful information at this stage and a trigger for remembering observations made during field inspections. Issues of spatial scale can cause some confusion during these discussions. Whilst the hydrologist should be focused on describing conditions through a river reach, ecologists may be more confident in dealing with condition at individual cross-sections, the scale at which much ecological research is undertaken. If this is the case, a discussion of how to up-scale this knowledge to the reach-scale may be required.

5.4 Time-Series Analysis

Environmental conditions in rivers change dramatically in response to fluctuations in flow. There is an unlimited range of flow statistics available for characterising flow variations. Choosing an ecologically meaningful statistic is fundamental to an environmental flow study. The best approach is to consider the mechanisms by which flow variations influence the stream ecosystem and the time-scales over which these mechanisms operate. In some cases, the ecological response to environmental conditions is slow and reflects the average conditions through time. The availability of habitat for fish is commonly treated in this way. Fish may be able to seek refuge or increase their density in poorer quality habitat for shorter periods when habitat availability is reduced, but if these periods persist for the longer term, it may be possible that the assemblage of fish species will shift to one dominated by species adapted to these new environmental conditions. In other cases, it is the extremes in environmental conditions which are important. Dry spells when the streambed dries can have important effects on benthic fauna as can flood spates which fill wetlands.

To inform the selection of a time series analysis, the question must be asked "Does this flow issue relate to episodic events or to conditions that persist for longer periods?" Where the average conditions are important, the analysis might be a cumulative distribution analysis which gives percentile values of the relevant hydraulic metric. Where the "disturbance" type events are important, the time series analysis should be event-based.

It is sometimes possible to view a particular flow-ecology linkage in either way. For the example of fish habitat, we could consider the average availability of fish habitat over a particular season of the year. Alternatively we could focus on "events" when the fish habitat is absent. The selection of the appropriate analysis needs to be informed by ecological knowledge and where this is lacking, by sound opinion of specialists in the relevant field. Careful selection and documentation of the time-series analysis is necessary so that later studies, building on this work, use the same approach.

There are different approaches for the event-based analysis, although all require the selection of some lower (or upper) flow threshold which defines the onset of the high (or low) flow event. The most common approach is to use a frequency-magnitude analysis based on an analysis of peak (or minimum) values for each event. This is analogous to flood frequency analysis (using the partial flood series). Using a frequency analysis, the historical sequence of event peaks (or minimum) can be ranked from lowest to highest and the average recurrence interval for exceeding each peak (or minimum) value calculated.

Another common approach is a spells analysis which involves a similar frequency analysis to the analysis of peaks, except based on the duration of each event. In contrast to the analysis of peak values, the results of spells analysis is particularly sensitive to the selection of flow threshold. This approach is useful when there is a binary response to flow and variations in flow above or below the threshold are not considered important.

Unfortunately, few flow issues actually exhibit a binary response about a single flow threshold. In most cases, higher or lower flows, will lead to a different or enhanced ecological effect. For example, inundation of wetlands occurs once flows exceed the channel capacity but in many cases, additional wetlands become inundated as flow increases above this threshold level. In this case, consideration of wetland inundation using a spells analysis with the channel capacity as the threshold will fail to represent the variation in degree of wetland inundation for different flood events. To overcome this shortcoming, it is necessary to either consider multiple flow thresholds or use a frequency-magnitude analysis based on an event characteristic other than duration. In the wetland example, the peak flow or inundation area may be more appropriate.

When events are rare, i.e. they occur no more than once per year, the spell analysis is relatively straightforward. For more frequent events, care must be taken to correctly define criteria for the end of events. The simple approach is to define the end as the time at which the flow drops back below the flow threshold but there are two problems with this approach. For some cases, a period of time is required between events for the second event to have an independent ecological effect. The inundation of channel benches to entrain leaf litter is an example of this where closely spaced events are unlikely to result in additional organic matter input. In such cases an appropriate period of time can be specified as the time that must lapse before a second event is considered independent. The second problem with defining the end of events by a flow threshold is that two ecologically important events may occur without the flow dropping back below the threshold in the intervening period. Again, for the example of bench inundation, flow may be above the threshold for bench inundation for an entire irrigation season but several pulses superimposed on this elevated flow will result in leaf entrainment. Such pulses will only be considered as a single event although several have occurred. In such cases, an event independence criteria based on the time between peak values may be more appropriate in such cases.

Another consideration for choosing a time-series analysis is the season of the year during which the flow-ecology linkage is of concern. In the case of issues related to plant growth in temperate regions, the time-series analysis might be restricted to the spring-summer period. Cues for fish migrations and spawning are frequently required in specific months according to their life-cycle. Seasonal analysis is also important when the effect of regulation varies over the year such as for the case of irrigation releases which lead to increased flows in the drier months and reduced flows in the wetter months.

5.5 Calculating Environmental Flow Statistics

The name "Flow Events Method" refers to the procedure of analysing flow regimes based on hydraulic criteria and time-series analysis to evaluate the ecological effect of flow variations associated with particular flow-ecology linkages (Stewardson and Gippel, 2003). An example of this analysis for four flow-ecology linkages is provided in Chapter 2. To further demonstrate the Flow Events Method, this section develops flow statistics for evaluating the effect of flow regulation on benthic fauna through modifications to the frequency and extent of bed drying.

Using the Flow Events Method, the hydrograph (Figure 19a) is transformed to a time series of area of wetted perimeter of the channel (Figure 19b) using the relation between wetted perimeter and discharge (Figure 19c). The threshold discharge at which the bed begins to be exposed can be defined objectively using Gippel and Stewardson's (1998) method and is depicted by the maximum wetted perimeter (Figure 19b). In this case, we define the events by the minimum wetted perimeter during the event. If extreme events are important, the minimum wetted perimeters from each year are extracted and a frequency analysis is performed using these minimums. The frequency analysis reveals the average interval between years in which events are exceeded (Figure 19d). The second analysis, used when more frequent events are important, provides a similar result, although the magnitudes for the more frequent events are greater than when using the annual series (Figure 19e). The cumulative frequency distribution analysis uses the wetted perimeter calculated for every day within the season of interest (in this case the entire year), and gives the probability that on any day the wetted perimeter will be less than some given level (Figure 19f).

To examine how flow events are affected under different flow management scenarios, the frequency distributions of events with and without the effects of regulation are compared (Figure 20). Figure 20a indicates a larger range of event magnitudes than for the case of Figure 20b in both the regulated and unregulated regime. Both Figure 20a and Figure 20b show a similar change in event magnitudes for a given recurrence interval. However, the recurrence intervals for particular event magnitudes are substantially more affected in Figure 20b. It might be that the system represented in Figure 20b is more vulnerable to changes than Figure 20a because the system is not adapted to wide variations in the event magnitude. If this is the case, then changes in recurrence interval are more relevant than changes in the magnitude of events for a particular recurrence interval.

The River Analysis Package (RAP) is a software package available from the toolkit website (www.toolkit.net.au) which can be used to calculate these metrics. It is possible to use RAP to derive habitat rating curves using output from a 1D hydraulic model. Flow or habitat time-series and be analyzed in a variety of ways including frequency-magnitude analysis of peaks, flow duration analysis and low- or high-flow spells analysis.

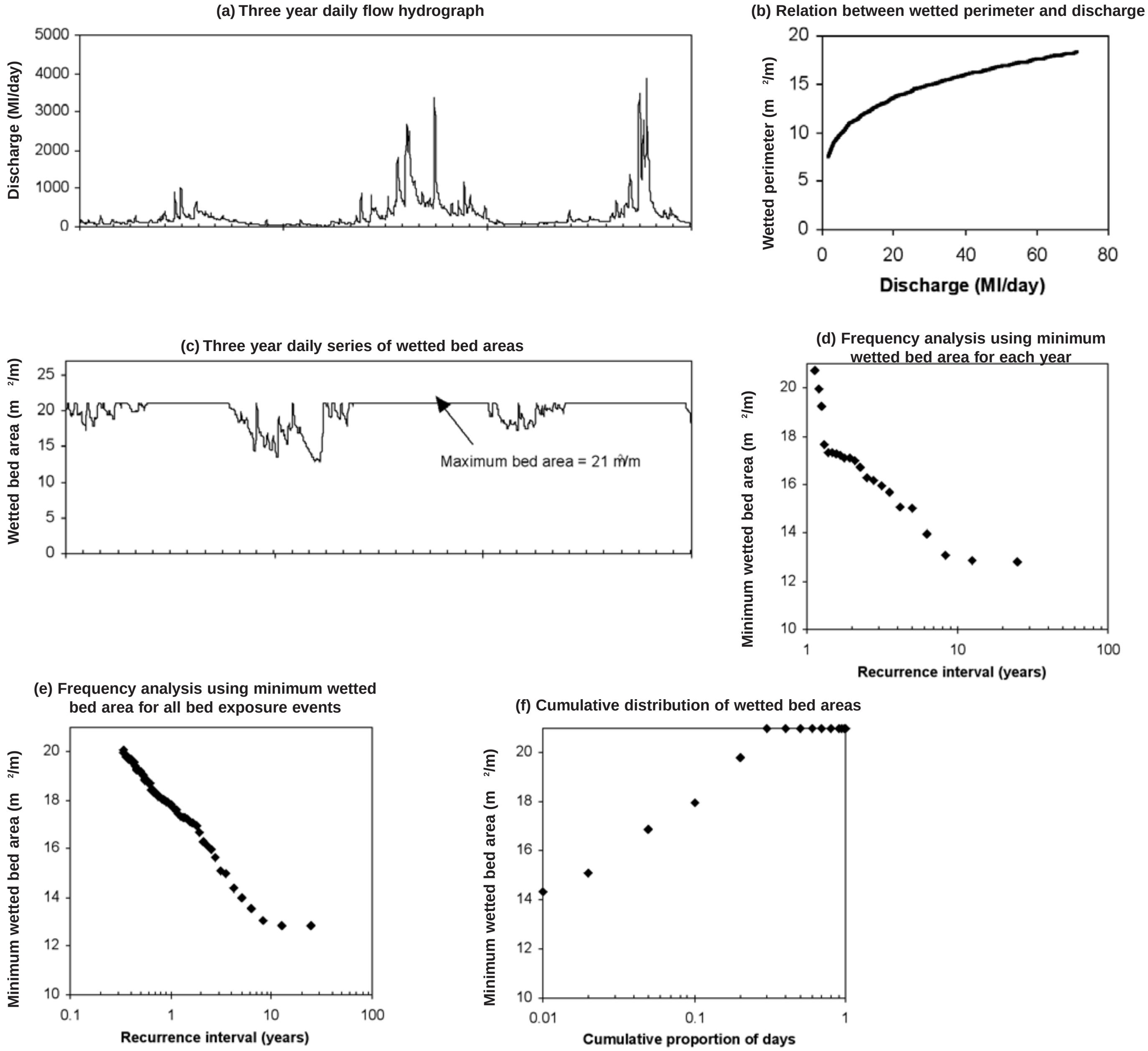


Figure 19. Procedure Used for Time-series Analysis of Flow Events (a) Three Year Hydrograph, (b) Relation between Wetted Perimeter and Discharge (c) Time-series of Wetted Perimeter, (d) Frequency Analysis of Series of Annual Peak Flow Event Magnitudes (e) Frequency Analysis of Series of all Event Magnitudes and (f) Cumulative Frequency Analysis for the Magnitude of an Event based on Values on all days.

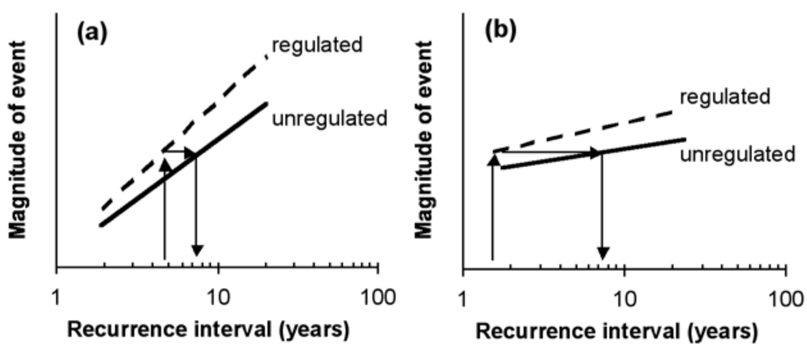


Figure 20. Effect of Flow Regulation on the Frequency of Flow Events for a River Reach with (a) Large Variation in the Magnitude of Events and (b) Little Variation in the Magnitude of Events. This Figure is Intended to Provide a General Illustration of the Results of the Flow Events Analysis, so No Scale has been Provided on the y-axis. In Practice the y-axis Units and Scale will Depend on the Definition of the Flow Event.

6. Future Developments

In most cases, the environmental flow statistics derived using the methods described in this report are based on hypothesised linkages between flow and ecological responses. Whilst some evidence may exist to support these hypotheses in some cases there is a need to test these models of flow regimes influences on aquatic ecosystems. To be useful in environmental flow management, these tests are probably best undertaken at reach scale using data from multiple reaches. These are unlikely to be studies with experimental manipulations of the flow regimes. Rather they would be empirical studies where the expected variations in ecological characteristics would be compared to the observed variations for sites with different natural and regulated flow regimes. Of course such studies will be confounded by other factors influencing stream ecosystems. However, one might expect that if the hypotheses were correct, then the flow statistics would explain a portion of the variation in ecological characteristics. Such tests are underway in Queensland and Victoria as part of the CRC for Catchment Hydrology and CRC for Freshwater Ecology research program. Further work in this area will be required in the coming years.

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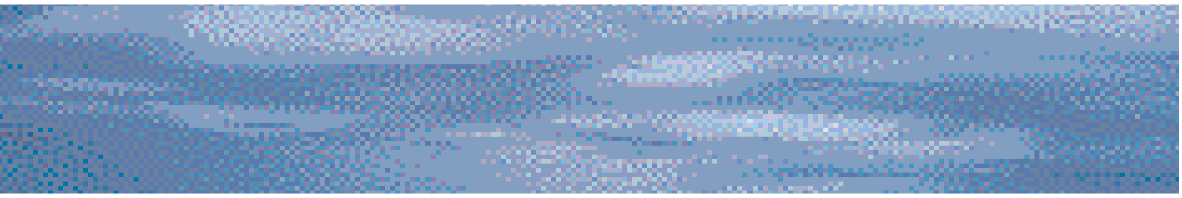

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