

# Applying the Flow Events Method in an Environmental Flow Study of the Broken River

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**Abstract:** Developing environmental flow rules and targets for rivers is assisted by the modelling of ecosystem response to changes in flow regime. Reliable ecological response models are not yet available, so modelling approaches should allow for the combined input of available knowledge and expert judgement. This paper demonstrates the application of a new method for analysing flow regime changes for environmental flow studies called the Flow Events Method. The approach includes modelling daily flow series, modelling hydraulic characteristics of selected reaches, and characterising important aspects of the flow regime affecting a particular component of the stream ecosystem. A multi-disciplinary team develops the method of analysing the flow regime collaboratively. In this paper, the Flow Events Method is applied to the Broken River, a regulated river in north central Victoria, Australia.

**Keywords:** Environmental flows; Stream habitat assessment; Flow variability; Modelling

## 1. INTRODUCTION

The environmental flow problem is beset with challenges for water resource planning. In particular, the knowledge base with which to evaluate the ecological impact of changes in flow regime is poor or inaccessible to all but a few experts in the field. There is no standard analytical procedure and no simple response functions for modelling the ecological impact of changes in flow regime in Australia. As a consequence, managers often rely on the opinion of individuals or panels of experts when developing environmental flow management rules. The procedures adopted in practice vary depending on the hydrological and ecological information available and the experience of the investigators. A reliance on expert opinion can mean that the logic of an environmental flow recommendation is not explicitly recorded, making it hard to interrogate, defend or refer to in future studies. It is therefore important that environmental flow investigations specify the procedure used to derive an

environmental flow, including the specific ecological processes considered and ecological consequences of implementing various alternative environmental flow scenarios. This will allow for (i) review of the logic used in the study, (ii) more defensible results, and (iii) development of the analysis in response to future needs.

The Flow Events Method has been developed by the CRC for Catchment Hydrology as a method to support environmental flow studies. It is intended to be flexible rather than prescriptive, so that it can be adapted to individual project needs. The method encourages the use of available ecological knowledge and opinion and, where necessary, provides a systematic approach for proceeding where knowledge is lacking. The method is also useful for documenting the logic of an environmental flow recommendation, examining assumptions held by experts or other stakeholders, and for developing hypotheses regarding the impact of changes in flow regime on the stream ecosystem. The flow events method is not a step-

by-step procedure for calculating environmental flow requirements; rather it is a tool to assist experienced practitioners in developing an environmental flow recommendation. This paper demonstrates the method by application to the Broken River in North-Central Victoria, Australia.

## 2. BACKGROUND TO THE BROKEN RIVER STUDY

The Broken River is situated in North-Central Victoria, Australia (Figure 1). The Broken River flows generally north to Benalla and then west to join the Goulburn River at Shepparton. During extreme floods, flow spills from the channel downstream of Benalla and into Broken Creek. Broken Creek flows into the Murray upstream of its confluence with the Goulburn River.

Diversions for irrigation, stock and domestic uses occur along the length of the river downstream of Lake Nillahcootie. Summer-autumn irrigation demands are met through releases of water from two storages, Lake Nillahcootie and Lake Mokoan. Lake Mokoan is an off-stream storage filled by flow diversions from the Broken River at Broken Weir and Hollands Creek at Hollands Weir.



Figure 1. The Broken River Catchment.

As part of a process to define the bulk water entitlements within the catchment, the Department of Natural Resources and Environment (DNRE) has undertaken a study to evaluate the environmental impact of current water

management practices and recommend environmental flow requirements for the river. DNRE commissioned a scientific panel, managed by the Cooperative Research Centre for Freshwater Ecology, to carry out this study. This panel considered environmental flow requirements along the length of the Broken River using data for three reaches. This paper presents the analyses of the scientific panel for one of these reaches immediately downstream of Broken Weir.

## 3. MODELLING

### 3.1 Daily Flow Model

The first step in the flow events method is to assemble daily flow series for the project sites under the regulated and unregulated conditions. These series are used to evaluate how regulation has affected the flow regime. The simplest approach is to use recorded flow series for periods (i) prior to and (ii) since regulation. However, in many cases flow records will not be available for a pre-regulation period. It is also common to have long gaps in streamflow records when gauges were not functioning properly. Another difficulty with this approach is the confounding effects of climate and catchment changes.

A better approach, and the one adopted here, is to use daily flow series simulated for the same period with and without the effects of regulation. The available flow data for the Broken River (Table 1) were most complete between 1/7/74 to 30/4/98, so historical flows for this period were chosen as representing the regulated condition.

Table 1 Streamflow data for the upper Broken River.

Station	Years Operated	% <sup>1</sup>
404218 Nillahcootie spillway <sup>2</sup>	Jan-70-Mar-01	3
404220 Nillahcootie outlet <sup>3</sup>	May-68-May-00	0
404206 Moorngag on Broken R <sup>2</sup>	May-57-Sep-00	0
404213 U/S Broken Weir <sup>2</sup>	Jun-72-Dec-74	0
Diversions at Broken Weir <sup>3</sup>	Jul-74-Apr-01	0
404208 Lima on Moonee Cr <sup>2</sup>	May-55-Jun-00	17
Nillahcootie storage level <sup>2</sup>	Dec-93-Mar-01	0
Nillahcootie storage volume <sup>3</sup>	May-68-Apr-01	50

<sup>1</sup> Column shows percentage of record that is missing

<sup>2</sup> Data supplied by Thiess Environmental Services

<sup>3</sup> Data supplied by Goulburn-Murray Water

Natural flows at the study site were modelled for the same period using two steps:

1. Modelling inflows to Lake Nillahcootie

2. Routing modelled and gauged tributary flows to the study site downstream of Broken Weir

The availability of streamflow data for calibrating these models is typical of that available for regulated rivers in south-east Australia, in that records are discontinuous and often not concurrent. It is common practice not to monitor dam inflows. Some records are incomplete and others consist of daily gauge readings rather than continuous records. For much of the period, storage levels in Lake Nillahcootie were recorded weekly rather than daily.

In this project, inflows to Lake Nillahcootie were estimated using a different method for times when the spillway was and was not operating. During times the dam was full, inflows were calculated from spillway and outlet flows using a reverse routing procedure. At other times, a rainfall runoff model was used to estimate inflows.

The reverse routing procedure, used for periods when the spillway was operating, predicted the daily inflow  $I(t)$  for day  $t$  as

$$I(t) = Q(h(t)) + A(h(t)) \frac{dh(t)}{dt}$$

Where  $Q(h(t))$  is the outflow as a function of storage level  $h$ , and  $A(h)$  is the surface area of the storage. To approximate the derivative we used

$$\frac{dh(t)}{dt} = \frac{h(t + \Delta) - h(t - \Delta)}{2\Delta}$$

Where  $\Delta$  is the time step, one day in this case. These relations were derived using the reverse routing analysis of Zoppou [1999] applied to Fenton's [1992] reservoir routing equation. The reverse routing procedure was applied to every day that the spillway was operating except days on which spillway flows began or ended.

At times when the spillway was not operating, a lumped conceptual model was used to represent reservoir inflows. This model used scaled pan evaporation and rainfall as input and represented changes in storage within the reservoir by accounting for flow releases and evaporative and rainfall fluxes at the reservoir surface. Rainfall and pan evaporation are recorded at a station by the reservoir. The model parameters were calibrated to provide the best fit with observed changes in storage level.

There is no gauge at the study site, located just downstream of Broken Weir. A flow routing model was used to estimate flows at this site for the regulated and unregulated condition. The routing model took the form of a linear transfer function. The flow at the downstream end of the reach on the  $i^{\text{th}}$  day ( $Q'_i$ ) was expressed as linear function of the current and last  $n$  days flow at the upstream end of the reach ( $Q_{u,i}$ ). Multiple input flow series ( $u = 1$  to  $p$ ) were used to account for tributary inflows. The routing model can be expressed as

$$Q'_i = \sum_{u=1}^p \sum_{j=0}^n k_{u,j} Q_{u,i-j}$$

Where  $k_{u,j}$  is the transfer function coefficient for the  $u^{\text{th}}$  inflow series and a lag time of  $j$  days. The routing model accounted for ungauged tributary inflows by using coefficients for a particular inflow series that summed to greater than 1.

For the regulated condition, flows recorded at Moorngag on the Broken River and at Lima on Moonee Creek (now called Lima East Creek) were routed to upstream of Broken Weir. Flows at the study site were then estimated by subtracting recorded diversions at the weir from weir inflows estimated using the routing model. The transfer function coefficients were calibrated for this reach using the available flow records at these three sites between June 1972 and December 1974.

To simulate natural flows at the study site, a streamflow record for ungauged tributary inflows between Lake Nillahcootie and Moorngag was generated by subtracting dam releases and spills from flows recorded at Moorngag. Simulated inflows to Lake Nillahcootie were added to this generated flow series to simulate a natural flow series at Moorngag. Routing effects between the dam and Moorngag were neglected because of the relatively short reach length. The calibrated routing model was then used to estimate natural flows at the study site.

### 3.2 Hydraulic Model

The hydraulic characteristics of the study site were modelled using HEC-RAS, a one-dimensional gradually varied flow analysis software package produced by the US Army Corps of Engineers. To obtain a representative sample of conditions at the site, 15 evenly spaced (at 50 m) cross-sections were included in this model. An additional three-cross-sections were added to improve model performance. The 18 cross-sections were surveyed during a period of low flows. The model provided

water surface profiles for the reach for a range of discharges. Model output included the wetted perimeter, surface width and area for each cross-section for a range of discharges.

## **4. THE KEY FLOW EVENTS**

### **4.1 Developing the Flow Events Analysis**

After first modelling the hydrological data, the next step in the flow events method is to identify the key aspects of the flow regime influencing the stream ecosystem. These aspects are referred to as flow events and each flow event is associated with a particular ecological response. River geomorphology, floodplain connectivity, macrophytes, macroinvertebrates and fish communities and water quality were all considered at this stage. Where ecological knowledge is poor, the flow events and responses can be considered as hypotheses. These hypotheses can guide performance monitoring of environmental flows regimes within an adaptive management framework. The sharing of conceptual models by the multidisciplinary team helps to refine environmental flow recommendations that accommodate the needs of different ecosystem components.

The flow events that were identified as important for the environmental flow study of the Broken River were:

- Stranding of fish during rapid flow reductions,
- Washout of fish during rapid flow increases,
- Loss of slow water for fish larvae,
- Drying of the streambed,
- Loss of shallow water for macrophytes, and
- Changes in bench inundation.

Of these, the first two points are discussed in the following sections. The flow events were evaluated using hydraulic parameters that measure the severity of the event. For example, drying of the streambed was characterised by the area of wetted perimeter of the channel. The project team must also select a method of characterising the time sequence of flow events. In designing this time-series analysis it is necessary to consider:

- a) the months in which the events are ecologically important,
- b) whether extreme events, more frequent events or average conditions are important, and
- c) what degree of change in these flow events is acceptable.

For the Broken River, the flow events analysis was developed progressively through meetings of the

scientific panel. The initial meeting included a two-day field trip to sites along the river and presentations by the local water authority and community representatives.

The flow events method is specifically intended to make use of available ecological knowledge and facilitate the use of expert judgement where this knowledge is lacking. To do this successfully, it is necessary to establish an effective dialogue between the ecologists and modeller. The modeller must provide useful information to the ecologists and the ecologists must in turn focus the modeller's analysis to detect the important aspects of the flow regime and how these may have been altered by regulation. An effective method of analysis may not be obvious at the start of the project but is sought iteratively by the project team. In this project we found the panel coordinator played a particularly important role in progressing the dialogue between the modeller and ecologists. The coordinator ensured that all panel members understood and contributed to the development of the flow events analysis. Whilst meetings were important for the development of the method, time was required to digest preliminary results presented at meetings and follow-up discussions often proved particularly fruitful. The optimum arrangement is probably to hold three or four meetings in a relatively short period of time. This would ensure continuity between meetings but allow participants time to consider new information.

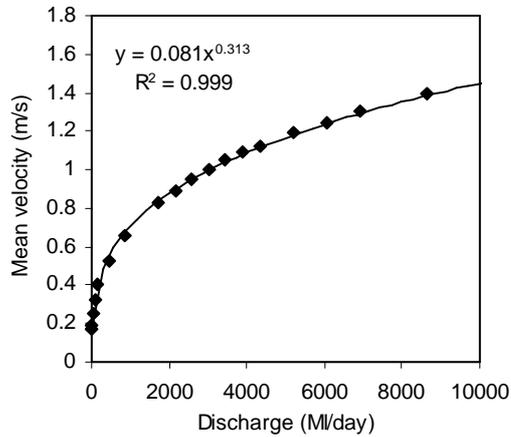
The process of developing a flow events analysis is not prescribed and the commitment of the entire project team to development of a shared understanding of the river hydrology and ecology is required for a successful project. The process may be simplified in future projects if the flow event analysis developed in this project and elsewhere is used as a guide.

### **4.2 Washout of Fish During Rapid Flow Increases**

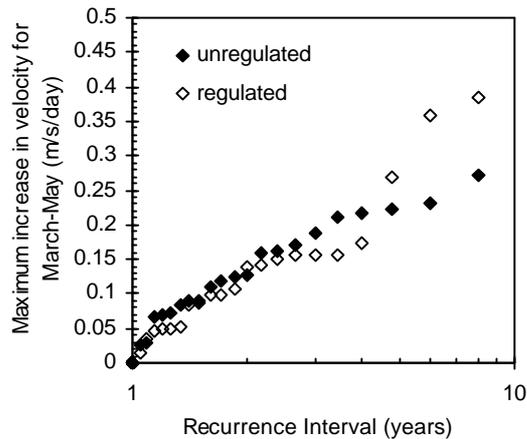
Rapid increases in flow may washout some stream organisms, especially larval fish as they make upstream migrations during autumn. It was decided that the risk of washout was most likely to be related to the rate of change in velocity. The mean of the cross-sectional velocities (Figure 2) was used as indicative of changes in the velocity distribution throughout the reach.

The maximum daily changes in the mean velocity were estimated for 3 periods in each year (Dec-Feb, Mar-May, Oct). The periods were specified

by the panel based on knowledge of the life cycles of native fish found at the site. These peaks are presented as a plot showing the average recurrence interval between peak events in which the rate of increase in velocity was exceeded (Figure 3). Results for all three periods of the year were similar and indicated little change as a result of flow regulation.



**Figure 2** Relation between mean velocity and discharge at the study reach.

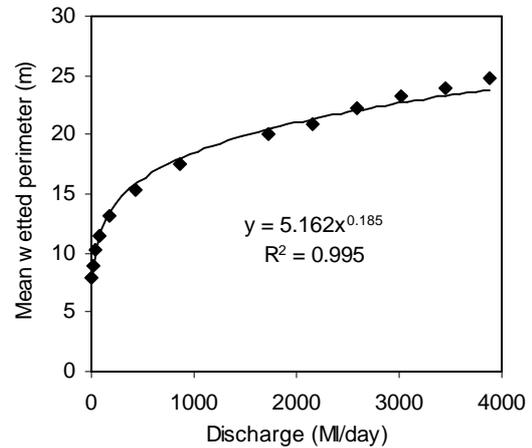


**Figure 3** Average recurrence interval for peak washout events in March, April and May.

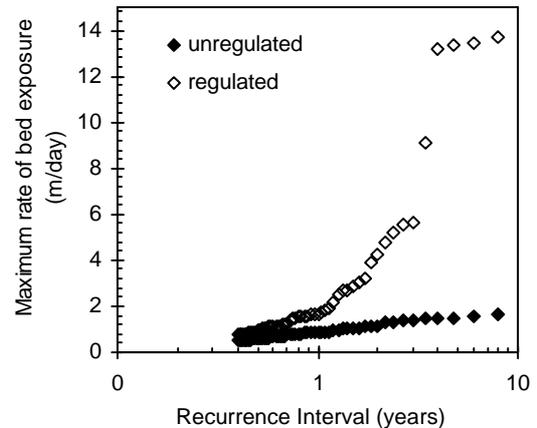
#### 4.3 Stranding of Fish During Rapid Flow Reductions

Fish may become stranded during unusually rapid flow reductions. The rate of reduction in the average wetted perimeter is used to evaluate these stranding events. The relation between mean wetted perimeter and discharge is obtained from the hydraulic model output (Figure 4). The same periods of the year were considered for stranding events as for washout events.

Figure 5 shows the results of the flow events analysis for the March, April and May season. Similar results were obtained for the other periods of the year. The plot shows the average recurrence interval between flow reductions exceeding a range of values. Note that this analysis included all flow reduction, not just the peak events for the season. Flow regulation substantially increased the magnitude of these stranding events.



**Figure 4** Relation between mean wetted perimeter and discharge at the study reach.



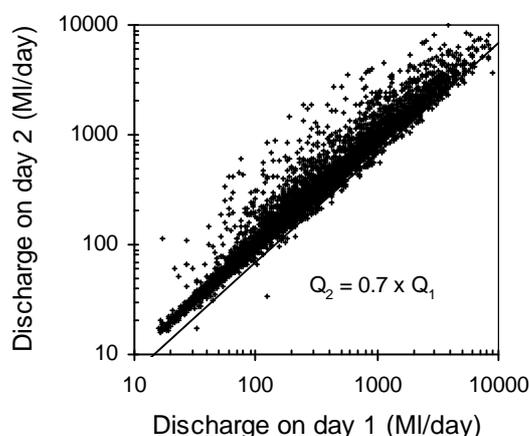
**Figure 5** Average recurrence interval for peak stranding events in March, April and May.

#### 5. ENVIRONMENTAL FLOW

An advantage of the Flow Events Method is that environmental flow targets and rules can be designed to address specific environmental issues. In this case, flow regulation has little effect on the rates of increase in discharge, so there is no need to develop an environmental flow rule to address this issue. However, flow regulation has substantially enhanced the rate of bed exposure associated with reductions in discharge. To overcome this problem, an environmental flow rule has been designed to

ensure that rates of reduction in discharge associated with operation of Lake Nillahcootie and the Lake Mokoan diversion do not exceed those that would occur naturally. It is reasonable to expect that the stream ecosystem is adapted to flow variations that lie within the range experienced naturally.

Without the effects of regulation, rates of rise of flow, associated with the onset of a storm event in the catchment, are generally greater than rates of fall associated with the receding limb of the storm event. This is apparent when the flow is plotted on consecutive days for the study site (Figure 6). The lower boundary to data points in this plot is a function of the hydrological characteristics of the catchment.



**Figure 6** Discharge on consecutive days at the study site for the unregulated condition

To ensure that natural rates of fall in discharge are preserved in the regulated regime, it was recommended that discharges on any day are no lower than 0.7 times the discharge on the previous day. This rule, indicated by the line in Figure 6, was selected so that 95% of the data points in Figure 6 lie above the line. The rule will ensure that reductions in flow resulting from operations of the release valve at Lake Nillahcootie or diversions to Lake Mokoan, replicate the natural recession curves observed in the unregulated hydrograph.

## 6. CONCLUSIONS

The Flow Events Method is an approach to developing environmental flow rules or targets that facilitates the use of available ecological knowledge and, where necessary, expert judgement. The method clearly identifies the ecological effects of flow regulation and the benefits of environmental flows in terms of reversing these effects.

This paper describes a successful application of the Flow Events Method to a site on the Broken River. It was found that flow regulation had little effect on the rate of increase in flows. However the rate of flow reductions were substantially increased as a result of flow regulation, increasing the risk of fish stranding. This effect of flow regulation is likely to occur in many regulated systems. Unregulated flows tend to have rapid increase in flow in response to storm events, but relatively slow rates of recession. As a consequence, river ecosystems are more likely to be sensitive to enhanced rates of flow reduction. A simple environmental flow rule was established to ensure regulated flow reduction were similar to natural flow recession curves.

A procedure is presented for obtaining a daily flow series for the natural and regulated condition, for the same period of time. The method makes use of the available data, including incomplete records. The method of modelling inflows to a reservoir by a combination of reverse routing spillway flows and modelling flows at other times using a rainfall-runoff model is novel. This approach has the benefit of not requiring accurate predictions from the runoff model for many of the high flow events passing over the spillway.

The procedure for developing the flow events analysis is not tightly prescribed. Rather the analysis evolves iteratively through discussions between the multi-disciplinary project team. A coordinator is particularly important to ensure everyone contributes to the analysis and there is a shared understanding of how the river system responds to flow regulation.

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