RIVER RESEARCH AND APPLICATIONS

River. Res. Applic. 23: 933-946 (2007)

Published online 15 August 2007 in Wiley InterScience (www.interscience.wiley.com) DOI: 10.1002/rra.1016

MULTIPLE LINES OF EVIDENCE FOR THE BENEFICIAL EFFECTS OF ENVIRONMENTAL FLOWS IN TWO LOWLAND RIVERS IN VICTORIA, AUSTRALIA

P. R. LIND, B. J. ROBSON* and B. D. MITCHELL

School of Life and Environmental Sciences, Deakin University, P.O. Box 423, Warrnambool 3280, Victoria, Australia

ABSTRACT

The aim of this study was to identify whether environmental flows released into two lowland rivers (the Glenelg and Wimmera Rivers, western Victoria, Australia) during the spring to autumn period had successfully ameliorated the negative effects of multiple human impacts. Macroinvertebrates and a range of physico-chemical variables were sampled from three reaches in each river. Both rivers were sampled during three environmental release seasons with average-sized releases (1997–1998, 1998-1999 and 2001-2002) and two drought seasons with limited releases (1999-2000 and 2000-2001). The effects of releasing average-sized environmental flows on macroinvertebrates and physico-chemical variables were assessed by comparison with data from the two drought seasons. For the Glenelg River, data from a reference season prior to the release of environmental flows (1995-1996) was also compared to data from the five environmental flow seasons. Multivariate analyses revealed four pieces of evidence indicating that the release of environmental flows effectively slowed the process of environmental degradation in the Glenelg River but not in the Wimmera River: (1) the magnitude of the river discharge was dependent on the size of environmental flow releases; (2) in the Wimmera River, water quality deteriorated markedly during the two drought seasons and correlated strongly with macroinvertebrate assemblage structure, but this was not observed in the Glenelg River; (3) the taxonomic composition of the macroinvertebrate assemblages among contrasting flow release seasons reflected the severe deterioration in water quality of the Wimmera River; (4) despite two drought seasons with minimal environmental flow releases, the macroinvertebrate assemblage in the Glenelg River did not differ from the average-release seasons, nor did it return to a pre-environmental flows condition. Therefore, it appears that environmental flow releases did sustain the macroinvertebrate assemblage and maintain reasonable water quality in the Glenelg River. However, in the Wimmera River, release volumes were too small to maintain low salinities and were associated with marked changes in the macroinvertebrate assemblage. Therefore, there are multiple lines of evidence that environmental flow releases of sufficient magnitude may slow the process of degradation in a regulated lowland river. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: macroinvertebrates; salinization; river regulation; environmental water allocation; environmental flows

Received 8 February 2007; Accepted 8 February 2007

INTRODUCTION

Environmental flows are increasingly being used to protect river ecosystems from the negative effects of flow regulation both in Australia (Arthington and Pusey, 1993) and overseas (Tharme, 2003). Environmental flows may be allocated for several purposes such as to provide spawning cues for fish, to alter bed morphology, to restore connectivity between river reaches and floodplains, to mimic some elements of the pre-regulation flow regime or to protect rivers from disturbances arising from human impacts (e.g. salinization or sedimentation). While there are many published methods (e.g. Arthrington and Pusey, 1993; Tharme, 2003) for determining the environmental flow requirements of lowland rivers there are few published evaluations as to whether environmental flows actually deliver the proposed benefits to river ecosystems (but see Shannon *et al.*, 2001). In particular, no studies have substantiated in-channel benefits of environmental flows for lowland rivers that suffer multiple human impacts. Unfortunately, doubt about the effectiveness of environmental flows in delivering ecological benefits can hinder further environmental water allocations where there are competing water users.

^{*}Correspondence to: B. J. Robson, School of Life and Environmental Sciences, Deakin University, P.O. Box 423, Warrnambool 3280, Victoria, Australia. E-mail: belinda.robson@deakin.edu.au



Many environmental impacts have a distinct starting point in time, analogous to a spatial point source for pollution and may be amenable to a Before-After-Control-Impact (BACI) approach (Downes *et al.*, 2002). However, the release of environmental flows may have no discernable starting point in time, or may create patterns that are difficult to distinguish from natural fluctuations. Indeed, the release of environmental flows may even be designed to mimic natural flow conditions, exacerbating the difficulty in determining whether they have had a beneficial impact on river ecosystems. For example, the impact of the release of a very distinct flooding flow on invertebrates and algae was difficult to disentangle from background seasonal flow conditions (Shannon *et al.*, 2001). Another aspect of this problem is that where environmental flows are allocated to prevent further degradation of river ecosystems, success may be defined as no change in water quality or biotic assemblages, creating potential difficulties if hypothesis tests have low statistical power. A further challenge for assessing the effectiveness of environmental flows is that BACI designs require the comparison of control and impact sites; that is, comparable rivers that lack an environmental flow release. Comparable rivers may be very difficult to find, especially where most rivers are far from pristine. Particularly in Australia, the relatively arid landscape reduces the number of rivers to choose from and inflates river-to-river differences such that it is usually impossible to find even one plausibly comparable river to use as a control.

Given this situation, the best approach for detecting the effects of environmental flows is to identify phenomena that cannot be explained by other processes (Downes *et al.*, 2002). This approach relies on the identification of deviations from background patterns and examination of these patterns for evidence of the suspected impact. Multiple lines of evidence that support a particular conclusion are required in such an approach (Downes *et al.*, 2002). It also requires clear *a priori* expectations of the types of impacts expected from a particular environmental flow regime and therefore types of evidence that would indicate beneficial effects from the flow releases.

The aim of this study was to use this approach to identify whether environmental flows released into the Glenelg and Wimmera Rivers, in western Victoria, Australia had successfully ameliorated the negative effects of flow regulation. Evidence for this success was determined *a priori* to be: (1) macroinvertebrate assemblages in the Glenelg River in seasons with an environmental release had a greater diversity of taxa than during the pre-release season; (2) surface water quality in both rivers did not decline below acceptable standards (e.g. salinity maintained below 3‰) in seasons with an average-sized flow release, compared with seasons that had limited flow releases (drought seasons); (3) lack of strong longitudinal patterns in water quality or macroinvertebrate assemblage composition, that might result from insufficient flows reaching downstream reaches in both rivers; (4) limited change in macroinvertebrate assemblage composition among release seasons in both rivers, in particular, no loss of macroinvertebrate taxa known to be 'sensitive' to declining water quality; (5) little association between water quality and macroinvertebrate assemblage composition in seasons with an average-sized flow releases (i.e. drought seasons, where water quality or habitat loss might limit assemblage structure) in both rivers.

METHODS

Study area

The Glenelg Basin has a catchment area of about 12,660 km² and a mean annual discharge of 725,000 ML, two-thirds of which occurs from August to October (Department of Water Resources, 1989). The Wimmera Basin, despite covering 24,010 km² or 10.3% of Victoria's total area, has a mean annual discharge of 210,000 ML or only 0.9% of total State discharge. Around 90% of flow in the Wimmera River occurs during winter (Department of Water Resources, 1989). Climate in the Glenelg Basin is Mediterranean, characterized by generally warm and dry summers (10–27°C) with cool and wet winters (5–15°C). In the semi-arid Wimmera Basin, air temperatures range from 11–30°C and 4–15°C during the hotter and colder months respectively. Mean annual rainfall ranges from 550 mm in the centre of the Glenelg Basin to more than 900 mm in the Grampians Ranges in the northeast (Department of Water Resources, 1989). In the Wimmera Basin, mean annual rainfall ranges from 425–550 mm in the central Wimmera Plains, declining to 250 mm in the far north. Over 65% of the Glenelg Basin and almost 85% of the Wimmera Basin have been cleared for grazing and broad acre cropping (Department of Water Resources, 1989).

Like many other lowland rivers (Thoms and Sheldon, 2000), the Glenelg and Wimmera Rivers are highly regulated due to the storage, diversion and abstraction of water resources. Both catchments have largely been cleared of native vegetation leading to the movement of excess amounts of sediment into the river channels (Erskine, 1994; Mitchell *et al.*, 1996). Clearing has also led to increased salinity levels in both rivers, but particularly the Wimmera River, due to the intrusion of saline groundwater into river pools (Lind *et al.*, 2006). Consequently, both rivers are subject to multiple human impacts (sedimentation, salinization and loss of native vegetation) that are exacerbated by flow regulation. Therefore, the aim of releasing environmental flows over the drier summer–autumn period (October–June) was to maintain inundation of the riverbed, improve water quality and to provide habitat compensation during low flows to ameliorate the effects of sedimentation and salinization (Anderson and Morison, 1989; Mitchell *et al.*, 1996). This type of release is termed a 'sustaining environmental flow' as the intent was to sustain river condition over this dry period of the year, when environmental impacts were likely to be most severe.

Sustaining environmental flows

The release of sustaining environmental flows into the Glenelg and Wimmera Rivers occurs during the driest part of the year, generally between October and June, described in this study as a 'release season'. The term 'seasonal' thus refers to different release seasons (and not to climatic seasons) of which there were five in total. Due to ongoing drought conditions during this study, the total volume of environmental flows varied amongst the five release seasons and was exceptionally low in 1999–2000 and 2000–2001 (Figure 1a). This corresponded with low total



Figure 1. (a) Total volume of environmental flows released into the Glenelg and Wimmera Rivers during the five release seasons studied. Discharge data was obtained from the Wimmera Catchment Management Authority, and (b) Total volume of water delivered to Fulhams Bridge on the Glenelg River (Reach 2) and Kenny's Ford on the Wimmera River (Reach 1) for each of the five release seasons. Discharge data was obtained from the Victorian Water Quality Monitoring Network

discharges at the study reaches during these two seasons (Figure 1b). Comparison of environmental releases and discharge volumes (Figure 1a and b) shows that the releases accounted for the bulk of flows through the study reaches in all release seasons. Note that the release of a sustaining environmental flow is not a sudden, short-term burst of water such as those used to simulate flooding. Releases were intended to be continuous at 50 ML per day (at Reach 1—Horsham) in the Wimmera River throughout the release season and to be continuous, but declining by steps in the Glenelg River, during the first half of the release season. However, the limited quantity of water available throughout the study meant that these levels were rarely reached.

The Glenelg and Wimmera River systems differ in the location of release points (Figure 2). For the Glenelg River, direct hypolimnetic releases were made from Rocklands Reservoir. For the Wimmera River, releases are made from storage reservoirs throughout the Grampians into open channels and tributaries such as the McKenzie River. No differences in water quality between the rivers appear to arise from these differences in release methods (Lind, 2004).

The recommended flow levels at compliance points in both rivers (see Anderson and Morison, 1989; Mitchell *et al.*, 1996; Sinclair Knight Merz, 2002, 2003) were met often in 1997–1998 and 1998–1999 (Glenelg: 80% of days January–May; Wimmera: 60% of days October - May) and less than half the time in 2001–2002 (Glenelg: 46% of days; Wimmera: 34% days). During the two drought seasons, compliance was rarely achieved (Glenelg: 8–26% of days, Wimmera: 10–14% of days). In addition, Sinclair Knight Merz (2002) recommended a period of zero flow for the Wimmera River with a duration of 5–24 days. This was achieved in 1997–1998 and 1998–1999, but was vastly exceeded in the other three seasons (1999–2000: single period of 170 days; 2000–2001 two periods of 63 and 88 days; 2001–2002 single period of 66 days).

Study design and sampling

Three reaches on each river were sampled, spread across the segment of each river where discharge was influenced by the release of sustaining environmental flows (Figure 2). In the Glenelg River, flow releases (of the size of the full allocation of water) were only intended to supplement flows in the upper, intermittently flowing section of the river and were not required in the lower, perennial parts of the river. Although, during this study the amounts of water available for release were always smaller than the planned release volumes. In the Wimmera



Figure 2. Environmental flow release points in the (a) Glenelg River and (b) Wimmera River. The filled ovals on the line representing each river are the three study sites with the distance between the release points and study reaches presented as approximate river kilometres. The location and latitude and longitude coordinates for each study reach are as follows. Glenelg: R1–Balmoral 141°51′′25′E 37°14′′16′S, R2–Fulhams 141°50′′53′E 37°09′′07′S, R3–Harrow 141°35′′43′E 37°09′′59′S. Wimmera: R1–Kenny's Ford 142°06′′49′E 37°14′′16′S, R2–Lochiel 141°58′′29′E 36°24′30′S, R3–Tarranyurk 141°59′′05′E 36°11′′59′S. Note that the diagram is not to scale

River, flow releases were intended to reach the terminal lakes in this system, but the quantity of water required to overcome evaporation and other losses and reach the lakes, was never available for release.

The variable pattern of river discharge among seasons (described above) created a unique opportunity to test the effectiveness of environmental flow releases in two ways: by comparison of a pre-release reference season (1995–1996) to the environmental release seasons in the Glenelg River only, and by comparing the average-release seasons (1997–1998, 1998–1999, 2001–2002) to the limited-release seasons (1999–2000, 2000–2001) within both rivers; because during the limited-release seasons river discharge was similar to pre-release conditions. That is, although there were small environmental flow releases during the drought, the total discharge remained very low, thus effectively giving the comparison of two non-release seasons with three average volume release seasons.

Therefore, the following null hypotheses were:

- 1. Macroinvertebrate assemblage composition and water quality did not differ between the pre-release season and the environmental release seasons in the Glenelg River.
- 2. Macroinvertebrate assemblage composition did not differ among the environmental release seasons in the Glenelg and Wimmera Rivers (separately).
- 3. Water quality did not differ among the environmental release seasons in the Glenelg and Wimmera Rivers (separately).
- 4. Macroinvertebrate assemblage composition was not related to water quality in either river or in any release season.

In each of the release seasons there were three sampling times at haphazard intervals of approximately eight weeks from December–May. Macroinvertebrates were sampled from macrophyte stands in reaches using a ten minute sweep (in total) of all macrophyte stands present in each reach with a 250 μ m mesh dip net. Pre-release data from the Glenelg River was collected using the same methods and this data has previously been reported in Mitchell *et al.* (1996). After collection, macroinvertebrate samples were preserved in 70% ethanol and individuals counted and identified to the lowest practical taxonomic level. Analysis of a more intensively sampled three-season dataset confirmed that the sampling of macrophytes was sufficient to detect the effects of flow releases (Lind, 2004).

Temperature (°C), dissolved oxygen (mg1⁻¹), per cent saturation of oxygen, pH, salinity (ppt), electrical conductivity (μ s cm⁻¹ at 25°C) and turbidity (ntu) were recorded from each run habitat on each sampling occasion in all release seasons (see Lind, 2004 for details of sampling methodology). Suspended solids, total nitrogen and total phosphorus did not show any patterns (Lind, 2004) so are not presented here.

Statistical analysis

All multivariate analyses were carried out using PRIMER, version 5 (Clarke and Gorley, 2001). Macroinvertebrate species by abundance data was fourth-root transformed and a dissimilarity matrix calculated using the Bray-Curtis similarity measure. Non-metric multi-dimensional scaling (nMDS) was used to produce ordination plots. Hypothesis tests were performed on the Bray-Curtis dissimilarity matrix using one-way ANOSIM tests (each season was a different level and data from the three reaches (each sampled three times within a season) were used as the sample units). Post-hoc Pairwise comparisons were used to compare across seasons. SIMPER analyses were used to identify macroinvertebrate taxa most representative of the *a priori* sample groupings used in the ANOSIM tests by computing the average dissimilarity between all pairs of inter-group samples and breaking this down into separate contributions from each taxon (see Clark and Warwick, 1994).

Physico-chemical data was log₁₀-transformed where necessary to remove right-skewness and stabilize variance for construction of a Euclidean distance matrix. A correlation-based principal component analysis (PCA) was used to display these data in an ordination plot and to determine which variables contributed most to the variation among samples.

The physico-chemical and macroinvertebrate data were related using the BIOENV procedure which determined weighted Spearman rank correlations between the Bray-Curtis dissimilarity measure (macroinvertebrate data) and Euclidean distances (physico-chemical data). The weighted Spearman rank correlation coefficient ranges between -1 and 1, where 1 is complete agreement between the two matrices and zero is the absence of any match between

the two patterns (Clarke and Warwick, 1994). Salinity and dissolved oxygen $(mg l^{-1})$ were omitted from the PCA and BIOENV analyses as they were highly correlated with electrical conductivity and per centage saturation of dissolved oxygen respectively.

RESULTS

Comparison of the environmental flow release seasons with the reference season (1995–1996) in the Glenelg River

The reference season of 1995–96, prior to the allocation of environmental releases in the Glenelg River, was a low-flow season with a total discharge of 3948 ML and is comparable to 1999–2000 (Figure 1b). Physico-chemical conditions during the reference season did not differ from those in the five subsequent environmental release seasons (Figure 3a). In contrast, ANOSIM showed that the macroinvertebrate assemblage composition did differ in the 1995–96 reference season from all subsequent environmental release seasons (Global R = 0.395, P < 0.001) (Figure 4). There is no indication of a return towards this composition in either of the low-flow seasons in 1999–2000 or 2000–2001.

Abundances of macroinvertebrate taxa were generally lower in 1995–1996 than in the environmental release seasons (Figure 5). There were also changes in the dominant taxa: the trichopteran *Archaeophylax* sp and leptophlebiid mayflies were relatively abundant in 1995–1996 community composition, but were did not contribute highly during the environmental release seasons. BIOENV analysis for the 1995–1996 data showed that temperature and electrical conductivity were best correlated with the macroinvertebrate assemblage composition, but there was almost no match at all between the macroinvertebrate and physico-chemical matrices (Table I). During the five environmental flow release seasons a variety of physico-chemical variables were correlated with the macroinvertebrate assemblage but there was no consistent pattern from season to season (Table I). The correlations between matrices were larger during the environmental flow release seasons, but did not increase or decrease during the two drought seasons (1999–2000 and 2000–2001). Therefore, following the release of environmental flows after 1995–1996, macroinvertebrate abundances increased but diversity showed little change and assemblages were still only moderately correlated with the physico-chemical environment.

Physico-chemical conditions at different levels of environmental flow release

During the 1999–2000 and 2000–2001 release seasons, the volume of environmental flows released and consequent river discharge were lower than the other release seasons (Figure 1a and b). This low discharge was not associated with changes in the physico-chemical environment in either river with the exception of increases in electrical conductivity (Figures 3 and 6).

There was a slight electrical conductivity gradient in the Glenelg River in all seasons except during the low release season of 2000–2001 when levels were similar at all reaches (Figure 6). Importantly, electrical conductivity was markedly higher in the Glenelg River during the two low release seasons (1999–2000 and 2000–2001) and decreased to prior levels once releases increased in 2001–2002 (Figure 6). In the Wimmera River, electrical conductivity displayed a strong downstream gradient, increasing enormously at the downstream reach (Figures 3 and 6). At the upper and middle reach, there was little variation in electrical conductivity among release seasons, but at the downstream reach, they became extremely high (> 20‰) in the two low release seasons and had not returned to prior levels when flows increased in 2001–2002. Therefore, surface water quality did decline below acceptable standards (i.e. salinity maintained below 3%) during the drought seasons in the Wimmera River when flow releases were limited.

Macroinvertebrate assemblages at different levels of environmental flow releases

Significant differences were detected between the macroinvertebrate assemblage composition of the Glenelg River among seasons (Global R = 0.264, P < 0.001). The nMDS ordination of the Glenelg River samples for all five



b) Wimmera River



Figure 3. Correlation based principal components analysis (PCA) ordination plot of log transformed instantaneous temperature (°C), per cent saturation of dissolved oxygen, pH, electrical conductivity (us/cm @ 25°C) and turbidity (ntu) from each of the study sites on the a) Glenelg River and b) Wimmera River during each of the five environmental flow release seasons. The two principal components account for 64.4% and 70.2% of the variation in the physico-chemical environmental of the Glenelg and Wimmera Rivers respectively. The main physico-chemical parameters that contributed to the overall variation for the Glenelg River were; PC1 temperature +ve, per centage saturation of dissolved oxygen -ve and electrical conductivity +ve: PC2 electrical conductivity +ve and per cent saturation of dissolved oxygen +ve. The main physico-chemical parameters that contributed to the overall variation for the Wimmera River were; PC1 per cent saturation of dissolved oxygen -ve and electrical conductivity -ve: PC2 temperature +ve, electrical conductivity -ve and per cent saturation of dissolved oxygen -ve. Samples have been highlighted by their release season of origin. Samples are also presented as bubble-plots where the relative size of the bubbles represents the relative levels of per centage saturation of dissolved oxygen and electrical conductivity



Figure 4. Non metric multidimensional scaling (MDS) ordination plots generated from macroinvertebrate samples collected from the Glenelg River during the five environmental flow release seasons and the 1995–1996 reference season. Samples have been highlighted by their Season of origin. Stress = 0.16

release seasons show that macroinvertebrate assemblages in the latter two flow seasons (2000–2001, 2001–2002) were separated from the other three release seasons and were also more variable (Figure 7). Pairwise comparisons showed that macroinvertebrate assemblage composition did not differ between the 1998–1999 and 1999–2000 seasons or between the 2000–2001 and 2001–2002 seasons (Figure 8).

Significant differences were also detected in the macroinvertebrate assemblage composition of the Wimmera River among release seasons (Global R = 0.206, P < 0.001). The nMDS ordination of the Wimmera River samples for all five release seasons shows that there is less variation among seasons in the macroinvertebrate assemblage composition than for the Glenelg River (Figure 7). Pairwise comparisons indicate that adjacent release seasons did not differ except for 2000–2001 and 2001–2002 (Figure 8).

The taxonomic identity of the macroinvertebrates found in the Glenelg River remained stable over all five release seasons, with only changes in average abundances causing seasonal differences (Figure 5). During the initial low-flow season in 1999–2000, SIMPER analyses showed that there was a large increase in the average abundance of the numerically dominant taxa, especially gastropods (*Gabbia ventiginosa* and a species of hydrobiid) and the amphipod (*Austrochiltonia australis*). During the second low-flow season in 2000–2001, the average abundance of these taxa decreased, followed by little change in assemblage composition in 2001–2002.

In 1997–1998 and 1998–1999 in the Wimmera River, assemblage composition was dominated by chironomids, hemiptera (*Micronecta* sp.), crustacea (*Paratya australiensis, Austrochiltonia australis*), some trichopterans (*Notalina* sp., *Oecetis* sp., *Hellyethira* sp. and *Triplectides* sp.), zygopterans (*Ischnura heterosticta*, Coenagrionidae sp.) and microcrustacea (cladocerans and copepods) (Figure 5). With the onset of low flows in 1999–2000, abundances of chironomids and the microcrustacea increased as well as the amphipod Austrochiltonia australis in 2000–2001. Despite larger environmental flow releases, the assemblage remained dominated by chironomids, amphipods and microcrustacea in 2001–2002.

Relationship between the physico-chemical environment and macroinvertebrate assemblage

Macroinvertebrate assemblages in the Wimmera River correlated better with the physico-chemical variables than did assemblages in the Glenelg River (Table I). In particular, Wimmera River assemblages showed stronger correlations with water quality in the two low flow seasons (1999–2000 and 2000–2001) than in other seasons (Table I). In seasons with higher discharge, this association was weaker. In contrast, there was no clearly dominant



Figure 5. Average abundance (columns) and per centage contribution (line) of the top ten taxa principally responsible for contributing to the average Bray-Curtis dissimilarity between macroinvertebrate community assemblages from each of the five study seasons in the Glenelg and Wimmera Rivers and the 1995–1996 pre-environmental release season in the Glenelg River. Error bars represent standard errors. The SIMPER analyses were conducted on fourthth root, standardized macroinvertebrate data. Chir = Chironominae sp, Arch = Archaeophylax sp, Micr = Micronecta sp, Anis = Anisocentropus sp, Lept = Leptophlebidae sp, Hydr = Hydrobiidae sp, Hell = Hellyethira sp, Phys = Physa acuta, Aust = Austrochiltonia australis, Gabb = Gabbia ventiginosa, Nota = Notalina sp, Ostr = Ostracoda sp 1, Baet = Baetidae sp, Tasm = Tasmanocoenis sp, Para = Paratya australiensis, Clad = Cladocera, Oece = Oecetis sp, Cope = Copepoda, Isch = Ischnura heterosticta, Coen = Coenagrionidae sp, Cera = Ceratopogoninae larvae, Trip = Triplectides sp, Feri = Ferrissia sp, Tany = Tanypodinae sp and Lumb = Lumbriculus variegatus

Chir Clad Micr Nece Isch Hell Cope Nota Coen Coen

1999-00

Chir Cope Isch Nota Phys Feri Clad Ostr Hell

2000-01

physico-chemical variable associated with either the assemblage composition or the size of environmental release in the Glenelg River.

DISCUSSION

Comparison of the pre-environmental flow season and the five release seasons in the Glenelg River did not show evidence of increased numbers of macroinvertebrate species after allocation of environmental flows. However, the

Cope Aust Isch

Hell

1997-98

Chir Dece Micr

Isch Para Nota

1998-99

Ostr Coen Trip Cope Clad Isch

2001-02

Aust

[any

Ostr Nota Lum

Cope

	1995–1996	1997–1998	1998–1999	1999–2000	2000-2001	2001-2002
Glenelg River	Temp	pН	Temp	Temp	Temp	Temp
	EC	ÊC	DO	DO	pH	0.35
	0.06	Turb	EC	EC	ÊC	_
	_	0.41	Turb	0.35	0.29	_
	_	_	0.25	_	_	_
Wimmera River	N/A	EC	DO	pН	DO	Temp
	_	0.53	pН	ÊC	EC	pH
	_	—	0.31	0.65	0.76	ÊC
	—	—	—	—		0.39

Table I. Weighted Spearman correlation coefficients generated by the BIOENV procedure, listing those physico-chemical variables that best explain the observed macroinvertebrate community composition for the Glenelg and Wimmera Rivers

Analyses were conducted for each of the five release seasons for each river and the 1995–96 reference season in the Glenelg River. $EC = electrical \text{ conductivity } (\mu s \text{ cm}^{-1} @ 25 °C)$, Turb = turbidity (ntu), Temp = temperature (°C), DO = per cent saturation of dissolved oxygen.

macroinvertebrate assemblage in the river did change after flow allocation with increased invertebrate abundances. In addition, the species composition remained relatively stable across both drought and average release seasons, suggesting considerable resistance to drought conditions. The lack of change between 1998–1999 and the first low flow season of 1999–2000 may suggest that assemblages in the Glenelg had some capacity to buffer themselves against the onset of low flows. Furthermore, the lack of change between the second low flow season of 2000–2001 and the return to higher flows in 2001–2002 may suggest a lag time in recovery after an increase in environmental releases following a period of prolonged low flow.

The main effect of low flows was to further increase invertebrate abundances, apparently a concentration effect and consistent with effects reported elsewhere (Suren *et al.*, 2003). Water quality differed little among seasons but was not correlated to river discharge and only poorly associated with macroinvertebrate assemblage structure. River macroinvertebrates, especially those found in Mediterranean and semi-arid climates are relatively salt tolerant (Mitchell and Richards, 1992; Marshall and Bailey, 2004; Kefford *et al.*, 2005). Salinity remained below 3‰ in the Glenelg River in all five release seasons and the reference season. Furthermore, there was no longitudinal pattern among reaches in either water quality or macroinvertebrate assemblage structure (Lind *et al.*, 2006). Therefore, these lines of evidence indicate that the sustaining environmental flows released into the Glenelg River, although below recommended levels, were sufficient to prevent further degradation of water quality or macroinvertebrate assemblages. Even during the drought years, when the environmental flow comprised the majority of river discharge in the segment of river studied, no marked decline was observed. However, without the environmental flow, the Glenelg River would have ceased to flow during the two drought seasons and had this occurred, declines in water quality and macroinvertebrate assemblages would probably have been recorded.



Figure 6. Instantaneous recordings of electrical conductivity from each of the run habitats in the Glenelg and Wimmera Rivers. Columns represent mean values across all sampling occasions within each reach and release season and error bars represent ± 1 standard error. G = Glenelg, W = Wimmera, R = Run, 1 = Reach 1 (most upstream), 2 = Reach 2, 3 = Reach 3 (most downstream). Note the difference in the y-axis scale for the electrical conductivity charts between the Glenelg and Wimmera Rivers



Figure 7. Non metric multidimensional scaling (MDS) ordination plots generated from macroinvertebrate samples collected from the Glenelg River (top) and Wimmera River (bottom). Samples have been highlighted by their season of origin. Glenelg ordination Stress = 0.18, Wimmera ordination Stress = 0.15

In contrast, salinity at the most downstream reach in the Wimmera was always > 5% and during the drought seasons was > 20%. However, it remained below 3% at the upstream and middle reaches in all five release seasons. Therefore there was a strong longitudinal pattern in water quality (see also Lind *et al.*, 2006) that indicated that the environmental flow releases were insufficient to influence water quality at the most downstream reach. This pattern was strongly associated with changes in the macroinvertebrate assemblages, shown by both the BIOENV analysis and the salt-tolerant types of macroinvertebrates found at that reach (Lind *et al.*, 2006). The abundance of zooplanktonic microcrustacea such as copepods, which are tolerant of both still waters and salinity further support these conclusions. The lack of change in macroinvertebrate composition between 1998–99 and the first low flow season of 1999–2000 may suggest an ability to buffer against the onset of low flows. The differences that were detected between the low flow season of 2000–2001 and the reinstatement of higher flows in 2001–2002 may suggest a relatively rapid response to the reinstatement of higher environmental releases. Therefore, these lines of evidence indicate that the environmental flow allocations in the Wimmera River were insufficient to prevent degradation from continuing at the most downstream reach studied.



Figure 8. *R* values generated from pairwise comparisons of seasons from a one-way ANOSIM testing for differences between the five environmental flow release seasons in the a) Glenelg River and b) Wimmera River. Black bars indicate statistically significant differences (P < 0.05)

The detection of significant environmental impacts in the Wimmera River further strengthens our conclusions regarding the Glenelg River. Assessments of environmental impact are characterized by a need to minimize Type II error more than Type I error (Downes *et al.*, 2002). That is, to minimize the chance of failing to detect an impact if it really exists at the risk of false positives. This is often very difficult when the effect size expected from an impact is unknown. Detection of the impacts of environmental flows is fraught with these risks, because impacts are essentially 'negative' (i.e. no decline in river conditions) and the magnitude of impacts poorly known. The broad range of conditions in this study, enabling detection of significant degradation in the Wimmera River, ensures that

had there been similar effects in the Glenelg River, they would have been detected. These results reinforce the need for impact studies to be conducted over relevant time periods. In this case, several release seasons and a range of total discharge were needed to demonstrate that sustaining environmental flows can slow the process of degradation in lowland rivers subject to multiple disturbances.

Owing to the design used, inferences from these results are restricted to the segment of each river sampled and not the river as a whole. This is an observational study comparing patterns in macroinvertebrate assemblages to patterns in physico-chemical conditions. Therefore, it cannot definitively show a causal link between the release of environmental flows and the different patterns observed in the two rivers. However, this study does provide consistent and multiple lines of evidence (the pattern of discharge among seasons with different levels of environmental flows released, the relationships between the physico-chemical conditions and macroinvertebrate assemblages, the pattern of change in physico-chemical conditions and macroinvertebrate assemblages under different levels of releases and the taxonomic composition of the macroinvertebrates at different reaches and seasons) supporting the conclusion that sustaining environmental flows were successful in maintaining ecological condition in the Glenelg River, but less successful in the Wimmera River.

This is the first published study that provides multiple lines of evidence of sustained benefits to the in-channel physico-chemical environment and macroinvertebrate assemblages due to the release of environmental flows over several years. Some short-term studies using experimental environmental flow releases have found no lasting benefits for macroinvertebrates and benthic algae (e.g. Shannon *et al.*, 2001). Others have shown considerable benefits for floodplain-forest nesting waterbirds (Stewart and Harper, 2002) and responses by macroinvertebrates in floodplain wetlands (Hillman and Quinn, 2002). Significant alterations to river ecosystems resulting from multiple human impacts may constrain the response of macroinvertebrates to environmental flow releases (Shannon *et al.*, 2001) and furthermore, impacts such as nutrient enrichment (Suren *et al.*, 2003) and drought may exacerbate the effects of low flows (Humphries and Baldwin 2003). This study has shown that sustaining environmental flows can slow the process of degradation in lowland rivers. Sustaining environmental flows differ from releases designed to mimic flooding events (e.g. Shannon *et al.*, 2001; Hillman and Quinn, 2002; Stewart and Harper, 2002) because they do not imitate pre-regulation conditions. Rather, they are aimed at mitigating the negative effects of multiple human impacts that prevent the viability of a return to pre-regulation conditions. For rivers where a return to pre-regulation conditions is not possible, environmental flow releases may still be a useful tool for river management.

ACKNOWLEDGEMENTS

This research was funded by the Department of Natural Resources and Environment, Victoria. Peter Lind was supported by a Deakin University Postgraduate Scholarship. We would like to thank the many staff and students who helped in the field, and the proprietors of the Hindmarsh Hotel, Jeparit and The Hermitage, Harrow for providing accommodation. John Martin, Wimmera-Mallee Water and Theiss Environmental Services provided flow gauging information. Peter Fairweather, Ed Chester, Alecia Bellgrove and Ty Matthews all provided extensive and constructive comments on the analysis and presentation of the data. Gerry Quinn provided helpful comments on the manuscript.

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