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The effect of Mowamba River and Jindabyne Dam environmental flow releases on macroinvertebrate assemblages in the Snowy River 2000-2008

Snowy flow response monitoring and modelling

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Cover image: Mowamba Weir on the Mowamba River with an environmental water release.

More information

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Abstract

The construction of the Snowy Mountains Scheme (Scheme) between 1955 and 1967 for power generation and the provision of water for irrigation in the Murray and Murrumbidgee river catchments diverted approximately 96% of flow from the Snowy River downstream of Jindabyne Dam as measured at Dalgety. The first environmental flow releases to the Snowy River occurred by temporarily releasing water from the Mowamba River weir between August 2002 and January 2006. Once the Jindabyne Dam upgrades were completed, subsequent environmental flows were released from the dam post 2006 and occurred throughout the study period.

This report analyses the existing macroinvertebrate data from 2000 to 2008 to document changes in the Snowy River as a result of releases from the Mowamba River and Jindabyne Dam, in particular to determine if there is a lag effect since the previous assessment of the Environmental Flow Regime (EFR). Additionally, the document discusses the mechanisms, and potential limitations of each flow regime to produce change on aquatic macroinvertebrate assemblages of the Snowy River downstream of Jindabyne.

The median of the mean daily flows in the upland macro-reach of the Snowy River increased by 101% (from 44 to 91 Mld^{-1}) after the provision of environmental flow releases from the temporarily “turning out” the aqueduct at the Mowamba Weir. This increased by a further 10.8% (from 91 to 102 Mld^{-1}) after flows were later reintroduced from Jindabyne Dam. Flow magnitude in reference sites decreased between Mowamba River and Jindabyne Dam flow regimes, indicating that the period of Jindabyne Dam EFR was naturally the drier of the two flow regimes.

The macroinvertebrate fauna of the upper Snowy River and reference sites remained distinct throughout the study. However significant positive linear trends were identified in Bray Curtis similarity measure for both pool and riffle samples. This indicates that, although remaining distinct, Snowy River and reference site assemblages were becoming more similar over time. This change was influenced by both changes to Snowy River and reference site taxa. Decreases in reference site families: Oniscigastridae, Conoesucidae, Gripopterygidae, Leptophlebiidae, Glossosomatidae; and decreases in Snowy River taxa: Caenidae, Corbiculidae, Tricladida, and Gomphidae; were both responsible for these changes. These observed biological patterns did not provide evidence that the environmental flows were responsible for the altered Snowy River assemblage composition. The reason for this slight increase in similarity (5-10% change) between the Snowy River and reference sites could not be attributable to any specific environmental variable.

Both Mowamba River tributary and Jindabyne Dam environmental releases were limited in effecting change to macroinvertebrate assemblages. This is likely to be the result of: flows not being of sufficient magnitude to initiate physical responses in the river (i.e. peak discharge rates of the EFR were below the thresholds for sediment entrainment, pool mixing and riffle maintenance); recolonisation of fauna being impeded by barriers to invertebrate drift; and the inability of flow regimes to alter water temperatures within the Snowy River to become similar to thermal regimes of snow melt rivers of the Snowy Mountains.

The following recommendations should be considered as part of the evaluation of the Mowamba River as an option for environmental water allocations to the Snowy River:

- Evaluate the mechanisms for the lack of response, including evaluating the three main limitations to recovery identified by the Snowy Flow Response Monitoring and Modelling program.

  Barriers

  - Undertake an evaluation of the limitations of barriers on invertebrate drift and successful colonisation within the Snowy River.

Thermal regime

- Review the existing water quality data for the Mowamba, Thredbo and Snowy Rivers. In particular review the continuous water temperature data for the Snowy River.
- Undertake thermal studies to determine the thermal tolerances of the key reference river taxa that discriminate reference samples from Snowy River samples.

Habitat condition

- Undertake studies to quantify the effect of fine sediment on aquatic macroinvertebrates in both pools and riffles of the Snowy River.
- Quantify volumes of fine sediment and nutrients that could be/are currently introduced into the Snowy River from the Mowamba River tributary to determine the threat that this river could pose to sedimentation and water quality in the Snowy River.

Due to additional entitlements obtained for the Snowy River, the annual flow delivered into the future will be much greater, allowing a much higher degree of variability and flexibility with regards to the flows delivered. As a result of these factors, this report makes the following flow management recommendations:

- In order to improve the in-stream physical habitat of the river, greater priority should be given to releasing events of greater magnitude (>1,000 MLd^{-1}), duration and frequency than has occurred since environmental water releases to the Snowy River began in 2002. These releases need to be made from Jindabyne Dam as the Mowamba tributary is not large enough to provide events of the magnitude required.
- The study shows limited daily flow variability from releases from Jindabyne Dam, but this is due to low entitlements and the specific flow recommendations provided. Greater daily flow variability (particularly with regards to flows <5,000ML/day) can easily be incorporated into the Snowy River EFR using the existing infrastructure at Jindabyne Dam. Natural patterns of variability can be incorporated into the flow recommendations by using a nearby unregulated system like the Thredbo River as an analogue for the Snowy River below Jindabyne. If required, additional specific channel maintenance events like those discussed above can also be added to the flow regime if required.
- Once significant improvements in physical habitat have occurred in the Snowy River then reconsider the role of tributaries in the provision of ecosystem services such as the provision of carbon, silica, invertebrate drift and seed propagules.

In addition to the above flow management recommendations, the following recommendations should be considered as part of the evaluation of future environmental water releases to the Snowy River:

- Continued monitoring and assessment of macroinvertebrates and their response to future environmental flows provided to the Snowy River.

1. Introduction

River rehabilitation and ecological responses to environmental flow regimes of tributaries and dams

Flow essentially drives most riverine processes (Poff *et al.* 1997; Lancaster 2008; Poff and Zimmerman 2010) and its hydrologic and hydraulic flow regime influence the system directly through physical disturbance (scour and sedimentation), temperature, allochthonous input (Svendsen *et al*. 2008) and connectivity (Stanford *et al.* 1996; Svendsen *et al*. 2008). These abiotic variables effect macroinvertebrate food webs, life cycles, mortality, diversity (Poff *et al*.1997; Bunn and Arthington 2002; Yarnell *et al.* 2010), and their behavioural adaptations (Lytle 2008).

Regulation of flow has a profound impact on rivers (Poff *et al.*1997; Bunn and Arthington 2002). The understanding of how regulation has impeded or truncated natural flow regime, as well as the operations of the dam itself is essential to the adaptive management and ecological comprehension of the these systems (Stanford *et al.* 1996; Weringer and Morton 1996; Poff and Hart 2002; Poff *et al.* 2003; Yarnell *et al*. 2010;). Alterations in flow regime components such as magnitude and frequency, timing, duration, and rate of change can lead to ecological responses including the loss of sensitive species, disruption to life cycles, altered aquatic communities, modification of food web structure, concentration of aquatic organisms, loss of riffle habitat for aquatic species, and stranding of aquatic species (Poff *et al* 1997).

Rehabilitation of regulated rivers requires mimicking of flows that resemble natural flow conditions that occurred prior to the construction of dam infrastructure. In the Snowy River, the pre-regulation flow regime was characterised by a predictable spring snowmelt, constant base flows, a summer low flow and rainfall driven flood events (Morton *et al.* 2010). Although the system was a rain-snowmelt driven system, the snow melt recession is considered a primary disturbance that alters stream morphology and successional changes in riparian and aquatic habitats (Yarnell *et al.* 2010). These disturbances are thus influenced by magnitude, rate of change, and timing of the snowmelt recession (Yarnell *et al.* 2010; Morton *et al.* 2010).

Tributaries are regarded as an important component of stream rehabilitation and play a significant role in the delivery of water, sediment, organic matter, and nutrients to the main stream (Gomi *et al.* 2002). Through the creation of habitat diversity and food web alteration, tributaries can provide hot spots of stream habitat heterogeneity, productivity and aquatic macroinvertebrate diversity in the main channel upstream and downstream of the confluence (Rice *et al.* 2001 Benda *et al.* 2004; Kiffney *et al*. 2006; Rice *et al*. 2006; Svendsen *et al.* 2008; Dye 2010). Tributaries provide river connectivity to head water and network systems allowing the flow of energy, migration and dispersal of aquatic fauna (Stanford *et al.* 1996; Bunn and Arthington 2002; Gomi *et al*. 2002). Tributary connectivity may also serve to affect macroinvertebrate community patterns through changing food sources or input of coarse materials to provide a biotic structure more similar to upstream reaches (Minshall *et al.*1985).

Hot spots of aquatic macroinvertebrate diversity near tributary confluences, however, have not been observed in some Australian upland streams (Mac Nally *et al.* 2011). It has also been postulated that upland streams in southern NSW with low carrying capacity, low discharges and flow velocities than main-stems are unlikely to deposit coarse wood debris at tributary junctions (Wallis *et al.* 2009). Channel sedimentation can also occur at and downstream of tributary confluences in unregulated rivers (Petts 1984). Tributaries are thought to be a major source of fine sediment within the Snowy River below Jindabyne Dam, which have contributed to the infilling of the main channel (Erskine *et al*.1999).

Without the complete removal of impoundments, environmental flows from dams are limited in their capacity to mimic natural flow and thermal regimes (Standford *et al.* 2006; Poff and Hart 2002). Dam discharges drastically reduce delivery rates of natural allocthonous sediment and nutrient inputs, and also limit connectivity to upstream tributaries to allow dispersal and recolonisation of macroinvertebrates downstream (Gomi *et al.* 2002). However, dam discharge can be used to re-instate river hydrological heterogeneity by reintroducing variable flows (Stanford *et al.* 1996) or imitating the natural flow dynamics of a snowmelt recession (Yarnell *et al.* 2010). Environmental flows from dams can also deliver high peak flows to: induce scour, reset periphyton growth, redistribute sediments and ultimately to provide greater food, stream and habitat heterogeneity.

Environmental flows commenced in Snowy River in August 2002. These flows were provided by the Mowamba River, a tributary of the Snowy River and were delivered by the "turning out" of the aqueduct on the Mowamba Weir. The aqueduct had the capacity to divert all flows up to 523 Mld^{-1} from the Mowamba River to Jindabyne Dam (Morton *et al.* 2010) and the "turning out" allowed the Mowamba River tributary to overtop the weir and flow into the Snowy River approximately 2 kilometres below Jindabyne Dam. After the completion of the Jindabyne Dam outlet infrastructure in 2006, the Mowamba River aqueduct was reinstated and environmental water flows were subsequently released from the new outlet works at Jindabyne Dam. The new outlet works released water from the epilimnion within Jindabyne Dam, to avoid poor hypolimnetic water quality being delivered to the Snowy River.

Brooks *et al*. (2011) completed the first assessment of the influence of the environmental flow regime (EFR) on macroinvertebrates for the period 2002-2005. The EFR during this time was provided by Mowamba River tributary. The study found that the environmental flows (2002-2005) did not alter the macroinvertebrate assemblage in the Snowy River to become more similar to the reference sites.

This study incorporates the flow regime from Mowamba River tributary and subsequent flows provided by Jindabyne Dam. The objectives of this report are:

- To determine if environmental flow releases changed macroinvertebrate assemblages to become more similar to unregulated reference streams (2000-2008); and
- To assess the capacity of Mowamba River tributary and Jindabyne Dam EFR to influence changes in macroinvertebrate assemblages in the Snowy River.

2. Methods

2.1 Study Area

The Snowy River, prior to flow regulation, flowed from near the summit of Mt. Kosciuszko in the south eastern highlands of New South Wales to the southern Australian coast in Victoria. Four major water storages were constructed in the upper river as part of the Snowy Mountains Scheme (Scheme) between 1955 and 1967, the largest being Lake Eucumbene and then Lake Jindabyne. The smaller storages of Guthega Dam and Island Bend are in the reaches above Jindabyne Dam (Morton *et al*. 2010). In addition, flows from the Mowamba River catchment were diverted by aqueduct to Jindabyne Dam (Figure 1).

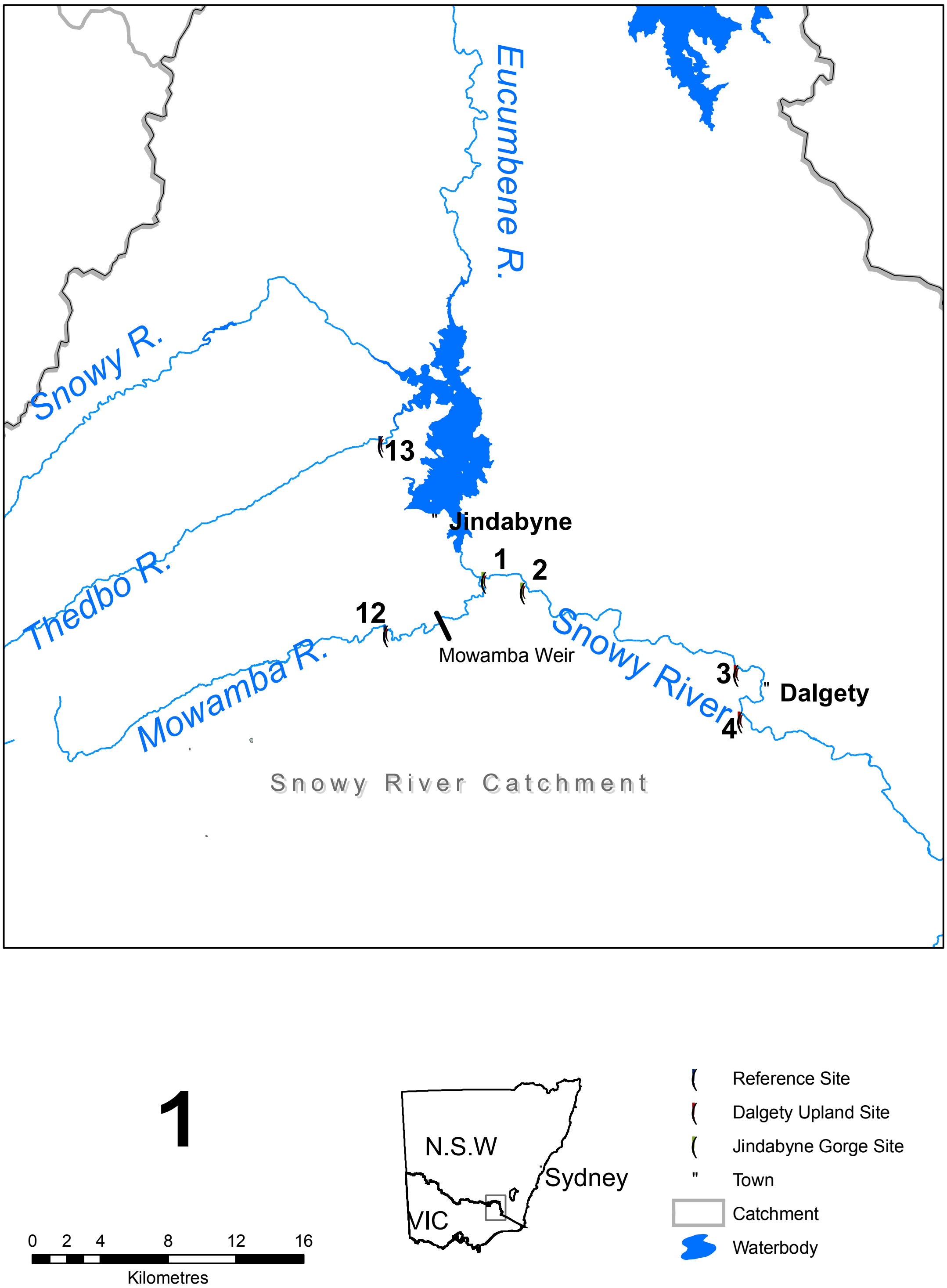
Sites were grouped into two distinct reaches based upon geomorphology, habitat and distance downstream from the release point. These reaches are Jindabyne Gorge and Dalgety Uplands (Figure 1). It was expected that macroinvertebrate assemblages of the Jindabyne Gorge and the Dalgety Uplands may respond differently to the environmental flow regimes. The magnitude of the response may also be affected by the sites proximity to flow release point. We would expect more prominent responses in sites closer to the release points of Mowamba River tributary or Jindabyne Dam.

Jindabyne Gorge runs 11.5km downstream of Jindabyne Dam. Its channel is deeply incised. Granite bedrock and boulders laterally and vertically confine the channel, producing a steep slope. The river consists of gravel riffles, rapids and cascades with boulder and bedrock steps separating long remnant pools (Eskine and Webb 2000). The gorge also supports a well vegetated riparian zone. The Mowamba River is the major tributary of this reach. The two test sites in this reach are the Snowy River downstream of the junction with the Mowamba River (Site 1) and the Snowy River upstream of Sugar Loaf Creek (Site 2).

The Dalgety Uplands is typified by a gentler bed slope. The channel consists of well-developed side, point and mid-channel bars of sand; gravel pools are relatively shallow and are floored by fine-grained sediment laminae (Erskine and Webb 2000). Pools are shallow and typically 2 to 3m in depth. The Dalgety Upland sites have relatively little riparian vegetation; are used for grazing of sheep and cattle; and stock access in this section of the river is common. The two test sites of this reach of the Snowy River are: Snowy River at Rockwell (Site 3) and the Snowy River downstream of Blackburn Creek (Site 4).

The macroinvertebrates of these groups were compared to macroinvertebrate data collected from upstream unregulated sections of Mowamba and Thredbo River reference sites. Mowamba River is unregulated from its headwaters to Mowamba weir. The monitoring site is composed of a meandering gravel bed river set within an alluvial floodplain with occasion granite bedrock outcrop. Stock has access in the middle and lower reaches of the Mowamba River, with the upper reaches located in a National Park. Thredbo River is the larger and least disturbed of the two reference sites and is predominantly located in a National Park and the flow is unregulated from the headwaters to Jindabyne Dam. The site reach has alternating floodplain pockets; the channel has a greater slope and is composed of larger cobble/boulder riffle substrate.

Figure 1 Upper Snowy River catchment showing the location of Snowy River sites (Jindabyne Gorge and Dalgety, reference sites).

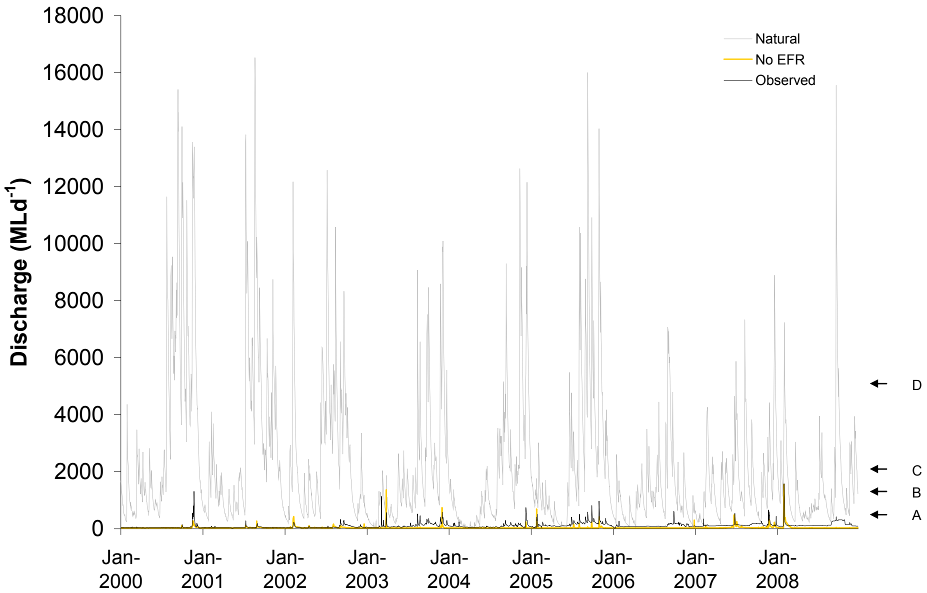


2.2 Hydrology

The construction of the Scheme and Jindabyne Dam has affected all components of the flow regime in the Snowy River below Jindabyne, with a reduction in flow variability, base flows, large spring snowmelt flows and large floods (Figure 2). Introducing increased base flow variability and flow events to scour and rearrange substratum are general protocols for restoration of regulated rivers (Standford and Ward 1996). Previous modelling suggests that in the Snowy River events greater than 1,000 Mld^{-1} (Figure 2 B) are necessary to transport fines from the bed of the river, and events of greater than ~ 2,000 Mld^{-1} (Figure 2 C) are required to scour periphyton in riffles for riffle habitat maintenance (Reinfields and Williams 2008) .

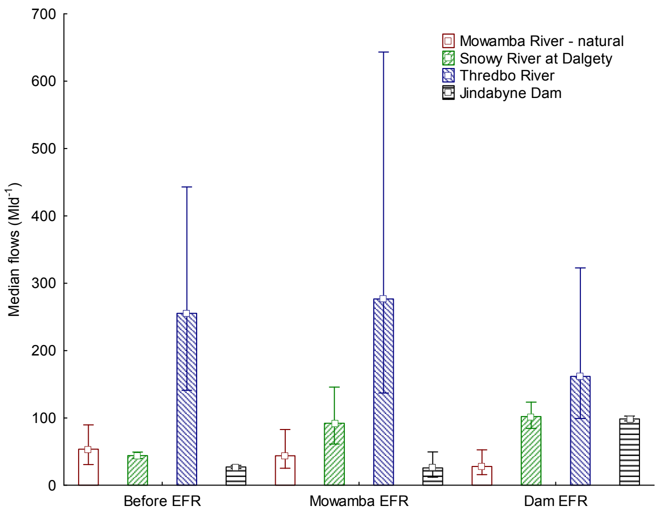
Since 2002, the river has been provided with two different environmental flow regimes. These were provided by two different release points: the Mowamba River and Jindabyne Dam. The first stage of environmental releases provided by Mowamba River tributary between 28 August 2002 and January 2006 was only capable of introducing to the Snowy River small daily flows that were previously being diverted through the Mowamba aqueduct (flows less than 523 Mld^{-1}). Releases from the Mowamba River provided a small seasonal snow melt signal in the Snowy River during September–October, a small increase in the daily magnitude of discharge (Figure 3), and the timing of the discharge was synchronised with natural events (Morton *et. al.* 2010).

Figure 2 Discharge for the Snowy River at Dalgety (i) natural, (ii) without EFR and (iii) observed, 2000-2008. A- peak diversion rate for Mowamba; B-threshold for the breakdown of thermal stratification, and movement of fine sediment; C- riffle maintenance threshold and D-maximum discharge rate from the cone valves at Jindabyne.



Median daily flow in the Snowy River increased by 101% (from 44 to 91 Mld^{-1}) following the introduction of Mowamba River EFR. This included a base flow of approximately 44 Mld^{-1} from Jindabyne Dam in addition to releases from Mowamba River. The Mowamba River median flow actually decreased 18% (from 53.3 to 43.8 Mld^{-1}) during this time. Thredbo River mean daily flow increased 7.5 % (from 255.2 Mld^{-1} to 276 Mld^{-1}) for this time period (Figure 3). The maximum daily discharge in the upper Snowy River during the EFR was approximately 1000 $Mld^{-1}$and occurred only twice during the Mowamba River flow regime measured at Dalgety.

Figure 3 Median daily discharge (percentile 25th% and 75th %) for the Mowamba, Snowy, and Thredbo rivers and releases from Jindabyne Dam (April 2001-Febuary 2008).



Jindabyne Dam has two mechanisms to deliver flow releases to the Snowy River. These are via new outlet works that have a maximum flow capacity 5,000 Mld^{-1} (Figure 2 D) and the radial gated spillway which has a theoretical maximum discharge capacity of 259,200Mld^{-1}. The flow regime from Jindabyne Dam (post January 2006) increased the median of the mean daily flow of the Snowy River 10.8% (from 91 to 102 Mld^{-1}), but provided minimal daily variation. Mowamba River tributary flows decreased 36% (from 43.8 to 27.9 Mld^{-1}) and Thredbo River median mean daily flow decreased 42% (from 276.6 to 161.75 Mld^{-1}) reflective of the drought persisting in this time period (Figure 3). Maximum daily discharge was 1,990 Mld^{-1} during the Jindabyne Dam flow regime measured at Dalgety.

2.3 Water Temperature

Snowy River median water temperatures were consistently greater than reference sites Mowamba River and Thredbo River (Coleman *et al.* in prep). Continuous water temperature data were only available from Dalgety Uplands and Mowamba River for the period of this study. The data showed that the greatest median water temperature differences between Dalgety Uplands and Mowamba River occurred in spring (approximately 4ºC). Previous temperature studies found a small significant increase in diurnal range and variability of daily fluctuations at Snowy River at Dalgety during the Mowamba EFR, however this was deemed not to be ecologically significant (Bevitt and Jones 2008). Diurnal water temperature variability was also measured to be consistently higher in the Mowamba River than in the Snowy River, which is likely to be because of the greater natural flow variability and smaller stream size of the Mowamba River (Bevitt and Jones 2008).

Coleman *et al.* (in prep) analysis of Jindabyne Gorge water quality data available from 2009-2011 found that greatest median thermal differences between Jindabyne Gorge and Mowamba River sites were greatest in autumn/winter and that the greatest differences between Dalgety Uplands and Mowamba River occurred in spring. This indicates a greater influence of air temperature at sites further distance downstream of Jindabyne Dam as they are warmed or cooled according to atmospheric temperatures depending on the time of the year. Despite differing flow regimes, there was no significant difference between water temperatures of pre flow, Mowamba River and Jindabyne Dam flow regimes (Kruskal-Wallis χ^2 = 2.61 p = 0.27 df = 2) measured at Dalgety.

2.4 Design and field sampling methods.

To test the prediction that the EFR would alter macroinvertebrate composition in the regulated Snowy River, we sampled assemblages from both riffles and pool edges at six sites throughout the upper Snowy River area using a modified BACI-type design suitable for monitoring rehabilitation projects (Downes *et al.* 2002). Four sites were sampled in the Snowy River below Jindabyne Dam and were subject to the EFR. Additional sites were sampled in other rivers and were used as reference sites for the study. Two reference sites (Sites 12 and 13) were chosen from nearby unregulated rivers to represent the target ecological condition of the Snowy River following the EFR. It is possible that the invertebrates within the reference sites were different to those in the Snowy River prior to regulation, and potentially this makes interpretation of our results difficult. However, these rivers were chosen because they were major tributaries of the Snowy River prior to regulation (contributing approximately 30% to Snowy River flow); possessed similar snowmelt hydrological regimes and large proportions of the upstream catchment were situated within Kosciusko National Park. Therefore, they were likely to contain comparable macroinvertebrate fauna to the pre-regulation Snowy River and thus were deemed suitable reference sites and a desired target condition.

All sites were sampled for macroinvertebrates twice per year (autumn and spring) from autumn 2000 to autumn 2008. Macroinvertebrates were sampled from three random points in each of two riffles and edges of two pools at each site (total number of subsamples for each habitat=6). Pool-edge samples were collected from depths of 0.2-0.5m within 2m of the bank. A suction sampler described by Brooks (1994) was placed over the substrate and operated for one minute at each sampling location. The sample was washed thoroughly over a 2-mm mesh sieve nested above a 500-µm mesh sieve. All material retained by the 2-mm sieve was placed in a large white tray and all invertebrates present were picked out on site into a jar of 70% ethanol. All material retained on the 500-µm mesh sieve was preserved in 70% ethanol for laboratory sorting.

2.5 Laboratory procedures

All macroinvertebrates (except for segmented and unsegmented worms) were identified to family level. The segmented worms were identified to class (Oligochaeta) and unsegmented worms to phylum, except for flatworms which were identified to order (Tricladida). For individual taxa with extremely high abundance (>1000 estimated during sorting), 25% sub-samples were taken using the methods described by Marchant (1989a). Typically, these abundant taxa were Oligochaeta, Chironomidae and Caenidae.

2.6 Data Analysis

At each site and within each habitat, the macroinvertebrate data from the six subsamples were averaged prior to statistical analyses, giving a representative sample for each site for each sampling occasion. This was because “site” is the appropriate spatial replicate relevant to our hypotheses (see below), and the six subsamples were taken to improve the precision of our estimates of macroinvertebrate assemblages at each site (see Downes *et al.* 2002 and Downes 2010 for the rationale behind compositing samples and appropriate choice of replicate).

Three response variables were calculated comparing each Snowy River site with both reference sites in the study. These were: the mean of the differences in family richness between the reference sites and each Snowy River site; mean of the difference in density between the reference sites and each Snowy River site; and mean assemblage similarity (Bray-Curtis similarity) between reference sites and each Snowy River site. For each variable, the comparisons between the four Snowy River sites and reference sites resulted in n=4 for each time in the analyses.

These response variables were used to test the hypothesis that: The macroinvertebrate density, family richness and assemblage composition within the riffles and pool edges of the upper Snowy River (Sites 1, 2, 3 and 4) will become more similar to those of the reference sites (Sites 12 and 13) after the commencement of the environmental flow regime.

Monitoring rehabilitation projects requires that success is defined as *no difference* between reference and impacted rivers, and poses a logical problem in testing a null hypothesis (Downes *et al.* 2002). Therefore, using response variables that represent differences between reference sites and Snowy River sites allowed us to construct logical null hypotheses of *no difference* that could be rejected if environmental flows successfully rehabilitate the river.

The hypotheses were tested using a single-factor repeated-measures analysis of variance. For the analyses of response variables relating to H_1, there were four replicates (site 1-reference, site 2-reference, site 3-reference and site 4-reference) and eleven times (five pre-EFR and twelve with-EFR sampling occasions). Site-reference represent the ‘subjects’ and the sampling occasions were the repeated measures made on each ‘subject’.

Linear trends through time were tested for all response variables. The linear trend tested whether there was a trend before environmental flows and whether a trend existed after the commencement of environmental flows. This type of trend tests for stable differences between the site groupings prior to the EFR and lagged responses in the dependent variables after the introduction of the EFR. The effect of the EFR could be reflected in both positive and negative trends in the density and family richness variables, depending on the whether the variables were predominantly greater than or less than zero prior to the EFR. In both situations, the trends should be towards zero (negative trend) if the reference and Snowy River macroinvertebrates become more similar under the EFR (i.e., no difference between reference and Snowy River sites), and away from zero (positive trend) if the macroinvertebrates of the control and Snowy River sites become more dissimilar under the EFR. Only positive linear trends in assemblage similarity (Bray-Curtis) were anticipated for (reference-Snowy River comparisons).

Transformation ($\log_{10}$) of the density-based response variables was required to ensure data normality. For the calculation of the Bray-Curtis similarity measure, densities of all families were 4^{th} root-transformed to reduce differences in scale among variables, but still retain information regarding relative abundances.

Non-metric multidimensional scaling (NMDS, Clarke 1993) was undertaken to assess the macroinvertebrate assemblage patterns. The Similarity Percentages procedure (SIMPER) was performed on each pre EFR, Mowamba EFR and Jindabyne Dam EFR flow period. This was used to identify the main taxa responsible for spatial and temporal patterns, if any, observed in the NMDS. The taxa were plotted through time to assess their contribution to any observed increases in similarity between Snowy River and reference sites. PRIMER 6 software was used for the NMDS and SIMPER procedures.

3. Results

3.1 Pool edges

3.1.1 Snowy River- Jindabyne Gorge

A total of 64 invertebrate families were found at the Jindabyne Gorge sites as similarly were the reference sites over the 17 sampling occasions. Jindabyne Gorge sites appeared to have comparative greater family richness than reference sites over the sampling period (Figure 4a). The density of the Jindabyne Gorge sites samples ranged (13-2541). Densities of Jindabyne Gorge sites were generally greater than reference sites of which reference density ranged (0-574) (Figure 4b).

There was no significant linear trend for family richness, $\log_{10}$ density or assemblage similarity before or after the implementation of the Mowamba River and Jindabyne Dam EFR's. Assemblage composition of Snowy River and reference sites became slightly more similar through time (4.5% change in similarity) to reference sites (Figure 5a, b). But this linear trend was not significant (Table 1).

Table 1. Pool edge repeated measures results of difference in mean family richness, mean $\log_{10}$ density and Bray-Curtis similarity measure for Snowy River at Jindabyne Gorge before and after commencement of EFR's.

			Autumn 2000-Autumn 2002		Spring 2002-Autumn2008	
	Source of variation	**d.f.**	**MS**	**F**	**MS**	**F**
Richness	**Linear Trend**	**1**	22.50	5.40	4.20	0.51
	Error	**3**	4.17		8.13	
Density	**Linear Trend**	**1**	0.02	0.345	<0.01	<0.01
	Error	**3**	0.05		0.08	
Similarity	**Linear Trend**	**1**	8.78	3.46	458.50	7.80
	Error	**3**	2.54		58.82	

P*<0.05, **<0.01

3.1.2 Snowy River- Dalgety Uplands

A total of 62 invertebrate families were found at the Dalgety Uplands sites over the 17 sampling occasions compared to 64 families found in the reference sites. The Dalgety Uplands sites typically had less taxa than the reference sites (Figure 4a). The number of individuals in the Dalgety Upland sites ranged (46 – 2795) per $0.07m^2$ and densities were consistently greater than reference sites (Figure 4b) which had a smaller range (0-574) in site density.

The repeated measures ANOVA results indicate no linear trend before or after EFR's for both family richness and density variables (Table 2). No linear trend was evident for assemblage similarity before EFR however a significant positive linear trend was detected after (Table 2). Dalgety Upland sites became slightly more similar (5.6% change in similarity) through time to reference sites (Figure 5a,c).

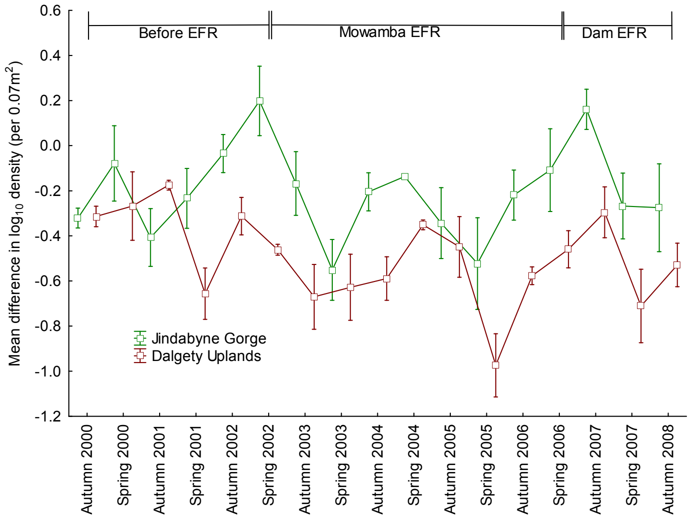
Table 2. Pool edge repeated measures results of difference in mean family richness, mean $\log_{10}$ density and Bray-Curtis similarity measure for Snowy River at Dalgety Uplands before and after commencement of EFR's.

			Autumn 2000-Autumn 2002		Spring 2002-Autumn2008	
	Source of variation	**d.f.**	**MS**	**F**	**MS**	**F**
Richness	**Linear Trend**	**1**	1.60	0.19	17.13	1.56
	Error	**3**	8.67		10.10	
Density	**Linear Trend**	**1**	0.14	2.95	0.03	0.27
	Error	**3**	0.05		0.10	
Similarity	**Linear Trend**	**1**	15.04	0.67	244.92	**29.80***
	Error	**3**	22.55		8.22	

P*<0.05, **<0.01

Figure 4 Pool macroinvertebrate difference between Snowy River and reference sites before EFR, and with Mowamba EFR and Jindabyne Dam EFR. a) Mean family richness. b) Mean $\log_{10}$ density (error bars ± 1 S.E.).

a)



b)

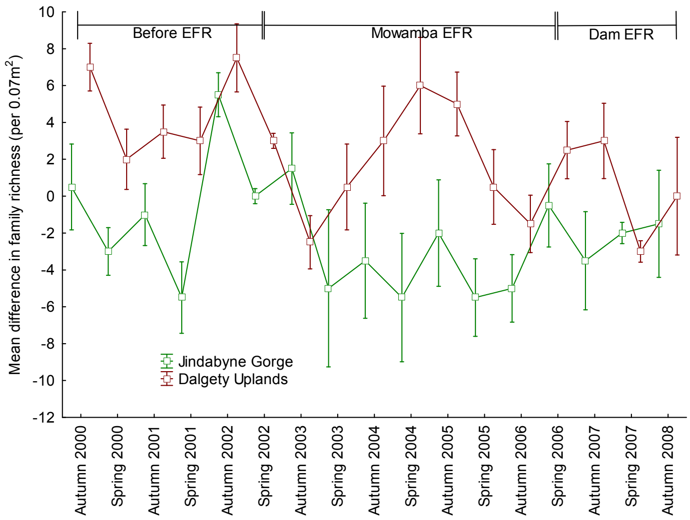
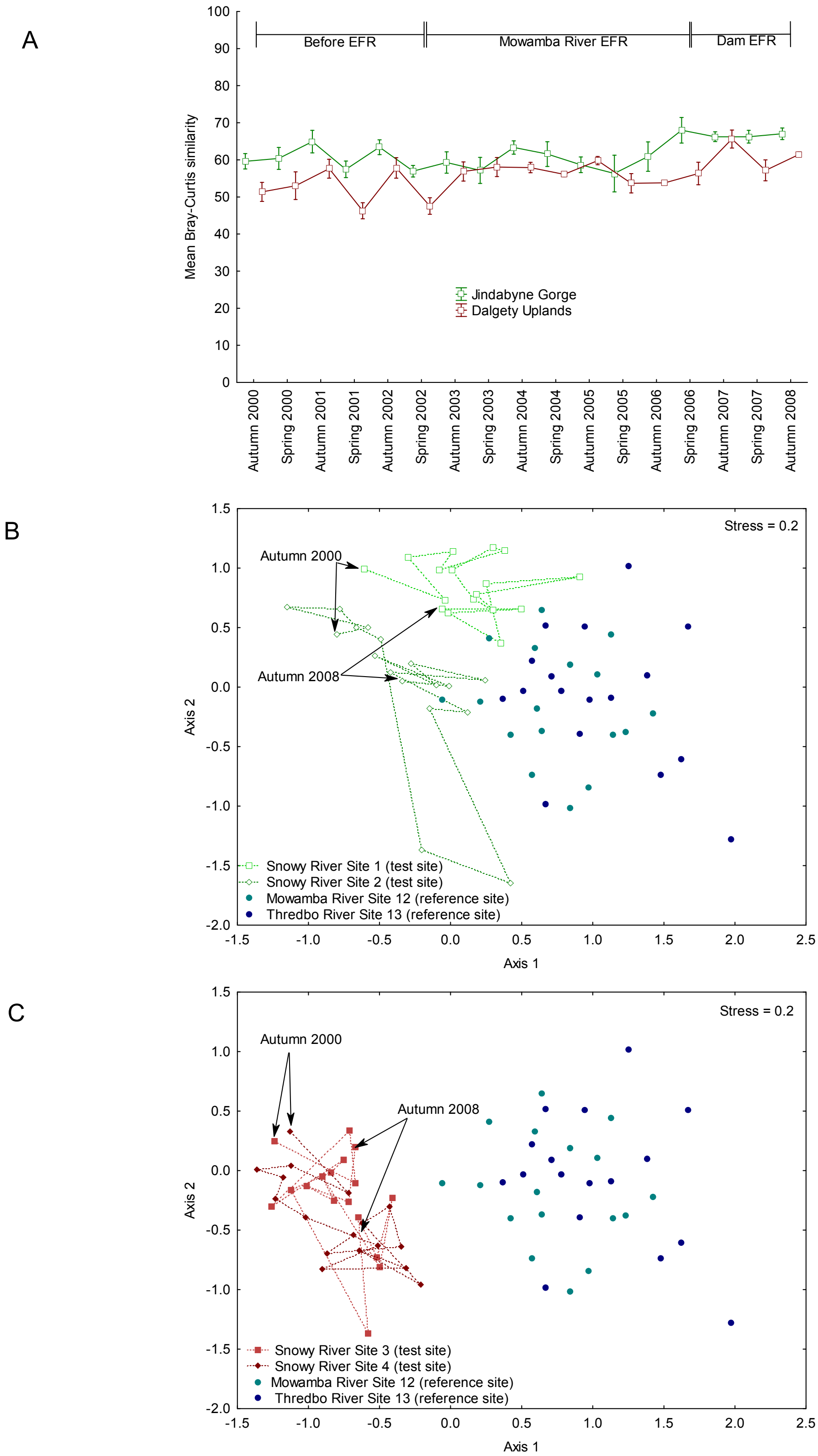


Figure 5 **Macroinvertebrate assemblage composition in pool edges (Bray-Curtis similarity) from autumn 2000- autumn 2008. a) mean assemblage similarity between Snowy River sites and reference sites (error bars ± 1 S.E.) b) nMDS ordination of Snowy River Jindabyne Gorge sites and reference sites and c) nMDS ordination of Snowy River Dalgety Uplands sites and reference sites. Lines denote trajectory of Snowy River sites through time.**



3.1.3 Family contributions to pool edge dissimilarity through time

The taxa that distinguished the Snowy River (Jindabyne Gorge and Dalgety Uplands sites) from reference sites were the families Baetidae, Gripopterygidae, Oniscigastridae, Gomphidae and Class Oligochaeta and suborder Tricladida (Figure 6). In general Baetidae, Gripopterygidae, and Oniscigastridae had greater densities in reference sites compared to Snowy River sites. Gomphidae, Oligochaeta and Tricladida had greater densities in Snowy River sites.

Declines in Snowy River family density were observed in Tricladida, (Jindabyne Gorge and Dalgety Uplands) Gomphidae (Dalgety Uplands only) and Gripopterygidae (Jindabyne Gorge only). In reference sites the families Gripopterygidae and Oniscigastridae declined in density. The only family to increase markedly over time was Baetidae, which increased in reference sites and to lesser degree Jindabyne Gorge sites. The class Oligochaeta showed no obvious trends through time. Changes to biotic similarity were the result of the densities of Gripopterygidae and Oniscigastridae in reference sites declining to levels found in the Snowy River sites. Reduction in Tricladida density in the Snowy River to become more like the densities of reference sites also contributed to the changes in biotic similarity. Changes to similarity are not the result of the introduction of new families or the increases in density of previously impaired taxa such as Gripopterygidae and Oniscigastridae in the Snowy River.

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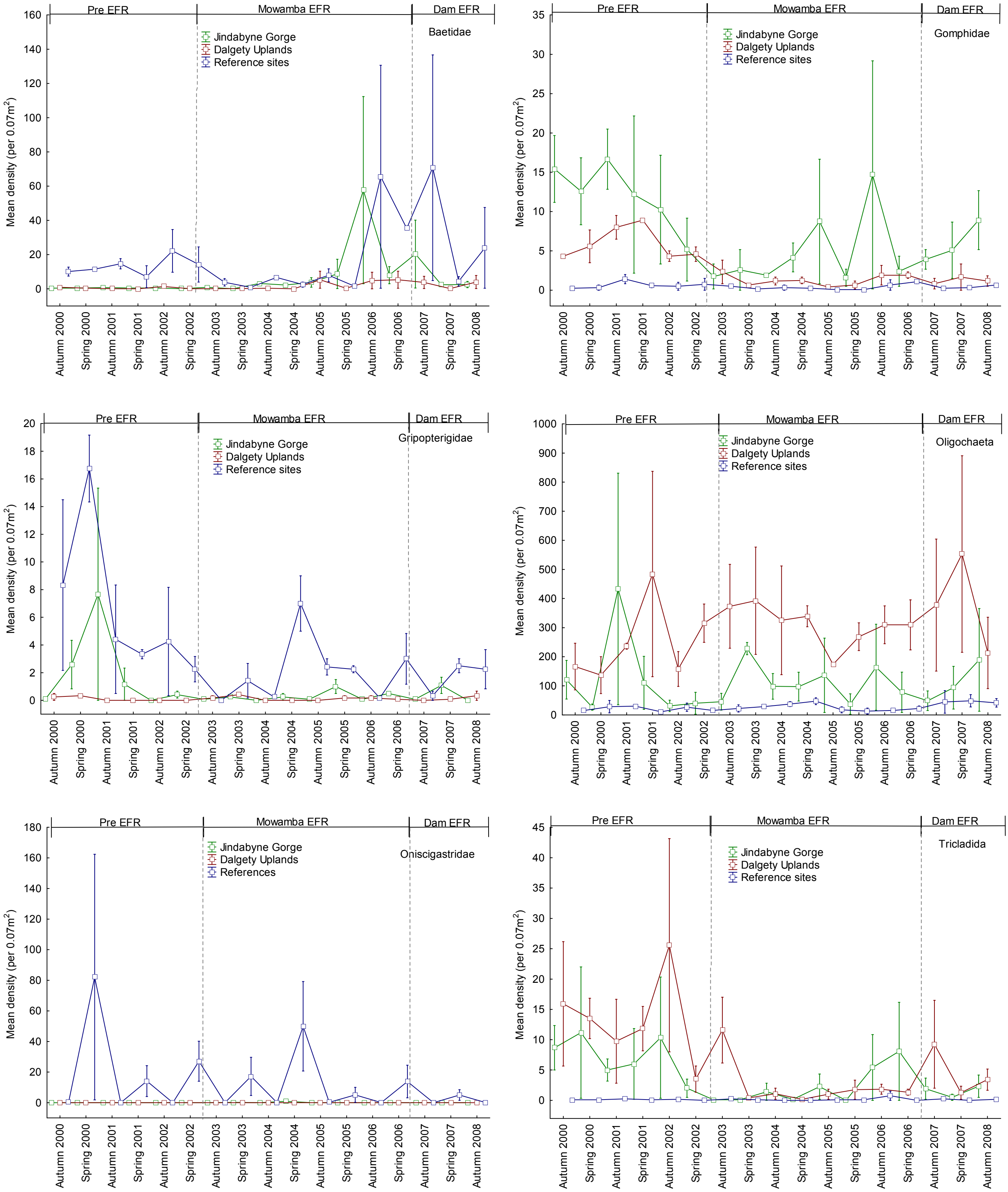
Figure 6. Mean density of pool edge macroinvertebrate families that contributed most to pre EFR differences between Snowy River (Jindabyne Gorge), Snowy River (Dalgety Uplands) and reference sites from autumn 2000 to autumn 2008 (error bars ± 1 S.E.).



3.2 Riffles

3.2.1 Snowy River- Jindabyne Gorge

A total of 56 invertebrate families were collected in the Snowy River (Jindabyne Gorge) riffles compared with 58 families in the reference sites. The range of gorge riffle densities were (0 -1436). The reference sites density ranged from (3-965).

The repeated measures ANOVA showed no linear trend before or after the EFR's for family richness and log_{10} density (Table 3; Figure 7). A significant linear trend was not evident for similarity before EFR's however there was a positive significant trend after (Table 3; Figure 8a). Snowy River - Jindabyne Gorge test sites became slightly more similar (12% change in similarity) to reference sites through time (Figure 8 a, b).

Table 3. Riffle repeated measures results of difference in mean family richness, mean log_{10} density and Bray-Curtis similarity measure for Snowy River at Jindabyne Gorge before and after commencement of EFR's.

			Autumn 2000-Autumn 2002		Spring 2002-Autumn2008	
	Source of variation	**d.f.**	**MS**	**F**	**MS**	**F**
Richness	**Linear Trend**	**1**	0.40	<0.01	6.61	0.21
	Error	**3**	43.80		31.28	
Density	**Linear Trend**	**1**	0.01	0.11	<0.01	<0.01
	Error	**3**	0.09		0.09	
Similarity	**Linear Trend**	**1**	163.42	2.11	1249.66	**2268.55****
	Error	**3**	77.44		0.55	

P*<0.05, **<0.01

3.2.2 Snowy River- Dalgety Uplands

A total of 53 families were found in Snowy River (Dalgety Uplands) riffles compared to a total of 58 families in the reference sites. The individual number of invertebrates ranged (10-2557) for the Snowy River and (3-965) for reference sites.

There was no significant linear trend for difference between Snowy River and reference site mean family richness before or after the introduction of the EFR's. There was a significant positive linear trend in invertebrate density observed after the implementation of the EFR's (Table 4; Figure 7). Assemblage similarity between Snowy River and reference sites showed a negative linear trend prior to environmental flows and a positive linear trend after (Table 4; Figure 8a). Snowy River (Dalgety Upland) sites became slightly more similar (11% change in similarity) to reference sites over time (Figure 8a, c).

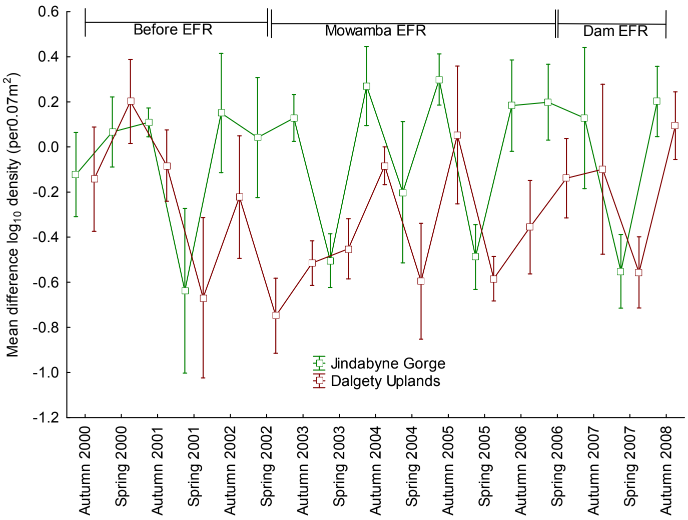
Table 4 Riffle repeated measures results of difference in mean family richness, mean $\log_{10}$ density and Bray-Curtis similarity measure for Snowy River at Jindabyne Gorge before and after commencement of EFR's.

			Autumn 2000-Autumn 2002		Spring 2002-Autumn2008	
	Source of variation	**d.f.**	**MS**	**F**	**MS**	**F**
Richness	**Linear Trend**	**1**	24.03	0.22	728.44	1.35
	Error	**3**	109.63		539.22	
Density	**Linear Trend**	**1**	0.42	5.37	0.87	**20.64***
	Error	**3**	0.08		0.04	
Similarity	**Linear Trend**	**1**	659.79	**21.76***	1027.80	**130.23****
	Error	**3**	30.32		7.89	

P*<0.05, **<0.01

Figure 7. Riffle macroinvertebrates difference between Snowy River and reference sites before EFR, and with Mowamba EFR and Jindabyne Dam EFR. A) Mean family richness. B) Mean log_{10} density (error bars ± 1 S.E.).

A



B

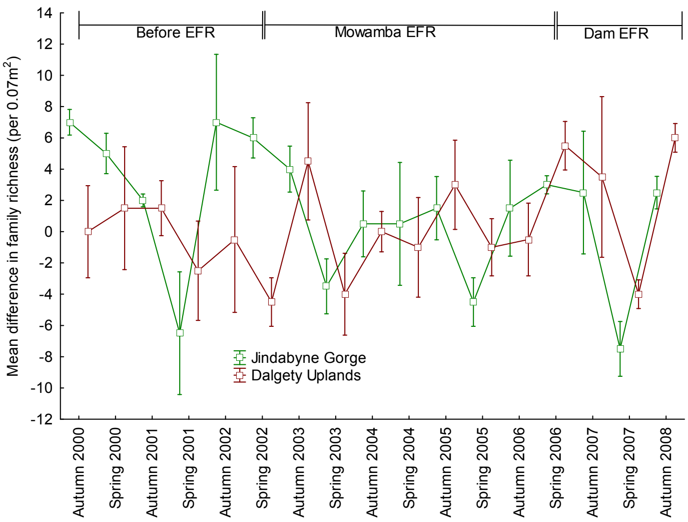
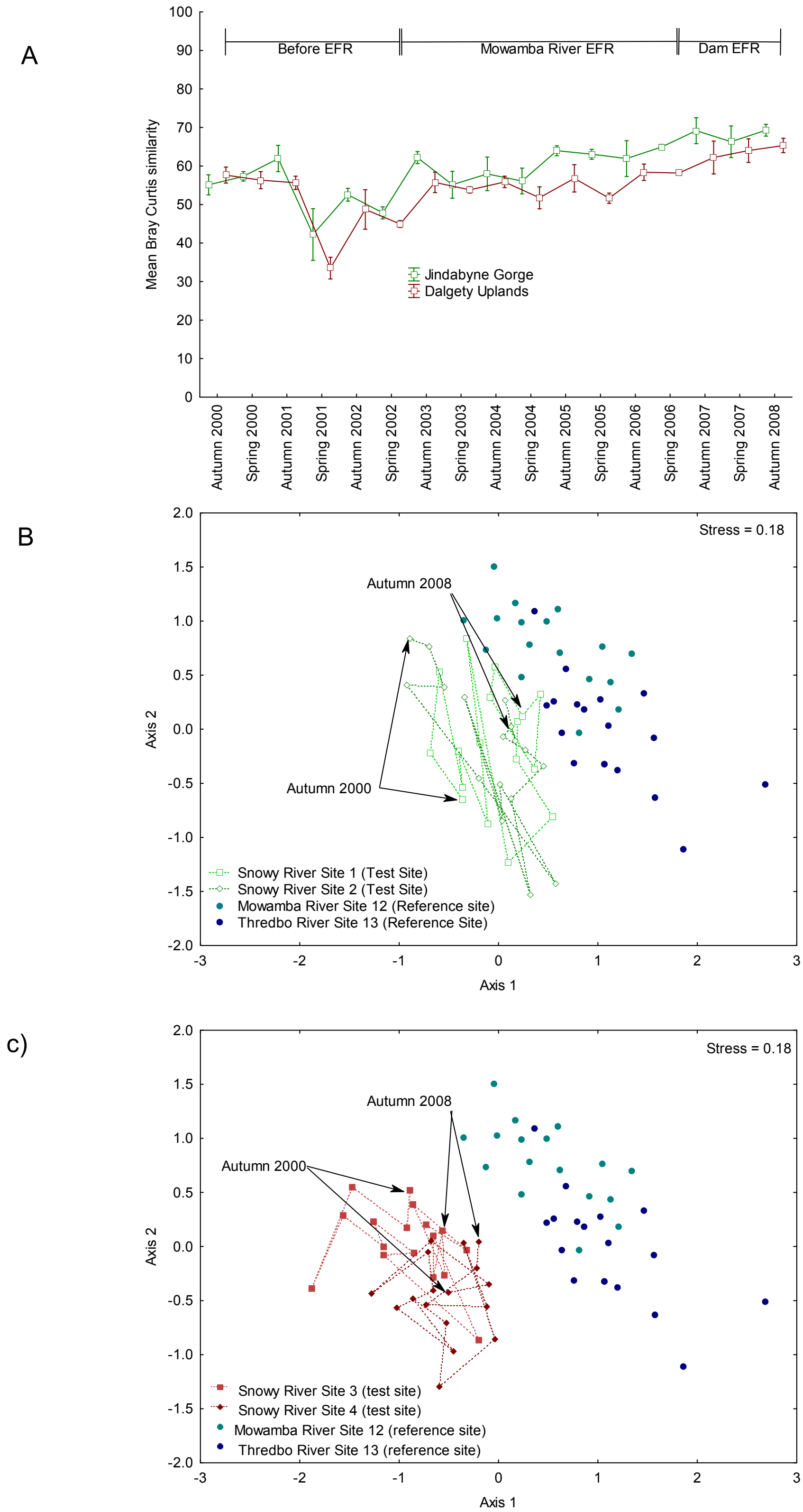


Figure 8. Macroinvertebrate assemblage composition in riffles (Bray-Curtis similarity) from autumn 2000- autumn 2008. A) mean assemblage similarity between Snowy River sites and reference sites (error bars ± 1 S.E.), B) nMDS ordination of Snowy River Jindabyne Gorge sites and reference sites and C) nMDS ordination of Snowy River Dalgety Uplands sites and reference sites. Lines denote trajectory of Snowy River sites through time.



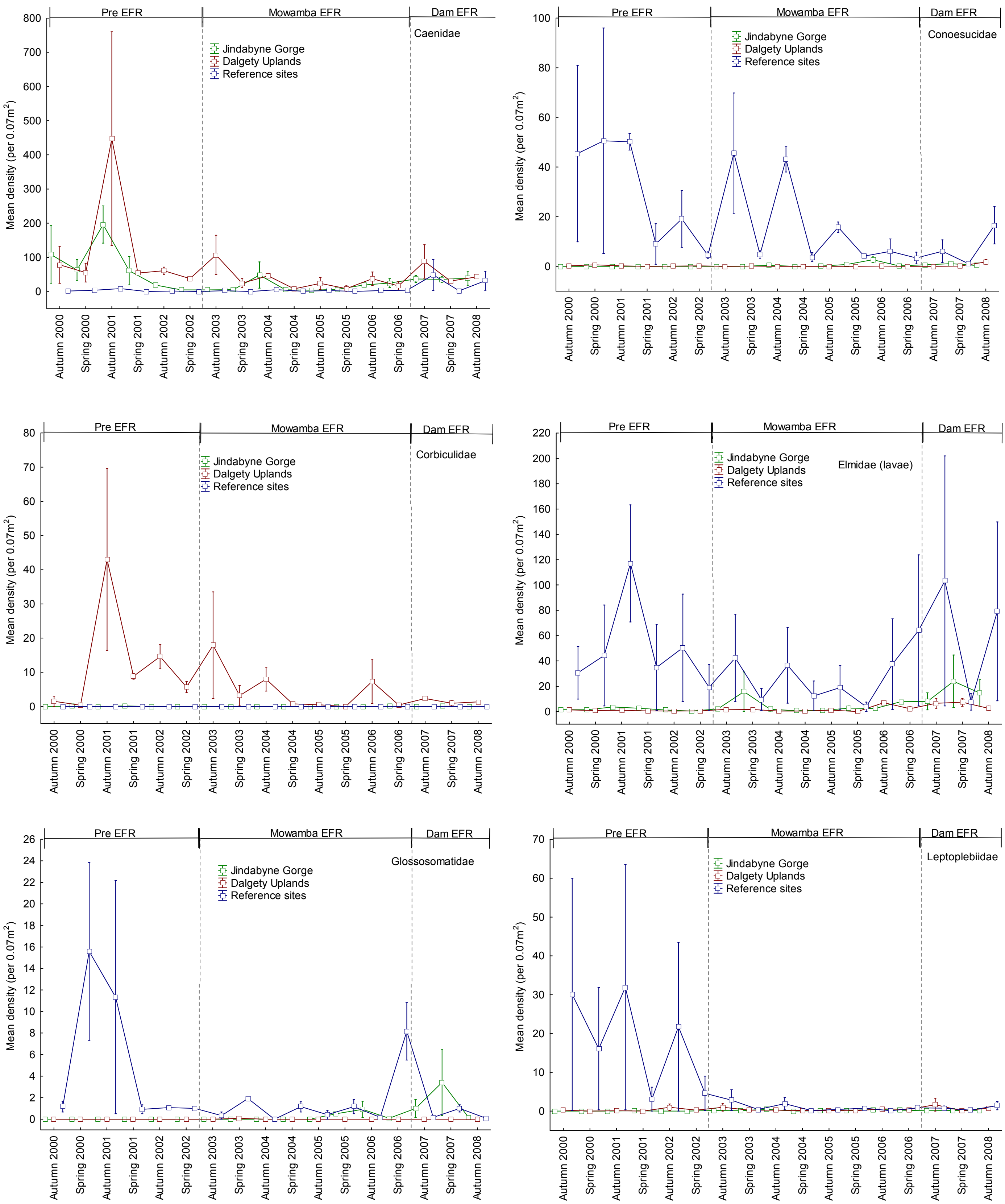
3.2.3 Family contributions to riffle dissimilarity through time

The taxa that distinguished Snowy River (Jindabyne Gorge and Dalgety Uplands) and reference site riffles before the EFR's were the families Caenidae, Conoesucidae, Corbiculidae, Elmidae (larvae), Glossosomatidae, and Leptophlebiidae (Figure 9). Conoesucidae, Elmidae (larvae), Glossosomatidae and Leptophlebiidae had greater densities in reference sites than Snowy River sites. Caenidae and Corbiculidae had greater densities in Snowy River sites than reference sites.

Temporal declines in Snowy River family density were observed for Caenidae (Jindabyne Gorge and Dalgety Uplands) and Corbiculidae (Dalgety Uplands only). In reference sites Leptophlebiidae, Conoesucidae, and to a less extent Glossosomatidae declined in family density. Elmidae (larvae) showed no obvious trends through time in either reference or Snowy River sites.

It appears that declines in individual family densities are responsible for Snowy River and reference site becoming more similar. Changes to similarity measure are likely the result of both reductions in reference sites (Conoesucidae and Leptophlebiidae) and Snowy River sites (Caenidae and Corbiculidae). Changes to similarity are not the result of the introduction of new families or the increase in density through time of specific taxa.

Figure 9. Mean density of riffle macroinvertebrate families that contributed most to pre EFR differences between Snowy River (Jindabyne Gorge), Snowy River (Dalgety Uplands) and reference sites from autumn 2000 to autumn 2008 (error bars ± 1 S.E.).



4. Discussion

Pool edge and riffle macroinvertebrate assemblages became more similar to unregulated reference sites over the study period. The biotic similarity of reference and Snowy River pool assemblages increased by approximately 5% and riffle assemblages increased by 10% after the introduction of both Mowamba River and Jindabyne Dam environmental flow regimes. The increases in similarity between Jindabyne Gorge riffle and Dalgety Upland pool and riffle to reference assemblages showed significant positive linear trends. These slight changes to macroinvertebrate assemblages did not appear to be caused by environmental flows from the Mowamba River or Jindabyne Dam. This is because the increases in assemblage similarity between reference and Snowy River were equally attributable to declines in densities of some taxa in unregulated reference sites (Oniscigastridae, Conoesucidae, Gripopterygidae, Leptophlebiidae, Glossosomatidae) and to taxa declines in Snowy River sites (Caenidae, Corbiculidae, Tricladida, and Gomphidae).

We acknowledged that stream recovery may be small; and that the period of time within the study may not be adequate to distinguish improvements or changes to macroinvertebrate assemblages from environmental flows. However, regardless of effect size, and/or a lagged recovery at least half of the changes were driven by declines in reference site taxa; and there were essentially no major alterations to riverine processes as a result of the environmental flows. Hence, despite Snowy River and reference sites becoming slightly more similar we conclude environmental flows caused no change to invertebrate assemblages. We suggest that the lack of change was caused by a number of constraints on recovery: existing barriers to invertebrate dispersal, altered thermal regime and the effect of fine sediment on habitat condition. Below we discuss these possible limitations to the recovery of macroinvertebrate assemblages during the Mowamba River and Jindabyne Dam environmental flow regimes.

4.1 Limits to river recovery

Barriers to dispersal

The Snowy River is disconnected to most of its upstream catchment by Jindabyne Dam and also by Mowamba weir on the Mowamba River, the first major downstream tributary of the Snowy River below Jindabyne Dam. This discontinuity could have limited potential invertebrate dispersal to the Snowy River from the Snowy River above Jindabyne Dam and from Mowamba River during the study.

During the Jindabyne Dam environmental flow regime, colonisation through drift would only be possible by small base flows passed through the Mowamba weir (approximately 3 Mld^{-1}) or through high flow events in the Mowamba River overtopping the weir (flows >523 Mld^{-1}). The next unregulated tributary, Wullwye Creek, is non-snowmelt, intermittent and flows into the Snowy River approximately 22 km downstream of Jindabyne Dam. The next major perennial tributary (non rain shadow affected) is the Delegate River approximately 65km downstream of Jindabyne Dam.

Tributaries allow connectivity and are important in stream rehabilitation by providing some of their natural dynamic character to the main channel (Stanford *et al*. 1996; Poff *et al.*1997) and assist in the dispersal of aquatic organisms (Stanford *et al.* 1996; Gomi *et al*. 2002; Bunn and Arthington 2002). Macroinvertebrate drift is considered the principal mechanism to colonisation and potential recovery from disturbance (Death 2008). The Mowamba River tributary provides connectivity to headwater streams and has the potential to foster macroinvertebrate biodiversity within the catchment through downstream recruitment processes. It is reasonable to assume that dispersal of macroinvertebrates from Mowamba River into the Snowy River was likely to occur over the four year flow regime provided by the “turning out” of Mowamba weir (*sensu* Katano *et al.* 2009). However, significant colonisation of reference stream families did not occur in the Snowy River. Brooks *et al.* (2011) considered Mowamba River a key dispersal pathway for families Elmidae, Conoesucidae (riffles) Oniscigastridae (pools) into the Snowy River via downstream drift. Mowamba weir may have remained a barrier to macroinvertebrate drift and impeded passage by drifting organisms despite the weir overtopping (Marchant 1989; Marchant and Hehir 2002; Brooks *et al*. 2011).

It has been argued that full macroinvertebrate recovery in regulated rivers may not occur unless major dispersal barriers are removed (Marchant and Hehir 2002). Other management options include modifying or partially decommissioning Mowamba Weir during key seasons/times of day, or when flows permit passive transport through the weir. Jindabyne Dam cannot be managed to overcome its barrier effect to macroinvertebrate dispersal due to its sheer size and infrastructure constraints.

Thermal Regime

The Mowamba River and Jindabyne Dam environmental flow regimes were unable to regulate warmer water temperatures in the Snowy River to become more similar to the cooler snow-melt reference streams. This may have limited the ability of the flow regimes to alter invertebrate assemblages by decreasing the densities of thermally tolerant families and increasing the densities of stenophiles.

The median water temperature of the Snowy River was generally warmer (3-5 C°) than reference streams depending on time of the year and there was no significant difference in median water temperatures between each flow regime measured at Dalgety. This is unsurprising as the Mowamba release consisted of relatively small volumes (median 43.8 Mld^{-1}) and was combined with Jindabyne Dam base flow releases (median 44 Mld^{-1}). Jindabyne Dam releases were warmer than Mowamba River releases as they were extracted from surface waters from above the thermocline within the dam. The surface water is warm and stable due to the large thermal mass of Jindabyne Dam and subsequent environmental releases into the Snowy River are likely to have diluted any thermal contributions from Mowamba River.

The thermal regime of regulated rivers is considered to be just as important as flow in the rehabilitation of aquatic invertebrate communities (Lessard and Hayes 2002; Haidekker A. 2004; Jackson *et al.* 2007; Rader *et al.* 2008). Studies in the regulated upper Colorado River found that flow impaired reaches with a partially restored natural thermal regime exhibited similar diversity and assemblages to unregulated reference sites and showed recovery in richness and abundance of stone flies, caddis flies and aquatic beetles (Rader and Ward 1988; Rader *et al.* 2008). The site also showed a long term increase in diversity post-flood events, whilst regulated sites with no thermal restoration returned to pre-flood assemblages. Even with a significant flood event, recovery of macroinvertebrate families such as Gripopterygidae, Conoesucidae, Glossosomatidae, and Elmidae families in the Snowy River may not take place because of continued thermal impairment. Brooks *et al.* (2011) suggested that the poor representation of Oniscigastridae could also be related to the warmer water temperatures in the Snowy River.

Habitat Condition

Rivers downstream of dams that divert large proportions of flow generally have increased levels of deposited fine sediment and reduced hydraulic diversity (Baker *et al.* 2011). These alterations to river function can have adverse affects on benthic macroinvertebrate assemblages (Angradi 1999). Fine sediment contributions may affect river recovery through decreasing habitat heterogeneity; impacting upon primary productivity; and decreasing faunal diversity (Woods and Armitage 1997). In the upper Snowy River, sedimentation by a combination of bed and bank deposition with bioclastic material has reduced the amount of available aquatic habitat, caused channel contraction and pool infilling (Erskine *et al.* 1999; Rose 2011). Existing sediment from the construction of Jindabyne Dam, local catchment runoff, and sediment input from tributaries are likely sources of fine sediment in the Snowy River. This is likely to be exacerbated by the 2002-2003 bushfire (Russell *et al.* 2008; Rose 2011) and agricultural landuse.

Reduced flow in the main-stem of regulated rivers may not be able to adequately distribute these sediment contributions resulting in bed aggradations, and thus exacerbate the effect of impoundments (Petts 1984; Erskine *et al*. 1999; Svendsen *et al.* 2008).

Families that favour silty environments were still prevalent in Snowy River and differentiated assemblages from the reference sites, Mowamba River and Thredbo River. Caenidae, Chironimidae and Oligochaeta that characterise the Snowy River were thought to be associated with sedimentation and excessive periphytic growth and related to river regulation by Jindabyne Dam (Brooks *et al.* 2011). In the Snowy River the taxa Oligochaeta (pools) remained numerically higher in density to reference sites after both Mowamba and Jindabyne Dam flow regimes. The contribution of Chironimidae to dissimilarity was not as clear as those found in previous studies (Brooks *et al.* 2011), however higher densities were consistently observed in the in Snowy River compared to reference sites in each of the flow regime periods. The reduction in Caenidae density is thought to be unrelated to minor increases in river discharge as the flows were not sufficient to adequately redistribute fine or coarse sediment in the Snowy River.

Events greater than ~ 1,000 Mld^{-1} are necessary to transport fines from the bed of the river, and events of ~ 2,000 Mld^{-1} are required to scour periphyton from the riffles in the Snowy River (Reinfelds and Williams *et al.* 2008; Williams *et al.* 2010). The Mowamba River EFR peak flows briefly exceeded 1000 Mld^{-1} only on two occasions. Jindabyne Dam flow releases were greater in magnitude than the flows released from Mowamba River, achieving peak flow rates of 1,990 Mld^{-1}. While these flows have surpassed the modelled sediment entrainment of 1000 Mld^{-1}, it appears this was not sufficient to cause flow induced changes to macroinvertebrate assemblages. Flows of 2000-3000 Mld^{-1} magnitude will be required to cause sufficient sheer stress to scour and rework substrate particularly in riffle environments to alter habitat, food sources, and ultimately alter macroinvertebrate assemblages.

5. Conclusion

Macroinvertebrate assemblages of the Snowy River below Jindabyne Dam became slightly more similar to assemblages occurring in nearby unregulated rivers after the flow releases provided by Jindabyne Dam and Mowamba River. However, these changes were unrelated to the EFRs. The flow regimes were reasoned not to have influenced macroinvertebrate assemblages because of a number of local and landscape factors limiting the recovery of affected fauna. These factors were: barriers to dispersal, habitat condition, and thermal regime.

Colonisation of invertebrates from the Mowamba River into the Snowy River was likely to be inhibited by the dispersal barrier of Mowamba weir. Invertebrate colonists were also restricted by the unchanged environmental conditions (sedimentation and temperature), suppressing new colonists or the recovery of extant invertebrate populations.

High levels of fine sediments and biogenic material were likely to favour the macroinvertebrates strongly associated with regulation (taxa in high densities in the Snowy River compared with reference sites) and remained a major local environmental constraint on recovery. The EFRs did not appear to improve the high levels of fine sediments and invertebrates detrimentally affected by regulation remained impaired due to the unchanged silt laden habitats. The elevated temperature regime of the Snowy River remained unchanged with the introduction of the EFRs and is likely to have contributed to a subdued faunal recovery.

Significant changes to the EFR which incorporate increases in base flows and the frequency, magnitude and duration of high flow events should alleviate the local environmental limits to recovery in the Snowy River. However, rehabilitation of the aquatic biota in the upper Snowy River requires the potential dispersal constraints within the Mowamba River to also be addressed.

6. Recommendations

The following recommendations should be considered as part of the evaluation of the Mowamba River as an option for environmental water allocations to the Snowy River:

- Evaluate the mechanisms for the lack of response, including evaluating the three main limitations to recovery identified by the Snowy Flow Response Monitoring and Modelling program.

  Barriers

  - Undertake an evaluation of the limitations of barriers on invertebrate drift and successful colonisation within the Snowy River.

  Thermal regime

  - Review the existing water quality data for the Mowamba, Thredbo and Snowy Rivers. In particular review the continuous water temperature data for the Snowy River.
  - Undertake thermal studies to determine the thermal tolerances of the key reference river taxa that discriminate reference samples from Snowy River samples.

  Habitat condition

  - Undertake studies to quantify the effect of fine sediment on aquatic macroinvertebrates in both pools and riffles of the Snowy River.
  - Quantify volumes of fine sediment and nutrients that could be/are currently introduced into the Snowy River from the Mowamba River tributary to determine the threat that this river could pose to sedimentation and water quality in the Snowy River.

Due to additional entitlements obtained for the Snowy River, the annual flow delivered into the future will be much greater, allowing a much greater degree of variability and flexibility with regards to the flows delivered. As a result of these factors, this report makes the following flow management recommendations:

- In order to improve the in-stream physical habitat of the river, greater priority should be given to releasing events of greater magnitude (>1,000 MLd^{-1}), duration and frequency than has occurred since environmental water releases to the Snowy River began in 2002. These releases need to be made from Jindabyne Dam as the Mowamba tributary is not large enough to provide events of the magnitude required.
- The study shows limited daily flow variability from releases from Jindabyne Dam, but this is due to low entitlements and the specific flow recommendations provided. Greater daily flow variability (particularly with regards to flows <5,000ML/day) can easily be incorporated into the Snowy River EFR using the existing infrastructure at Jindabyne Dam. Natural patterns of variability can be incorporated into the flow recommendations by using a nearby unregulated system like the Thredbo River as an analogue for the Snowy River below Jindabyne. If required, additional specific channel maintenance events like those discussed above can also be added to the flow regime if required.
- Once significant improvements in physical habitat have occurred in the Snowy River then reconsider the role of tributaries in the provision of ecosystem services such as the provision of carbon, silica, invertebrate drift and seed propagules.

In addition to the above flow management recommendations, the following recommendations should be considered as part of the evaluation of future environmental water releases to the Snowy River:

- Continued monitoring and assessment of macroinvertebrates and their response to future environmental flows provided to the Snowy River.

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