Effects of the decommissioning of Lake Mokoan on fish community structure in the Broken River: One-year progress report.*

Prepared for:

The Goulburn-Broken Catchment Management Authority

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Broken River at Goomalibee. Photo: Rick Stoffels

Executive summary

- Lake Mokoan was decommissioned during 2008/09 due to inefficiencies in operation (large amount of evaporative water loss relative to running costs) and poor water quality.

- Lake Mokoan inputs to the Broken River have, historically, significantly increased turbidity and nutrient loads within the lower Broken River.

- In 2008 the Goulburn-Broken CMA funded a replicated, multi-year BACI experiment to determine the effect of the Mokoan decommissioning on the fish communities within the Broken River, primarily as a response to the expected drop in turbidity levels.

- After one year of this experiment, we report significant and strong differences in the riverine fish community between reaches above Casey's Weir—hence above the influence of Lake Mokoan (hereafter 'upstream reach')—and below Casey's Weir—hence having historically received inputs from Lake Mokoan (hereafter 'downstream reach').

- Analysis of habitat structure yielded no significant difference between reaches with respect to woody complexity and most other physical variables that characterise the water velocity and depth structure of the river. By contrast, these analyses showed that habitat structure yielded differences between reaches with respect to other habitat variables, particularly the structure of the aquatic macrophyte communities within each reach.

- The upstream reach appears to contain more *Vallisneria australis*, *Phragmites australis*, *Persicaria decipiens* and *Cyperus* sp. than the downstream reach, although *Ludwigia peploides* was more common downstream, within the turbid reach.

- The upstream reach is characterised by small-bodied fishes such as rainbowfish (native, N), *Melanotaenia fluviatilis*, carp-gudgeons (N), *Hypseleotris* sp., mosquitofish (introduced/exotic, E), *Gambusia holbrooki*, and European carp (E), *Cyprinus carpio*.

- The downstream reach is characterised by Murray cod (N), *Maccullochella peelii peelii*, golden perch (N), *Macquaria ambigua*, and less small-bodied fishes and European carp.

- We report that, after one year, turbidity within the lower Broken River has dropped significantly, such that turbidity within the upstream and downstream reaches are now comparable. Within the downstream reach, mean turbidity over the years 2006-2008 was 173.28 NTU, which contrasts strongly with the mean turbidity recorded by this

study during 2009, 55.18 NTU. Thus turbidity during the early stages of the Mokoan decommissioning is already ~30% of what it was during the three years prior to decommissioning.

- One year of data is insufficient to determine whether the decommissioning of Lake Mokoan will alter fish community and/or habitat structure within the Broken River—ongoing monitoring will shed light on these issues.

- Six hypotheses to explain the strong, significant differences in fish community structure within the Broken River between upstream and downstream reaches are presented, only five of which are related to the decommissioning of Lake Mokoan. These six hypotheses are:

    o Turbidity promotes the piscivorous feeding of Murray cod and golden perch, which lowers the abundance of small-bodied fishes in turbid reaches, but increases the abundance of large-bodied natives.

    o Turbidity suppresses the feeding rate of small-bodied fishes such as carp-gudgeons and rainbowfish, which in turn has lowered their productivity in the downstream reach of the Broken River.

    o Turbidity detrimentally affects the physiology of fish species in a way that is inversely proportionate to their body size.

    o High nutrient inputs from Lake Mokoan have affected the prey community of large-bodied and small-bodied prey species differentially, such that the food web structure above Casey's Weir favours small-bodied fishes, while the food web structure downstream favours large-bodied natives.

    o Turbidity decreases the abundance of submerged and emergent macrophytes, which in turn reduces feeding, refuge and/or spawning habitat for small-bodied fishes.

    o Casey's weir limits the upstream migration of Murray cod and/or golden perch, and their increased abundance downstream of Casey's Weir results in increased piscivory, which then suppresses the abundance of small-bodied fishes.

- This research also contains many value-added components, whereby we seek to improve our understanding of Murray cod and golden perch population dynamics in small, lowland rivers, and the environmental drivers of fish community structure in such systems.

    o With respect to the large-bodied fish community (golden perch, Murray cod, European carp), we report a significant correlation between fish community structure and river management practices—either Mokoan inputs (turbidity

and/or nutrients) or the barrier effect of Casey's Weir have a strong influence on large-bodied fish communities within the Broken river. However, in addition to river management practices, woody debris, depth heterogeneity, flow heterogeneity and macrophyte community structure all are significantly associated with large-bodied fish community structure within the Broken River.

o   With respect to small-bodied fish communities (rainbowfish, carp-gudgeons, smelt, mosquitofish), piscivores (Murray cod and golden perch) may be having a strong influence on the small-bodied fish community. Indeed, we report a significant negative relationship between the abundances of piscivore and small-bodied fishes.

o   After one year of the investigation we report recapture rates of golden perch and Murray cod in excess of 5%, showing that the Broken River may be particularly conducive to the estimation of demographic parameters for structured population models. We may be able to estimate certain demographic parameters (population density, survivorships), after our second year of investigation.

o   Currently, both Murray cod and golden perch exhibit a high degree of site fidelity, at least at the scale of 100 metres or less.

Broken River at Brookwell Park. Photo: Rick Stoffels.

1. Introduction

1.1. Turbidity and freshwater fishes

Many catchment and river management practices influence the quality of runoff, hence the turbidity of streams and rivers that receive that runoff. However, we have almost no understanding of how turbidity influences Australian native fishes. Turbidity may affect fishes in both direct and indirect ways. For example, turbidity may directly interfere with cues (visual, mechanical) fish utilise to catch prey or their physiology (e.g. respiration), whereas it may indirectly affect fishes by reducing levels of primary production, which in turn results in reduced prey productivity. Moreover, turbidity may have both positive and negative effects on freshwater fish. For example, the light scattering effect of turbidity may decrease the foraging efficiency of certain piscivorous fishes, hence limiting their production. By contrast, turbidity may serve as a form of refuge for certain fishes, thus enabling them to forage within places, or during times, that would otherwise be dangerous. This increase in foraging freedom may, in turn, result in an increase in growth rates, hence population production. Preliminary data from the Broken River shows that the abundance of certain small fish species may be negatively correlated with turbidity, but an experiment is needed to disentangle the effects of turbidity from the many other factors that potentially covary with turbidity in The Broken River.

Experimentally determining the effect of turbidity on fish community structure *in situ*, at a large spatial scale is extremely problematic due to the difficulty of varying turbidity at large spatial scales. However, the Broken River presents us with an interesting natural turbidity experiment, whereby reaches above Casey's Weir are typically clear and reaches below Casey's Weir are typically turbid, a pattern obvious from satellite imagery alone (Figure 1). This difference is caused by turbid inputs from an adjacent shallow lake, Lake Mokoan (Figure 1).

Thus we have access to large-scale spatial variation in turbidity, which we can utilise to obtain insight as to how turbidity influences fish community structure, *in situ*. In addition, the decommissioning of Lake Mokoan enables a rare opportunity to conduct an ecosystem-scale experiment that will improve our understanding of how turbidity

influences the productivity of fish populations in lowland rivers. That is, the decommissioning of Lake Mokoan enables a BACI experimental design (before (pre-decomissioning), after (post-decomissioning), control (upstream of Casey's Weir, hereafter CW), implementation/impact (downstream of CW)), one that is known to be particularly powerful when it comes to elucidating the impact of ecological variables, such as turbidity.

Figure 1. Satellite image of Broken River above and below the turbid input from Lake Mokoan, which is coming from the right of the image. Casey's Weir is the structure in the image's top left; direction of flow is from bottom-right to top-left.

The objectives of this study are to:

1. Determine whether there was a difference in fish community structure between the clear and turbid reaches of the Broken River.

2. Determine whether any such differences in community structure diminish after the decommissioning of Lake Mokoan.

3. Determine whether there are any differences in fish condition between the clear and turbid reaches of the Broken River.

4. Conduct habitat structure analyses to: A) Determine whether reaches contained significantly different in-stream habitat structure—habitat structure that should not be affected by historical operations of Lake Mokoan. Essentially, we wished to determine whether the decommissioning BACI experiment was confounded by in-stream habitat differences between reaches—differences which would remain unaffected by Lake Mokoan decommissioning; B) Determine spatial and temporal patterns in habitat structure, such that we may acquire a better understanding of how Lake Mokoan operations may have influenced overall, multivariate habitat structure within the Broken River.

The present report summarises our findings after the first year of research, during which we sampled the fish community four times: spring of 2008, summer 2009, autumn 2009, winter 2009. The spring and summer samples were essentially pre-decommissioning sampling events, while the autumn and winter sampling events were post-decommissioning sampling events.

1.2. Study system and history of Lake Mokoan decommissioning

The Broken River Basin is a sub-catchment of the southern Murray-Darling Basin, and has a mean annual discharge of approximately 325 GL (Cottingham et al. 2001). The Broken River itself is a small, lowland river with a mean annual discharge below Casey's Weir of 236 GL (Cottingham et al. 2001) and is a tributary of the Goulburn River, which, in turn, flows into the Murray River (Figure 3). The river experiences relatively moderate levels of regulation, imposed by four major regulation structures: Lake Nillahcootie and Lake Mokoan, Casey's Weir and Gowangardie Weir. The present study is directly concerned with Lake Mokoan and Casey's Weir only.

Lake Mokoan was constructed in 1971 as an off-stream storage, with a maximum capacity of 365,000 ML, a surface area of 7,890 ha and a maximum depth of 7 m when full. Lake Mokoan was filled by diversions from Holland's Creek and the Broken River each year and traditionally supplied approximately 22,000 ML to downstream diverters and irrigators annually. Its construction resulted in the flooding

of a sequence of natural wetlands, including Winton, Green, Ashmeads, Taminick, Lindsays, Humphries, Saddlers and Black Swamps (URS 2003; Figure 2). Preparatory work for the decommissioning of Lake Mokoan commenced during 2008, with outputs to the Broken River ceasing during January 2009. The reasoning underlying the decommissioning of Lake Mokoan is presented below in Section 1.3.

Figure 2. Panorama view of Lake Mokoan, October 2009, after drainage. Photo: Wayne Tennant.

The other control structure of immediate relevance to this study is Casey's Weir, which is located 15 km downstream of Benalla and was constructed in 1885 to divert flows into the Broken Creek system (Figure 3). Water is diverted at Casey's Weir to support the irrigation requirements on Broken Creek. Water from Casey's weir also supplies water to small, local towns. Casey's Weir would have traditionally represented an impassable barrier to fish movement along the Broken River, however, a vertical slot fishway was constructed during 2005, which may promote the movement of fishes around the weir (ARI 2006; Figure 4).
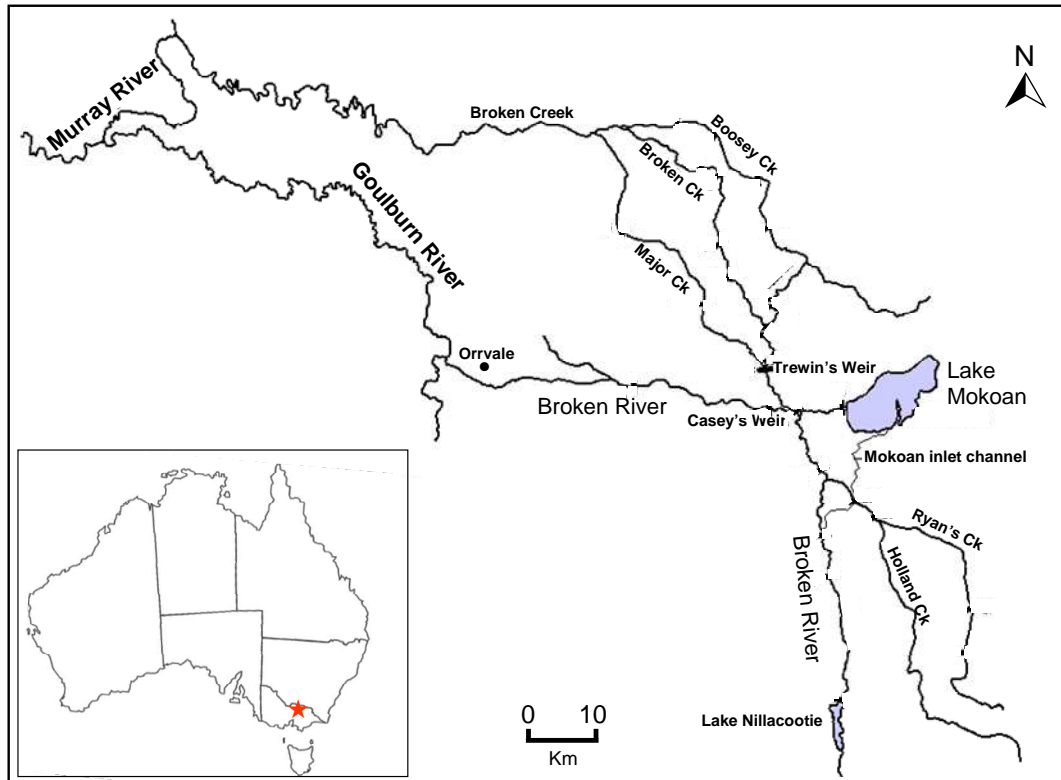
Figure 3. Map of the Broken River Basin, showing water diversion from the Broken river above Benalla, into Lake Mokoan, and then return to Broken River, immediately above Casey's Weir. (Map prepared by Susanne Watkins, MDFRC).

Figure 4. Vertical slot fishway on Casey's Weir. Photo: Rick Stoffels.

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1.3. Reasons for decommissioning Lake Mokoan and water quality impacts

The three primary reasons for the decommissioning of Lake Mokoan were: 1) evaporative water loss; 2) the costs associated with operating the lake, including the equitable sharing of these costs; and 3) poor water quality, both within the lake itself and incipient effects on the Broken River downstream of Lake Mokoan (URS 2003).

Research has indicated that Lake Mokoan was extremely inefficient as a water storage, losing as much as 50,000 ML per annum (URS 2003), which is approximately 21% of mean annual discharge below Casey's Weir. Moreover, the total annual cost of operating and maintaining Lake Mokoan in 2001/02 was $676,000, with an additional $54,000 spent by Department of Sustainability and Environment on fish stocking, legislative compliance management and research (URS 2003).
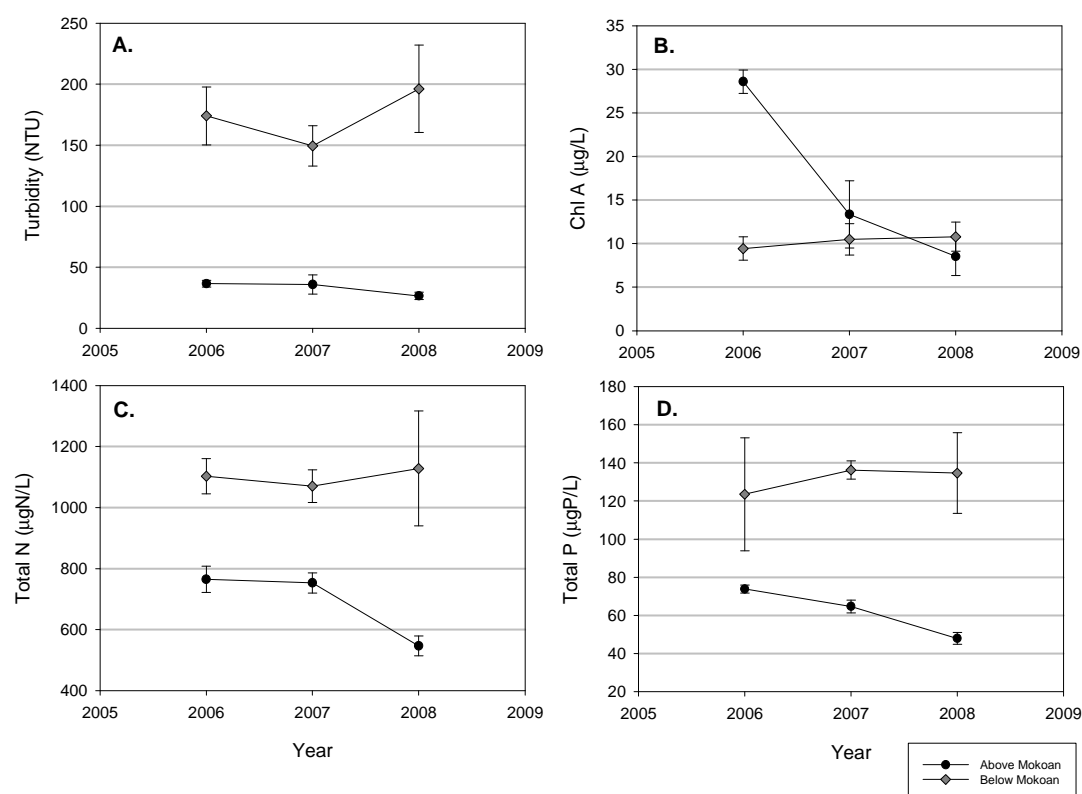
Figure 5. Mean (+/- St.Dev.) values of water quality variables within the Broken River upstream and downstream of Lake Mokoan from 2006-2008. Means are calculated across multiple sites located within the upstream reach (black circles; n = 3) and downstream reach (grey diamonds; n = 6). Each site is characterised by a mean value for that year. Data courtesy of MDFRC Drought Monitoring Project.

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Of particular relevance to the present study, is the fact that Lake Mokoan has been characterised by very poor water quality since the early 1980s. In particular, the lake has been characterised by high nutrient—hence algae—concentrations, and very high turbidity, caused by a combination of the following: a generally shallow profile, underlying fine clays, orientation of the lake's long axis with the prevailing southwesterly winds, and the proliferation of common carp, *Cyprinus carpio*, which are known to resuspend fine sediments in such water bodies. It follows that the water quality within the Broken River downstream of Lake Mokoan was also significantly decreased by the operation of Lake Mokoan. Indeed, Figure 5 shows the trends in certain water quality variables within the Broken River during the three years prior to the decommissioning of Lake Mokoan, and it is clear that turbidity, total N and total P are all significantly higher downstream of Lake Mokoan. Chlorophyll A (ChlA) is a coarse indicator of algal concentrations within the water column, and Figure 5B shows that there may be a significant difference in chlorophyll A concentrations between reaches, but perhaps not in the direction expected. That is, chlorophyll A concentrations are generally higher upstream of Lake Mokoan, during the three years of investigation, although it is obvious that any significant difference would be primarily due to the data collected in 2006 (Figure 5B).

2. Materials and Methods

It is well known that BACI experimental designs provide a powerful tool for making inferences about ecological responses. The BACI design we utilised here can be represented using the following schematic:

Impact   **Control**

Before

Casey's Weir

After
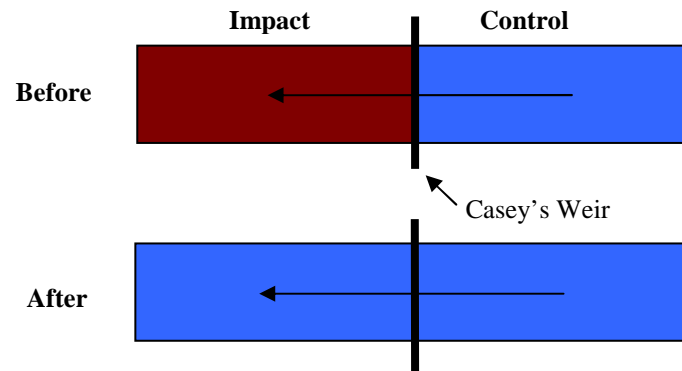
2.1. Fish sampling

We sampled two "reaches" within the Broken River, each of which can be divided into five "sites." The two reaches corresponded to the two turbidity treatments, above Casey's Weir (clear) and below Casey's Weir (turbid), and each replicate site consisted of 200m of river. The fish community at each of the ten sites (Table 1) was sampled in November 2008 (spring 08), January 2009 (summer 09), March 2009 (autumn 09) and June 2009 (winter 09), and was sampled using backpack electrofishing for large-bodied fish and fine-mesh fyke nets for small-bodied fish.

Table 1. Sampling sites in order from uppermost to lowermost. Map names refer to VICMAPs. Latitudes and longitudes come from Google Earth.

Upstream of Casey's Weir

#	Site name	Grid ref	Map name, #	Latitude	Longitude
1	Holdsworth Rd	064567	Benalla, 8024-1-1 1st edn.	36°31'44.17"S	145°57'20.25"E
2	Morago	062576	Benalla, 8024-1-1 1st edn.	36°31'13.14"S	145°57'9.29"E
3	Scholes	064587	Benalla, 8024-1-1 1st edn.	36°30'39.92"S	145°57'20.10"E
4	Glenkara	057596	Benalla, 8024-1-1 1st edn.	36°30'7.74"S	145°56'57.62"E
5	Mokoan Park	058607	Goorambat, 8025-2-2, 1st edn.	36°29'45.46"S	145°57'2.14"E

Downstream of Casey's Weir

#	Site name	Grid ref	Map name, #	Latitude	Longitude
6	Brookwell Park	031635	Goorambat, 8025-2-2, 1st edn.	36°28'1.15"S	145°55'8.24"E
7	Quinn Rd	014637	Goorambat, 8025-2-2, 1st edn.	36°27'53.71"S	145°54'3.06"E
8	Rupertsdale	001641	Goorambat, 8025-2-2, 1st edn.	36°27'47.57"S	145°53'10.22"E
9	Goomalibee Upper	978642	Upotipotpon, 8025-2-3 1st edn.	36°27'39.59"S	145°51'40.10"E
10	Goomalibee Lower	897658	Upotipotpon, 8025-2-3 1st edn.	36°27'13.68"S	145°51'18.62"E

Eight fine-mesh fykes were randomly positioned within each of the ten sites such that the cod-end was always upstream and the wings downstream (Figure 6). To ensure sampling for small-bodied fish was random with respect to the environment, we set up a 20 point grid and then randomly selected eight points from that twenty (there are $\binom{20}{8} = 125,970$ unique sampling arrangements at each site using this scheme): Ten transects, each of which was 20m apart, were established perpendicular to the stream edge, and 20 sampling points were then defined where each of these transects

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intersected the bank. Fykes were set for approximately two hours at each site—the approximate time it took to electrofish the site for large-bodied fishes. However, the total amount of time each net was set was also recorded so that we could standardise catch by time. All fish captured in fykes were identified and enumerated. Total lengths were measured from a random sub-sample of ten fish of each species, from each net.

Each site was exhaustively fished for large-bodied species using single-pass backpack electrofishing. This involved fishing as much of the 200m stretch as possible, and identifying, weighing and measuring the length of all large-bodied species captured. Small-bodied fishes were ignored, since we deemed fine-mesh fykes a far less biased sampling method for such species. Abundances were standardised by electrofishing "on-time." All Murray cod, *Maccullochella peelii peelii*, and golden perch, *Macquaria ambigua*, above 200mm total length (TL) were tagged with a unique passive integrated transponder (PIT) for subsequent identification of individual fish. Tags were obtained from Hallprint's distributorship of ENSID Technologies Ltd's (ENSID's) food-safe ruggedised RFID PIT tags (11 x 2.7 mm).

Figure 6. Example of randomised fyke arrangement at site 10, Goomalibee Lower. Photo: Slade Allen-Ankins.

2.2. Habitat mapping

We determined the habitat structure at each site for two primary reasons: 1) to determine whether any differences in fish community structure between turbid and clear reaches were confounded by habitat structure; 2) we wished to determine whether habitat structure explains any additional variance in fish community structure both within (within either clear or turbid reaches) and among (across all sites) treatments or reaches. For both summer and winter 2009, habitat mapping was conducted along each of ten transects that were randomly positioned within each site; a unique set of transects was randomly selected for each habitat mapping event. At each transect we recorded stream width, temperature, conductivity, dissolved oxygen (concentration, mg/l; DO), pH, dissolved oxygen (percent saturation; DO%), and turbidity. Quadrats (50cm x 50cm) were established 1m in from the southern stream edge, then every 2m thereafter. Within each quadrat we recorded the following: (A) depth; (B) flow at the surface, mid-column and on the bottom; (C) the presence/absence of fine (≤5cm diameter), medium (>5 but ≤ 25cm diameter) and coarse (>25cm diameter) woody debris; (D) presence/absence of emergent and submergent macrophyte species; (E) presence/absence of trailing (overhanging and touching water) vegetation types; (F) presence/absence of silt (<0.5mm), sand/gravel (0.5-16mm) or pebbles/cobbles (>16mm; modified Wentworth scale). The results are shown in Section 3.

2.3. Data analysis

2.3.1. Fish data

Fyke abundance data were standardised to mean numbers per fyke, per hour, while electrofishing abundance data were standardised to numbers per hour of electrofishing "on-time." These catch per unit effort (CPUE) data were used to determine spatial and temporal patterns in diversity and community structure. We also wished to examine spatial and temporal patterns in species biomass, so to this end we calculated measures of relative biomass at each site as follows: Two matrices (species × site/sampling-event) were constructed; one that contained mean individual mass (g) of species captured using fyke nets (matrix F) and the other containing mean individual mass (g) of large-bodied species captured using electrofishing (matrix E). Calculating

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mean individual mass for E was self-explanatory, since all large-bodied fishes captured were weighed. However, mean individual mass of all small-bodied species was estimated from length data only, using length-mass regressions, the details of which are given in Appendix 1. Matrices E and F were then summed to give matrix C, whose entries were the mean individual mass at each site and sampling event. Occasionally, young size-classes of large-bodied species were recorded in fykes as well as small bodied species. In this event, the entry in C was the weighted average of the corresponding mean masses in F and E, where the weights were the number of individuals that were weighed in each sample.

To obtain a relative estimate of biomass for each species at each site and sampling time, we then multiplied each mean individual mass by the corresponding CPUE-value for that species, at that site and sampling time. This relative estimate of fish biomass at each site and sampling time is hereafter referred to as "biomass per unit effort," BPUE.

We conducted two-factor analyses of variance (anova) on three response variables: (1) total BPUE, which is simply the sum of BPUE values across species for each site and sampling time; (2) Shannon diversity, *H'*; (3) Pielou's evenness index. Shannon diversity is sensitive to both richness (total number of species present) and how evenly species abundances are distributed across all species in a sample, while Pielou's evenness index, as the name suggests, is a diversity measure more sensitive to how evenly distributed species' abundances are across samples. The two factors for these anovas were "reach" (upstream, downstream) and "season" (spring, summer, autumn, winter).

To remove kurtosis and skewness in the BPUE data, it was subjected to a Box-Cox transformation, after which the data was not significantly non-normal (Lilliefors test; $\alpha = 0.05$). This transformation also homogenized variances. Shannon's diversity analyses were conducted on untransformed data, since they met the assumption of normality (Lilliefors test; $\alpha = 0.05$), however, Pielou's evenness data was subjected to a Box-Cox transformation on $x_i + 1$ data (where x_i is the ith individual observation), after which the data was not significantly non-normal (Lilliefors test; $\alpha = 0.05$).

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To determine patterns in community structure between reaches and among seasons we used non- and semi-parametric multivariate analyses (PRIMER-E v. 6; PERMANOVA+ 2008). CPUE abundance data were square-root transformed prior to calculation of Bray-Curtis similarity. These data were then analysed with a two-way crossed PERMANOVA. We are most interested in the interaction term, which gives us an indication of whether the community structure differences between upstream and downstream reaches are changing through time, hence as a consequence of decommissioning.

2.3.2. Habitat data

Substrate, depth and water velocity data were recorded from a total of 938 quadrats (hence ~94 per site) in summer 09, while the same data were recorded from a total of 906 quadrats (hence ~91 per site) in winter 09. Submerged and trailing substrate variables consisted of the proportion of all quadrats at a site containing each substrate. The full list of 30 substrate variables is given in Appendix 4.

As stated above, three water velocity measurements (surface, mid-column and bottom) and depth (cm) were recorded from each quadrat. These data were utilised to create three depth and four velocity variables. We first explain the calculation of the depth variables, but in order to do this clearly, we must first introduce some notation: Let n_s be the total number of quadrats utilised at a site, and n_t the number of quadrats utilised along the tth transect, $t = 1,\ldots,10$. The first depth variable was mean depth, which was simply the mean depth across all of the n_s depth readings at each site. The second depth variable was longitudinal variation in depth, which was calculated by first obtaining the mean depth across each of the n_t depth measurements taken along each of the ten transects utilised at a site, then obtaining the standard deviation of mean depth across these ten transects. Mean lateral variation in water velocity at each site, the third depth variable, was calculated by obtaining the standard deviation across the n_t depth measurements for each transect, then obtaining the mean of these ten standard deviations.

In order to explain the water velocity variables calculated at each site, define the mean water velocity at quadrat q, on transect t as $\bar{v}_{q,t} = (v_{q,t,surface} + v_{q,t,mid} + v_{q,t,bottom})/3$, where $v_{q,t,surface}$, $v_{q,t,mid}$ and $v_{q,t,bottom}$ are the velocities recorded at the surface, mid-

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column and bottom of quadrat q, transect t, respectively. Note that $q = 1,\ldots,n_t$. Further, define the mean water velocity at transect t as $\bar{v}_t = n_t^{-1} \sum_{q=1}^{n_t} \bar{v}_{q,t}$. Finally, let $s_{q,t}$ equal the standard deviation in velocity throughout the water column—hence across $v_{q,t,surface}$, $v_{q,t,mid}$ and $v_{q,t,bottom}$—at quadrat q on transect t.

Now, the first velocity variable was overall mean velocity at a site, which was calculated by obtaining $\bar{v}_{q,t}$ for each of the n_s quadrats at a site, then the overall mean velocity across all of the n_s $\bar{v}_{q,t}$ values. Longitudinal variation in water velocity at a site, the second velocity variable, was calculated by obtaining the standard deviation of the ten $\bar{v}_t$ values. Third, mean lateral variation in water velocity was calculated by determining the standard deviation of the n_t $\bar{v}_{q,t}$ values along transect t, then calculating the mean of these ten standard deviations. Fourth, we calculated the overall mean vertical standard deviation in water velocity at a site, $\bar{s}_{q,t}$, by determining the mean of the n_s $s_{q,t}$ values at that site.

Our first objective with respect to analysis of habitat structure was to determine whether reaches contained significantly different in-stream habitat structure that should not be affected by historical operations of Lake Mokoan. Essentially, we wished to determine whether the decommissioning BACI experiment was confounded by in-stream habitat differences between reaches—differences which would remain unaffected by Lake Mokoan decommissioning. Towards this end, we conducted a single-factor PERMANOVA on a matrix of dissimilarities (Euclidean distance), obtained using normalised in-stream habitat variables. However, we only included variables that we felt would not be affected by the operation of Lake Mokoan. Variables entered into the analysis were: CWD, MWD, FWD, clay, silt, sand, cobbles, bedrock, mean depth, mean velocity, longitudinal variation in depth, longitudinal variation in velocity, lateral variation in depth, lateral variation in velocity, mean vertical variation in velocity ($\bar{s}_{q,t}$) and stream width. We call this variable set, Set U, (U for "unaffected" by Mokoan decommissioning) hereafter. Aquatic plant and water quality variables were excluded as they may have been historically influenced by the operation of Lake Mokoan.

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Our second objective with respect to analysis of habitat structure was simply to determine spatial and temporal patterns in habitat structure, such that we may acquire a better understanding of how Lake Mokoan operations may have influenced overall, multivariate habitat structure within the Broken River. To this end, we conducted semi-parametric multivariate analyses on the following environmental variables: 28 substrate variables (given in Appendix 4, but without TrailBlackberry and TrailGrass, which were not common to both seasons). Seven depth and flow variables, described immediately above, as well as stream width. Four water quality variables, temperature, conductivity, pH and turbidity (dissolved oxygen, both as a concentration (mg/L) and as saturation (% saturation) was not common to both seasons hence omitted). Thus multivariate analyses were conducted on 40 environmental variables in total. We call this variable set, Set A (A for "affected" by Mokoan decommissioning), hereafter. These variables were first log(x+1)-transformed to reduce skewness, then normalised, because they are measured using different units. We utilised a two-way crossed PERMANOVA design to test for differences in habitat structure between seasons, irrespective of reach, differences between reach, irrespective of season, and any interaction effect between these two factors. We attempted to visualise any differences in multivariate habitat structure using principle components analysis (PCA).

2.3.3. Relationships between habitat and fish community structure

In addition to determining whether fish community and habitat structure differed between reaches upstream and downstream of Lake Mokoan, and between seasons, we also aimed to determine whether there was any correlation between fish community structure and habitat structure across the ten sites. In doing so, we wished to improve our understanding of the drivers of fish community structure within the Broken River and lowland rivers in general.

The BEST routine in PRIMER was used to determine multivariate correlation between fish communities and habitat variables. We utilised mean fish CPUE for each site, averaged across four seasons, and mean habitat structure, averaged across summer and winter, such that any correlations reported here represent the correlations averaged across a year. We separated analyses for large-bodied and small-bodied

species, because our hypothesis was that large-bodied species—piscivores in particular—are important drivers of the structure of small-bodied fish communities, hence piscivore abundance should really be included as a potential explanatory variable in analyses of patterns in small-bodied fish community structure. We removed all variables that we believed were not particularly relevant to fish communities, such as trailing emergent macrophytes, like *Cyperus*, leaving 26 habitat variables entering the BEST analyses for large-bodied species. In addition to these 26 habitat variables we included total piscivore CPUE (Murray cod CPUE + golden perch CPUE) in the set of potential explanatory variables for the analysis of small-bodied fish communities.

3. Results

3.1. Patterns in fish biomass and diversity

3.1.1. Total fish biomass

There was no significant difference in total fish BPUE between the upstream and downstream reaches ($F = 1.3$; $P = 0.2917$; Figure 7), nor was there a significant effect of season on fish BPUE ($F = 2.59$; $P = 0.1174$; Figure 7). The interaction between season and reach was also insignificant ($F = 1.1$; $P = 0.365$; Figure 7).
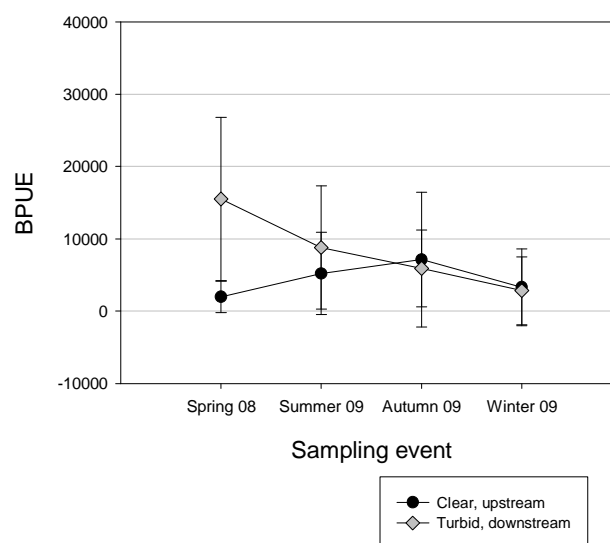
Figure 7. Mean total fish biomass per unit effort (BPUE; +/- St.Dev.) obtained in reaches upstream and downstream of Lake Mokoan, within four seasons. Lake Mokoan was decommissioned in summer 09.

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3.1.2. Fish diversity

Both fish diversity and evenness were significantly higher downstream of Lake Mokoan (Figure 8; *H'*: $F = 9.08$; $P = 0.0002$. Pielou's: $F = 3.97$; $P = 0.0163$), while there was no significant overall effect of season on either of these response variables (Figure 8; *H'*: $F = 1.66$; $P = 0.2063$. Pielou's: $F = 0$; $P = 0.9785$). However, there was a significant interaction effect between *H'* and season (Figure 8; *H'*: $F = 4.1$; $P = 0.0143$), indicating that the way in which diversity varies through time is dependent on whether we are upstream or downstream of Lake Mokoan's influence. A similar interaction effect was not significant for evenness (Figure 8; *H'*: $F = 2.09$; $P = 0.1208$).
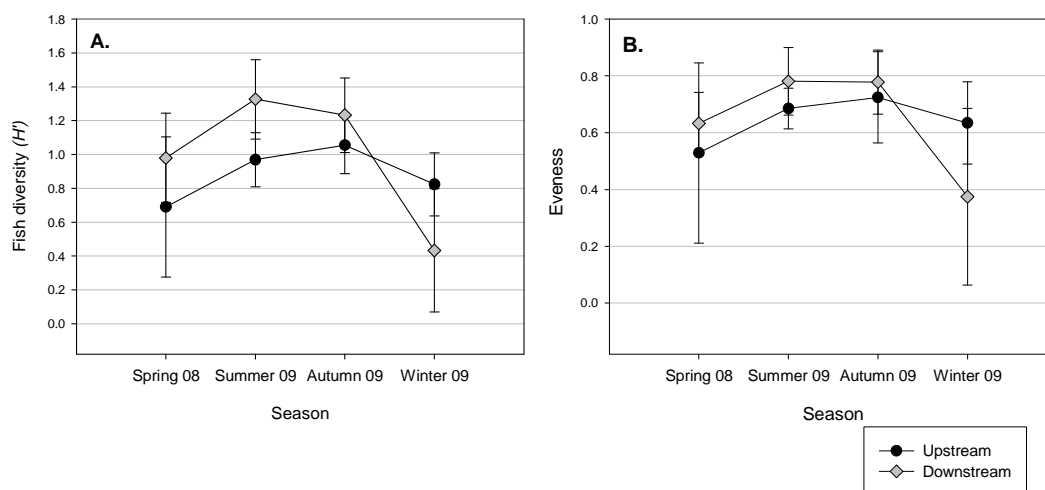
Figure 8. Mean (+/- St. Dev.) Shannon's diversity (A) and species evenness (B) in reaches upstream and downstream of Lake Mokoan, and within each season of sampling. Lake Mokoan was decommissioned in Summer 09.

3.2. Fish community structure

All terms of the two-way crossed PERMANOVA were significant (Table 2). The significant interaction term (Reach x Season) shows that the difference in fish community structure between the upstream and the downstream reach is itself changing through time (Table 2). That is, the difference in fish community structure we observed in spring 08 is not the same as the difference we observe in winter 09. Interaction effects are difficult to visualise in multivariate space, but Figure 9 shows that the strong differences in community structure that are apparent in spring and summer begin to diminish in autumn and winter.

To determine what species are actually driving some of the community structure differences reported above, we conducted a 2-way crossed SIMPER analysis (Clarke and Warwick 2001). Table 3 gives the details of the species' responsible for driving community differences between reaches. Murray cod, carp, golden perch and carp-gudgeons are the species primarily responsible for driving differences in community structure between upstream and downstream reaches of the Broken River. Carp and carp-gudgeons are more abundant in the clear reaches, above Casey's Weir, while Murray cod and golden perch are more abundant in the turbid reaches, below Casey's Weir.

Table 2. Two-way PERMANOVA table for CPUE abundance data.

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Reach	1	10198	10198	9.2224	0.0001	9957
Season	3	22248	7415.9	6.7062	0.0001	9918
Reach x Season	3	12750	4250.1	3.8434	0.0001	9927
Res	32	35386	1105.8			
Total	39	80583				

Table 3. Results of the SIMPER analysis explaining the species that discriminate upstream reaches from downstream reaches, irrespective of season. Columns most relevant are the % contribution to discrimination (second from right) and cumulative % contribution to discrimination (far right). These columns give the contribution, as a percentage, that each species makes to the overall difference between treatments.

Species	Upstream Mean abundance	Downstream Mean abundance	Av.Diss	Diss/SD	Contribution %	Cumulative %
M.peelii peelii	0.13	1.94	11.58	1.31	18.83	18.83
C.carpio	2.07	0.68	11.40	0.93	18.54	37.37
M.ambigua	1.65	2.09	10.20	1.00	16.59	53.96
Hypseleotris	2.69	0.85	9.96	1.17	16.20	70.16
C.auratus	0.35	0.70	8.24	0.70	13.40	83.56
M.fluviatilis	1.68	0.77	6.11	0.98	9.93	93.49
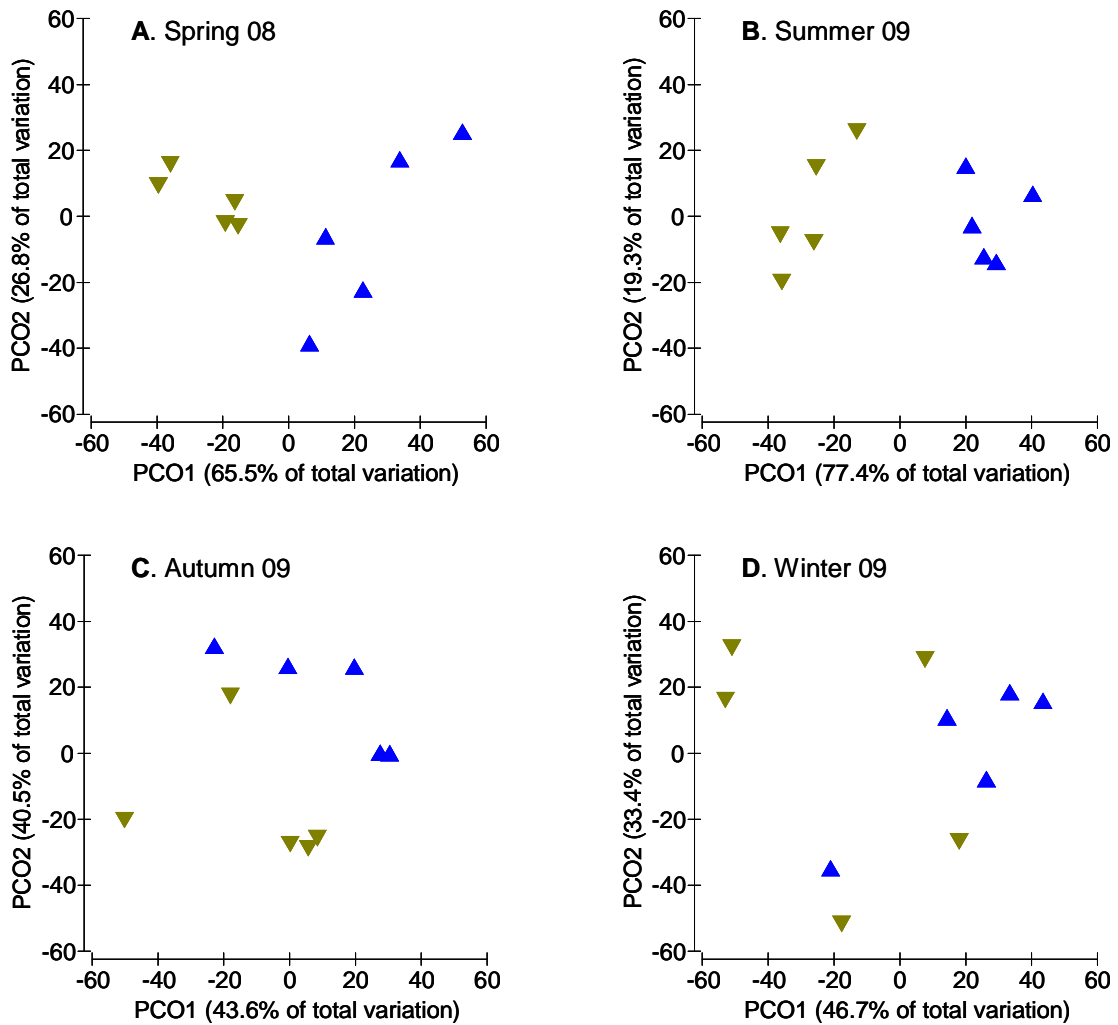
Figure 9. Principal co-ordinate (PCO) ordination of sites above (blue) and below (brown) Lake Mokoan for each season sampled so far. Samples closer together have more similar community compositions than samples that are further apart. Lake Mokoan was decommissioned in Summer 2009.

3.3. Golden perch and Murray cod—growth, movement and demographics in the Broken River

The details of Murray cod and golden perch tagged within the Broken River as part of this study are given in Table 4. Thus far, 7.4% of tagged Murray cod have been recaptured, while 5.1% of tagged golden perch have been recaptured. Such recapture rates are quite good for a fish capture-recapture study such as this within its first year of operation, and we expect to see recapture rates increase within the next year. It is still too early to estimate demographic parameters such as population size and

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survivorship—we will need more recaptures before we can reliably estimate such parameters.

Recaptured fish appeared to be healthy and no recaptured fish had left the site within which it was originally tagged, indicating high site fidelity at this stage. Over the spring and summer months, one golden perch had grown at a rate of 0.29 mm · d^{-1}, (where d is a 24 hour period) however we could not obtain a growth rate estimate of the other golden perch recaptured, since it escaped before we could obtain a length estimate after first tagging in spring 08. One Murray cod recaptured had only grown a total of 16mm between spring 08 and winter 09, yielding a growth rate of approximately 0.08 mm · d^{-1}, while the other cod recaptured as part of this study had grown 2mm between autumn and winter 09, yielding a growth rate of approximately 0.024 mm · d^{-1}. In time, we hope to construct a seasonal growth curve for these species, such that we may better understand how season affects the growth rate of these species of high socio-economic importance. Further, collection of this growth rate data, in conjunction with the collection of habitat data, may help us elucidate how environmental conditions drive the production of these species.

Table 4. Counts of Murray cod and golden perch captured, tagged and recaptured within each season of the study so far. Only individuals greater than 200mm TL were implanted with a PIT.

	Murray cod			Golden perch		
	Captured	Tagged	Recaptured	Captured	Tagged	Recaptured
Spring 08	19	10	0	21	12	0
Summer 09	14	9	0	16	7	0
Autumn 09	10	7	0	26	10	1
Winter 09	3	1	2	16	10	1
Totals	46	27	2	79	39	2

Mean catch rates of both Murray cod and golden perch were not significantly different over the sampling trips, although there appeared to be a general downward trend in the catch rates of both species (Figure 10). It is difficult to say whether this trend is a "real" trend or just random noise at this stage—further sampling will help elucidate whether this trend is an artefact of sampling (interaction between seasonal environmental conditions and sampling efficacy) or a genuine pattern, one that is

perhaps induced by our sampling technique (e.g. "sampling-savvy" fish that better avoid sampling gears as sites are repeatedly sampled through time).
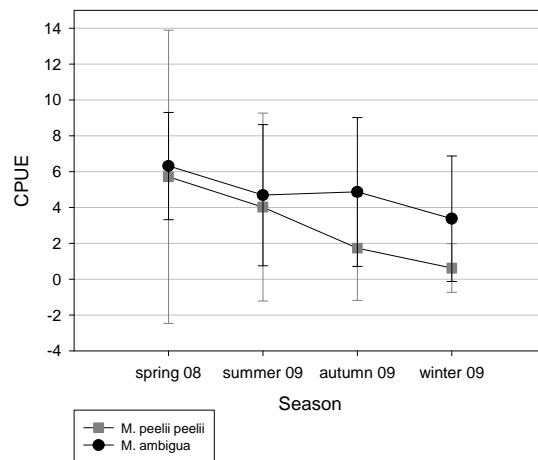
Figure 10. Mean overall CPUE (+/- St. Dev.) of golden perch (*M. ambigua*) and Murray cod (*M. peelii peelii*) as a function of season.

3.4. Condition of Murray cod and golden perch

All condition analyses will be conducted on Murray cod and golden perch only, as it has proved too difficult to obtain condition estimates of small bodied fish in a non-lethal manner. If we were to obtain reliable estimates of condition of small bodied fish, we would need to bring sub-samples back to the laboratory, which, in turn, would require new permits.

Insufficient numbers of Murray cod were obtained above Casey's Weir to make any meaningful comparisons of fish condition between upstream and downstream reaches. However, we have compared the condition of golden perch between upstream and downstream reaches, and found no significant difference (Figure 11).

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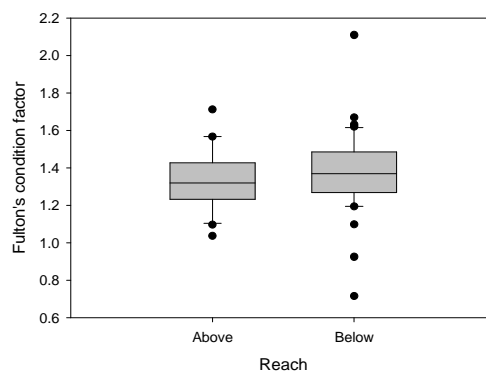
Figure 11. Condition of golden perch captured in the Broken River above and below Casey's Weir. Box boundaries from closest to x-axis to farthest are 25th and 75th percentiles. Error bars indicate 10th and 90th percentiles about mean. Line in middle of box indicates median condition index and dots indicate outliers—those outside the 10th and 90th percentiles.

3.5. Habitat structure

3.5.1. Spatial and temporal patterns in water quality

A summary of the water quality at each of the ten sites in spring 08, autumn 09 and winter 09 is given in Appendix 2 (summer data lost due to extreme air temperatures causing equipment malfunction). The only two water quality variables measured that are obviously affected by Lake Mokoan are turbidity and conductivity, SpC. It would clearly have been profitable to measure nutrient changes, given the patterns presented in Figure 5, however, such inclusions increase the expense of the monitoring. Figure 12A shows that there is a significant interaction effect between season and reach on turbidity, such that turbidity significantly declines in the downstream reach, while changes in the upstream reach are minimal (Two-factor ANOVA; $P < 0.01$). Such an interaction effect shows that, since the decommissioning of Lake Mokoan, turbidity has declined in the downstream reach, such that there is no noticeable difference in turbidity levels between the two reaches by June 2009. With respect to conductivity, both season and reach had a significant impact (Two-factor ANOVA; $P < 0.01$); conductivity is consistently higher downstream of Lake Mokoan, and is highest in summer, followed by spring, and lowest in winter (Figure 12B). The conductivity observed in summer may be due to subtle increases in salinity over the warmer months. However, we cannot determine exactly which solutes are causing these conductivity patterns without more detailed analyses. There was no interaction effect between season and reach on conductivity, implying that the spatial and temporal patterns in conductivity have not yet been influenced by the decommissioning of Lake Mokoan (Figure 12B).
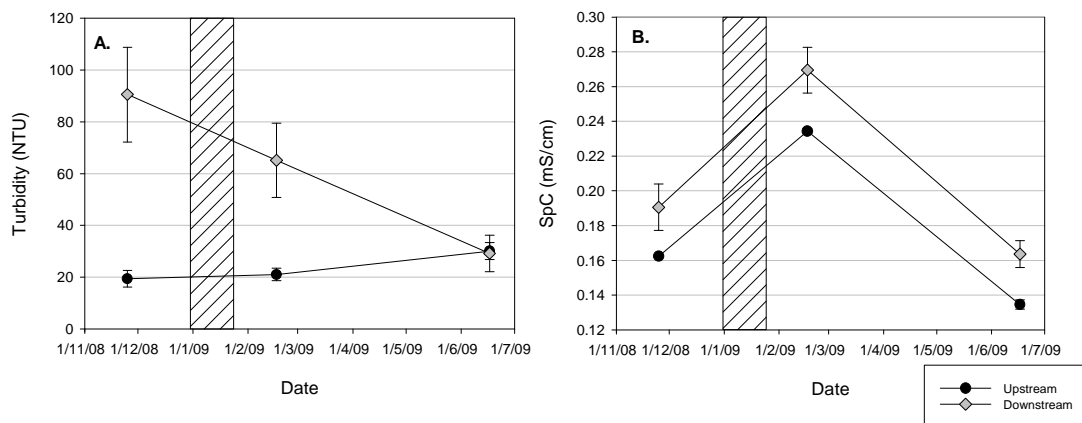
Figure 12. Temporal trends in mean turbidity (A, NTU; +/- St. Dev.) and mean conductivity (B, SpC (mS/cm); +/- St. Dev.) within the Broken River, in reaches upstream and downstream of Casey's Weir, hence the influence of Lake Mokoan. Summer data here are taken from the habitat mapping trip (Appendix 3). Autumn data were not included due to the draining of Lake Benalla during that period, which caused lowered water quality above Lake Mokoan, in the upstream reach. Hatched column indicates period of decommissioning, hence ceased inputs from Lake Mokoan.

The only other water quality variable worthy of particular attention is dissolved oxygen concentration during the winter 09. There are two reasons for this: 1) dissolved oxygen will be excluded from the multivariate analyses below, because the dissolved oxygen was not recorded for the summer habitat mapping, so we subject it to univariate analysis here; 2) dissolved oxygen concentrations during the winter are significantly different between reaches (T-test; $P < 0.05$), with dissolved oxygen concentrations being significantly higher downstream of Lake Mokoan (Figure 13). The possible mechanisms underlying this pattern are not obvious, and furthermore, it is unlikely that the difference reported in Figure 13 has a significant effect on fish performance. However, we must be cautious in making such inferences, as our knowledge of how environmental drivers affect the physiological performance of Australian freshwater fishes is indeed rudimentary.

Figure 13. Box plots of dissolved oxygen concentrations upstream and downstream of Lake Mokoan. Box boundaries from closest to x-axis to farthest are 25th and 75th percentiles. Error bars indicate 10th and 90th percentiles about mean. Line in middle of box indicates median condition index and dots indicate outliers—those outside the 10th and 90th percentiles.
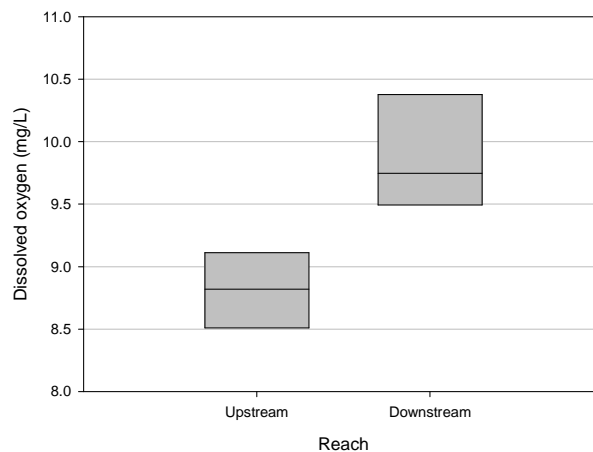
3.5.2. Spatial and temporal patterns in habitat structure

We did not detect any significant differences in habitat-structure between reaches (P = 0.1415), when including only those in-stream environmental variables deemed to be unaffected by Lake Mokoan operations—environmental variable set U. However, when utilising the complete environmental variable set, some of which may be affected by Lake Mokoan decommissioning (Set A), PERMANOVA revealed significant differences in habitat structure between reaches and between seasons, but there was no significant interaction effect between these two factors (alpha level of 0.05). The lack of an interaction effect implies that, although the decommissioning of Lake Mokoan is having a significant effect on turbidity, changes in overall structure of habitat are yet to be manifest. The top ten environmental variables driving differences between reaches, irrespective of season, and between seasons, irrespective of reach, are given in Table 5. One feature of Table 5 is particularly noticeable: no single individual variable stands out as having an overwhelming influence on the differences in habitat structure among treatments, as indicated by the very gradual declines in individual percentage contributions across the top ten variables selected by SIMPER. Therefore, although, for example, turbidity is shown as the most important variable shaping differences in overall habitat structure between reaches, it is not having a much stronger effect than other environmental variables, such as macrophyte species.

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Table 5. Results of SIMPER analysis to determine the environmental variables driving the differences between reaches and between seasons within the Broken River. Contrib % indicates the individual percentage contribution that environmental variable makes to the difference, while Cum. % indicates the cumulative contribution that variable plus the preceding variables make to the difference.

Upstream vs. Downstream			Summer vs. Winter		
Variable	**Contrib%**	**Cum.%**	**Variable**	**Contrib%**	**Cum.%**
Turbidity	3.98	3.98	Temperature	4.63	4.63
Ludwigia peploides	3.37	7.34	Conductivity	4.44	9.07
MeanDepth	3.30	10.65	Silt	3.67	12.74
Vallisneria australis	3.27	13.92	*Ludwigia peploides*	3.26	16.00
MeanVertStdVelocity	3.18	17.10	Turbidity	3.26	19.25
Persicaria decipiens	2.99	20.09	MeanVertStdVelocity	3.18	22.43
Cyperus	2.96	23.05	FWD (1-5cm dia)	3.00	25.43
Azolla	2.96	26.01	CWD (>20cm dia)	2.96	28.39
Phragmites	2.93	28.95	Filamentous Algae	2.84	31.22
MWD (5-20cm dia)	2.89	31.84	*Juncus*	2.78	34.01

3.5.3. Relationships between habitat structure and fish community structure

So far we have shown that fish community structure is significantly different between the clear and turbid reaches of the Broken River, and that habitat structure also differs between reaches. We now determine whether there is a statistically significant correlation between in-stream habitat structure and fish community structure across sites, using the BEST procedure (Clarke and Warwick 2001).

The best model describing the relationship between the structure of large-bodied fish communities and habitat included turbidity, longitudinal variation in depth, *Phragmites*, and the presence of riparian wattles. These variables alone explained 54.7% of the variance in fish community structure across all ten sites within the Broken River. *Vallisneria australis* was also an important explanatory variable in other good models. The inclusion of riparian wattles in the set of best explanatory variables is surprising, and may at first seem like a misleading correlation (rather than a valid component of causation). It is possible, however, that riparian wattles contribute stream inputs—food, cover, etc.—that large-bodied species respond to, or they may be indicative of the "health" of the riparian plant community bordering a particular site.
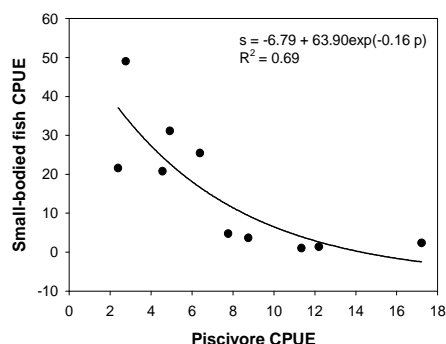
Turbidity was a major explanatory variable of spatial patterns in the structure of large-bodied fish communities. However, most of the variance in turbidity can be accounted for by dividing up our sites into those upstream of Casey's Weir and those downstream of Casey's Weir, hence by partitioning our sites into those receiving and not receiving Mokoan inputs. It follows that sites serving as "turbidity" treatments are confounded by the presence of Casey's Weir itself, and a fish pass that may select for certain species or size classes, hence potentially biasing any analysis that attempts to link in-stream habitat structure to fish community structure. Essentially, within the Broken River we may have a situation whereby the effects of habitat variables on fish community structure are dependent on which reach the fish are in, upstream or downstream. In statistical terms, it is quite possible that we have an interactive (multiplicative) effect between reach (upstream vs. downstream) and habitat variables on large-bodied fish community structure.

To properly account for interactive effects here we would need to implement distance-based linear modelling and distance-based redundancy analysis, which isn't worth the effort at this stage of the project. However, we can obtain some clues as to whether there are interactive effects between reach and the suite of habitat variables on fish community structure by analysing the relationship between habitat and fish communities one reach at a time. To this end, we divided the large-bodied fish data into upstream and downstream sets and conducted BEST analyses, similar to that outlined above.

For the upstream reach, above Casey's Weir, the best predictors of large-bodied fish community structure were medium woody debris, sand, cobbles, *Phragmites*, lateral heterogeneity in water velocity and the presence of riparian wattles. Interestingly, these variables explained 88% of the variation in large-bodied fish community structure.

Within the downstream reach, below Casey's Weir, the best predictors of large-bodied fish community structure were longitudinal heterogeneity in depth, presence of riparian wattles, and *Vallisneria australis*. Surprisngly, these habitat variables explained 98.8% of the variation in large-bodied fish community structure within the downstream reach.

For small-bodied fish species, the best predictors of community structure were medium woody debris, turbidity, and the abundance of piscivores (Murray cod CPUE + golden perch CPUE). Together, these three variables explained 79.4% of the variation in small-bodied fish community structure. Indeed, the strong negative relationship between piscivore and small-bodied fish abundance can be seen in Figure 14.

Within the plot: $s = -6.79 + 63.90\exp(-0.16\,p)$ and $R^2 = 0.69$. Axes: Small-bodied fish CPUE (y-axis) versus Piscivore CPUE (x-axis).

Figure 14. Small-bodied fish abundance as a function of piscivore abundance (Murray cod CPUE + golden perch CPUE). In equation, s denotes small-bodied fish abundance while p denotes piscivore abundance.

4. Discussion

4.1. General patterns in water quality and habitat structure

Lake Mokoan has had significant impacts on water quality within the Broken River. In particular, turbidity, total nitrogen and total phosphorous were all significantly higher within the Broken River downstream of Lake Mokoan, prior to decommissioning (nutrient data not collected by this study—see Section 1.3). Since the decommissioning of Lake Mokoan during the 2008/09 summer, turbidity has significantly declined within the downstream reach, such that turbidity levels within the reaches upstream and downstream of Casey's Weir are indistinguishable. Unfortunately, we did not have sufficient funding to monitor nutrient levels following decommissioning.

There are significant differences in multivariate habitat structure between the reaches upstream and downstream of Lake Mokoan. This significant difference in habitat structure is primarily driven by aquatic plants species, in addition to water quality

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(turbidity). Aquatic plant species such as *Vallisneria australis*, *Phragmites australis*, *Persicaria decipiens* and *Cyperus* sp., are more abundant upstream of Casey's Weir. Hence it may be possible that turbidity and/or higher nutrient levels within the downstream reach have decreased the abundance of these aquatic plants. Such a hypothesis is certainly plausible with respect to completely submerged macrophytes, such as *V. australis*, whose productivity (photosynthesis) may be hampered by the light scattering effect of turbidity. It follows that the decommissioning of Lake Mokoan may also alter the structure of aquatic plant communities within the Broken River. However, although the present study will detect certain major changes in the aquatic plant community as a consequence of the decommissioning of Lake Mokoan, determining the effect of this decommissioning on aquatic plant biodiversity in more detail would have to be the subject of a separate investigation.

4.2. General patterns in fish community structure within the Broken River

The structure of the fish community differs significantly and strongly between reaches upstream and downstream of Casey's Weir. The upstream reach is characterised by small-bodied fishes such as carp-gudgeons, rainbowfish and mosquitofish, as well as carp, while the downstream reach is characterised by large-bodied natives such as Murray cod and golden perch. Furthermore, the downstream reach is characterised by a more diverse fish community than that found upstream of Casey's Weir. After the decommissioning of Lake Mokoan fish community structures in the upstream and downstream reaches have converged, but this is most likely an effect of season, rather than an effect of decommissioning *per se*—we would have to monitor changes in the fish community for at least another year to remove the confounding influence of season, if we are to determine any potential influence of the decommissioning on fish community structure.

Despite this, we can be confident that there is something about the operation of Lake Mokoan and/or Casey's Weir that significantly alters the structure of the fish community within the Broken River. However, a paradox arises: within the downstream reach, where water quality is lower, we find a fish community structure that is generally considered more desirable than that which is found upstream, where water quality is higher. That is, downstream of Lake Mokoan we have a fish

community characterised by native sportfish (Murray cod), less carp and greater diversity. Does this mean that the decommissioning of Lake Mokoan will result in the downstream reach becoming more like the upstream reach, and thus contain less Murray cod and more carp? Not necessarily, and we present some hypotheses to explain the observed patterns in fish community structure below, which have nothing to do with the operation of Lake Mokoan *per se*. Indeed, the hypotheses we confer below can be classified under two overarching management drivers: Casey's Weir and Mokoan inputs.

4.3. Hypotheses to explain observed patterns in fish community structure within the Broken River: Effects of Lake Mokoan inputs.

The first set of hypotheses that we present to explain the patterns in fish community structure within the Broken River are all based on the assumption that inputs from Lake Mokoan comprise the driving variables. It follows, therefore, that if any of these hypotheses individually, or in combination, account for the majority of the variance in fish community structure within the Broken River, then we should see a convergence in fish community structure following decommissioning. The hypotheses are as follows:

Hypothesis 1. Turbidity promotes the piscivorous feeding of Murray cod and golden perch, which lowers the abundance of small-bodied fishes in turbid reaches, but increases the abundance of large-bodied natives.

Hypothesis 2. Turbidity suppresses the feeding rate of small-bodied fishes such as carp-gudgeons and rainbowfish, which in turn has lowered their productivity in the downstream reach of the Broken River.

Hypothesis 3. Turbidity detrimentally affects the physiology of fish species in a way that is inversely proportionate to their body size.

Hypothesis 4. High nutrient inputs from Lake Mokoan have affected the prey community of large-bodied and small-bodied prey species differentially, such that the food web structure above Casey's Weir favours small-bodied fishes, while the food web structure downstream favours large-bodied natives.

Hypothesis 5. Turbidity decreases the abundance of submerged and emergent macrophytes, which in turn reduces feeding, refuge and/or spawning habitat for small-bodied fishes.

We can only test hypotheses one and two with a series of behavioural experiments. With respect to Hypothesis 1, increased levels of turbidity may make aquatic predators feel safer while foraging (e.g. Gregory and Northcote 1992). Therefore, it is possible that large piscivores such as Murray cod and golden perch feed more freely in the more turbid, downstream reach of the Broken River because the turbidity provides a form of cover, which may be particularly important in a small lowland river such as the Broken. Implicit in Hypothesis 1 is the assumption that large-bodied native fishes significantly suppress the abundance of small-bodied fishes. This assumption appears reasonable, given Murray cod and golden perch feed on small-bodied fishes (Lintermans 2007), but scientifically rigorous examinations of the trophic ecology of Australian fishes are very rare, and we are not aware of any such research having been undertaken on the Broken River fishes.

Unfortunately, our knowledge of how turbidity affects the biology of Australian freshwater fishes is extremely poor, so it is very difficult to comment on the plausibility of Hypotheses 1 and 2. However, motivated by the spatial patterns presented here, an Honours student of the MDFRC recently conducted a series of experiments to determine whether clay turbidity affected the consumption rate of juvenile Murray cod feeding on macroinvertebrates, and found that turbidity significantly lowers the consumption rate of juvenile Murray cod (Maffei et al. *in prep*). Of course, this result contradicts the pattern observed in the field, where we find more adult cod inhabiting turbid reaches. The result of Maffei et al. (*in prep.*) is, however, a solid one, so perhaps the turbidity below Casey's Weir is still limiting the recruitment of juvenile Murray cod, but perhaps affecting adult Murray cod in some other favourable way.

Hypothesis 3 can also only be tested using laboratory experiments. Suspended solids can affect gill performance—hence metabolism and productivity—by epithelium lifting, hyperplasia in the pillar system, and reduction of epithelial volume (Au *et al*. 2004). It is possible that small fish are particularly susceptible to the detrimental effects of turbidity, because their gills have more delicate structure than that of larger fishes. Fish biologists are only recently coming to terms with the effect turbidity can have on respiratory performance, and Hypothesis 3 is certainly worthy of further

experimental investigation, given many of Australia's catchments are deforested, and characterised by drought, pulsed rain events and bushfires, all of which increase the suspended sediment load of inland waters (Bruton 1985; Wood and Armitage 1997). The MDFRC has recently invested in the most recent technology that will enable us to conduct rigorous physiological experiments to determine the effect of fine suspended sediment on metabolic performance of key fish species within the Broken River.

Hypothesis 4 is more difficult to test. Turbidity affects the overall productivity of primary producers through light attenuation, siltation, and abrasion, for example. Turbidity also affects the micro-scale habitat structure of invertebrates (Wood and Armitage 1997). Therefore, turbidity may affect the types of prey species present in a reach and, in turn, the types of predatory fish in a reach. Furthermore, nutrient enrichment alters productivity of biofilms, which in turn alters productivity of the food chains they support (Carpenter and Kitchell 1993). We presented some data above—not collected by this study—which clearly shows nutrient levels are significantly higher downstream of Caseys Weir. Therefore, it is quite plausible that Mokoan inputs have increased production of the prey types that drive production of large-bodied native fish in lowland rivers. For example, it was observed that *Macrobrachium australiense*—an important prey item for large-bodied natives—may have been more abundant in the turbid reaches of the Broken River. However, quantitative invertebrate sampling would have to be conducted to confirm this observation. The issue of how management interventions affect food web structure and dynamics, and how food web structure in turn affects the ecology of Australian freshwater fish is greatly underappreciated within Australia.

The fifth hypothesis, that turbidity limits the spawning habitat of small-bodied fishes, is quite plausible. Species like rainbowfish utilise macrophytes as substrate for egg attachment (Pusey et al. 2004; Lintermans 2007). Turbidity decreases macrophyte productivity (Wood and Armitage 1997), which, in turn, may limit the spawning success of species such as rainbowfish. Indeed, the habitat analyses presented here show that certain key macrophyte species are more common in the clear reaches of the Broken River. It should be noted, however, that this hypothesis cannot explain why large-bodied natives are more common downstream of Casey's Weir, within the turbid reach.

4.4. Hypotheses to explain observed patterns in fish community structure within the Broken River: Effects of Casey's Weir.

This second set of hypotheses is based on the assumption that water coming from Lake Mokoan is not the major driving force underlying the strong patterns in fish community structure that we have reported, but that Casey's Weir itself is driving the differentiation of fish community structure within the Broken River. It follows that if the hypothesis presented below—there is only one hypothesis within this second set— explains most of the variance in fish community structure within the Broken River, then we should not see a convergence of fish community structures upstream and downstream of Casey's Weir over time, following the decommissioning of Lake Mokoan.

> *Hypothesis 6.*   Casey's weir limits the upstream migration of Murray cod and/or golden perch, and their increased abundance downstream of Casey's Weir results in increased piscivory, which then suppresses the abundance of small-bodied fishes.

Hypothesis 6 states that Casey's Weir limits the upstream distribution of large-bodied natives, and that these large-bodied fishes then predate on small-bodied fishes, lowering their abundance. Implicit in this hypothesis is two assumptions: first, the vertical slot fishway on Casey's Weir is, to some degree, ineffective, and second, the large-bodied native subpopulations upstream of Casey's Weir require migrants from downstream reaches to remain productive. The Arthur Rylah Institute conducted a study to determine the effectiveness of the fish pass on Casey's Weir, and although fish were detected utilising the fish pass, they did not utilise methods that would enable us to quantify exactly how effective the fish pass is (ARI 2006). For example, detecting the presence or absence of fish in the fishway simply shows that movement around the barrier is *possible*—it does not show how *probable* it is, on a per capita basis, nor whether that probability is conditional on size. It is possible that only a small proportion of the large-bodied native fish populations are utilising the fishway.

The sixth hypothesis that we have presented here is testable under the current research framework being utilised. All large-bodied natives caught are being implanted with a small PIT, such that, over a number of years, we will gain a clear, scientifically

rigorous, hence defensible, understanding of how golden perch and Murray cod move through the Broken River. If Casey's Weir is limiting the movement of either golden perch or Murray cod, we should detect substantial movement *within* reaches (reach upstream of Casey's Weir vs. reach downstream of Casey's Weir), but not *between* reaches. Moreover, this capture-mark-recapture investigation will also give us a great deal of information about population demographics and behaviour, information that is pivotal to the quantitative management of fishes in lowland rivers. However, the success of such mark-recapture investigations rests on having the ability to conduct research over several years.

4.5. A note on synergies between, and exclusivity of, hypotheses

Thus we have at least six hypotheses that may explain the highly significant patterns in fish community structure presented in this report. The first five hypotheses concern inputs from Lake Mokoan, while the sixth concerns just Casey's Weir and the limit to fish movement it may represent. It is important to note that these hypotheses are not mutually exclusive, and the likely scenario is that many of these hypotheses act together to account for the variance in fish community structure within the Broken River. For example, Maffei *et al.* (*in prep*.) provide very strong evidence that turbidity negatively impacts the feeding of juvenile Murray cod. Their study, combined with many others conducted overseas (Utne-Palm 2002) implies that turbidity generally has a negative impact on freshwater fish feeding. Therefore, Hypothesis 2 probably accounts for at least some of the variance in fish community structure within the Broken River, but it obviously cannot explain the entire pattern, since we have shown here that fish diversity and production of certain socially and economically important species is actually higher within the turbid reach of the Broken River.

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Appendices

Appendix 1. Parameters and statistics of the regression equations used to derive wet mass (in grams) of fishes from length data (in mm). TL = FL for species that have forked caudal fins. Power equation ($M = aL^b$, where M is mass (g) and L is length (mm)) fitted using non-linear least-squares regression. For *Melanotaenia fluviatilis*, we utilised the regression equation from a morphologically similar congener, *M. duboulayi*.

Species	SL/TL	a	b	n	R^2	Min L	Max L	Source
Carassius auratus	TL	5.2×10^{-6}	3.2391	105	0.997	?	410	Morgan et al. (2005)
Cyprinus carpio	TL	2.647×10^{-3}	2.207	16	0.9161	331	630	This study
Gambusia holbrooki	TL	1.498×10^{-5}	2.913	398	0.9443	17	54	Lachlan River population, MDFRC data (Amina Price)
Hypseleotris sp.	TL	1.805×10^{-5}	2.851	424	0.9406	16	55	Lachlan River population, MDFRC data (Amina Price)
Maccullochella peelii peelii	TL	6.184×10^{-5}	2.734	38	0.9793	178	625	This study
Macquria ambigua	TL	1.97×10^{-5}	2.939	61	0.9714	97	435	This study
Melanotaenia duboulayi	SL	1×10^{-5}	3.124	1093	0.985	16	82	Pusey et al. (2004); this equation utilised for *M. fluviatilis*
Retropinna semoni	SL	0.5×10^{-5}	3.227	475	0.956	21	63	Pusey et al. (2004)

Appendix 2. Physico-chemical data obtained from each site during A. November 2008, B. March 2009, and C. June 2009. Unfortunately, the equipment we used to record these data (Quanta Hydrolab) overheated and malfunctioned due to the extremely hot weather at the time the summer 09 sampling occurred. Consequently, we have no physical and chemical data corresponding to the summer fish sampling trip.

A.

Date	Site	Temperature (°C)	SpC (mS/cm)	DO (mg/l)	pH	TDS (g/l)	DO% (Sat)	Turbidity (NTU)
24/11/2008	1	17.06	0.163	7.69	7.93	0.1	80.7	17.8
24/11/2008	2	18.83	0.162	8.9	8.27	0.1	96.7	16.6
25/11/2008	3	17.83	0.162	7.07	8.18	.	.	24.3
25/11/2008	4	22.07	0.162	8.72	8.52	0.1	100.02	17.3
25/11/2008	5	18.51	0.163	7.4	8.2	0.1	79.7	21
25/11/2008	6	22.81	0.172	8.81	8.59	0.1	103.6	63.9
26/11/2008	7	19.09	0.186	7.67	8.4	.	.	80.8
26/11/2008	8	21.41	0.19	7.97	8.48	0.1	91.1	94.8
27/11/2008	9	20.03	0.197	7.4	8.29	.	.	105
27/11/2008	10	20.4	0.208	7.17	8.28	.	.	108

B.

Date	Site	Temperature (°C)	SpC (mS/cm)	DO (mg/l)	pH	TDS (g/l)	DO% (Sat)	Turbidity (NTU)
27/04/2009	1	11.43	0.209	8.7	7.36	0.1	80.1	90.8
28/04/2009	2	10.99	0.216	8.74	7.33	0.1	80.8	71.4
28/04/2009	3	11.85	0.215	9.18	7.48	0.1	86.6	84.7
28/04/2009	4	12.05	0.214	9.07	7.56	0.1	85.9	98.1
29/04/2009	5	10.68	0.214	8.56	7.48	0.1	78.5	72.7
29/04/2009	6	11.38	0.201	9.17	7.65	0.1	85.5	110
29/04/2009	7	11.93	0.214	9.42	7.72	0.1	88.7	81.7
30/04/2009	8	10.28	0.205	9.33	7.51	0.1	84.9	91.9
30/04/2009	9	11.39	0.213	9.77	7.99	0.1	91.1	103
30/04/2009	10	10.28	0.219	9.77	7.85	0.1	88.9	97

C.

Date	Site	Temperature (°C)	SpC (mS/cm)	DO (mg/l)	pH	TDS (g/l)	DO% (Sat)	Turbidity (NTU)
15/06/2009	1	7.35	0.133	10.72	7.08	0.1	90.2	31.2
15/06/2009	2	8.19	0.132	10.65	7.59	0.1	91.6	33
16/06/2009	3	6.89	0.135	10.23	7.59	0.1	85.3	32.9
16/06/2009	4	8.19	0.134	10.78	7.62	0.1	92.7	25.8
17/06/2009	5	7.08	0.139	10.37	7.82	0.1	86.8	27.5
17/06/2009	6	7.21	0.15	10.63	8.04	0.1	89.3	40.9
18/06/2009	7	6.39	0.17	10.53	7.48	0.1	87.7	29.4
18/06/2009	8	8.14	0.166	10.74	7.92	0.1	92.3	28.3
19/06/2009	9	6.78	0.167	11.37	7.77	0.1	94.5	24.9
19/06/2009	10	7.8	0.165	11.87	8.2	0.1	101.2	22.7

Appendix 3. Mean (top) and standard deviation (bottom) of certain physical/chemical variables recorded from each Broken River site during (A) the week of the 16th of February 2009, and (B) the week of the 29th of June 2009. The dissolved oxygen probe broke during the summer habitat mapping, so no dissolved oxygen data could be recorded, and salinity was not recorded during the winter sampling event.

A.

Site	Temperature (°C)	SpC (mS/cm)	pH	Salinity	Turbidity (NTU)
1	22.951	0.2328	7.367	0.11	19
	1.080231	0.000422	0.249891	1.46E-17	1.939645
2	22.535	0.235	7.335	0.11	22.53
	0.136239	0.000471	0.066374	1.46E-17	2.21713
3	23.784	0.2351	7.417	0.109	22.52
	0.06467	0.000316	0.072273	0.003162	1.944679
4	24.957	0.233	7.627	0.11	17.91
	0.260173	2.93E-17	0.030203	1.46E-17	1.235089
5	23.094	0.236	7.276	0.11	23.35
	0.02675	5.85E-17	0.029889	1.46E-17	2.405665
6	24.672	0.2562	7.6	0.12	46.96
	0.162125	0.000632	0.080966	2.93E-17	3.143317
7	22.973	0.2623	7.436	0.13	59.95
	0.037727	0.000483	0.06867	2.93E-17	2.399653
8	23.11	0.2627	7.521	0.13	59.12
	0.402299	0.000483	0.03178	2.93E-17	3.787934
9	22.424	0.2784	7.653	0.13	79.33
	0.355065	0.001174	0.041913	2.93E-17	2.184821
10	22.512	0.2879	7.558	0.14	80.36
	0.091627	0.000568	0.064773	2.93E-17	2.504751

B.

Site	Temperature (°C)	SpC (mS/cm)	D.O. (mg/L)	pH	D.O.(%)	Turbidity (NTU)
1	10.866	0.1129	9.325	7.298	85.47	63.67
	0.033731	0.000316	0.164671	0.140855	1.555671	6.436364
2	10.962	0.111	8.899	7.041	81.76	56.57
	0.015492	1.46E-17	0.097005	0.085693	0.88594	2.812689
3	11.441	0.112	8.819	7.156	83.61	54.69
	0.108674	1.46E-17	0.594333	0.020111	0.939799	2.352044
4	10.72	0.112	8.648	7.062	78.98	53.14
	0.026667	1.46E-17	0.160264	0.097388	1.50761	0.74117
5	10.799	0.1136	8.373	7.327	76.64	48.27
	0.017288	0.000516	0.474319	0.168987	4.354359	1.748047
6	10.025	0.1268	9.747	7.302	87.61	32.19
	0.039511	0.000422	0.106463	0.043153	0.886253	1.332041
7	10.69	0.1348	9.567	7.344	87.93	44.35
	0.297583	0.000422	0.173785	0.110875	1.540599	2.609065
8	10.133	0.1351	9.42	7.259	84.85	46.94
	0.030203	0.000316	0.054365	0.091706	0.467262	2.104598
9	10.39	0.1362	10.202	7.679	92.5	53
	0.019437	0.000422	0.090774	0.084387	0.820569	1.508494
10	9.148	0.1327	10.554	7.487	92.96	49.626
	0.043153	0.001059	0.463254	0.026268	4.156441	14.84285

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Appendix 4. List of substrate variables recorded as present or absent in each quadrat during habitat mapping of each site.

Woody substrates	Inorganic substrates	Submerged and emergent macrophytes	Trailing vegetation
CWD (>20cm Ø)	Clay (<0.5mm Ø, hard & compacted)	*Phragmites australis*	TrailWillow
MWD (5-20cm Ø)	Silt (<0.5mm Ø, soft & loose)	*Persicaria decipiens*	TrailRedGum
FWD (1-5cm Ø)	Sand (0.5-16mm Ø)	*Ludwigia peploides*	Trail*Phragmites*
	Cobbles (> 16mm Ø)	*Vallisneria australis*	Trail*Cyperus*
	Bedrock (solid rock)	*Elatine* sp.	TrailBlackWattle
		Cyperus sp.	Trail*Juncus*
		Juncus sp.	TrailBlackberry
		Typha sp.	TrailGrass
		Grass	
		Azolla sp.	
		Filamentous algae	
		Willow root	
		Redgum root	
		Blackberry	