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Pike Anabranch Fish Intervention Monitoring 2013–2016


C. M. Bice, S. L. Gehrig and B. P. Zampatti

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EXECUTIVE SUMMARY

The Pike Anabranch and Floodplain is one of three large anabranch systems in the Riverland region of the lower River Murray, South Australia. The Pike Anabranch bypasses Lock and Weir No. 5 and the resulting head differential (total >3 m), creates a diverse range of aquatic habitats across the system, comprised of permanently flowing creeks, lagoons and backwaters. Nonetheless, at present the system is degraded due to decreased frequency of floodplain inundation, limited capacity to vary flows within the system and multiple barriers to flow and fish passage.

As part of the *Riverine Recovery Project* (RRP) several management interventions have been undertaken within the Pike Anabranch with the objective of improving capacity to vary flow to the system, increasing hydrological connectivity and mitigating barriers to fish passage. Specifically, the interventions have included an upgrade to the inlet regulator at Deep Creek (including construction of a vertical-slot fishway), construction of new regulators at Banks B and C, and removal of Coombs Bridge, Bank H and Snake Creek Stock Crossing. Ultimately, these interventions will result in increased capacity to vary flow to the Pike Anabranch under conditions of within-channel flow in the River Murray (<45,000 ML.day^{-1}), from ~300 ML.day^{-1} up to ~750 ML.day^{-1}, and significantly improve hydrological connectivity within the system and between the Pike Anabranch system and River Murray.

The current project was developed to assess the influence of interventions in the Pike Anabranch system as part of the RRP, on fish and fish habitats. It was hypothesised that increased flow to the system and accompanying increases in hydraulically diverse lotic habitat and increased connectivity, would result in significant changes to fish assemblage structure (i.e. species composition and abundance) and recruitment, habitat (vegetated and hydraulic) and fish-habitat associations, including increases in the abundance of species that prefer hydraulically diverse environments (e.g. Murray cod [*Maccullochella peelii*] and golden perch [*Macquaria ambigua ambigua*]). A before-after-control-impact (BACI) monitoring design was developed to assess the response of fish assemblages, instream habitat and hydraulic habitat to the planned interventions. Nonetheless, changes to the construction program under RRP and the related *South Australian Riverland Floodplain Integrated Infrastructure Program* (SARFIIP) dictated that several interventions initially planned (i.e. upgrade replacement of Banks D–G) were not completed and flow to the system has not yet been substantially altered. As such, the current project could not

meet the initial aim of assessing change in fish and fish-habitat related ecological patterns in relation to management interventions, but presents insight on natural variability in the above parameters over the period 2013–2016 that will form a basis for assessing the influence of interventions under RRP and SARFIIP in the future.

A series of sites were sampled in the autumn of 2013 (n = 16), 2015 (n = 18) and 2016 (n = 18), representative of three treatments: 1) impact sites (n = 7–9) – creeks within the Pike Anabranch system likely to experience changes in hydrology and hydraulic characteristics as a result of the interventions; 2) creek reference sites (n = 6) – creeks within the Pike Anabranch system unlikely to experience changes to hydrology and hydraulic characteristics as a result of the interventions; and 3) river reference sites (n = 3) – sites in the River Murray main channel unlikely to experience changes to hydrology and hydraulic characteristics as a result of the interventions. Each site was sampled with standardised boat electrofishing and microhabitat cover was quantitatively assessed. Hydraulic habitat characterisation was undertaken using an acoustic Doppler current profiler (ADCP) at a subset of impact and control sites.

A total of 29,073 fish from 16 species were sampled from 2013–2016. Bony herring (*Nematalosa erebi*) was the most abundant species sampled, followed by unspecked hardyhead (*Craterocephalus fulvus*) and Australian smelt (*Retropinna semoni*). Total fish abundance (all species combined) and assemblage structure (i.e. species composition and abundance) differed significantly between years driven by substantial increases in the abundance of medium- and small-bodied generalist species (i.e. bony herring, unspecked hardyhead, Australian smelt and Murray rainbowfish [*Melanotaenia fluviatilis*]), and decreases in abundances of the large-bodied golden perch and common carp (*Cyprinus carpio*) from 2013 to 2016. These changes in abundance reflect a transition from a period of high-flow (2010–2013) to relatively low-flow (2013–2016) in the River Murray, and the influence of hydrology on habitat availability and critical life history processes.

A substantial increase in the cover of floating, submerged and emergent macrophytes in the Pike Anabranch, in association with low-flow conditions immediately preceding monitoring in 2015 and 2016, increased the area of favourable habitat for small-bodied generalist species and likely facilitated increased abundance. In contrast, a lack of elevated within-channel flow events and overbank floods in the years immediately preceding 2015 and 2016 has likely resulted in lower recruitment and subsequently lower abundance of golden perch and common carp in 2015–2016, relative to 2013. This is supported by length-frequency analysis, with no juvenile golden perch

<150 mm total length sampled in 2015 or 2016. This pattern of change in fish assemblage structure appears consistent among sites across the floodplain geomorphic region of the lower River Murray (e.g. Chowilla, Katarapko), indicating the scale of influence of hydrology on biotic patterns is greater than the 'site-scale'. This has important implications for the management of these sites. Furthermore, the disparity between sampling years highlights the dynamism of the lower River Murray ecosystem and importance of understanding this dynamism, to elucidate potential intervention-induced alterations to biotic patterns in the future.

Juvenile Murray cod were sampled within the Pike Anabranch in 2015 and 2016, following previous non-detection at the site. This suggests certain creeks within the Pike system may currently provide habitats favourable for local-scale recruitment of the species. Encouragingly, impact sites, those where flow stands to be increased through interventions under RRP, are characterised by high proportions of cover of woody debris. Lotic habitats with high levels of cover of woody debris are preferred habitat for all life stages of Murray cod.

Whilst flow to the system has not yet been substantially altered, the Deep Creek Regulator was discharging approximately 250 $ML.d^{-1}$ during hydraulic habitat assessment in 2016, compared to approximately 150 $ML.d^{-1}$ during 2015. Creeks under the influence of increased discharge exhibited mean water velocities 0.01–0.1 $m.s^{-1}$ greater than in 2015, accompanied by greater levels of turbulence and circulation. Improvement of hydraulic complexity at sites that received marginally elevated discharge is suggestive of broader scale improvement to hydraulic habitat likely upon the completion of instream management interventions and greater flow delivery to the system under SARFIIP.

Data collected on fish assemblages, recruitment, habitat availability, fish–habitat associations and hydraulics from 2013–2016 provide a basis for assessing change in these parameters following completion of instream interventions under RRP and SARFIIP. Furthermore, the current data and methodology would provide a means of assessing ongoing site 'condition' in regards to fish-related targets under future operation of floodplain infrastructure as part of SARFIIP.

1. INTRODUCTION

1.1. Background

River regulation and water abstraction in the Murray-Darling Basin (MDB) have dramatically altered the natural flow regime of the lower River Murray (e.g. Maheshwari *et al.* 1995). The construction of a series of low-level weirs along the main channel of the lower River Murray in the 1920s and 1930s transformed a dynamic lotic environment to one characterised by a series of lentic weir pools with limited hydraulic complexity and increased water level stability (e.g. Walker 2006). The frequency and duration of floodplain inundation has decreased, whilst periods of elevated within-channel flow have also been reduced (e.g. Maheshwari *et al.* 1995). Subsequently, the ecological character of the lower River Murray has transformed, with declines in species adapted to lotic environments (e.g. Murray cod (*Maccullochella peelii*) and the riverine mussel (*Alathyria jacksoni*)) and increased prevalence of generalist species or those adapted to stable environments (e.g. common carp (*Cyprinus carpio*) and weeping willow (*Salix babylonica*)) (Walker 1985, Walker and Thoms 1993).

The Pike Anabranch and Floodplain is one of three large (~6,700 ha) anabranch systems (Chowilla, Katarapko and Pike) in the Riverland region of the lower River Murray, South Australia. The anabranch system bypasses Lock and Weir no. 5 and thus a head differential (>3 m) is created across the system, resulting in a diverse range of aquatic habitats, including fast-flowing creeks, slow-flowing creeks and backwaters. Flowing water habitats such as these are now absent under regulated conditions in the lower River Murray main channel.

Whilst the Pike Anabranch supports a diverse fish assemblage (Beyer *et al.* 2010) it is nevertheless considered to be highly degraded due to the impacts of river regulation. On a catchment-scale, river regulation and water abstraction in the MDB has reduced flooding frequency and duration, with various accompanying impacts (e.g. floodplain salinisation). On a local-scale, flow to the system was limited by the operational constraints of the inlet structures (i.e. Margaret Dowling inlet and Deep Creek inlet and associated bridges) and further fragmented by a range of additional structures (i.e. earthen levee banks, Snake Creek stock crossing and Coombs Bridge). Under low flows, these structures represent barriers to fish passage, restricting the movement of fish both within the system and between the anabranch system and River Murray main channel.

The Pike Anabranch system is now the focus of substantial environmental rehabilitation effort under both the *Riverine Recovery Project* (RRP; *Murray Futures Program*) and *South Australian Riverland Floodplain Integrated Infrastructure Project* (SARFIIP). Management interventions under RRP are primarily focused upon instream outcomes, including improving connectivity and the capacity to vary flow to the system, whilst interventions under SARFIIP are largely focused upon the installation and upgrade of specific structures to allow broad-scale engineered floodplain inundation. On-ground works under RRP commenced in 2013 and were completed in 2015. Major interventions under SARFIIP are expected to be ongoing from 2016 to 2019. Specific interventions under RRP were initially planned to include,

1. Early Works program: Upgrade of Deep Creek inlet regulator and associated bridge to improve hydraulic connectivity, increase flow volumes and facilitate fish passage (includes fishway construction on the Deep Creek Regulator).
2. Stage 1: Improved hydrological connectivity and fish passage throughout the Pike Anabranch system through removal/upgrades of Banks D, F, F1, H, G and Coombs Bridge.
3. Stage 2: Improved anabranch hydraulics during natural flood events through the replacement of Banks B, B2 and C (includes construction of fish friendly culverts).

Changes to the RRP and SARFIIP construction program during 2015 dictated that Banks D–G were not removed/upgraded under RRP, but will be removed upon the construction of the Tanyaca Creek regulator in 2019. The completed works under RRP have resulted in increased capacity to vary flow to the Pike Anabranch system (from ~300 $ML.day^{-1}$ to ~750 $ML.day^{-1}$) during periods of within-channel flow in the River Murray (i.e. <45,000 $ML.day^{-1}$) and the potential to influence the area of hydraulically complex lotic habitat within the system. Furthermore, the removal of banks and construction of fishways has improved connectivity and capacity for fish movement. Ultimately, the interventions will predominantly influence the inner part of the system (i.e. Deep Creek, Margaret Dowling Creek, Mundic Creek, Tanyaca Creek, Rumpagunyah Creek and the lower Pike River), potentially increasing the area of favourable habitat for a range of native fish species within the Pike system and facilitating fish movement within and between the Pike Anabranch and main channel. Nonetheless, as of autumn 2016, given Banks D–G were not removed/upgraded as initially planned, flow to the system has not been substantially altered from that prior to the upgrade of the Deep Creek regulator, and will not be increased until components of SARFIIP are completed.

An understanding of the influence of management interventions under RRP on ecological patterns and processes is fundamental to inform system operation and management. A three–year fish monitoring program, adopting a before-after-control-impact (BACI) experimental design, was initiated in 2013 (Bice *et al.* 2013), with the aims of assessing changes in fish assemblage structure, recruitment, habitat and fish–habitat associations in relation to RRP management interventions, as part of a broader package of investigations that also includes the assessment of the newly constructed Deep Creek fishway (Bice *et al.* 2016). Meeting these aims, however, was compromised by the changes in the RRP and SARFIIP construction programs. Nonetheless, the current report presents the findings of the three years of fish assemblage monitoring (2013–2016), which will represent 'reference' data to assess changes in site 'condition' following completion of RRP and SARFIIP in regards to fish-related objectives and targets.

1.2. Objectives

The objectives of the project were to investigate: 1) spatio-temporal variation in fish assemblage structure (i.e. species composition and abundance); 2) recruitment; and 3) habitat (vegetated and hydraulic) and fish-habitat associations, within the Pike Anabranch system from 2013 to 2016. It was hypothesised that increases in lotic habitat and increased connectivity will result in significant changes to fish assemblage structure and recruitment, habitat (vegetated and hydraulic) and fish-habitat associations, including increases in the abundance of species that prefer hydraulically diverse environments (e.g. Murray cod, golden perch). Whilst this hypothesis could not be tested at present, the data collected present a basis to do so in the future.

2. METHODS

2.1. Site selection

A range of reference (creek reference, *n* = 6 and river reference, *n* = 3) and impact (*n* = 9) sites were selected from the Pike Anabranch system and adjacent River Murray, to be sampled before and after the completion of interventions under RRP, congruent with the BACI experimental approach (Table 1; Figure 1). Impact sites were selected on creeks within the Pike Anabranch system most likely to experience alteration to connectivity, hydrology and hydraulic characteristics as a result of the interventions under the RRP. In contrast, reference sites were selected where the hydrology was unlikely to be influenced by interventions over the study period and included sites on creeks within the Pike Anabranch (creek reference sites) and sites on the main river channel (river reference sites). In 2013, Sites 1–16 were sampled; these sites were monitored again, whilst Sites 17 (Deep Creek) and 18 (Margaret-Dowling Creek) were also sampled in 2015 and 2016. Where possible, site selection followed Beyer *et al.* (2010). All sites were initially assigned to a mesohabitat category (i.e. fast-flowing habitats, slow-flowing habitats, backwaters and River Murray main channel habitats) by visual estimation following Beyer *et al.* (2010), but some were later quantified following hydraulic habitat characterisation. Sites were categorised based on mean water velocity (*sensu* Zampatti *et al.* 2011), where fast-flowing habitats were characterised as having mean velocities >0.18 m s^{-1}, slow-flowing habitats 0.05–0.18 m s^{-1} and backwaters <0.05 m s^{-1}. Sites in the River Murray are classified as ‘main channel’ mesohabitats (Table 1).

Table 1. Site number, site name, treatment (impact, creek reference and river reference sites), latitude and longitude and flow type (1 = fast flowing anabranches, 2 = slow flowing anabranches, 3 = backwaters, 4 = main channel) for sites sampled within the Pike Anabranch system in 2013. *indicates sites where ADCP transects were undertaken.

Site no.	Site name	Treatment	Latitude	Longitude	Flow type
1	Mundic H Bank access	Impact	S34˚12.984’	E140˚47.105’	3
2	Downstream Bank D	Impact	S34˚13.599’	E140˚46.203’	3
3	Tanyaca Creek*	Impact	S34˚13.388’	E140˚45.495’	3
4	Tanyaca Creek (d/s horseshoe)*	Impact	S34˚14.404’	E140˚45.074’	2
5	Lower Pike*	Impact	S34˚15.580’	E140˚45.554’	2
6	Lower Pike (Simarloo)*	Impact	S34˚16.459’	E140˚43.974’	2
7	Lower Pike (d/s of Lyrup Rd)	Impact	S34˚15.712’	E140˚41.223’	3
8	Mundic to Pike Cutting*	Reference (creek)	S34˚11.966’	E140˚47.624’	1
9	Upper Pike (d/s) Pike Lagoon	Reference (creek)	S34˚12.927’	E140˚48.020’	2
10	Coomb’s Bridge (d/s bridge)*	Reference (creek)	S34˚13.435’	E140˚48.537’	2
11	Lower Snake Creek	Reference (creek)	S34˚14.267’	E140˚46.262’	3
12	Upper Pike (cliffs)	Reference (creek)	S34˚14.262’	E140˚49.550’	2
13	Pike River (downstream of Col Col)	Reference (creek)	S34˚15.304’	E140˚46.153’	3
14	Main channel Murray (u/s Lock 5)	Reference (river)	S34˚11.028’	E140˚46.421’	4
15	Main channel Murray (d/s Lk 5)	Reference (river)	S34˚13.550’	E140˚44.150’	4
16	Main channel Murray (d/s Pike Junction)	Reference (river)	S34˚15.268’	E140˚40.646’	4
17	Deep Creek	Impact	S34˚11.455’	E140˚46.506	1
18	Margaret-Dowling Creek	Impact	S34˚11.169’	E140˚47.097	1

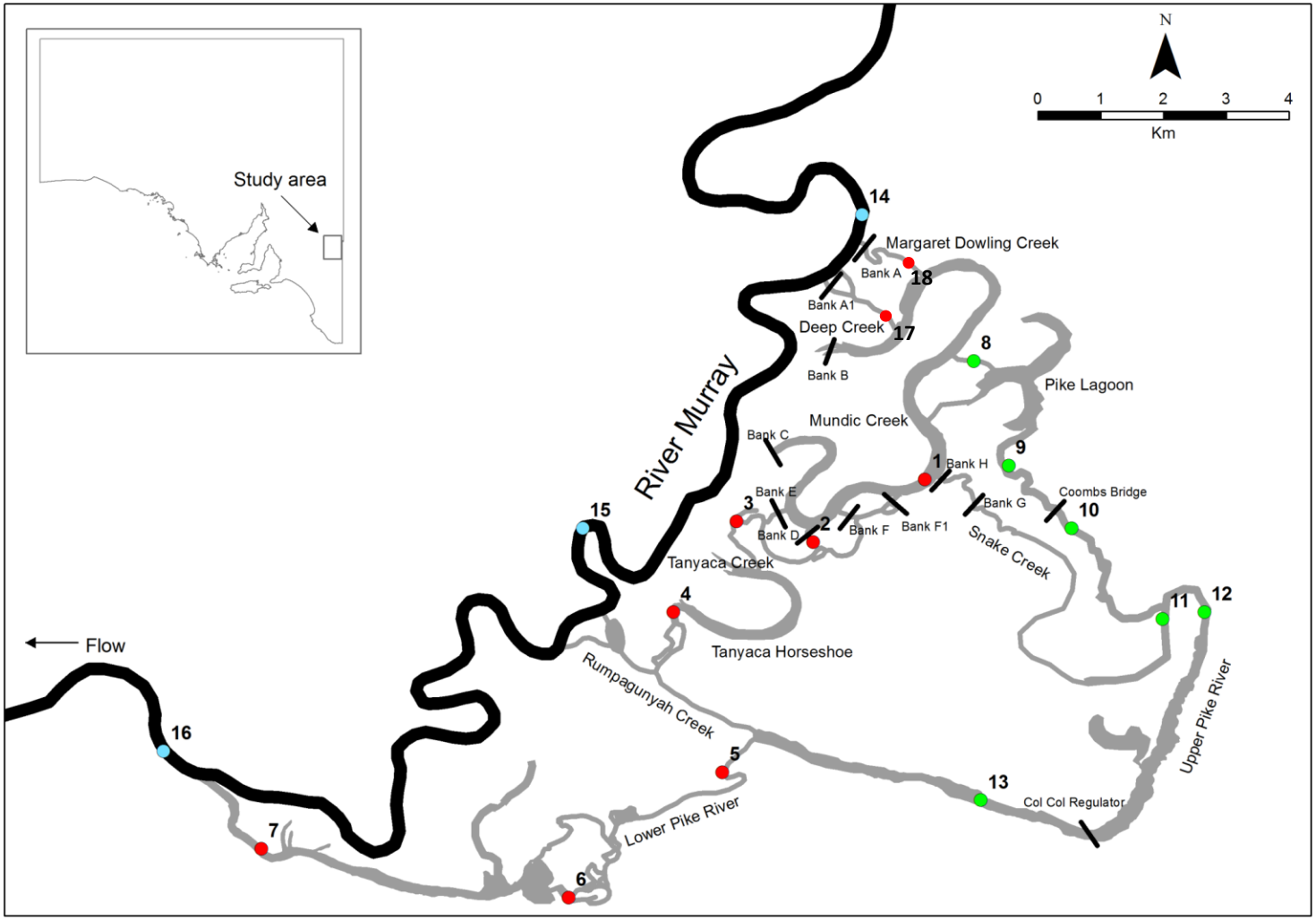

Figure 1. Map of the Pike Anabranch and adjacent River Murray showing the location of impact (red circles), creek reference (green circles) and river reference (blue circles) sites sampled in 2013, 2015 and 2016 (NOTE: sites 17 and 18 were not sampled in 2013). The position of earthen banks and regulators is also indicated (NOTE: Coombs Bridge has now been removed, whilst structures at banks B and C, and Deep Creek, have been upgraded).

2.2. Data collection

Fish assemblage structure and recruitment

Fish assemblages at all sites were sampled in April in 2013 (08/04–19/04), 2015 (07/04–23/04) and 2016 (04/04–14/04) using standardised boat electrofishing. This is a proven method to effectively and rapidly sample both large and small-bodied fish in the littoral zone of turbid lowland rivers and creeks (Faragher and Rodgers 1997), and is commonly used in anabranches and the main channel of the lower River Murray (Baumgartner *et al.* 2008, Zampatti *et al.* 2011). Fish were sampled from the littoral zone using a Smith-Root® 5 kW electrofishing unit. At each site, 12 (six on each bank) x 90 second (power on time) 'electrofishing shots' were conducted during daylight hours and fish were dip-netted by a team of two netters and placed in a live well. Only 8 shots could be conducted at Site 18 in 2015 and 2016 due to a snag obstructing the upstream portion of the creek. For each electrofishing shot, all sampled fish were identified, enumerated and a sub-sample of up to 20 individuals per species measured (mm) for fork length (FL) or total length (TL) depending on tail morphology. Any positively identified fish unable to be dip netted were recorded as 'observed' and included in abundance measures.

Instream habitat availability

Simultaneous to electrofishing surveys, quantitative visual assessments of percentage cover of instream microhabitat types (vegetation and structural elements) were undertaken within the area of each electrofishing shot. Vegetation was recorded to individual taxa and categorised based on the following functional groups: emergent, submerged, floating, amphibious, terrestrial and floodplain taxa (modified from classification framework devised by Brock and Casanova (1997) to suit plant communities of the lower River Murray). Where necessary, submerged vegetation was sampled using a van Veen grab to verify identification to species. Woody debris, tree roots, rock and man-made pontoons were classified as 'structural' microhabitats. Woody debris were further categorised depending on the size of the wood (i.e. WD 1: twigs and branches with diameters < 1 cm, WD 2: branches with diameters 1–5 cm and WD 3: branches and trunks with diameters > 5 cm). The remaining area that was neither vegetated nor contained structural habitat was classified as 'open water'.

Hydraulic habitat characterisation

Hydraulic habitat was characterised in all years, but the method used in 2015 and 2016 was refined from that of 2013. Cross-sectional velocity profiles were measured at seven sites (five

impact and two creek reference) (Table 1) using a boat mounted SonTek River Surveyor M9 acoustic Doppler current profiler (ADCP). At each site, three transects were undertaken separated by approximately 100 m (in 2013, one transect was undertaken per site). For specific details on the operation of ADCP units see Shields and Rigby (2005). The ADCP records various data including depth, heading, echo intensity and velocity, in several planes, and can generate cross-sectional velocity profiles of streams with velocity readings provided across grided 'cells'. These data can also be used to investigate complex flow phenomena such as turbulence and circulation or flow rotation (e.g. eddies) (Crowder and Diplas 2002), which may be biologically relevant to fish assemblage patterns and vegetation cover.

Data generated from ADCP transects were first viewed in the SonTek ADCP software package RiverSurveyor Live. Data were then exported to MATLAB (The Mathworks Inc. 2010) and interpolated across grids with equal cell sizes using the Delaney triangulation scattered data function, to produce cross-sectional velocity plots. Output data were then used to calculate the following hydraulic metrics 1) discharge ($m^3.s^{-1}$), 2) mean depth (m), 3) cross-sectional area (m^2), 4) mean velocity (U, $m.s^{-1}$), 5) modified vertical circulation metric (M_3, s^{-1}), 6) modified horizontal circulation metric (M_4, s^{-1}), 7) Reynolds number (*Re*), and 8) Froude number (*Fr*).

The vertical and horizontal modified circulation metrics are spatial hydraulic metrics developed by Crowder and Diplas (2000) to quantify flow complexity over a defined area; in this case, river cross-sections as measured by ADCP transects. The modified circulation metrics expand on the point calculation of vorticity, which is defined as twice the rate at which a fluid rotates about its vertical axis (Crowder and Diplas 2000, 2002). Vorticity is a point measure, but the modified circulation metrics (M_3 and M_4) (after Shields and Rigby 2005) build upon the calculation of vorticity and represent a weighted average of absolute vorticity (i.e. flow rotation) in the vertical and horizontal planes per unit area, transverse to the channel, and are a measure of the strength and frequency of eddies in a river cross-section (Figure 2). Calculation of M_3 is explained by Equation 1, where w represents velocity in the vertical plane z and v represents velocity in the lateral plane y. Calculation of M_4 is explained by Equation 2 where v represents velocity in the lateral plane y and u represents velocity in the lateral plane x. Absolute values of velocity are used so that the direction of calculation (i.e. clockwise or counter-clockwise) does not result in the cancellation of eddies of equal strength in opposing directions. Higher values of M_3 and M_4 indicate greater frequency and strength of eddies or greater levels of circulation (i.e. flow rotation) within a cross-section. Crowder and Diplas (2002) present an example of utilising M_3 to describe the hydraulic habitat surrounding a series of brown trout (*Salmo trutta*) redds (i.e. spawning sites)

relative to reaches without redds. Furthermore, this metric has been adopted by Shields and Rigby (2005) to analyse river habitat quality and found to be a good discriminator of differences in hydraulic conditions between modified and natural stream reaches.

Equation 1. $$M_3 = \frac{\sum\left|\left(\frac{\Delta w}{\Delta y} - \frac{\Delta v}{\Delta z}\right)\right| * \Delta y * \Delta z}{\sum \Delta y * \Delta z}$$

Equation 2. $$M_4 = \frac{\sum\left|\left(\frac{\Delta v}{\Delta x} - \frac{\Delta u}{\Delta y}\right)\right| * \Delta x * \Delta y}{\sum \Delta x * \Delta y}$$

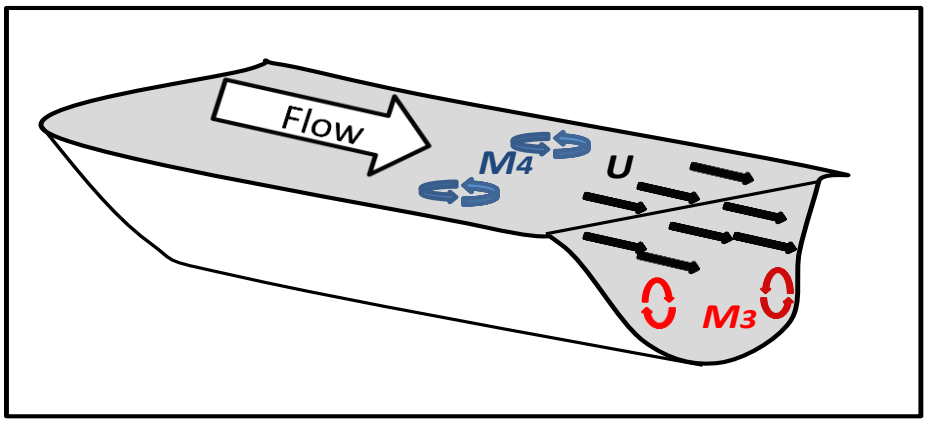

Figure 2. Schematic representation of a river reach and a subset of the hydraulic metrics measured (after Shields and Rigby 2005), downstream cross-sectional velocity (*U*) and vertical (M_3) and horizontal (M_4) modified circulation metrics, which represent the area weighted frequency and strength of eddies within a cross-section.

Reynolds number (*Re*) is a dimensionless metric that indicates whether flow in a channel is laminar or turbulent. In any open stream, flow is almost never laminar and thus the transition from laminar to turbulent flow is not of great importance (Gordon *et al.* 2004). Nonetheless, greater values of Reynolds number indicate greater levels of turbulence. Reynolds number is calculated using Equation 3, where *U* represents downstream cross-sectional velocity, *L* represents the hydraulic radius of a cross section (i.e. the cross-sectional area of the channel divided by the wetted perimeter [the river bed]) and *v* represents kinematic viscosity of water.

Equation 3. $$Re = \frac{U * L}{v}$$

Froude number (*Fr*) is a dimensionless metric that indicates the ratio of inertial to gravitational forces, where gravity encourages water to flow down an elevation gradient and inertial forces indicate the waters compulsion to follow this path (Gordon *et al.* 2004). The Froude number is calculated using Equation 4 where *U* represents downstream cross-sectional velocity, *D* represents average channel depth and *g* acceleration due to gravity (i.e. 9.81 $m.s^{-1}$). Values of *Fr* > 1 indicate supercritical or 'rapid' flow, whilst values < 1 indicate subcritical or 'tranquil' flow (Gordon *et al.* 2004). Much flow in large rivers like the lower River Murray, particularly under low flow, is likely to be subcritical, but higher relative values indicate a greater prevalence of faster flowing habitats and in streams can indicate a greater prevalence of 'riffles' over 'pool' habitat (Lamouroux and Souchon 2002).

Equation 4. $$\boldsymbol{Fr = \frac{U}{\sqrt{g * D}}}$$

2.3. Data analysis

Spatio-temporal variation in fish assemblages was investigated by assessing changes in total fish abundance (all species combined), species richness and fish assemblage structure (i.e. species composition and individual species abundance). Differences in the total fish abundance ($fish.site^{-1}$, all species combined) between years and treatments were analysed using uni-variate two-factor PERMANOVA (permutational ANOVA and MANOVA), in the software package PRIMER v. 6.1.12 and PERMANOVA+ (Anderson *et al.* 2008). These analyses were performed on fourth-root transformed relative abundance data and a Euclidean distance similarity matrix. When significant differences occurred, pairwise comparisons were undertaken to determine 'groups' that were statistically different. To allow for multiple comparisons, a false discovery rate (FDR) procedure presented by Benjamini and Yekutieli (2001), hereafter the 'B–Y method' correction, was adopted ($\alpha = \sum_{i=1}^{n}(1/i)$; e.g. for $n_{comparisons}$ = 3, B-Y method α = 0.05/ (1/1 + 1/2 + 1/3) = 0.027) (Benjamini and Yekutieli 2001, Narum 2006). Species richness was qualitatively compared between years.

Differences in the structure of fish assemblages (i.e. species composition and abundance) and microhabitat cover (i.e. microhabitat type and proportional cover) was investigated using two-factor (i.e. year and treatment) PERMANOVA (Anderson 2001, Anderson and Ter Braak 2003). Analyses were performed on fish relative abundance data (fish.minute of $electrofishing^{-1}$) and microhabitat cover proportions, which were fourth root and arcsine transformed, respectively.

PERMANOVA was performed on Bray-Curtis similarity matrices (Bray and Curtis 1957). Non-Metric Multi-Dimensional Scaling (MDS), generated from the same matrices was used to visualise assemblages and microhabitat cover from different treatments (i.e. impact, creek reference, river reference). When significant differences occurred in main tests, pairwise comparisons were undertaken to determine 'groups' that were statistically different. To allow for multiple comparisons, the B–Y method FDR correction for significance was adopted. When differences occurred in fish assemblages or microhabitat cover between treatments, Similarity Percentages (SIMPER) analysis was used to determine the fish species or microhabitat types contributing to these differences and a 40% cumulative contribution cut-off was applied.

When differences occurred in fish assemblages and microhabitat cover between years and treatments, Indicator Species Analysis (ISA) (Dufrene and Legendre 1997) was also used to determine what fish species and microhabitat types characterised the assemblage/microhabitat cover in certain years and treatments, using the software package PCOrd v 5.12 (McCune and Mefford 2006). ISA combines information on the concentration of species abundance in a particular group and the faithfulness of occurrence of a species in a particular group (McCune *et al.* 2002). A perfect indicator of a particular group should be faithful to that group (always present) and exclusive to that group (never occurring in other groups) (McCune *et al.* 2002). This test produces indicator values (IV) for each species or microhabitat type in each group on the basis of the standards of the 'perfect indicator'. Perfect indication (100%) would occur when a species is always present in a statistical group and not in any other groups. Only species and microhabitats with an IV > 20 were accepted. Statistical significance ($\alpha = 0.05$) of each indicator value was tested by the Monte Carlo (randomisation) technique, where the real data are compared against (in the case for this study) 5000 runs of randomised data (Dufrene and Legendre 1997).

ISA was also used to investigate if the presence or absence of specific fish species was significantly associated (positively or negatively) with particular microhabitat types in each year. This test was used to determine whether a microhabitat type had a significantly greater proportion of cover when a fish species was either present or absent. Fish–microhabitat associations were investigated with all treatments pooled, and all microhabitats that contributed mean proportional cover of <0.01% and fish species with <5 individuals sampled were excluded from analyses. This analysis was undertaken separately for each fish species. Only microhabitats deemed significant ($\alpha = 0.05$) and with IV > 20 were considered to represent potential fish–microhabitat associations.

3. RESULTS

3.1. Hydrology

River Murray discharge to South Australia (QSA) has been highly variable since 2010 (Figure 3). Following an extended period of low discharge from 1997–2010, discharge increased dramatically in late 2010, peaking at ~93,000 ML.day^{-1} in February 2011, and resulting in widespread overbank flooding in the lower River Murray. This was followed by a subsequent smaller overbank flood in autumn 2012 and generally elevated discharge throughout much of 2012. Sampling in autumn 2013 occurred immediately following these high flow events, but during discharge (mean = 7,432 ML.day^{-1}) that approximated summer entitlement flow. Discharge from autumn 2013 to autumn 2015 was generally lower than the preceding years and characterised by within-channel flow events of ~25,000 and 18,000 ML.day^{-1} in September 2013 and August 2014, respectively. Nonetheless, discharge for much of this period was <10,000 ML.day^{-1} and during subsequent sampling in autumn 2015, approximated summer entitlement flow (mean = 6,427 ML.day^{-1}). Similarly, discharge throughout 2015/16 was predominantly <10,000 ML.day^{-1} and during sampling in autumn 2016, approximated summer entitlement flow (mean = 5,812 ML.day^{-1}). Flow to the Pike Anabranch was maintained at ~300 ML.day^{-1} during sampling in 2013 and 2015, but was ~400 ML.day^{-1} in 2016, following completion of the Deep Creek Regulator and a modest increase in inflow.

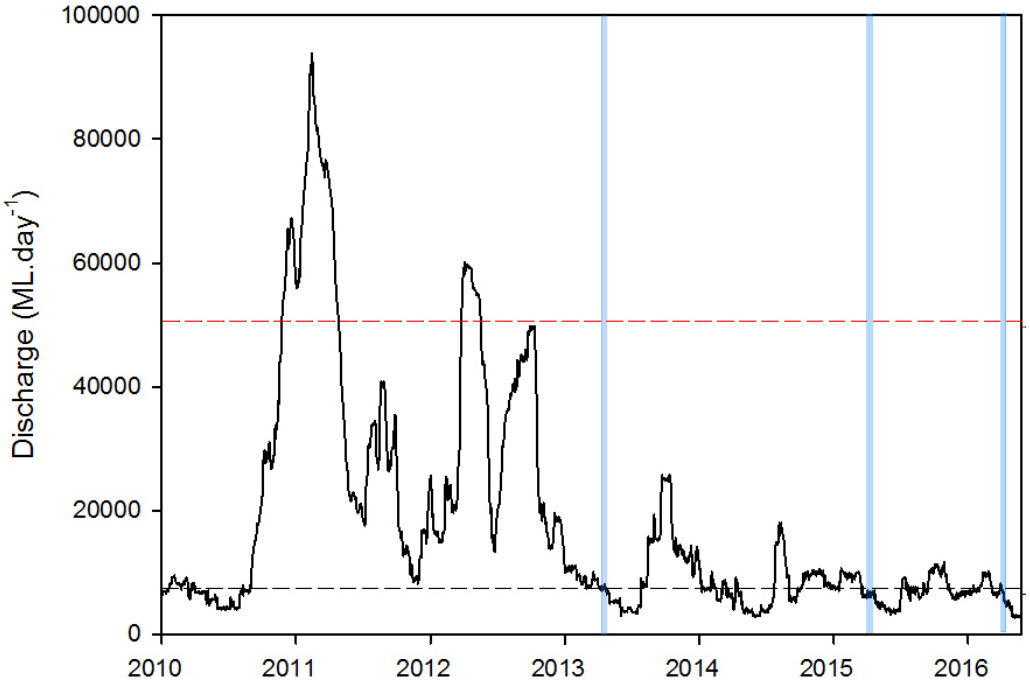

Figure 3. Daily River Murray discharge (ML.day^{-1}) to South Australia (QSA) from January 2010 to April 2016. Sampling events are indicated by the vertical blue lines. Dashed red line indicates approximate 'bank-full' flow in the lower River Murray, beyond which floodplain inundation occurs and the dashed black line represents summer entitlement flow (~7000 ML.day^{-1}).

3.2. Catch summary

A total of 29,073 fish from 16 species were sampled in 2013 (3,945 fish, 14 species), 2015 (10,668 fish, 15 species) and 2016 (14,460 fish, 16 species) (Tables 2–4). Bony herring (*Nematalosa erebi*) was the most abundant species sampled (~49% of total catch), followed by unspecked hardyhead (*Craterocephalus fulvus*; ~20%) and Australian smelt (*Retropinna semoni*; ~10%), and non-native goldfish (*Carassius auratus*; ~6%). The remaining 12 species comprised ~15% of the total catch.

Most species were widespread and sampled from ≥10 sites in each year (Tables 2–4), including bony herring (16–18 sites), common carp (15–18 sites), unspecked hardyhead (14–18 sites), goldfish (12–18 sites), Australian smelt (10–18 sites), Murray rainbowfish (*Melanotaenia fluviatilis*; 12–16 sites), golden perch (*Macquaria ambigua ambigua*; 11–14 sites), carp gudgeon complex (*Hypseleotris* spp.; 8–18 sites) and eastern gambusia (*Gambusia holbrooki*; 7–16 sites). Conversely, the remaining species were typically sampled from a restricted number of sites, including Murray cod (0–2 sites), silver perch (*Bidyanus bidyanus*; 2–5 sites), freshwater catfish (*Tandanus tandanus*; 4–7 sites), flat-headed gudgeon (*Philypnodon grandiceps*; 1–10 sites), dwarf flat-headed gudgeon (*Philypnodon macrostomus*; 2 sites), redfin perch (*Perca fluviatilis*; 1–2 sites) and oriental weatherloach (*Misgurnis anguillicaudatus*; 0–1 site). Most species were sampled across all mesohabitat types, with the exception of Murray cod, silver perch and freshwater catfish (not sampled from backwaters), redfin perch (not sampled from the river main channel) and oriental weatheloach (only sampled from backwaters).

Table 2. Summary of species and total numbers of fish captured across 16 sampling sites in Pike Anabranch system and adjacent River Murray in autumn 2013. Mesohabitats: F = fast-flowing, S = slow-flowing, B = backwater and R = river main channel. *denotes non-native species.

		Creek reference						River reference			Impact									
	Site No.	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**17**	**18**	**Total**
	Mesohabitat	**F**	**S**	**S**	**B**	**S**	**B**	**R**	**R**	**R**	**B**	**B**	**B**	**S**	**S**	**S**	**B**	**F**	**F**	
Common name	**Scientific name**																			
Murray cod	*Maccullochella peelii*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-	-	**0**
Golden perch	*Macquaria ambigua ambigua*	27	30	19	0	4	0	8	14	15	1	1	49	34	42	20	15	-	-	**279**
Silver perch	*Bidyanus bidyanus*	2	1	1	0	2	0	0	1	0	0	0	0	0	0	0	0	-	-	**7**
Freshwater catfish	*Tandanus tandanus*	1	1	1	0	0	0	1	2	4	0	0	0	0	1	0	0	-	-	**11**
Bony herring	*Nematalosa erebi*	402	76	93	50	62	10	28	401	162	106	109	96	178	205	149	176	-	-	**2,304**
Australian smelt	*Retropinna semoni*	1	0	2	5	0	9	0	9	11	0	1	2	2	0	0	8	-	-	**50**
Murray rainbowfish	*Melanotaenia fluviatilis*	11	6	5	0	0	0	22	3	15	2	1	3	6	0	6	28	-	-	**108**
Flat-headed gudgeon	*Philypnodon grandiceps*	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-	-	**1**
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	-	-	**2**
Unspecked hardyhead	*Craterocephalus fulvus*	10	2	20	7	4	1	2	0	6	73	2	3	0	1	7	6	-	-	**144**
Carp gudgeon complex	*Hypseleotris* spp.	6	0	3	0	0	0	1	0	0	15	1	4	0	3	0	2	-	-	**35**
Common carp*	*Cyprinus carpio*	68	49	39	30	47	0	23	13	9	16	55	296	51	64	81	24	-	-	**865**
Eastern gambusia*	*Gambusia holbrooki*	0	0	2	3	0	0	0	2	1	1	0	1	0	2	0	0	-	-	**12**
Goldfish*	*Carassius auratus*	14	1	3	22	19	0	1	0	0	1	9	39	9	6	1	0	-	-	**125**
Redfin perch*	*Perca fluviatilis*	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	-	-	**2**
Oriental weatherloach*	*Misgurnus anguillicaudatus*	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	-	-	**0**
	Total number	543	167	188	117	138	20	86	445	224	215	179	494	281	324	264	260	**-**	**-**	**3,945**
	Species richness	11	9	11	6	6	3	8	8	9	8	8	10	6	8	6	8	**-**	**-**	**14**

Table 3. Summary of species and total numbers of fish captured across 18 sampling sites in Pike Anabranch system and adjacent River Murray in autumn 2015. Mesohabitats: F = fast-flowing, S = slow-flowing, B = backwater and R = river main channel. *denotes non-native species.

		Creek reference						River reference			Impact									
	Site No.	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**17**	**18**	**Total**
	Mesohabitat	**F**	**S**	**S**	**B**	**S**	**B**	**R**	**R**	**R**	**B**	**B**	**B**	**S**	**S**	**S**	**B**	**F**	**F**	
Common name	**Scientific name**																			
Murray cod	*Maccullochella peelii*	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	2
Golden perch	*Macquaria ambigua ambigua*	16	9	0	0	0	0	9	8	9	5	0	5	8	12	6	2	1	3	93
Silver perch	*Bidyanus bidyanus*	1	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	5
Freshwater catfish	*Tandanus tandanus*	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	4
Bony herring	*Nematalosa erebi*	1535	159	495	112	866	77	73	1002	130	11	111	54	187	209	298	47	599	375	6340
Australian smelt	*Retropinna semoni*	127	61	64	71	114	31	2	199	20	54	8	7	38	4	22	3	124	55	1004
Murray rainbowfish	*Melanotaenia fluviatilis*	137	69	38	9	42	0	120	88	48	11	0	18	69	7	19	17	37	74	803
Flat-headed gudgeon	*Philypnodon grandiceps*	0	0	2	0	0	0	0	0	0	2	0	1	0	0	2	0	0	0	7
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2
Unspecked hardyhead	*Craterocephalus fulvus*	77	65	108	28	79	34	21	222	85	41	21	27	159	8	37	58	11	67	1148
Carp gudgeon complex	*Hypseleotris spp*	27	7	27	3	13	0	1	0	2	13	20	19	1	0	3	1	3	1	141
Common carp*	*Cyprinus carpio*	23	26	23	6	21	7	22	32	6	10	28	22	8	7	24	14	34	13	326
Eastern gambusia*	*Gambusia holbrooki*	9	7	4	0	4	0	4	2	0	1	114	7	7	5	2	0	0	9	175
Goldfish*	*Carassius auratus*	114	53	28	11	1	8	2	7	9	11	156	73	22	7	36	22	55	1	616
Redfin perch*	*Perca fluviatilis*	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2
Oriental weatherloach	*Misgurnus anguillicaudatus*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total number	**2069**	**456**	**791**	**240**	**1141**	**157**	**254**	**1563**	**309**	**160**	**458**	**233**	**499**	**259**	**449**	**165**	**865**	**600**	**10668**
	Species richness	**13**	**9**	**10**	**7**	**9**	**5**	**9**	**10**	**8**	**11**	**7**	**10**	**9**	**8**	**10**	**9**	**9**	**11**	**15**

Table 4. Summary of species and total numbers of fish captured across 18 sampling sites in Pike Anabranch system and adjacent River Murray in autumn 2016. Mesohabitats: F = fast-flowing, S = slow-flowing, B = backwater and R = river main channel. *denotes non-native species.

		Creek reference						River reference			Impact									
	Site No.	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**17**	**18**	**Total**
	Mesohabitat	**F**	**S**	**S**	**B**	**S**	**B**	**R**	**R**	**R**	**B**	**B**	**B**	**S**	**S**	**S**	**B**	**F**	**F**	
Common name	**Scientific name**																			
Murray cod	*Maccullochella peelii*	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**2**
Golden perch	*Macquaria ambigua ambigua*	7	0	0	0	0	0	7	4	4	0	0	2	8	11	12	7	1	3	**66**
Silver perch	*Bidyanus bidyanus*	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	**2**
Freshwater catfish	*Tandanus tandanus*	1	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	**4**
Bony herring	*Nematalosa erebi*	821	80	67	65	64	173	11	1509	213	59	212	59	622	969	210	131	161	80	**5506**
Australian smelt	*Retropinna semoni*	581	24	46	23	66	25	2	237	14	95	51	22	35	33	41	9	185	330	**1819**
Murray rainbowfish	*Melanotaenia fluviatilis*	96	54	23	6	13	0	50	32	28	67	0	8	31	16	22	38	31	25	**540**
Flat-headed gudgeon	*Philypnodon grandiceps*	2	0	0	2	0	1	1	1	1	15	0	1	2	0	0	1	0	0	**27**
Dwarf flat-headed gudgeon	*Philypnodon macrostomus*	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	**3**
Unspecked hardyhead	*Craterocephalus fulvus*	372	508	321	231	102	204	261	263	400	394	324	36	111	280	322	193	118	254	**4694**
Carp gudgeon complex	*Hypseleotris spp*	25	4	28	8	5	3	1	18	8	56	5	39	6	4	13	3	7	5	**238**
Common carp*	*Cyprinus carpio*	10	8	17	17	7	18	12	21	9	20	17	127	29	16	20	13	15	20	**396**
Eastern gambusia*	*Gambusia holbrooki*	34	5	4	4	17	0	11	22	13	0	4	5	22	16	37	12	10	10	**226**
Goldfish*	*Carassius auratus*	121	22	32	51	34	60	4	16	35	1	148	273	42	20	32	38	2	3	**934**
Redfin perch*	*Perca fluviatilis*	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
Oriental weatherloach*	*Misgurnus anguillicaudatus*	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	**2**
	Total number	**2070**	**707**	**539**	**407**	**313**	**484**	**360**	**2128**	**725**	**708**	**763**	**572**	**908**	**1393**	**709**	**445**	**530**	**730**	**14,460**
	Species richness	**12**	**10**	**8**	**9**	**10**	**7**	**10**	**14**	**10**	**9**	**8**	**10**	**10**	**9**	**9**	**10**	**9**	**9**	**16**

3.3. Spatio-temporal variability in fish assemblages

3.3.1. Total fish abundance and species richness

Total fish abundance (number of fish.site^{-1}, all species combined) was significantly different between years (*Pseudo-*$F_{2, 50}$ = 9.73, p = 0.003), but not between treatments (*Pseudo-*$F_{2, 50}$ = 0.09, p = 0.921), and the interaction between year and treatment was non-significant (*Pseudo-*$F_{4, 50}$ = 0.10, p = 0.589). Pairwise comparisons (B–Y corrected α = 0.027) indicated total abundance was similar between 2015 and 2016, but both years were significantly different from 2013. Indeed, total abundance in 2015 and 2016 was 2.4 and 3.3 times greater than abundance in 2013, respectively (Figure 4). Species richness increased from 2013 (14 species) to 2015 (15 species) to 2016 (16 species). All species sampled in 2013 were detected in subsequent years, but Murray cod were only detected in 2015 and 2016, and oriental weatherloach only in 2016 (Tables 2–4).

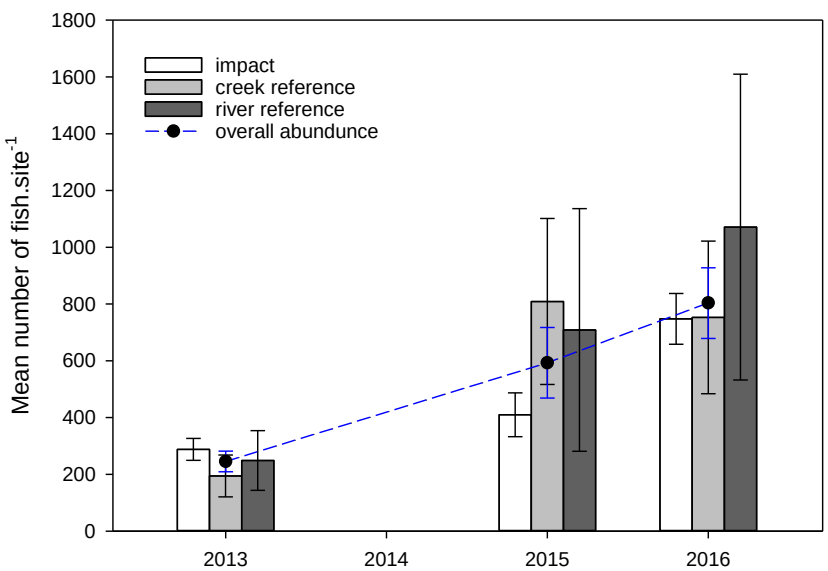

Figure 4. Relative abundance (fish.site^{-1} ± standard error [SE]) of fish (all species combined) sampled from impact (*white* bar*)*, creek reference (*light grey* bar) and river reference sites (*dark grey* bar), and overall site abundance (treatments combined) in the Pike Anabranch system and adjacent River Murray in 2013, 2015 and 2016.

3.3.2. Assemblage structure

Data from Site 13 in 2013 (creek reference, Pike River downstream of Col Col) represented a statistical outlier due to the few species and low numbers of fish sampled; subsequently, those data were removed from analyses as they may mask differences between years and treatments. MDS ordination of fish assemblage data exhibited grouping of samples by year (Figure 5), supported by PERMANOVA, which detected significant differences between years ($Pseudo\text{-}F_{2, 50}$ = 10.87, $p < 0.001$) and treatments ($Pseudo\text{-}F_{2, 50}$ = 3.04, $p = 0.006$), with no significant interaction ($Pseudo\text{-}F_{4, 50}$ = 0.71, $p = 0.808$). Pairwise comparisons revealed that the assemblage sampled in 2013 differed from both 2015 ($t = 2.98$, $p < 0.001$; B–Y method corrected α = 0.027) and 2016 ($t = 4.45$, $p < 0.001$), whilst assemblages in 2015 and 2016 were also significantly different ($t = 1.96$, $p = 0.002$). Pairwise comparison of treatments indicted that assemblages from river reference sites differed significantly from both impact ($t = 1.76$, $p = 0.010$; B–Y method corrected α = 0.027) and creek reference sites ($t = 1.85$, $p = 0.015$), but impact and creek reference sites were similar ($t = 1.65$, $p = 0.031$).

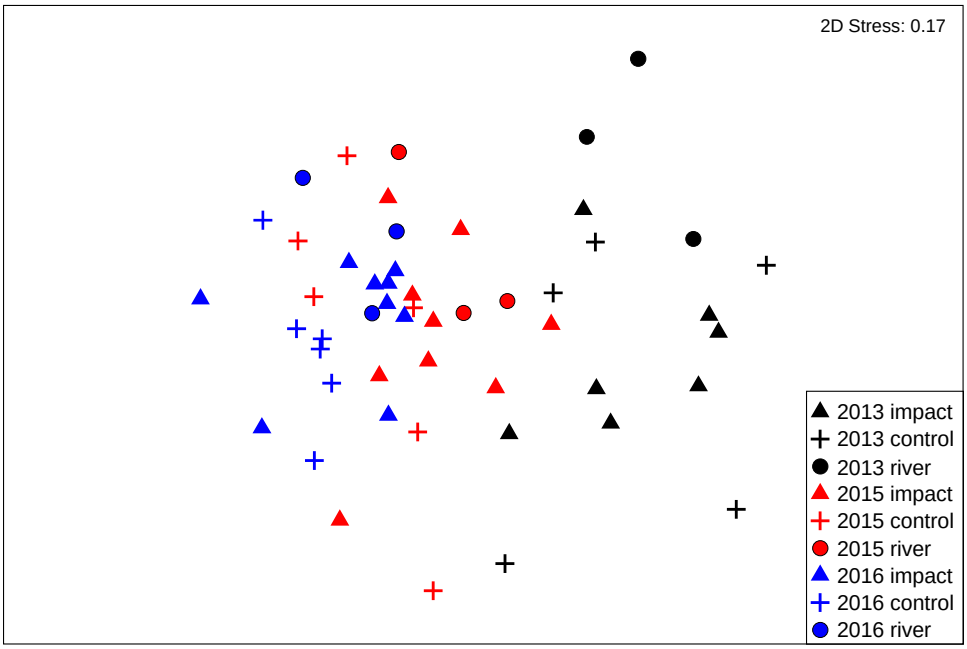

Figure 5. Non-metric multi-dimensional scaling (MDS) plot of fish assemblages sampled using electrofishing from impact (*triangles*), creek reference (*crosses*) and river reference sites (*circles*) during autumn 2013 (*black* symbols), 2015 (*red* symbols) and 2016 (*blue* symbols).

SIMPER indicated that the differences in assemblages between 2013 and subsequent years was due to greater abundances of small-bodied species in 2015 and 2016, namely Australian smelt, unspecked hardyhead, Murray rainbowfish and goldfish in 2015, and Australian smelt, unspecked hardyhead, eastern gambusia and goldfish in 2016 (Figure 6a). Differences between assemblages in 2015 and 2016 were driven by greater relative abundance of unspecked hardyhead and Australian smelt in 2016, but greater abundance of bony herring and Murray rainbowfish in 2015. ISA determined the assemblage in 2013 was characterised by greater abundance of the large-bodied golden perch (IV = 63.3, $p < 0.001$), common carp (IV = 58.8, $p < 0.001$) and freshwater catfish (IV = 28.8, $p = 0.044$), the assemblage in 2015 by Murray rainbowfish (IV = 49.6, $p = 0.017$), and the assemblage in 2016 by was characterised by greater abundance of Australian smelt (IV = 64.5, $p = 0.007$), unspecked hardyhead (IV = 77.8, $p < 0.001$), goldfish (IV = 54.6, $p = 0.047$), carp gudgeon (IV = 53.6, $p = 0.047$) and flat-headed gudgeon (IV = 42.1, $p = 0.009$) (Figure 6a). Changes in species-specific abundance were most appreciable for Australian smelt and unspecked hardyhead, with increases in abundance between 2013 and 2016 by factors of 38 and 27, respectively, whilst the abundances of golden perch and common carp in 2016 were 20% and 40% of abundance in 2013, respectively (Figure 6a)

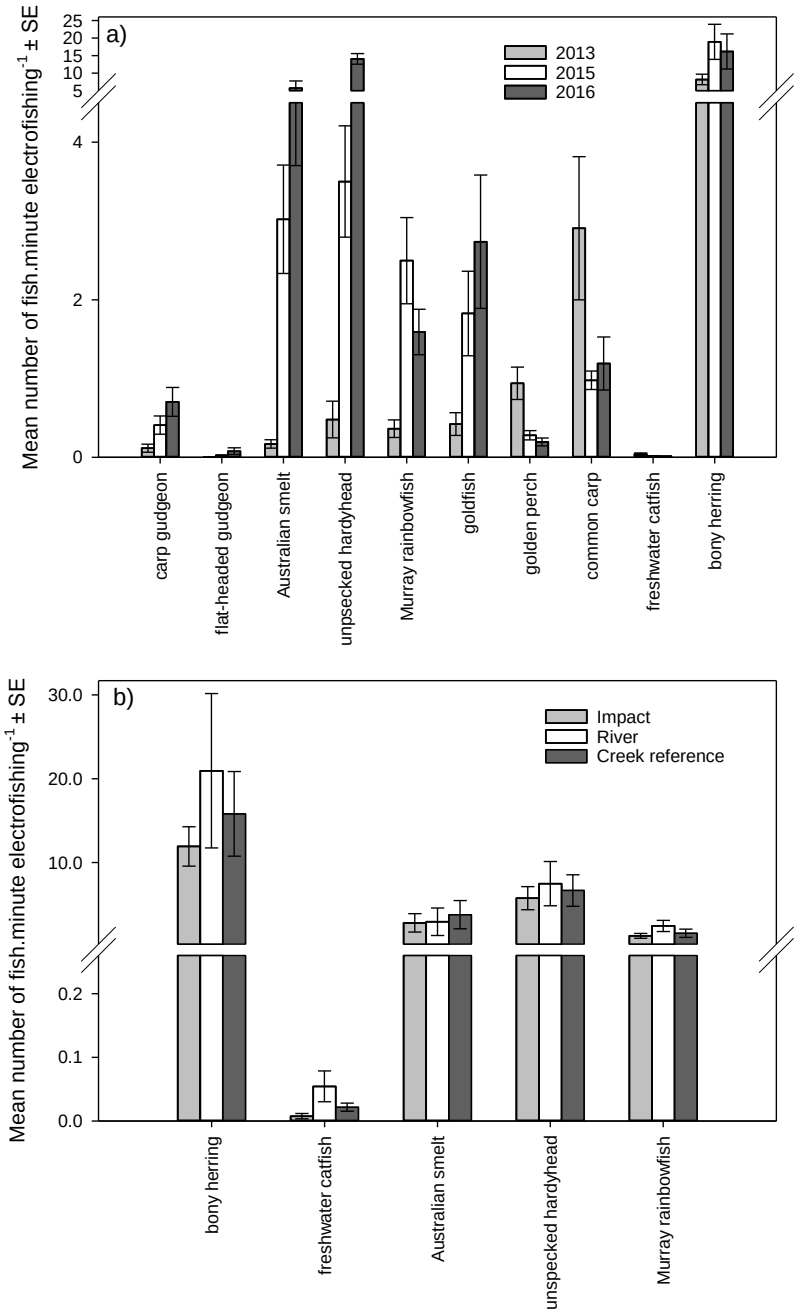

Figure 6. Relative abundance (number of fish.minute electrofishing^{-1}.electrofishing shot^{-1} ± SE) of species determined to contribute to differences between fish assemblages (SIMPER) or characterise the assemblage (ISA) between a) 2013 (*light grey* bar), 2015 (*white* bar) and 2016 (*dark grey* bar), and b) impact (*light grey* bar), river reference (*white* bar) and creek reference (*dark grey* bar) treatments.

SIMPER indicated differences in assemblages between river control and both impact and creek reference sites was due to greater abundances of Australian smelt, unspecked hardyhead and goldfish at impact and creek reference sites, but greater abundances of bony herring at river sites (Figure 6b). Furthermore, river reference sites were characterised by greater abundance of freshwater catfish (IV = 36.1, p = 0.020) and there were no significant indicators of impact or creek reference sites. Nonetheless, differences in abundances between treatments for these species were generally minor.

3.4. Fish recruitment in 2016

The small-bodied (adult length <100 mm) carp gudgeon (18–47 mm TL), Murray rainbowfish (23–78 mm FL), unspecked hardyhead (13–59 mm FL) and Australian smelt (24–62 mm FL) all exhibited broad length distributions and large proportions of individuals (typically >50%) likely to represent newly recruited young-of-the-year (YOY) cohorts (i.e. <40 mm length) (Figure 7). The length distributions of these species were similar across treatments, suggesting recent successful recruitment for these species within the Pike Anabranch system and the adjacent River Murray.

Bony herring exhibited similar length distributions across treatments, with broad size ranges (e.g. 26–374 m FL) and large proportions (>80%) of likely newly recruited YOY (<80 mm FL) (Figure 8a). Golden perch also exhibited similar length distributions across treatments, ranging 210–473, 286–482, and 145–534 mm TL at impact, creek reference and river reference sites, respectively, although only five individuals were sampled from creek reference sites (Figure 8b). Individuals 300–400 mm TL dominated the population.

Common carp exhibited a broad range of lengths across all treatments ranging 87–640, 88–610 and 73–682 mm FL at creek reference, river reference and impact sites, respectively (Figure 8c). Nonetheless, the length distribution from sites within the anabranch system were different to those from the River Murray, with fish <160 mm FL comprising ≥55% of the sampled population at creek reference and impact sites, compared to ~30% at river sites. Fish ≤120 mm FL, in all treatments, likely represented YOY.

Length-frequency distributions of goldfish were similar between creek reference, river reference and impact sites; all distributions were unimodal, but with a mode of 100–119 mm FL at creek reference sites, 80–99 mm FL at river reference sites and 60–79 mm FL at impact sites (Figure 8d). Nevertheless, recent recruitment was evident in all treatments.

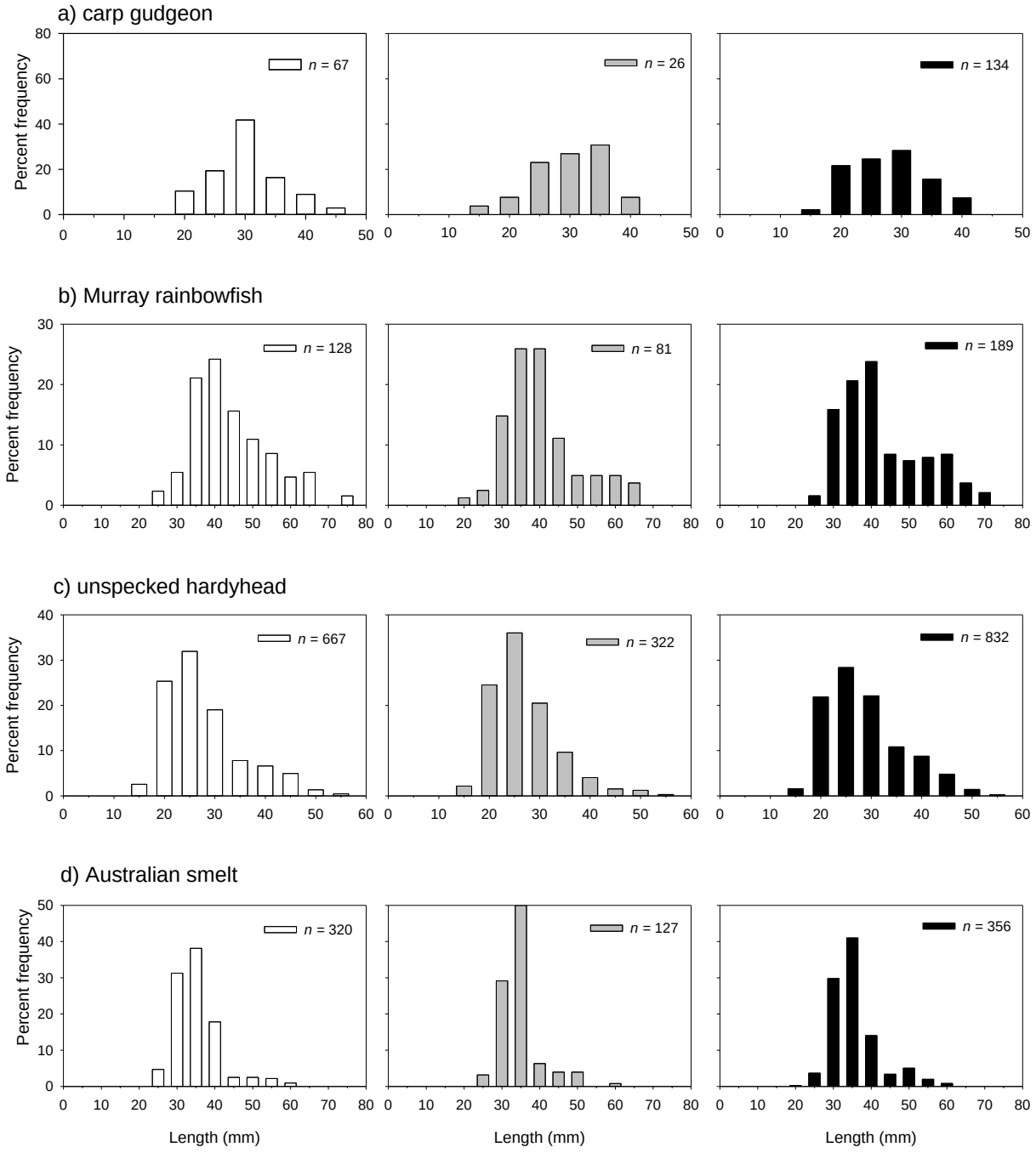

Figure 7. Length frequency distribution of a) carp gudgeon (TL), b) Murray rainbowfish (FL), c) unspecked hardyhead (FL) and d) Australian smelt (FL) at creek reference (*white* bar), river reference (*grey* bar) and impact (*black* bar) sites in autumn 2016.

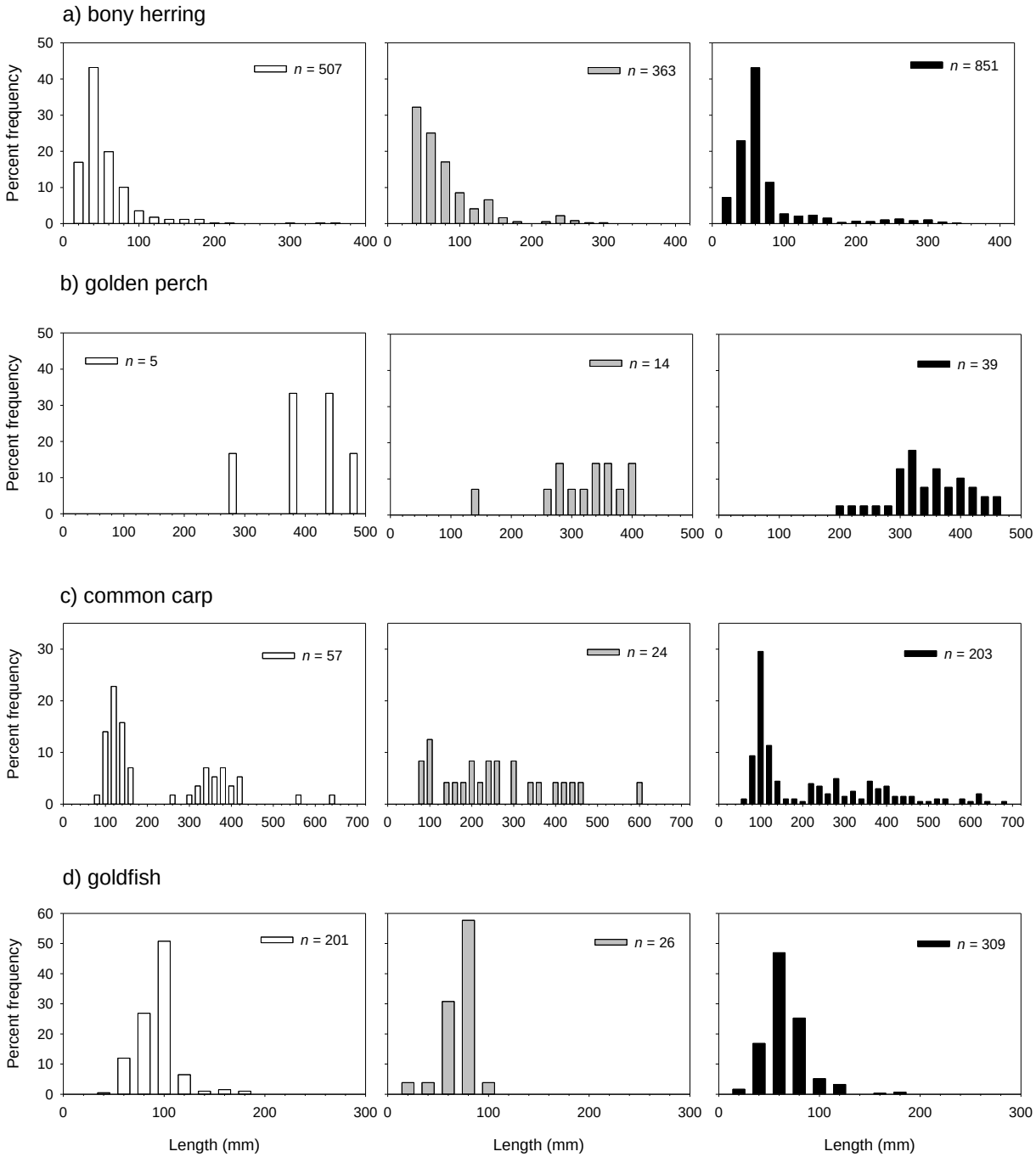

Figure 8. Length frequency distribution of a) bony herring (FL), b) golden perch (TL), c) common carp (FL) and d) goldfish (FL) at creek reference (*white* bar), river reference (*grey* bar) and impact (*black* bar) sites in autumn 2016.

Individual freshwater catfish, silver perch and Murray cod were sampled from creek reference and river reference treatments (Figure 9). A Murray cod sampled from Site 8 (Mundic to Pike Cutting) was 145 mm TL, representing a likely YOY individual (Figure 9a). All freshwater catfish and silver perch sampled were sub-adults or adults >240 mm in length (Figure 9b and c).

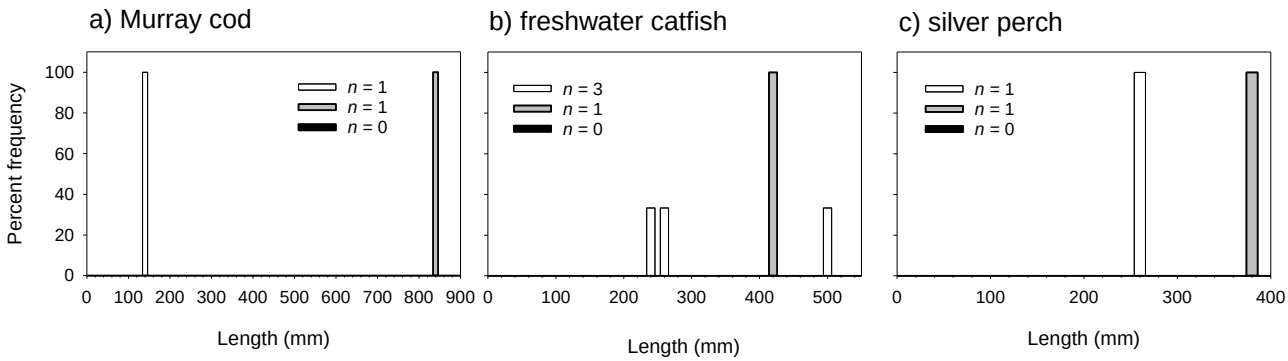

Figure 9. Length frequency distribution of a) Murray cod (TL), b) freshwater catfish (TL) and c) silver perch (FL) at creek reference (*white* bar), river reference (*grey* bar) and impact (*black* bar) sites in autumn 2016.

3.5. Microhabitat cover in 2016

A total of 23 different microhabitat types were observed in autumn 2016 across seven different functional groups (Table 5). The greatest number of different microhabitats were observed at impact and creek reference sites (20 microhabitats, six functional groups), and the least from river reference sites (15 microhabitats, six functional groups). The most common microhabitat types across all sites in 2016 were open water, woody debris (WD; categories 1–3 combined), the emergent *Typha domingensis*, floating *Azolla filiculoides* and submerged *Vallisneria australis*.

Table 5. Mean cover (mean proportional (%) cover.electrofishing shot^{-1} ± standard error) of microhabitats and functional types at creek reference, river reference and impact sites in 2013, 2015 and 2016. Recruit = seedlings/saplings.

Microhabitat	Functional Type	2013			2015			2016		
		Creek reference	River reference	Impact	Creek reference	River reference	Impact	Creek reference	River reference	Impact
Azolla filiculoides	Floating	0.72 ± 0.25	-	0.20 ± 0.13	0.55 ± 0.55	6.41 ± 0.0.66	6.88 ± 0.52	9.72 ± 0.92	3.17 ± 0.74	11.37 ± 0.86
Myriophyllum verrucosum	Submerged	-	-	0.21 ± 0.1	5.59 ± 0.68	11.86 ± 2.13	4.38 ± 0.65	0.14 ± 0.08	5.92 ± 1.55	0.12 ± 0.07
Potamogeton crispus	Submerged	-	-	-	-	1.61 ± 0.49	0.52 ± 0.16	-	-	-
Potamogeton tricarinatus	Submerged	-	-	-	-	4.86 ± 1.12	1.41 ± 0.32	-	6.06 ± 1.82	0.15 ± 0.14
Vallisneria australis	Submerged	-	-	-	4.13 ± 0.90	3.28 ± 1.15	3.15 ± 0.52	7.38 ± 1.44	7.78 ± 1.80	1.74 ± 0.55
Bolboschoenus caldwellii	Emergent	-	-	0.001	-	0.67 ± 0.36	1.34 ± 0.32	0.28 ± 0.03	0.64 ± 0.47	1.13 ± 0.37
Cyperus gymnocaulos	Emergent	0.03 ± 0.03	-	-	0.04 ± 0.04	-	0.05 ± 0.05	0.51 ± 0.21	-	0.64 ± 0.26
Juncus usitatus	Emergent	-	0.19 ± 0.15	0.05 ± 0.05	0.13 ± 0.08	-	0.06 ± 0.04	0.56 ± 0.20	-	0.29 ± 0.13
Phragmites australis	Emergent	1.50 ± 0.44	0.53 ± 0.32	0.05 ± 0.03	2.93 ± 0.51	6.31 ± 1.38	5.61 ± 1.16	0.67 ± 1.03	7.72 ± 1.24	5.44 ± 1.00
Salix babylonica	Emergent	0.15 ± 0.10	11.36 ± 4.57	-	0.04 ± 0.04	7.89 ± 3.09	-	-	8.19 ± 3.08	-
Schoenoplectus validus	Emergent	3.68 ± 1.01	0.89 ± 0.62	0.63 ± 0.23	4.54 ± 1.02	0.56 ± 0.39	1.34 ± 0.43	3.35 ± 0.92	0.64 ± 0.37	0.71 ± 0.25
Typha domingensis	Emergent	10.63 ± 1.55	11.03 ± 3.50	1.64 ± 0.50	17.43± 1.52	7.17 ± 2.03	9.93± 1.60	22.92 ± 1.96	13.89 ± 3.42	9.36 ± 1.74

Table 3 continued.

Microhabitat	Functional Type	2013			2015			2016		
		Creek reference	River reference	Impact	Creek reference	River reference	Impact	Creek reference	River reference	Impact
Aster subulatus	Amphibious	0.03 ± 0.02	-	0.01 ± 0.01	-	-	-	-	-	-
Cotula coronopifolia	Amphibious	-	-	-	0.14 ± 0.09	-	-	0.01 ± 0.01	-	-
Crassula helmsii	Amphibious	-	-	0.01 ± 0.01	0.23 ± 0.12	-	0.19 ± 0.02	-	-	-
Duma florulenta	Amphibious	0.15 ± 0.10	-	-	0.07 ± 0.66	-	0.23 ± .0.12	0.07 ± 0.07	-	0.08 ± 0.06
Ludwigia peploides	Amphibious	4.94 ± 0.69	0.19 ± 0.17	1.37 ± 0.35	2.49 ± 0.66	0.94 ± 0.39	3.46 ± 0.53	2.26 ± 0.77	0.53 ± 0.36	4.04 ± 0.56
Persicaria lapathifolia	Amphibious	0.34 ± 0.19	-	0.19 ± 0.11	0.65 ± 0.23	-	0.18 ± 0.10	0.25 ± 0.11	-	0.04 ± 0.05
Rumex bidens	Amphibious	-	-	-	-	-	0.27 ± 0.14	-	-	0.51 ± 0.23
Open water	N/A	64.23 ± 3.04	54.64 ± 5.37	52.56 ± 1.95	44.5 ± 2.52	31.22 ± 2.99	26.36 ± 1.47	36.40 ± 2.77	34.14 ± 2.81	35.34 ± 1.54
WD 1	Structural	2.22 ± 0.47	2.89 ± 0.77	5.94 ± 0.54	0.63± 0.24	1.72 ± 0.54	4.03 ± 0.53	0.79 ± 0.23	0.39 ± 0.22	3.98 ± 0.59
WD 2	Structural	3.60 ± 0.59	5.00 ± 0.91	10.42 ± 0.48	2.08 ± 0.44	3.61 ± 0.64	9.47 ± 0.69	2.1 ± 0.42	4.86 ± 1.05	9.96 ± 0.86
WD 3	Structural	5.04 ± 0.89	8.67 ± 1.28	17.01± 1.03	3.19 ± 0.67	7.39 ±1.49	12.99 ± 1.05	3.60 ± 0.86	4.5 ± 0.98	10.26 ± 0.94
Tree roots	Structural	2.53 ± 0.52	3.67 ± 0.87	6.88 ± 0.65	2.38 ± 0.58	2.67 ± 0.73	7.07 ± 0.68	2.88 ± 0.57	1.58 ± 0.54	4.87 ± 0.68
Rock	Structural	-	-	0.07 ± 0.05	-	-	0.11 ± 0.09	-	-	-
Man-made	Structural	0.08 ± 0.08	0.47 ± 0.33	0.08 ± 0.06	-	0.17 ± 0.17	0.11 ± 0.07	-	-	-

Table 3 continued.

Microhabitat	Functional Type	2013			2015			2016		
		Creek reference	River reference	Impact	Creek reference	River reference	Impact	Creek reference	River reference	Impact
Acacia stenophylla (adult)	Floodplain tree	-	0.33 ± 0.33	-	0.06 ± 0.06	1.19 ± 0.71	0.15 ± 0.11	0.03 ± 0.03	-	-
Eucalyptus camaldulensis (adult)	Floodplain tree	-	-	2.24 ± 0.60	0.05 ± 0.05	-	-	-	-	-
Eucalyptus camaldulensis (recruit)	Floodplain tree	0.07 ± 0.07	-	0.04 ± 0.04	-	-	-	0.10 ± 0.10	-	-
Lactuca serriola	Terrestrial	0.06 ± 0.06	-	-	-	-	-	-	-	-
Nicotiana glauca	Terrestrial	-	-	-	0.01 ± 0.01	-	-	-	-	-
Paspalum distichum	Terrestrial	-	0.14 ± 0.1	0.01 ± 0.01	0.21 ± 0.09	0.25 ± 0.18	0.30 ± 0.153	-	-	0.02 ± 0.02
Stemodia florulenta	Terrestrial	-	-	-	-	-	0.06 ± 0.06	-	-	-
	Total Microhabitats	**18**	**14**	**23**	**23**	**19**	**26**	**20**	**15**	**20**

3.6. Spatio-temporal variability in microhabitat cover

MDS ordination of instream microhabitat data exhibited grouping of sites by year (Figure 10). This was supported by PERMANOVA, which detected significant differences between years (*Pseudo-*$F_{2, 51}$ = 6.92, p < 0.001) and treatments (*Pseudo-*$F_{2, 51}$ = 6.77, p < 0.001), with no interaction (*Pseudo-*$F_{4, 51}$ = 0.48, p = 0.965). Pairwise comparisons revealed that microhabitat cover was significantly different between 2013 and both 2015 (t = 3.13, p < 0.001; B-Y method corrected α = 0.027) and 2016 (t = 3.17, p < 0.001), but 2015 and 2016 were not significantly different (t = 1.10, p = 0.267). Pairwise comparisons revealed microhabitats were significantly different between all comparisons of impact, creek reference and river reference sites (all comparisons p ≤ 0.008; B-Y method corrected α = 0.027).

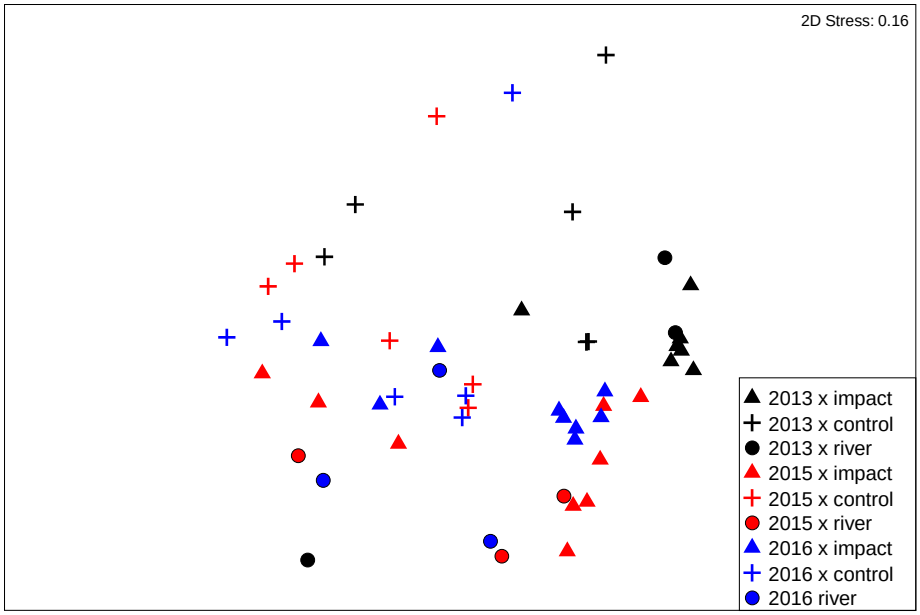

Figure 10. Non-metric multi-dimensional scaling (MDS) plot of proportional microhabitat cover measured during sampling of impact (*triangles*), creek reference (*inverted triangles*) and river reference site (*circles*) during autumn 2013 (*closed* symbols) and 2015 (*open* symbols).

SIMPER indicated the difference in microhabitat cover between 2013 and both 2015 and 2016, was driven by decreases in the cover of open water and WD 3, and increases in cover of the emergents *Typha domingensis* and *Phragmites australis*, and the floating *Azolla filiculoides* (Table 5; Figure 11). ISA determined that overall microhabitat cover in 2013 was characterised

by greater cover of open water (IV = 41.2, $p < 0.001$) and WD1 (IV = 40.6, $p = 0.047$), in 2015 by greater cover of the submerged *Myriophyllum verrucosum* (IV = 55.8, $p < 0.001$), *Potamogeton crispus* (IV = 27.8, $p = 0.007$) and *Vallisneria australis* (IV = 40.5, $p = 0.010$), and in 2016 by greater cover of the emergent *Phragmites australis* (IV = 46.2, $p = 0.007$) and floating *Azolla filiculoides* (IV = 50.5, $p < 0.001$)) (Table 5; Figure 11). From 2013 to 2016, the overall habitat area covered by emergent, floating and submerged macrophytes had increased from 11–25%, <1–9% and <1–7%, respectively, whilst open water decreased from 57% cover to 35% (Figure 11).

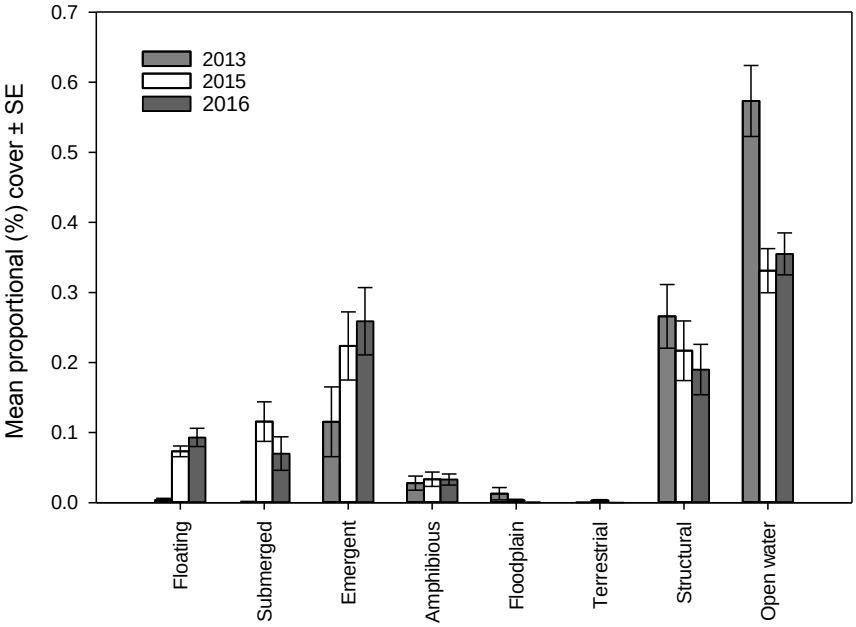

Figure 11. Mean proportional (%) cover per site ± standard error (SE) of microhabitat functional types across all sites sampled in 2013 (*light grey bar*), 2015 (*white bar*) and 2016 (*dark grey bar*)

SIMPER indicated differences in microhabitat cover between creek reference sites and other treatments, was due to typically greater cover of emergent *Typha domingensis* and open water, and comparatively lower cover of WD 2 and WD 3, submerged *Myriophyllum verrucosum* and the emergent tree *Salix babylonica* (Table 5). Differences between impact and river sites was due primarily to greater cover of the emergent *Typha domingensis* and *Phragmites australis*, emergent tree *Salix babylonica* and open water at river sites. ISA determined that microhabitat cover was characterised at creek reference sites by the amphibious *Persicaria lapathifolia* (IV = 31.8, p =

0.025), at impact sites by structural microhabitat types (WD1, IV = 44.8, p = 0.019; WD2, IV = 35.2, p < 0.001; WD3, IV = 46.9, p < 0.001; and tree roots IV = 42.9, p = 0.029), and at river reference sites by greater abundance of the floodplain tree *Acacia stenophylla* (IV = 30.9, p = 0.003), the emergent tree *Salix babylonica* (IV = 75.0, p < 0.001), submergent *Potamogeton tricarinatus* (IV = 44.3, p = 0.002) and man-made structures (e.g. pumps, concrete; IV = 23.6, p = 0.046) (Table 5).

3.7. Fish–microhabitat associations

Between eight and ten species of fish exhibited significant associations (positive and/or negative) with specific microhabitat types in each year, and these associations were often consistent among years (Table 6). The presence of golden perch was positively associated with structural microhabitats (e.g. WD1, WD2, WD3 and tree roots) in all years. Alternatively, Australian smelt were positively associated with open water, but negatively associated with structural microhabitats in all years. Murray rainbowfish, carp gudgeon, goldfish and eastern gambusia were associated with emergent (e.g. *Typha domingensis* and *Phragmites australis*), submergent (*Vallisneria australis*), floating (i.e. *Azolla filiculoides*) and/or amphibious (*Ludwigia peploides*) vegetation microhabitats in two of the three years. Silver perch and flat-headed gudgeon exhibited fewer significant association because they were generally sampled in low numbers, whilst few associations for common carp and unspecked hardyhead reflect the frequent occurrence of these species in electrofishing shots during sampling.

Table 6. Results of Indicator Species Analysis used to derive positive and negative fish-microhabitat associations from 2013, 2015 and 2016. Indicator Values (IV) for species in 'percentage of perfect indication' for that particular habitat type are presented in brackets. Perfect indication (100%) occurs when a microhabitat type is always present when a given fish species is present (positive association) or always present when a given fish species is absent (negative association). Only microhabitats deemed statistically significant ($p < 0.05$) and with IV value >20 are presented. NS = non-significant.

Common name	**Scientific name**	**2013**		**2015**		**2016**	
		Positive	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**
Golden perch	*Macquaria ambigua ambigua*	WD1 (39.2) WD2 (56.0) WD3 (53.1) Tree root (43.2)	Open water (53.3) *S. validus* (23.4)	WD2 (51.3) WD3 (52.4) Tree root (37.3)	NS	WD2 (47.4) WD3 (44.8) *P. australis* (36.6) *L. peploides* (26.5)	NS
Silver perch	*Bidyanus bidyanus*	*L. peploides* (60.1)	NS	WD2 (64.0)	NS	NS	NS
Bony herring	*Nematalosa erebi*	WD2 (61.9) WD3 (64.3) Tree root (46.0)	NS	NS	*T. domingensis* (40.3)	NS	*T. domingensis* (60.4) *S. validus* (22.5)
Australian smelt	*Retropinna semoni*	Open water (55.6)	WD1 (37.9) Tree root (36.4)	*T. domingensis* (34.8)	WD1 (24.5) WD2 (42.2) WD3 (41.2) *P. australis* (32.8)	Open water (53.3)	WD1 (23.9) WD2 (37.3) WD3 (38.2)
Murray rainbowfish	*Melanotaenia fluviatilis*	WD2 (44.0)	NS	*T. domingensis* (34.8) *P. australis* (32.5)	Open water (52.6) *V. australis* (32.6)	*T. domingensis* (36.6) *P. australis* (35.8) Tree root (31.1)	WD1 (26.1)
Flat-headed gudgeon	*Philypnodon grandiceps*	NS	NS	NS	NS	*S. validus* (20.8) *T. domingensis* (44.3) Tree root (37.4)	*A. filiculoides* (49.2)
Unspecked hardyhead	*Craterocephalus fulvus*	*L. peploides* (46.0)	NS	NS	NS	NS	WD1 (47.9)

Table 5 continued.

Common name	Scientific name	2013		2015		2016	
		Positive	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**
Carp gudgeon complex	*Hypseleotris* spp.	WD2 (49.1) WD3 (46.8) *L. peploides* (37.7) *T. domingensis* (34.9)	NS	WD2 (37.9) *T. domingensis* (38.9)	*V. australis* (34.4)	Tree root (27.8)	NS
Common carp	*Cyprinus carpio*	WD1 (36.4) WD2 (49.2) WD3 (47.0) Tree root (35.3)	Open water (56.4)	NS	NS	NS	NS
Eastern gambusia	*Gambusia holbrooki*	*A. filiculoides* (26.2) *S. validus* (31.6)	NS	WD3 (41.5) Tree root (32.2) *P. australis* (34.3)	NS	*A. filiculoides* (48.9) *L. peploides* (26.4) WD2 (37.9) WD3 (37.5)	NS
Goldfish	*Carassius auratus*	*L. peploides* (26.9) *S. validus* (17.8)	Open water (54.5)	WD1 (22.1) WD2 (42.0) Tree root (31.0) *L. peploides* (27.8)	*P. australis* (29.6)	*V. australis* (25.6)	*T. domingensis* (27.8) *P. australis* (29.6)

3.8. Hydraulic habitat characterisation

Hydraulic data were collected in 2013, 2015 and 2016 to provide a reference against which to assess change in hydraulic conditions within the system, following the completion of interventions. In 2015 and 2016, the methods were adapted to be more rigorous than those in 2013, and as such, results from only 2015 and 2016 are qualitatively compared.

Figure 12 presents an example of visual outputs from ADCP transects from Site 8; these data were then used to calculate hydraulic metrics. Most creeks in the system are narrow (7–50 m wide) and typically characterised by maximum depths <2 m (Table 7). Discharge varies between sites in association with position in the system, and differing contribution of flow sources. For instance, discharge at Site 5 (Figure 1) comprises contributions from the entire upper part of the system (upper Pike River, Tanyaca Creek and Rumpagunyah Creek), whilst discharge at Site 4 only represents flow channeled through Tanyaca Creek. Varied creek morphology and proximity of regulatory structures (e.g. earthen banks), interacts with variable discharge, to create variable hydraulic characteristics at monitoring sites (Table 7). In 2016, mean site velocities (*U*) ranged from 0.009 $m.s^{-1}$ at Site 3 (Tanyaca Creek) to 0.408 $m.s^{-1}$ at Site 17 (Deep Creek). Mean water velocity was also high at site 8 (Mundic to Pike Cutting, 0.237 $m.s^{-1}$), but at all other sites was <0.08 $m.s^{-1}$. Accordingly, the modified circulation metrics (M_3 and M_4), which represent measures of the frequency and strength of vertical and horizontal eddies, and both *Reynolds* and *Froude* numbers, measures of turbulence and the prevalence of 'fast-flowing habitat', were typically greatest at Sites 8 and 17, relative to all other sites.

Hydraulic metrics measured in 2016, were generally similar to 2015 (Table 7), but some marginal differences occurred, largely due to the completion of the Deep Creek Regulator and marginally greater flow through this creek in 2016 (~250 $ML.day^{-1}$) than 2015 (~150 $ML.day^{-1}$). Increased mean water velocities were noted at Deep Creek (increase of 0.1 $m.s^{-1}$), the Mundic to Pike Cutting (increase of 0.06 $m.s^{-1}$) and downstream of the now removed Coomb's Bridge (increase of 0.013 $m.s^{-1}$) in 2016, relative to 2015. These changes were typically accompanied by increases in circulation metrics (M_3 and M_4) and *Reynolds* and *Froude* numbers. The hydraulic data generated in the current project, provides a means to determine changes in hydraulic complexity following the planned interventions and increased flow to the system.

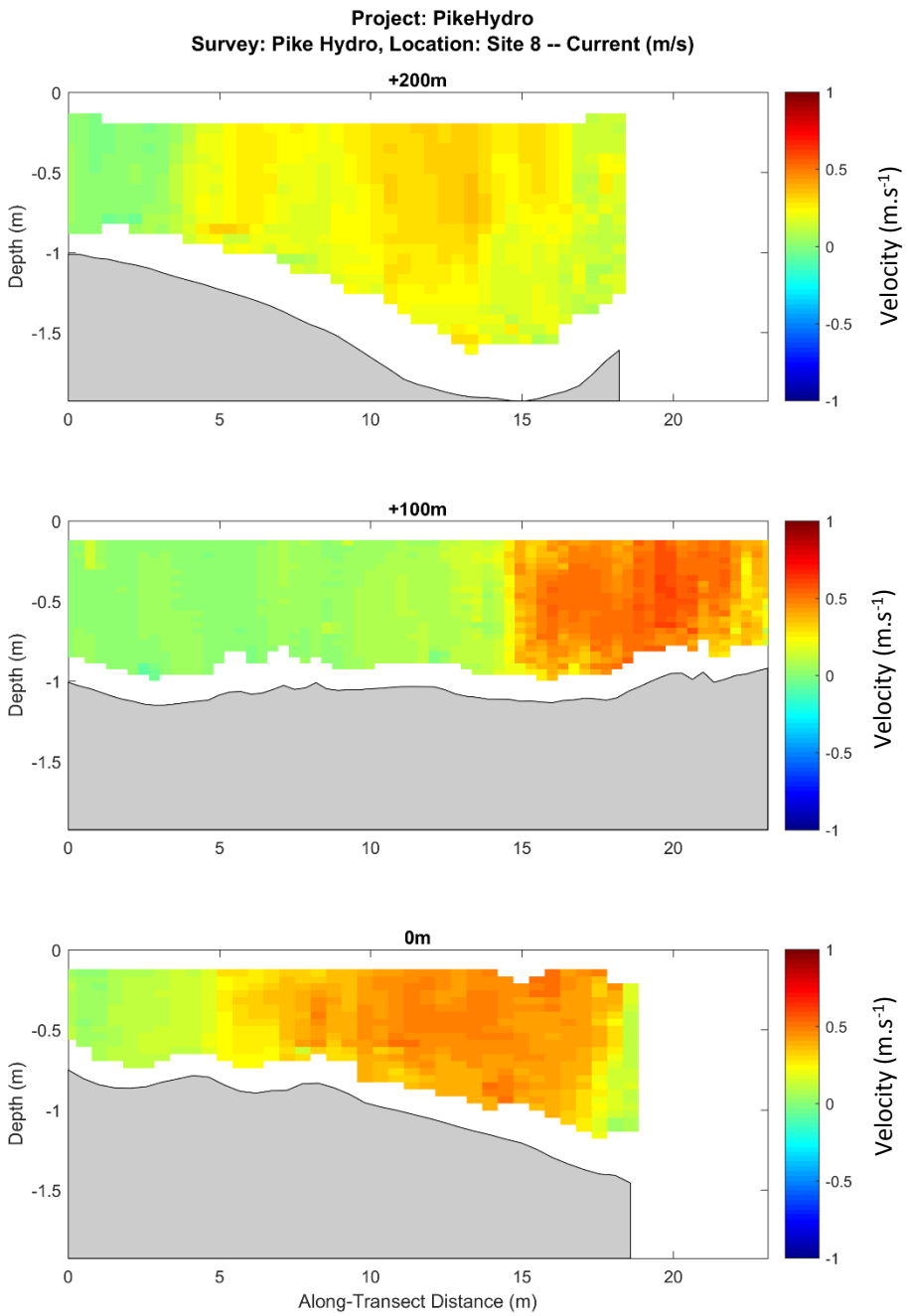

Figure 12. Cross-sectional water velocity profiles from three transects (+200 m, +100 m and 0 m) at Site 8 (Mundic to Pike Cutting) in autumn 2015. Cells are approximately 0.4 m long x 0.05 m high.

Table 7. Mean values (± SE) of hydraulic habitat metrics calculated from ADCP generated cross-sectional velocity profiles undertaken at sites in the Pike Anabranch system in autumn 2015 and 2016. Metrics presented are mean values of discharge ($m^3.s^{-1}$), transect length (m), max depth (m), cross-sectional area (m^2), downstream cross-sectional velocity (*U,* $m.s^{-1}$), the modified vertical circulation metric (M_3, s^{-1}), the modified horizontal circulation metric (M_4, s^{-1}), Reynolds number and Froude number calculated from three transects undertaken at each site.

			Impact			Reference	
Means	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 17**	**Site 8**	**Site 10**
			2015				
Discharge ($m^3.s^{-1}$)	0.31 ± 0.02	1.89 ± 0.02	9.52 ± 0.03	3.00 ± 0.07	1.48 ± 0.03	3.21 ± 0.06	4.14 ± 0.05
Transect length (m)	35.22 ± 1.03	34.03 ± 3.08	50.51 ± 0.84	37.10 ± 1.55	7.56 ± 0.61	24.64 ± 2.90	53.09 ± 2.14
Max depth (m)	1.20 ± 0.05	1.87 ± 0.19	3.61 ± 0.05	2.64 ± 0.13	1.20 ± 0.07	1.65 ± 0.111	1.72 ± 0.04
Area (m^2)	38.09 ± 1.98	44.20 ± 1.87	143.47 ± 0.89	66.05 ± 2.95	7.97 ± 0.77	28.80 ± 3.72	74.93 ± 3.77
U ($m.s^{-1}$)	0.009 ± 0.001	0.057 ± 0.003	0.078 ± 0.006	0.065 ± 0.004	0.291 ± 0.013	0.157 ± 0.021	0.065 ± 0.003
M_3 (s^{-1})	0.083 ± 0.017	0.084 ± 0.006	0.030 ± 0.002	0.037 ± 0.001	0.198 ± 0.003	0.154 ± 0.011	0.061 ± 0.006
M_4 (s^{-1})	0.025 ± 0.003	0.024 ± 0.001	0.017 ± 0.003	0.017 ± 0.001	0.088 ± 0.004	0.047 ± 0.003	0.020 ± 0.003
Reynolds number	965 ± 135	7527 ± 866	22061 ± 1646	11589 ± 606	30597 ± 1931	18404 ± 2881	9108 ± 424
Froude number	0.003 ± 0.000	0.016 ± 0.002	0.015 ± 0.001	0.016 ± 0.001	0.091 ± 0.008	0.047 ± 0.008	0.017 ± 0.001
			2016				
Discharge ($m^3.s^{-1}$)	0.28 ± 0.07	1.41 ± 0.10	8.73 ± 0.44	3.40 ± 0.10	3.11 ± 0.02	3.94 ± 0.07	5.43 ± 0.26
Transect length (m)	34.12 ± 0.93	29.28 ± 2.12	47.64 ± 1.17	34.60 ± 0.69	7.60 ± 0.35	19.98 ± 1.58	51.74 ± 2.30
Max depth (m)	1.12 ± 0.04	1.81 ± 0.22	3.54 ± 0.06	2.55 ± 0.09	1.54 ± 0.04	1.51 ± 0.23	1.78 ± 0.05
Area (m^2)	33.75 ± 1.92	35.20 ± 5.58	136.95 ± 2.26	58.23 ± 0.01	9.96 ± 0.34	23.68 ± 2.61	76.11 ± 5.61
U ($m.s^{-1}$)	0.009 ± 0.003	0.048 ± 0.007	0.072 ± 0.003	0.076 ± 0.005	0.408 ± 0.017	0.237 ± 0.040	0.078 ± 0.004
M_3 (s^{-1})	0.110 ± 0.015	0.014 ± 0.06	0.075 ± 0.024	0.055 ± 0.006	0.325 ± 0.073	0.194 ± 0.024	0.062 ± 0.003
M_4 (s^{-1})	0.029 ± 0.004	0.036 ± 0.008	0.034 ± 0.006	0.026 ± 0.002	0.15 ± 0.02	0.056 ± 0.004	0.020 ± 0.002
Reynolds number	872 ± 322	5716 ± 767	20652 ± 612	12660 ± 408	53666 ± 3347	27617 ± 3412	11382 ± 266
Froude number	0.003 ± 0.001	0.015 ± 0.003	0.014 ± 0.001	0.019 ± 0.002	0.114 ± 0.005	0.071 ± 0.015	0.021 ± 0.001

4. DISCUSSION

Under the *Riverine Recovery Project* (RRP), several interventions have been undertaken in the Pike Anabranch system with the aim of increasing capacity to vary flow to the system, including greater flow volumes, increasing hydrological connectivity and mitigating barriers to fish passage (DEWNR 2011). This includes the upgrade of the Deep Creek Regulator (including completion of a vertical-slot fishway), new regulators at Bank B, B2 and C (including 'fish friendly' baffles within culverts), and removal of Coombs Bridge, Bank H and Snake Creek Stock Crossing. Nonetheless, removal of Banks D, E, F, F1 and G has yet to occur and is now contingent on construction of the Tanyaca Creek Regulator under SARFIIP. Flow to the system has yet to be substantially altered from that prior to the upgrade of the Deep Creek regulator, due to these changes in the construction program. Notwithstanding, once the suite of interventions are completed, it is hypothesised that enhanced hydrological connectivity and flow to the system, and accompanying increases in lotic habitat, will result in significant changes to fish assemblage structure and recruitment, habitat (vegetated and hydraulic) and fish-habitat associations, including increases in the abundance of fish species that prefer hydraulically diverse environments (e.g. Murray cod, golden perch). Whilst the current project could not meet its initial aim of assessing change in fish and fish-habitat related ecological patterns in relation to management interventions, it presents insight on natural variability in the above parameters over the period 2013–2016 that will form a basis for assessing the influence of interventions under RRP and SARFIIP in the future.

Species richness increased between 2013 (14 species), 2015 (15 species) and 2016 (16 species) due to the detection of Murray cod in both 2015 and 2016, and detection of oriental weatherloach in 2016. These represent the first formal records of Murray cod (*vulnerable* under the *Environment Protection and Biodiversity Conservation Act 1999*) from the Pike Anabranch system and follow non-detection during a previous monitoring event at the site in 2009 (Beyer *et al.* 2010). This suggests that in its current state, certain creeks within the Pike Anabranch system (i.e. Margaret-Dowling Creek and the Pike to Mundic Cutting) likely provide favourable habitat for Murray cod and increased area of such habitat, following the completion of RRP and SARFIIP, and enhanced flow to the system, will likely benefit the species. Such a response would be of regional and State-wide significance.

Increased total fish abundance from 2013 to 2016 and changes in fish assemblage structure between years were driven by increased abundance of several small- and medium-bodied generalist species, but decreased abundance of certain large-bodied species. Bony herring was

the most abundant species in all years, but in 2015 and 2016, abundance was two to three-fold greater than in 2013. Other species exhibited continuous increases in abundance across the study period (i.e. 2013<2015<2016), including Australian smelt (20-fold and 39-fold increase), unspecked hardyhead (7-fold and 28-fold increase), carp gudgeon (three-fold and six-fold increase) and goldfish (four-fold and six-fold increase). Alternatively, golden perch and common carp abundances were 20–40% less in 2015 and 2016, than 2013. Similar changes in fish assemblage structure were observed at both Chowilla (SARDI unpublished data) and Katarapko Anabranches (Bice *et al.* 2015b) over the same period, and are likely related to the influence of variable hydrology on microhabitat availability and critical life history processes of different species. These changes are indicative of a transition from a period of high discharge (2010–2013) to a period of relatively low discharge (2013–2016), and are the inverse of patterns of change in assemblage structure observed in the region following the preceding transition from low (2005–2010) to high discharge (2010–2013) (Leigh *et al.* 2012, Wilson *et al.* 2012, Zampatti and Leigh 2013a, Bice *et al.* 2014).

Hydrology has a large influence on the distribution and cover of instream habitat (Resh *et al.* 1988). High flows often result in reductions in cover of submerged and emergent macrophytes due to increased water velocities and increased turbidity (Chambers *et al.* 1991). Conversely, low flows and subsequent stable water levels and low turbidity favour the proliferation of macrophytes. Several of the small-bodied species that increased in abundance from 2013 to 2016, are typically associated with vegetated habitats (Balcombe and Closs 2004, Bice *et al.* 2014), and indeed several were significantly associated with emergent (e.g. *Phragmites australis*), submergent (e.g. *Vallisneria spiralis*), amphibious (i.e. *Ludwigia peploides*) and/or floating (i.e. *Azolla filiculoides*) macrophytes throughout the study. The proportional cover of these microhabitats was substantially greater in 2015 and 2016, than in 2013. Furthermore, the 'low-flow recruitment hypothesis' proposes that the recruitment of many small-bodied native fish species is enhanced under low-flow conditions as a function of increased abundance and concentration of appropriate sized prey (Humphries *et al.* 1999). As such, a combination of increased area of favourable habitat and conditions for recruitment, likely resulted in the increases in abundance observed in these species.

Low abundances of golden perch and common carp, relative to 2013, are likely unrelated to flow-induced habitat alteration, but rather the influence of hydrology on spawning and recruitment. Golden perch are flow-cued spawners, relying on the coincidence of elevated discharge and temperature cues to stimulate spawning (Mallen-Cooper and Stuart 2003, Zampatti and Leigh

2013b). Additionally, whilst common carp do not require elevated discharge to spawn and recruit, enhanced abundance of larvae and juveniles is associated with floodplain inundation (King *et al.* 2003, Stuart and Jones 2006). Zampatti and Leigh (2013a) presented data on increases in abundance of golden perch in the lower River Murray as a result of spawning and dispersal of juveniles in association with flooding in 2010/11. There is also evidence of spawning and subsequent recruitment of this species in the lower River Murray from 2011/12 and 2012/13 (Ye *et al.* 2015a, 2015b). High discharge events and subsequently, favourable conditions for recruitment of golden perch and common carp, from 2010–2013, likely drove the elevated abundance observed in 2013. Low flow conditions and subsequent lack of significant spawning/recruitment events for these species in the previous three years, likely led to decreased abundance in 2015 and 2016, relative to 2013. This premise is supported by length-frequency data, with >80% of golden perch sampled >300 mm in length, which likely represent individuals ≥3 years of age (Anderson *et al.* 1992).

Differences between treatments, related to fish assemblages and microhabitat cover, reflected typical differences between main channel and anabranch habitats in the lower River Murray. Bony herring and freshwater catfish were most abundant in the main river channel, whilst Australian smelt, unspecked hardyhead and goldfish were most abundant in anabranch habitats; these spatial patterns of differing abundance are commonly observed in the lower River Murray (SARDI unpublished data). Furthermore, spatial differences in microhabitat were driven by greater relative cover of emergent *Salix babylonica* and the floodplain tree *Acacia stenophylla*, at river reference sites, and greater cover of woody debris within anabranch habitats, particularly at impact sites. This result is unsurprising given the general high abundance of *Salix babylonica* in the littoral zone of the lower River Murray main channel (Gehrig 2010). The high proportion of structural elements at impact sites is encouraging in light of the prospective interventions; large-bodied native species, including golden perch and Murray cod, have previously been shown to be positively associated with structural elements, including in the current study, particularly when accompanied by flowing water in the case of Murray cod (Crook *et al.* 2001, Koehn 2009). As such, the ‘physical template’ of favourable habitat for large-bodied native species is present at impact sites within the Pike Anabranch system, and it is hypothesised that provision of increased flow and hydraulic complexity at these sites will benefit these species.

Based on length-frequency distributions from 2016, all species, with the exception of golden perch, silver perch and freshwater catfish, exhibited signs of recent recruitment, although both silver perch and freshwater catfish were sampled in only low numbers. This includes Murray cod,

with an individual sampled likely representing a newly recruited young-of-the-year spawned the previous spring (2015). Murray cod spawn annually over a well-defined period in response to increasing water temperature, irrespective of flow conditions (Rowland 1998, Humphries 2005, Koehn and Harrington 2006). Nonetheless, broad-scale recruitment in the lower River Murray appears associated with years of elevated discharge, whilst low levels of local-scale recruitment may occur in permanent lotic anabranch habitats (e.g. Chowilla) (Zampatti *et al.* 2014). The capture of juvenile Murray cod in the Pike system in 2016 and 2015, suggests it may provide habitats favourable for local-scale recruitment of the species and is encouraging given remaining instream interventions under SARFIIP are likely to result in increases in the area of favourable habitat within the system.

Whilst flow to Pike Anabranch system is yet to be substantially increased since prior to interventions under RRP, hydraulic habitat assessment presents evidence of likely improvements upon the completion of instream works under SARFIIP. Increased discharge through Deep Creek of just 100 $ML.d^{-1}$ in 2016, relative to 2015, resulted in increases in mean water velocities of 0.01–0.1 $m.s^{-1}$ and associated increases in turbulence and circulation at sites under influence (i.e. Deep Creek, Mundic to Pike Cutting and Upper Pike River). Similar or greater improvements to hydraulic complexity may be expected at several locations in the Pike Anabranch system including Tanyaca Creek and the lower Pike River, and these improvements should benefit species that prefer lotic habitats.

5. CONCLUSIONS

The current report describes the results from three years of intervention monitoring in the Pike Anabranch system from 2013 to 2016, to assist in assessing change in fish assemblage structure, recruitment and habitat availability, and fish–habitat associations, following management interventions under RRP. Due to changes in the construction program of RRP and SARFIIP the project was unable to assess these changes at this point in time, but the data collected form a reference to do so upon the completion of interventions under RRP and SARFIIP. Notwithstanding, the results of the study highlight the temporal dynamism in fish assemblage structure and habitat availability in the lower River Murray as a function of variable hydrology. Furthermore, the consistency of these patterns among similar habitats across the region, including Chowilla (SARDI unpublished data) and Katarapko anabranches (Bice *et al.* 2015), suggests hydrology drives ecological patterns over large spatial-scales (100s km). This scale is far greater than the Pike Anabranch 'system-scale' and has implications for the management of this and other sites.

The disparity of fish assemblages and microhabitat cover between 2013, 2015 and 2016 indicates the importance of collecting multiple years of 'before' data. Assessing future changes in fish abundance and population dynamics, as well as habitat availability, will be reliant on differentiating change associated with interventions, and underlying changes associated with variable catchment hydrology. The collection of greater amounts of 'before' data, from periods of varying hydrology, provides greater power to differentiate the effects of interventions and catchment hydrology. Indeed substantial data now exists on fish species richness, distribution, abundance and recruitment, and habitat characteristics (i.e. microhabitat and hydraulic habitat) to assess changes in relation to management in the future.

The sampling of Murray cod from the Pike Anabranch system in 2015 and 2016 is encouraging given interventions under RRP will likely improve habitat quality for this threatened species within the system. The nature of fish habitat is fundamentally a product of the interplay between physical habitat and hydrodynamics; creeks in the Pike Anabranch system that will be subject to interventions, are characterised by high levels of cover of complex physical habitat, which upon increases in hydrodynamic variability, may favour native fish species, including Murray cod. The hydraulic data collected in 2016, suggest improvements in hydraulic complexity at some sites (i.e. increased water velocities, circulation and turbulence) as a function of slightly greater discharge through the Deep Creek Regulator in 2016 (~250 $ML.day^{-1}$) than in 2013 and 2015 (~150 $ML.day^{-1}$). These changes suggest a greater level of improvement to hydraulic complexity can be

expected in parts of the system following the completion of the Margaret-Dowling and Tanyaca Creek Regulators under SARFIIP and capacity to further increase flow and biological connectivity within the system. The hydraulic data collected in this project will provide a means to quantify purported increases in hydraulic complexity in the future.

Whilst, the current project was initiated to investigate biotic responses to interventions under RRP, it will also fulfill the role of assessing changes in 'condition' in regards to fish-related system targets following the completion and operation of infrastructure under SARFIIP. The current sampling methodology is suitable for this purpose, but allied hypothesis-driven investigations will be required to determine cause–effect mechanisms driving biotic patterns.

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