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Katarapko Fish Assemblage Condition Monitoring 2022

J. Fredberg and C. M. Bice

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SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

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EXECUTIVE SUMMARY

The Katarapko Anabranch system is one of three large anabranch systems in the Riverland region of the lower River Murray, South Australia. Katarapko comprises hydraulically diverse aquatic habitats including permanent fast-flowing and slow-flowing creeks, as well as backwaters. Flowing water habitats such as these are now largely absent under regulated conditions in the lower River Murray main channel. The associated floodplains of the system also support ecologically significant vegetation communities, including river red gum (*Eucalyptus camaldulensis*) and black box (*Eucalyptus largiflorens*) woodlands. In recent years, under the Riverine Recovery Program (RRP) and South Australian Riverland Floodplain Integrated Infrastructure Program (SARFIIP) a range of on-ground works (e.g. regulator/bank upgrade/construction and fishway construction) have been completed with the aim of promoting a hydrological regime that includes: improved connectivity and extension of lotic habitats under normal operating conditions; and more frequent floodplain inundation than would occur naturally under current conditions owing to managed inundation events. The operation of this infrastructure will be guided by the Katarapko Floodplain Operations Plans and a Monitoring, Evaluation, Reporting and Improvement (MERI) framework.

Fish are a key ecological attribute of the Katarapko Anabranch system that stand to be influenced by system management. As such, three fish-related ecological objectives have been developed for the system:

1. Restore and maintain resilient populations of large-bodied native fish – i.e. Murray cod (*Maccullochella peelii*) golden perch (*Macquaria ambigua*), silver perch (*Bidyanus bidyanus*), and freshwater catfish (*Tandanus tandanus*);

2. Restore and maintain resilient populations of native foraging generalists – e.g. Australian smelt (*Retropinna semoni*), bony herring (*Nematalosa erebi*), Murray rainbowfish (*Melanotaenia fluviatilis*) and unspecked hardyhead (*Craterocephalus fulvus*); and

3. Minimise the recruitment of introduced species – e.g. common carp (*Cyprinus carpio*).

These Ecological Objectives are associated with six fish assemblage and species-specific Ecological Targets and allied indices. These targets relate to species diversity and extent, the abundance of large-bodied native fish, and the recruitment of Murray cod, small-bodied generalist fishes and non-native fishes.

In 2022, a total of 7,527 fish were captured from 15 species (11 native and 4 non-native) from 14 sites. The most abundant native species were bony herring (37.2%) and Australian smelt (13.8%), whilst the remaining native species consisted of 7.8% of the total catch. Common carp (36.5%) and goldfish (3.8%) were the most abundant non-native species, whilst the remaining non-native species collectively comprised 0.86% of the total catch. Three species of conservation significance were collected. These were, Murray cod (*vulnerable* under the *EPBC Act 1999*), silver perch (*Endangered* under the *EPBC Act 1999*) and freshwater catfish (*protected* under the South Australian *Fisheries Management Act 2007*).

The fish assemblage sampled in 2022 differed from a grouping of sampling years that included 2009, 2010, 2015 and 2021, and a single-year grouping from 2011. The years 2009, 2010, 2015 and 2021 were each characterised by predominantly low within-channel flows and minor spring flow pulses. In 2022, however, sampling was preceded by persistent elevated within-channel flows (up to ~37,500 ML.day^{-1}). In contrast, sampling in 2011 immediately followed a prolonged period of overbank flooding from spring 2010–autumn 2011. Furthermore, certain species were consistently associated with specific mesohabitat types. Notably, Murray cod, golden perch and Murray rainbowfish were positively associated with river main channel habitats.

All fish-related Ecological Targets were partially or fully achieved in 2022. Species diversity exceeded the reference value, whilst extent indices were met for five of eleven target species. The abundance of Murray cod exhibited a positive trajectory relative to preceding sampling, and the recruitment target was met for the adult population but not for YOY fish. The abundance of freshwater catfish also exhibited a positive trajectory relative to preceding sampling, but golden and silver perch remained below the reference value. Recruitment was limited for most common small- and medium-bodied species, whilst recruitment for common carp increased from previous sampling years, with the recruitment index substantially above the reference value.

The results highlight potential positive responses (e.g. improvement in Murray cod metrics) to improvements to connectivity and hydrodynamics in the Katarapko Anabranch following RRP and SARFIIP works. Continued monitoring will provide greater insight and inform adaptive management of the system.

Keywords: Katarapko, anabranch, diversity, extent, recruitment, flow, native species, Murray cod.

1. INTRODUCTION

1.1. Background

The Katarapko Anabranch and Floodplain system is one of three large (>9,000 ha) anabranch systems that bypass Lock and Weir structures on the main river channel in the lower River Murray, South Australia (together with Chowilla and Pike). The Katarapko Anabranch bypasses Lock and Weir No. 4 generating a head differential of ~3.5 m between the main inlet through Eckert Creek (Bank J) and the confluence of Katarapko Creek and the River Murray. As such, Katarapko comprises hydraulically diverse aquatic habitats including permanent fast-flowing and slow-flowing creeks, as well as wetlands and backwaters. Permanent lotic (flowing water) habitats are now largely absent under regulated conditions in the lower River Murray main channel (Bice et al. 2017). Subsequently, the Katarapko Anabranch system supports a diversity of native aquatic biota including fishes of conservation concern (e.g. Murray cod (*Maccullochella peelii*), freshwater catfish (*Tandanus tandanus*), silver perch (*Bidyanus bidyanus*)) (Bice et al. 2015). For this reason, the site was considered a *Demonstration Reach* ('Katfish Reach') under the Murray-Darling Basin Authority's *Native Fish Strategy.* The associated floodplains of the systems also support ecologically significant vegetation communities that include river red gum (*Eucalyptus camaldulensis*) and black box (*Eucalyptus largiflorens*) woodlands, lignum (*Duma florulenta*) and chenopod shrublands, herblands (incl. flood responsive ephemeral communities).

Whilst the Katarapko Anabranch system supports significant aquatic and floodplain communities it was considered to be in a degraded state due to the impacts of river regulation. Due to the declining condition of long-lived floodplain vegetation and a need to meet environmental objectives with limited water, the South Australian Riverland Floodplains Integrated Infrastructure Program (SARFIIP) was initiated to facilitate engineered (managed) floodplain inundation at the Katarapko system with the aim of restoring floodplain condition and function (DEWNR 2017). The program involved a range of on-ground works including: the upgrade, installation and replacement of banks and flow regulating structures, construction of fishways, and a range of complementary measures. SARFIIP works were completed in 2020 and followed on from the Riverine Recovery Program (RRP, Murray Futures; DEWNR 2011), which included various in-channel remediation works. Together, this infrastructure will be used to promote a hydrological regime at Katarapko that includes: 1) improved connectivity and extension of lotic habitats under regulated conditions; and 2) more frequent floodplain inundation than would occur naturally under current conditions owing to managed inundation events. The operation of this infrastructure will be guided by the

Katarapko Floodplain Operations Plans and a Monitoring, Evaluation, Reporting and Improvement (MERI) framework.

Fish are a key ecological attribute of the Katarapko Anabranch system that are likely to be influenced by system management. As such, within the Operations Plan, three primary Ecological Objectives were developed for native fish, namely to:

1. Restore and maintain resilient populations of large-bodied native fish – i.e. Murray cod, golden perch (*Macquaria ambigua*), silver perch and freshwater catfish;
2. Restore and maintain resilient populations of native foraging generalists – e.g. Australian smelt (*Retropinna semoni*), bony herring (*Nematalosa erebi*), Murray rainbowfish (*Melanotaenia fluviatilis*) and unspecked hardyhead (*Craterocephalus fulvus*); and
3. Minimise the recruitment of introduced species – e.g. common carp (*Cyprinus carpio*).

In association with these Objectives, a total of six Ecological Targets were developed (Fredberg and Bice 2021), namely:

1. Maintenance or enhanced species diversity;
2. Maintenance or enhanced extent of species across the site as indicated by species-specific ‘extent index’;
3. Abundance (CPUE) of large-bodied native fish (i.e. Murray cod, freshwater catfish, golden perch and silver perch) exhibits a positive trajectory over a 5-year period from 2020;
4. Annual recruitment of foraging generalists is maintained or enhanced relative to historical levels, as indicated by species-specific ‘recruitment index’;
5. Recent recruitment of Murray cod to YOY and the adult population is evident as displayed by the presence of individuals <200 and 400–600 mm TL, respectively; and
6. Recruitment of common carp and goldfish do not increase in the absence of meeting key targets under managed inundations (e.g. improved condition of long-lived floodplain vegetation).

1.2. Objectives

The objectives of the project were to:

1) collect fish assemblage data from the Katarapko Anabranch system in autumn 2022, including species composition, distribution, abundance and recruitment;

2) provide an assessment of spatio-temporal variability in fish assemblages (species composition and abundance) relative to the period 2009–2022; and

3) assess the *condition* of the fish community with reference to defined Ecological Objectives and Targets.

2. METHODS

2.1. Study sites

Standardised electrofishing surveys have occurred in the Katarapko Anabranch and adjacent River Murray on seven occasions, namely: 2009, 2010, 2011, 2012, 2013, 2015 and 2021 (Leigh *et al.* 2009, 2012, Wilson *et al.* 2012, 2013, Bice *et al.* 2015) (Table 1 and Figure 1). In most years, the number of sites ranged from 13–15, but only four sites were sampled in 2012 and 2013 due to different objectives of monitoring in those years (Wilson *et al.* 2012, 2013) (Table 1 and Figure 1). As such, these years are excluded from analysis due to difference in sampling effort. In 2022, a total of 14 sites were sampled from 13–27 April, representing the range of permanent aquatic mesohabitats present within the Katarapko Anabranch (i.e. fast-flowing anabranches, slow-flowing anabranches, backwaters and the River Murray main channel). Fast-flowing habitats were characterised as having mean cross-sectional velocities >0.18 m.s^{-1}, slow-flowing habitats 0.05–0.18 m.s^{-1}, backwaters <0.05 m.s^{-1} and River Murray main channel <0.1 m.s^{-1} (Zampatti *et al.* 2008). Sites in the River Murray are classified as 'main channel' mesohabitats.

Table 1. Site number, site name, year sampled (indicated by *) and flow type (1 = fast flowing anabranches, 2 = slow flowing anabranches, 3 = backwaters, 4 = River Murray main channel) for sites sampled at Katarapko between 2009–2022 and used to calculate all indices and reference values for future condition monitoring reporting.

Site no.	Site name	2009	2010	2011	2015	2021	2022	Flow type
1	Eckert creek d/s weir	*	*		*	*	*	1
2	Eckert creek Wide Water	*	*	*	*	*	*	3
3	Eckert creek u/s log crossing	*	*	*	*	*	*	2
4	Eckert creek d/s log crossing	*	*	*	*	*	*	1
5	The Splash	*	*	*	*	*	*	3
6	Katarapko d/s weir	*	*	*	*	*	*	2
7	Katarapko Creek u/s (Katarapko Isl.)	*	*	*		*	*	2
9	Katarapko lower	*	*	*	*	*	*	2
10	Murray 3-4km d/s Lock 4	*	*	*	*	*	*	4
12	Murray d/s Katarapko junction	*	*	*	*	*	*	4
13	Eckert Creek below ford	*	*	*	*	*	*	2
14	Murray u/s Lock 4	*	*	*	*	*	*	4
20	Eckert widewater u/s^		*					3
22	Eckert Creek d/s Eckert weir^		*			*	*	1
24	Eckert Creek Southern arm					*	*	1

^previous fyke netting sites, however, a part of electrofishing sampling in 2012, 2013 and 2021-2022

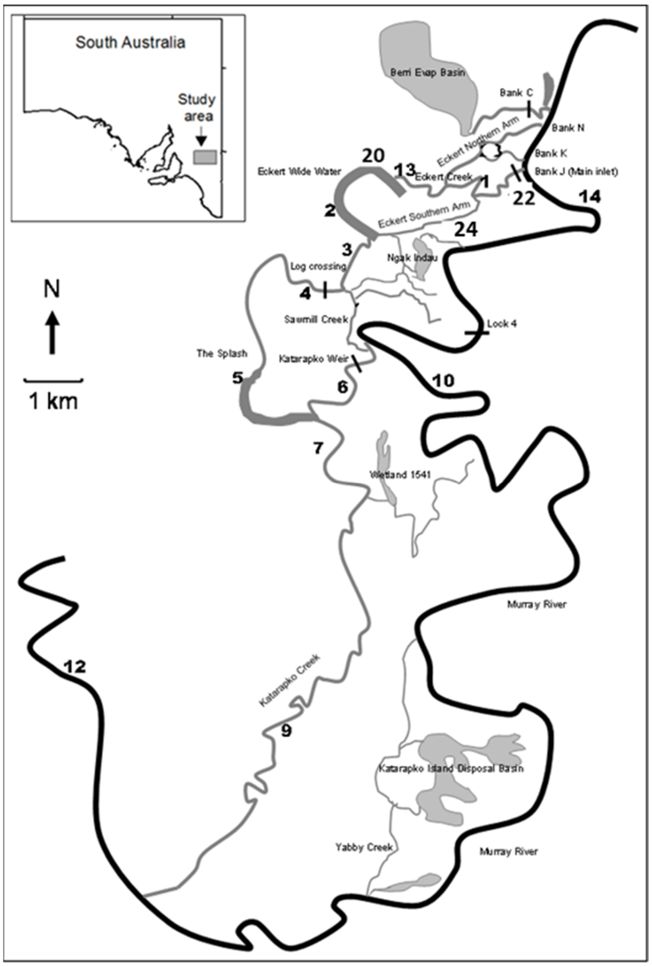

Figure 1. The 15 sites sampled between 2009–2022 as a part of condition monitoring in the Katarapko Anabranch system.

2.2. Data collection

In 2022, fish assemblages were sampled from 13–27 April using standardised boat electrofishing (5 kW Smith Root Model GPP electrofishing system). 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 (Fredberg et al. 2021, Ye et al. 2021). At each site, 12 x 90 second (power on time) electrofishing shots (6 on each bank) were undertaken in the littoral zone during daylight hours and fish were dip-netted by a team of two netters and placed in a live well. Fish from each shot were identified, counted, measured for length (± 1 mm, caudal fork length (FL) or total length, TL) and released after processing. Where large numbers of an individual species were collected a sub sample of 20 individuals were measured for length. Any positively identified fish unable to be dip netted were recorded as “observed” and included in the total catch.

2.3. Data analysis

Spatio-temporal variation in fish assemblages was investigated by assessing changes in total fish abundance (all species combined) and fish assemblage structure (i.e. species composition and individual species abundance). Differences in the relative abundance (CPUE, fish.min^{-1}) of fish sampled between years were analysed using uni-variate (similarity matrices calculated using Euclidean distances) single-factor PERMANOVA (permutational ANOVA) (Anderson and Ter Braak 2003) in the package PRIMER v. 6.1.12 and PERMANOVA+ (Anderson et al. 2008). When significant differences occurred in main tests, pairwise comparisons were undertaken to determine years that were statistically different. To allow for multiple comparisons, the B–Y method significance correction was adopted ($\alpha = \sum_{i=1}^{n}(1/i)$; e.g. for $n_{comparisons}$ = 12, B-Y method α = 0.05/ (1/1 + 1/2 + 1/3…..1/15) = 0.015) (Benjamini and Yekutieli 2001).

Differences in the structure of fish assemblages (i.e. species composition and abundance) was investigated using two-factor (i.e. year and mesohabitat) PERMANOVA (Anderson 2001, Anderson and Ter Braak 2003). Analyses were performed on Bray-Curtis similarity matrices (Bray and Curtis 1957) of fish relative abundance data (fish.minute of electrofishing^{-1}), which were previously fourth root transformed, and significance value of α = 0.05 was adopted. Non-Metric Multi-Dimensional Scaling (MDS) plots, generated from the same matrices were used to visualise assemblages from different years and mesohabitats (i.e. slow flowing, fast flowing and backwater). When significant differences occurred among mesohabitats in main tests, pairwise comparisons were undertaken to determine mesohabitats that were statistically different and the B–Y method significance was adopted.

To further investigate temporal variability in assemblage structure, group average clustering was performed on site pooled data (individual species CPUE, fish.min^{-1} for each year), and a cut off score of 85% similarity was used to determine the cluster groups based on species abundance. When difference occurred, Similarity of Percentages (SIMPER) analysis was used to determine species contributing to differences in assemblages (a 50% cumulative contribution cut-off was applied). Additionally, Indicator Species Analysis (ISA) was undertaken with the software package PC-Ord v. 5.12 (McCune and Mefford 2006) and used to determine species that characterised assemblages in different clusters (years) and determine species mesohabitat preferences. 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 for each species in each group on the basis of the standards of the perfect indicator and statistical significance of each indicator value is tested by a Monte Carlo (randomisation) technique, where the real data are compared against 5000 runs of randomised data (Dufrene and Legendre 1997).

2.4. Assessment of Ecological Targets

Fish-related Ecological Objectives and Targets were recently refined and associated indices developed by Fredberg and Bice (2021). This approach followed that applied at the Chowilla Anabranch under *The Living Murray Program* and guided by Robinson (2013). The below sections outline the calculation of 'reference' and 'index' values for each respective target. The original reference values calculated by Fredberg and Bice (2021) included data from sampling in 2012 and 2013. After further consideration, this data has been removed due to the limited sampling in those years, and reference values revised.

Target 1: Maintenance or enhanced species diversity

The diversity reference and index were derived using an 'expected vs predicted' approach as adapted from the SRA method outlined in Robinson (2013). An expectedness weight was developed for each native species for each mesohabitat type based on sampling data from 2009–2015. This time period incorporates a range of hydrological conditions likely to be experienced by fishes within Katarapko, including drought, within channel flow pulses and flood, and reference values derived from this dataset will likely prove suitable for assessing site condition through time. For each mesohabitat, the proportion of sites at which a species was sampled was calculated for every sampling year, and the mean of this value across years (hereafter called 'expectedness ratio') was used to calculate the 'expectedness weight' for each species (Table 2). Rarity scores were also assigned to each native species for each mesohabitat based upon expert opinion (Robinson 2013) (Table 2).

Table 2. Summary of rarity scores (*RS*), interpretation of expectedness ratio (*ER*) and expectedness weight to be assigned to fish species at the Katarapko Anabranch.

RS	Interpretation (expectedness ratio, *ER*)	Expectedness weight
1	Either rare or cryptic species. Expected to be collected in up to 20% of sites.	0.10
3	Locally abundant species. Expected to be collected in 20 to 70 % of sites.	0.45
5	Common and abundant species. Expected to be collected in 70 to 100% of sites.	0.85
0	Native species not historically recorded. Not included in expectedness calculations.	0

Rarity scores, mean expectedness ratio (i.e. proportional presence of native fish within mesohabitats) and associated expectedness weights for all native fish species using the standardised method are presented below in Table 3. These metrics are presented separately for each mesohabitat type. Non-native species are not included in diversity calculations.

The diversity index (*DI*) (i.e. no. species actually sampled/expected no. species) was calculated for each site within a mesohabitat. The mesohabitat diversity index presented in the results (Figure 7) is the mean of these site-specific indices from all sites within a particular mesohabitat. In turn, the site score is the mean of the mesohabitat indices. Values of *DI* >1.0 indicate diversity greater than the reference, whilst values <1.0 indicate diversity less than the reference.

Table 3. Rarity scores, expectedness ratio and expectedness weight for all native species sampled at Katarapko within fast-flowing, slow-flowing, main channel and backwater mesohabitats.

Species	Rarity score	Expectedness ratio	Expectedness weight
Fast-flowing			
Australian smelt	5	1	0.85
Bony herring	5	1	0.85
Carp gudgeon complex	3	0.93	0.85
Dwarf flat-headed gudgeon	1	0	0
Flat-headed gudgeon	3	0.56	0.45
Freshwater catfish	3	0.25	0.45
Golden perch	5	0.86	0.85
Murray cod	3	0	0
Murray rainbowfish	5	0.88	0.85
Silver perch	3	0.43	0.45
Spangled perch	0	0.12	0.10
Unspecked hardyhead	5	1	0.85
	Predicted no. species		10
	Expected no. species		6.55
Slow-flowing			
Australian smelt	5	0.96	0.85
Bony herring	5	1	0.85
Carp gudgeon complex	3	0.65	0.45
Dwarf flat-headed gudgeon	1	0.04	0.1
Flat-headed gudgeon	3	0.19	0.1
Freshwater catfish	3	0.12	0.1
Golden perch	5	0.89	0.85
Murray cod	3	0.09	0.1
Murray rainbowfish	5	1	0.85
Silver perch	3	0.46	0.45
Spangled perch	0	0	0
Unspecked hardyhead	5	1	0.85
	Predicted no. species		11
	Expected no. species		5.55
Main channel			
Australian smelt	5	1	0.85
Bony herring	5	1	0.85
Carp gudgeon complex	3	0.79	0.85
Dwarf flat-headed gudgeon	1	0.06	0.10
Flat-headed gudgeon	3	0.31	0.45
Freshwater catfish	3	0.31	0.45
Golden perch	5	1	0.85
Murray cod	3	0.48	0.45
Murray rainbowfish	5	1	0.85
Silver perch	3	0.52	0.45
Spangled perch	0	0.13	0.1
Unspecked hardyhead	5	1	0.85
	Predicted no. species		12
	Expected no. species		7.1
Backwater			
Australian smelt	5	0.92	0.85
Bony herring	5	1	0.85
Carp gudgeon complex	3	0.67	0.45
Dwarf flat-headed gudgeon	1	0	0
Flat-headed gudgeon	3	0.38	0.45
Freshwater catfish	3	0	0
Golden perch	5	0.54	0.45
Murray cod	3	0.25	0.45
Murray rainbowfish	5	0.54	0.45
Silver perch	3	0	0
Spangled perch	0	0	0
Unspecked hardyhead	5	1	0.85
	Predicted no. species		8
	Expected no. species		4.8

Target 2: Maintenance or enhanced extent of species across the site

An Extent Index (*EI*) was developed using the expectedness ratios calculated above (Table 3) as the 'reference value' (Robinson 2013). The expectedness ratio represents the mean distribution of individual native species across a mesohabitat type (i.e. proportion of sites within a mesohabitat where the species was sampled), annually across the entire study period (2009–2021).

The extent index is species-specific and is calculated as outlined below.

- *MH* = mesohabitat,
- R_{year} = ratio of sites where sampled in given year,
- *ER* = expected ratio for each mesohabitat type,
- *EI* = Study Site Extent Index,
- EI = mean($MH_1(R_{year}/ER_{MH1}) + MH_2(R_{year}/ER_{MH2}) + MH_3(R_{year}/ER_{MH3}) + MH_4(R_{year}/ER_{MH4})$),
    - *EI* = 0.75–1.25 represent stable extent/distribution
    - *EI* >1.25 represents increased extent/distribution
    - *EI* <0.75 represents decreased extent/distribution

Species with rarity scores of 0 (i.e. spangled perch (*Leiopotherapon unicolor*) were excluded. Furthermore, Murray cod, silver perch and freshwater catfish do not have an expectedness ratio in backwater mesohabitats, and dwarf flat-headed gudgeon (*Philypnodon macrostomus*) do not have an expectedness ratio in fast flowing mesohabitats, as they have not been sampled in these mesohabitat types in the Katarapko Anabranch during sampling events to date.

Target 3: Abundance (CPUE) of large-bodied native fish exhibit positive trajectories over a 5-year period from 2020

One of the key ecological targets for native fish in the Katarapko Anabranch system is to restore and maintain resilient populations of large-bodied native fish. Specifically, interventions that have improved flow in the anabranch system over spatial scales of 1–10s km stand to improve habitat quality for Murray cod, freshwater catfish, golden perch and silver perch. As such, specific targets were developed for these species that propose increasing trajectories of abundance relative to a reference value. For these species, this reference is the mean abundance (CPUE; fish.minute electrofishing^{-1}.site^{-1}) across all previous years of sampling at the Katarapko Anabranch (2009-2015). As such, the reference value for Murray cod = 0.01 fish.minute electrofishing^{-1}.site^{-1};

freshwater catfish = 0.02 fish.minute electrofishing^{-1}.site^{-1}; golden perch = 0.38 fish.minute electrofishing^{-1}.site^{-1} and silver perch = 0.04 fish.minute electrofishing^{-1}.site^{-1}.

Target 4: Annual recruitment of foraging generalists is maintained or enhanced

References and indices were developed for the following species, broadly representative of the small to medium-bodied fishes of the lower River Murray:

- Unspecked hardyhead;
- Murray rainbowfish;
- Australian smelt; and
- Bony herring

The index for these species incorporates both age/size structure and abundance. These species are short-lived (1–5 years) and are reliant upon annual recruitment. For these species, fish comprising the young-of-year (YOY) cohort in autumn (generally coinciding with condition monitoring surveys) will contribute to the reproductively mature adult population the following spawning season. Abundance is also included in the index, as reliance on an age/size structure alone may result in years where few fish are sampled being classified as years of 'successful' recruitment. For these species, length is an appropriate surrogate for more accurate estimates of age (e.g. otolith increment counts).

The reference value (Table 4) is the mean abundance of the YOY cohort from baseline data collected from 2009–2015, and is calculated as:

- X = site abundance (fish.minute electrofishing^{-1}.site^{-1}),
- $r_{standard}$ = set proportion YOY* (*Values of $r_{standard}$ were calculated as the mean proportion of the population comprised of young-of-the-year from 2009–2015.),
- Reference value (RV) = mean((X_{2009}*$r_{standard}$) + (X_{2010}*$r_{standard}$) +…….. (X_{2015}*$r_{standard}$))

Table 4. Species, typical length of the YOY cohort during annual sampling (based upon knowledge of species biology), the mean proportion of the population comprised by the YOY cohort ($r_{standard}$) and the recruitment index reference value (*RV*).

Species	Length YOY	$r_{standard}$	RV
Unspecked hardyhead	<40 mm FL	70%	3.35
Murray rainbowfish	<40 mm FL	30%	0.80
Australian smelt	<40 mm FL	48%	0.68
Bony herring	<100 mm FL	58%	8.28

The recruitment index for small-bodied species was calculated as:

- X_{year} = annual abundance (fish.minute electrofishing^{-1}.site^{-1}),
- r_{year} = annual proportion of YOY
- Annual recruitment value *(AV)* = $X_{year}*r_{year}$
- Recruitment index (*RI*) = *AV*/*RV*
    - Values of *RI* >1.0 represent enhanced recruitment relative to reference
    - Values of *RI* <1.0 represent diminished recruitment relative to reference

Target 5: Recent recruitment of Murray Cod to YOY and the adult population is evident as displayed by the presence of individuals <200 and 400–600 mm TL, respectively.

The recruitment index for Murray cod incorporates length frequency data only. Abundance is not included due to the low numbers of fish typically sampled. Murray cod recruitment is measured in two ways: 1) the proportion of YOY individuals; and 2) the proportion of fish that have reached sexual maturity. Recruitment to YOY, as indicated by the proportion of fish <200 mm TL, provides a useful measure of survival of recently spawned fish. The proportion of fish ranging 400–600 mm TL corresponds to individuals approximately 3–6 years of age in the lower River Murray (Zampatti et al. 2014) and the age at sexual maturity (Rowland 1998), thus representing recruitment to the adult population.

The reference value is the mean proportion of the population comprised of fish YOY <200 mm TL and 400–600 mm TL over the period 2009–2015. These values are 25% and 8% for fish <200 mm TL and 400–600 mm TL, respectively.

Target 6: Recruitment events for common carp and goldfish do not occur in the absence of meeting other key targets under managed inundations (e.g. improved condition of long-lived floodplain vegetation)

The recruitment indices for the non-native species, common carp and goldfish, followed the same approach for small-bodied native species and incorporates age/size structure and abundance. For common carp and goldfish, length is an appropriate method for discerning YOY individuals from autumn sampling. Length, however, is not a surrogate for more accurate estimates of age (e.g. otolith increment counts) for older individuals.

The reference values for these indices are effectively the mean abundance of the YOY cohort for these species surveyed from 2009–2015. The reference values are species-specific (Table 5) and were calculated using the following equation where X = site abundance (fish.minute electrofishing^{-1}.site^{-1}), and $r_{standard}$ = set proportion YOY.

Reference value (*RV*) = $mean((X_{2009}*r_{standard}) + (X_{2010}*r_{standard}) + \ldots\ldots (X_{2015}*r_{standard}))$

$r_{standard}$ was determined as the mean proportion of the population comprised of the YOY cohort across all previous sampling years (Table 5).

Table 5. Species, typical length of the YOY cohort during annual sampling (based upon knowledge of species biology), the mean proportion of the population comprised by the YOY cohort ($r_{standard}$) and the recruitment index reference value (*RV*) for select non-native fishes at the Katarapko Anabranch from 2009–2015.

Species	Length YOY	$r_{standard}$	*RV*
Common carp	<150 mm FL	33%	4.78
Goldfish	<100 mm FL	60%	2.85

To assess future trends in recruitment, for each future sampling year, recruitment index values (*RI*) will be calculated using the following equation, where X_{year} = annual abundance (fish.minute electrofishing^{-1}.site^{-1}), r_{year} = annual proportion of YOY.

Annual recruitment value *(AV)* = $X_{year}*r_{year}$

Recruitment index (*RI*) = *AV*/*RV*

- Values of *RI* >1.0 represent enhanced recruitment relative to reference
- Values of *RI* <1.0 represent diminished recruitment relative to reference

3. RESULTS

3.1. Hydrology

River Murray discharge to South Australia (QSA) has been highly variable since 2009. Following an extended period of low discharge from 1997–2010. Sampling in 2009 and 2010, occurred toward the end of this period during low within channel flows of ~3000 and ~6700 ML.day^{-1}, respectively. This was followed by significant flooding in summer-autumn 2010/11 (peak ~93,000 ML.day^{-1}), a subsequent smaller overbank flood in autumn 2012 (peak ~60,000 ML.day^{-1}) 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 sampling in autumn 2015, mean daily discharge was 6,427 ML.day^{-1}. Discharge from 2015–2021, has been characterised by predominantly within-channel flow (<12,000 ML.day^{-1}), punctuated by a large overbank flood that peaked at 95,000 ML.day^{-1} in late 2016, and in-channel pulses of 15,000–18,000 ML.day^{-1} in December 2017, October 2019 and November 2020. During sampling in autumn 2021, daily mean discharge was ~5,350 ML.day^{-1}. Discharge increased in August 2021 and was elevated through spring, before peaking in early January 2022 at ~37,500 ML.day^{-1} (Figure 2). At the time of sampling in 2022, flow into South Australia had eased slightly and ranged from 20,699– 22,265 ML.day^{-1} (Figure 2).

Prior to completion of the Bank J Regulator on Eckerts Creek – the primary influent creek to the Katarapko Anabranch – under normal operating conditions and within channel flows in the River Murray (i.e. <15,000 ML.day^{-1}), discharge through Eckerts Creek and the upper part of the Katarapko system was typically ~300 ML.day^{-1}. The upgrade to this structure, and the Log Crossing further downstream, increased capacity for discharge through the system. The Bank J Regulator can now discharge 200–600 ML.day^{-1} under normal upstream pool level, and up to ~1,300 ML.day^{-1} during weir pool raising and managed inundation events. Prior to sampling in 2022, the Bank J Regulator was discharging ~500 ML.day^{-1} when under normal operating conditions. In addition, from 8 September–24 December 2020 and 26 July–28 November 2021, floodplain infrastructure was operated in managed inundation events at the Katarapko system

The Splash Regulator was raised to a maximum height of 12.84 m AHD and 2.84 m above normal pool level in 2020 and to a maximum height of 13.31 m AHD and 3.31 m above normal pool level in 2021.

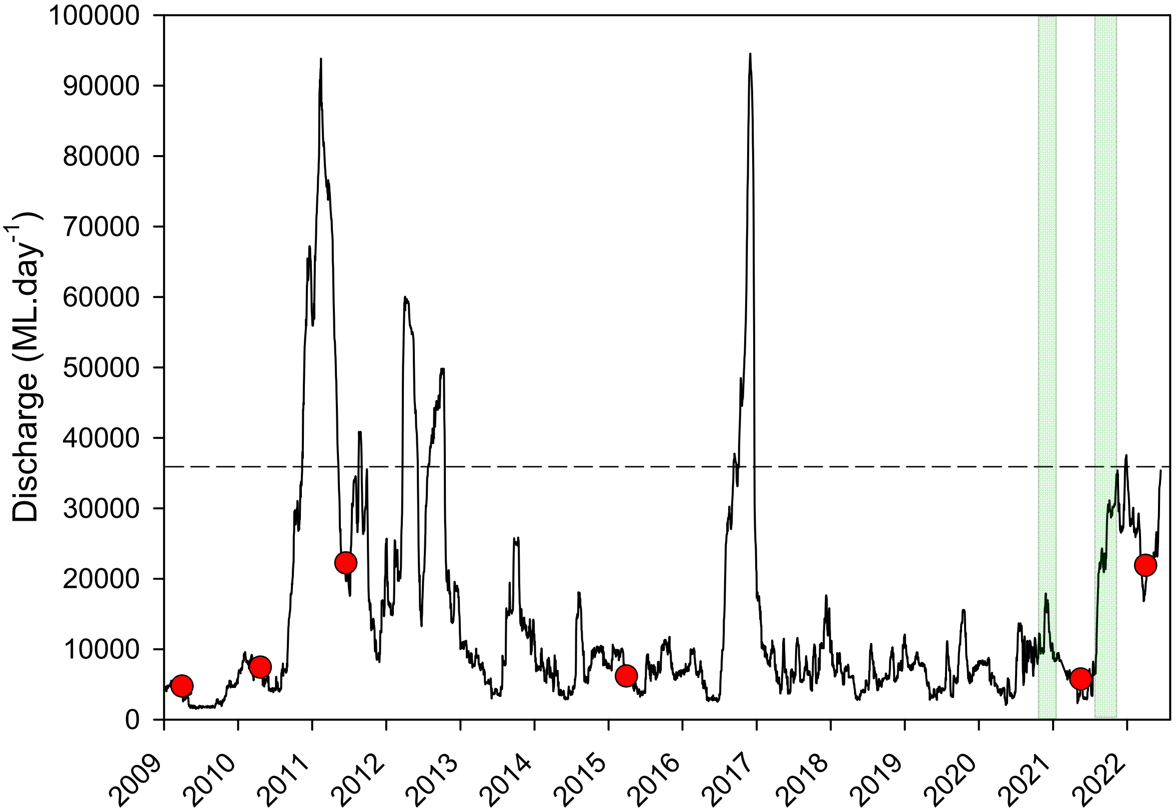

Figure 2. Mean daily flow (ML.d^{-1}) in the River Murray at the South Australian Border (Site A42610010) January 2009–June 2022 (DEW, Water Data SA). Red circles indicate sampling events, the dashed line represents approximate bankfull discharge at the Katarapko Anabranch (~35,000 ML.d^{-1}) and the green shaded areas represents regulator inundation within the Katarapko Anabranch in 2020 and 2021.

3.2. Catch summary

In 2022, a total of 7,527 fish were captured from 15 species (11 native and 4 non-native; Table 6). The most abundant native species were bony herring (37.2%) and Australian smelt (13.8%), whilst the remaining native species comprised 7.8% of the total catch (Table 6). Common carp (36.5%) and goldfish (3.8%) were the most abundant non-native species, whilst the remaining non-native species collectively comprised 0.86% of the total catch (Table 6). Three species of conservation significance were sampled, namely: Murray cod (*vulnerable* under the *EPBC Act 1999*); silver perch (*Endangered* under the *EPBC Act 1999*); and freshwater catfish (*protected* under the South Australian *Fisheries Management Act 2007*).

In the five years that surveyed comparable sites from 2009–2022, a total of 66,885 fish from 16 species (12 native and 4 non-native) were captured (Table 6). The most abundant species throughout this period were the small-to-medium-bodied native species, bony herring, unspecked hardyhead, Australian smelt and Murray rainbowfish, whilst common carp and goldfish were the most abundant non-native species.

Table 6. Total (black text) and standardised (fish.site-1) abundances (blue text) of fish captured from condition monitoring sites sampled in Katarapko and the adjacent River Murray from 2009–2022.

Species	2009	2010	2011	2015	2021	2022	Grand Total
Golden perch	69	116	558	78	39	76	936
(Macquaria ambigua)	4.9	6.4	37.2	6.5	2.8	5.4	
Murray cod	7	2	1	3	8	10	31
(Maccullochella peelii)	0.5	0.1	0.1	0.3	0.6	0.7	
Silver perch	5	16	26	5	-	9	61
(Bidyanus bidyanus)	0.4	0.9	1.7	0.4		0.6	
Freshwater catfish	2	9	4	4	2	6	27
(Tandanus tandanus)	0.1	0.5	0.3	0.3	0.1	0.4	
Bony herring	1708	8689	1259	4470	4582	2800	23644
(Nematalosa erebi)	122.0	490.3	83.9	372.5	327.3	200	
Australian smelt	110	665	412	394	2029	1036	4660
(Retropinna semoni)	7.9	37.7	27.5	32.8	144.9	74	
Murray rainbowfish	170	244	1935	536	462	260	3607
(Melantaenia fluviatilis)	12.1	13.6	129.0	44.7	33.0	18.6	
Flat-headed gudgeon	23	8	20	3	10	3	67
(Philypnodon grandiceps)	1.6	0.4	1.3	0.3	0.7	0.2	
Dwarf flat-headed gudgeon	1	-	1	-	-	1	3
(Philynodon macrostomus)	0.1		0.1			0.07	
Unspecked hardyhead	876	1421	797	1828	1201	197	6320
(Craterocephalus fulvus)	62.6	78.9	53.1	152.3	85.8	14.1	
Carp gudgeon spp.	45	76	84	25	41	24	295
(Hypseleotris spp.)	3.2	4.2	5.6	2.1	2.9	1.7	
Spangled perch	-	-	4	1	-	-	5
(Leipotherapon unicolour)			0.3	0.1			
Common carp*	200	287	16365	371	738	2750	20711
(Cyprinus carpio)	14.3	15.9	1091.0	30.9	52.7	196.4	
Gambusia*	52	54	278	61	39	26	510
(Gambusia holbrooki)	3.7	3.0	18.5	5.1	2.8	1.9	
Goldfish*	319	458	4621	240	33	290	5961
(Carassius auratus)	22.8	25.4	308.1	20.0	2.4	20.7	
Redfin perch*	1	1	1	3	2	39	47
(Perca fluviatilis)	0.1	0.1	0.1	0.3	0.1	2.8	
Total species	**15**	**14**	**16**	**15**	**13**	**15**	**16**
Total number of sites	**14**	**18**	**15**	**12**	**14**	**14**	
Total number of fish	**3,588**	**12,064**	**26,366**	**8,022**	**9,186**	**7,527**	**66,885**
Standardised total abundance	**256.3**	**677.6**	**1757.7**	**668.5**	**656.1**	**537.6**	

3.3. Temporal variation in fish abundance

Between 2009 and 2022, annual relative abundance of fish (all species combined) varied significantly among years (Figure 3; $Pseudo\text{-}F_{7, 94} = 13.029$, $p < 0.001$). Pairwise comparisons (B-Y corrected $\alpha = 0.015$) indicated abundance in 2011 was significantly greater than all other years, whilst abundance in 2009 was significantly less than in 2010, 2011, 2015, 2021 and 2022, but that all other comparisons were non-significant. As a proportion of the total catch, native fish numerically dominated in all years, with the exception of 2011 when non-native species comprised >75% of fish sampled (Figure 3). A relatively high proportion of non-native fish were also sampled in 2022 (~40%).

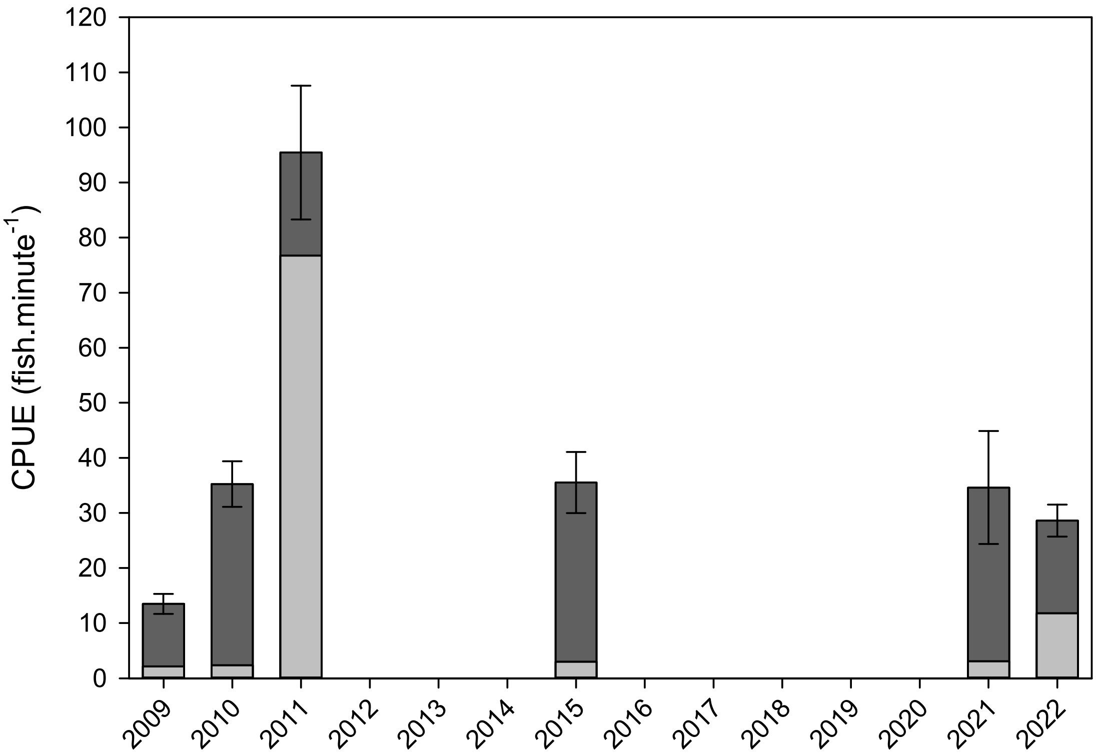

Figure 3. Mean (± SE) catch-per-unit-effort (CPUE) (fish.min^{-1}) of fish (all species combined) collected during standardised boat electrofishing surveys from 2009–2022 in the Katarapko Anabranch system and adjacent River Murray. Dark grey = native species, light grey = non-native species.

3.4. Spatio-temporal differences in fish assemblage structure

Two-factor PERMANOVA, performed on data from 2009–2022, detected significant differences in fish assemblages among years and mesohabitats, and no significant interaction (Table 7). This indicated that fish assemblages varied among years and mesohabitats, and that change through time was consistent among mesohabitats.

Table 7. PERMANOVA results comparing the relative abundances of fish between years and mesohabitats between 2009–2022. Significant *P* values are highlighted in bold.

Factor	***df***	***Pseudo-F***	***P***
Year	5, 76	8.1842	**0.001**
Mesohabitat	3, 76	5.6306	**0.001**
Year x mesohabitat	15, 76	1.0052	0.475

Pairwise comparisons revealed significant differences (B-Y corrected α = 0.02) in fish assemblages among mesohabitats for all comparisons (Table 8). In addition, cluster analysis and MDS indicated three distinct groupings of fish assemblages by sampling years (Figure 4). Namely, a group of assemblages sampled in 2009, 2010, 2015 and 2021 and single-year groupings of assemblages sampled in 2011 and 2022, respectively (Figure 4). A similar pattern of temporal variability was observed for fish assemblages among all mesohabitats (Figure 5a –5d).

Table 8. PERMANOVA pair-wise comparisons between fish assemblages among different mesohabitats in the Katarapko Anabranch between 2009–2022. Significant values are highlighted in bold (B-Y corrected α = 0.02).

Pairwise comparison		***t***	***p* value**
Mesohabitat	**Mesohabitat**		
Fast	Backwater	2.7028	**0.001**
Fast	Slow	2.3075	**0.001**
Fast	River	2.0988	**0.001**
Backwater	Slow	2.1945	**0.001**
Backwater	River	3.3971	**0.001**
Slow	River	1.9004	**0.004**

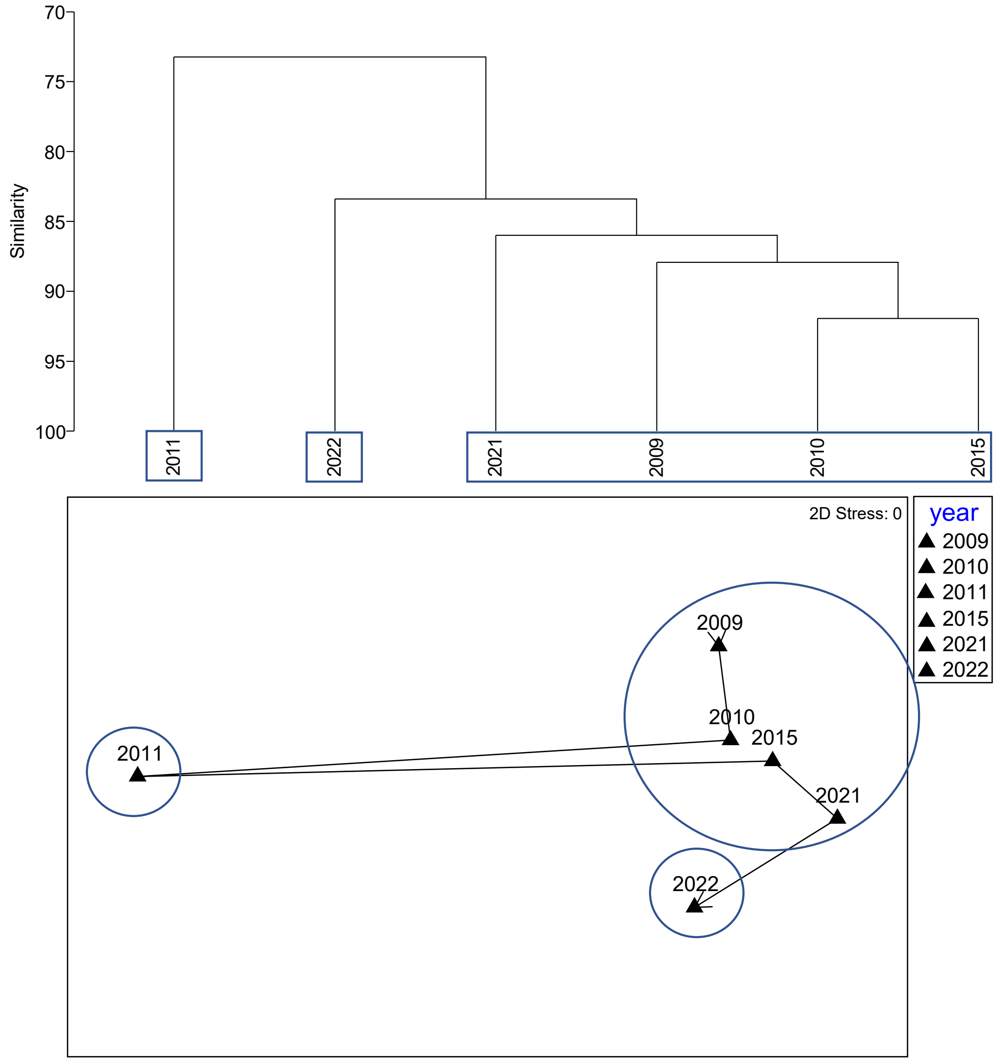

Figure 4. a) Dendrogram indicating fish assemblage clusters between 2009–2022; and b) Non-metric multi-dimensional scaling (MDS) plot of the same data.

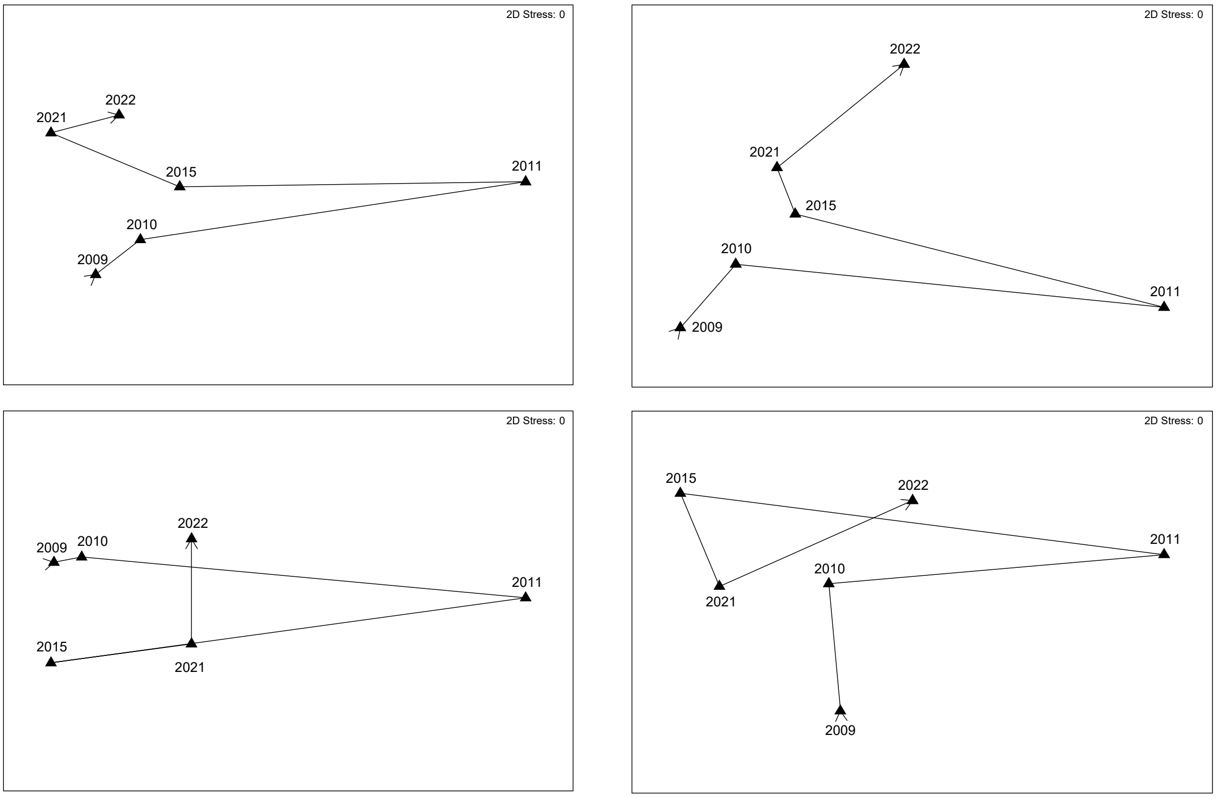

Figure 5. Non-metric multi-dimensional scaling (MDS) plots of a) fast-flowing, b) slow-flowing, c) backwater and d) river mesohabitats sampled between 2009–2022 (sites averaged).

SIMPER indicated that differences among the assemblage grouping of 2009, 2010, 2015 and 2021 and that from 2011 was driven primarily by greater abundances of non-native common carp and goldfish, and native Murray rainbowfish in 2011, and greater abundances of bony herring in the preceding cluster group (Appendix 1). Greater abundance of common carp, goldfish, Murray rainbowfish, and the native golden perch in 2011, also drove differences between 2011 and 2022. Differences among assemblages from 2022 and the grouping of 2009, 2010, 2015 and 2021, was primarily driven by greater abundance of common carp and redfin perch in 2022, and minor differences in abundance of several small-bodied native fishes. ISA of the same data suggested fish assemblages from 2011 were characterised by common carp, goldfish, gambusia, golden perch and Murray rainbowfish (Table 9), whilst the collective assemblages from sampling in 2009, 2010, 2015 and 2021 were characterised by the small-to-medium-bodied species bony herring, unspecked hardyhead and Australian smelt (Table 9). In 2022, fish assemblages were characterised by the non-native species, redfin perch (Table 9).

Indicator species analysis comparing mesohabitat types suggested fast-flowing mesohabitats were characterised by eastern gambusia, Australian smelt, redfin perch, and carp gudgeon complex (*Hypseleotris* spp.) (Table 10). Main river channel mesohabitats were characterised by Murray cod, golden perch and Murray rainbowfish, whilst no species were significantly associated with slow-flowing or backwater mesohabitats.

Table 9. Indicator species analysis comparing the relative abundance of fish between 2009–2022. (Year group 1 = 2011; Year group 2 = 2009, 2010, 2015, 2021; and Year group 3 = 2022). Significant *p*-values (α = 0.05) indicate that a species occurs in a higher relative abundance in a specific year group. Only significant indicators are presented.

Species	Year Group	Indicator value	*p* value
Common carp	1	31.7	0.0002
Goldfish	1	32.1	0.0002
Gambusia	1	28.4	0.0002
Golden perch	1	29.2	0.0002
Murray rainbowfish	1	26.6	0.0002
Bony Herring	2	20.6	0.0022
Australian smelt	2	21.8	0.0120
Unspecked hardyhead	2	20.6	0.0154
Redfin perch	3	50.8	0.0002

Table 10. Indicator species analysis comparing the relative abundance of fish in the four aquatic mesohabitats between 2009–2022. Significant *p*-values (α = 0.05) indicate that a species occurs in a higher relative abundance in a specific mesohabitat. Only significant indicators are presented.

Species	Mesohabitat	*P* - value
Gambusia	Fast	0.0002
Australian smelt	Fast	0.0082
Redfin perch	Fast	0.0070
Carp gudgeon spp.	Fast	0.0086
Murray cod	River	0.0064
Murray rainbowfish	River	0.0016
Golden perch	River	0.0004

3.5. Assessment of Ecological targets

Target 1: Maintenance or enhanced species diversity

In all sampling years, diversity was greater than the reference value across all mesohabitats (Figure 6a). The mean of mesohabitat diversity indices for each year was calculated to provide an overall site diversity score (Figure 6b). In all years, the site diversity score was greater than the reference value, with 2011 and 2022 having the highest diversity score out of all sampling years.

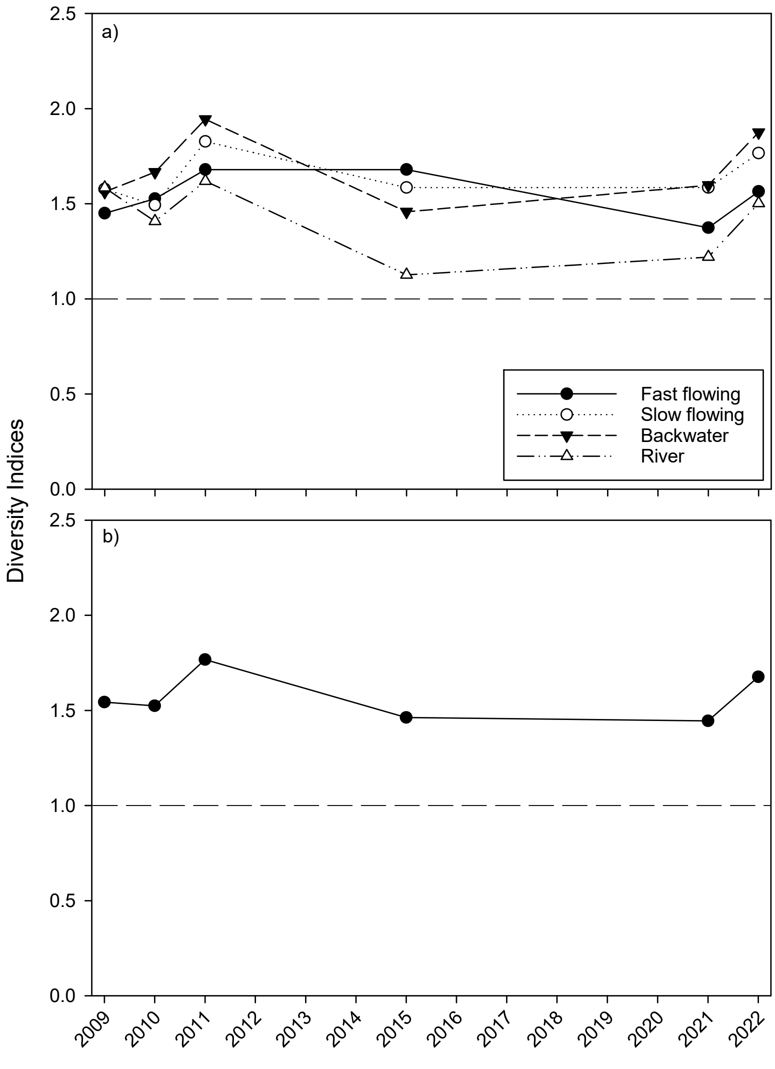

Figure 6. Diversity indices for a) fast-flowing, slow-flowing, backwater and main River channel mesohabitats and b) the calculated Site Diversity Index (*DI*), at the Katarapko Anabranch from 2009–2022.

Target 2: Maintenance or enhanced extent of species across the site

For large-bodied native fishes, the extent index varied among species (Figure 7a). Golden perch distribution was relatively stable across all years, with distribution being either above or just below the reference value. The extent index for Murray cod has varied, with distribution below the reference value in 2009–2010, 2015 and 2021, yet above reference in 2011 and 2022. Silver perch, however, only met the reference value in 2011, but an increase was observed in 2022, albeit being just below the reference. Similarly, freshwater catfish extent in 2010–2011 was either just below or equivalent to reference, with extent decreasing in 2015 and 2021. In 2022, however, extent increased substantially to be over the reference value. The extent index for the majority of small and medium-bodied species remained stable around the reference value in most sampling years, with the exception of high variability for dwarf flat-headed gudgeon and flat-headed gudgeon (Figure 7b). Nonetheless, all species met or were close to the reference value in 2022, apart from dwarf flat-headed gudgeon which were not sampled in this year and flat-headed gudgeon which were sampled in low numbers (Figure 7b).

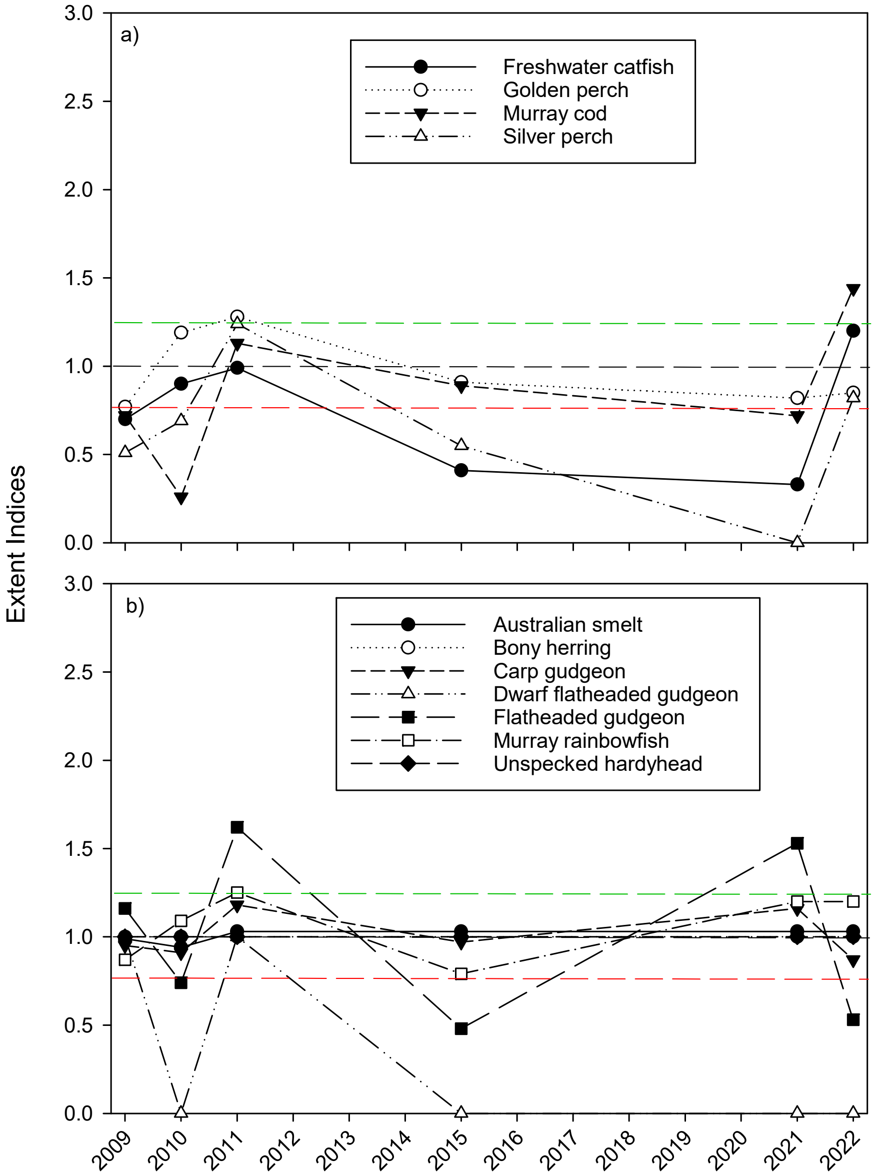

Figure 7. Extent Index (*EI*) scores for a) large-bodied native species and b) small- to medium-bodied native species at the Katarapko Anabranch from 2009–2022. Black dashed line represents extent equal to the reference, green dashed line extent 25% greater than reference and red dashed line extent 25% less than reference.

Target 3: Abundance (CPUE) of large-bodied native fish exhibit positive trajectories over a 5-year period from 2020

The abundance indices for Murray cod, freshwater catfish, golden perch and silver perch have been temporally variable at the Katarapko Anabranch. Murray cod abundance was above the reference in 2009 but was absent or in low abundance from sampling in 2010 and 2011. Since 2015, however, Murray cod have either met or exceeded the reference value and exhibited a positive trajectory in 2021 and 2022 (Figure 8a). For freshwater catfish abundances were above the reference value in 2010, 2015 and 2022, whilst for golden perch, abundances peaked in 2011, but have since been below the reference value from 2015–2022 (Figures 8b and 8c). Silver perch abundance was above the reference value between 2010–2011, but from 2012–2022 abundance for this species was below reference (Figure 8d). Nonetheless, all three species have exhibited positive trajectory across the past two years.

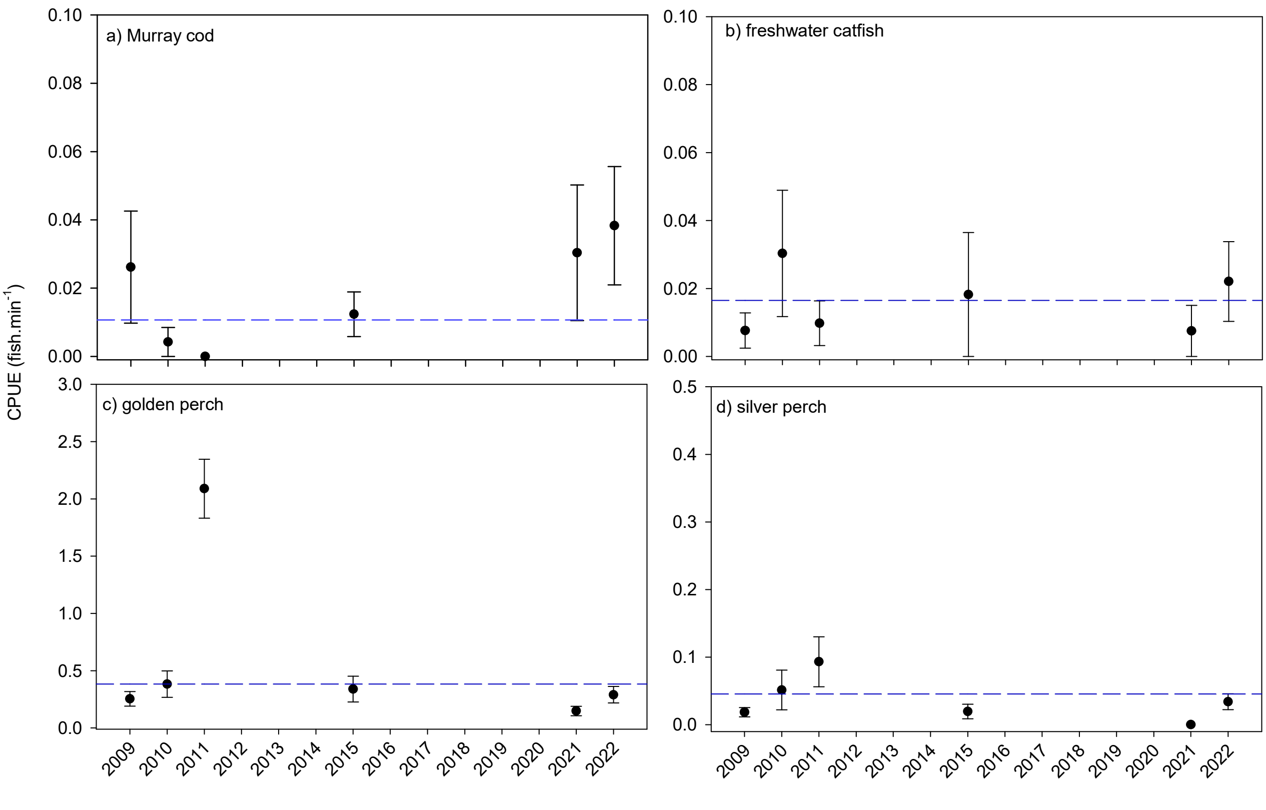

Figure 8. Mean abundance (CPUE; fish.minute electrofishing^{-1}.site^{-1}) ±SE for a) Murray cod, b) freshwater catfish, c) golden perch and d) silver perch at the Katarapko Anabranch between 2009–2022. The blue dashed line represents mean abundance equal to the reference value.

Target 4: Annual recruitment of foraging generalists is maintained or enhanced

For small and medium-bodied foraging generalists, recruitment indices have varied among species and sampling years, although recruitment was evident for most species in most years, no recruitment was observed for Australian smelt in 2011 (Figure 9). Common for all species, recruitment was limited after high flow in 2011, and apart from Australian smelt, this same pattern was observed in 2022 (Figure 9). In 2015 and 2021, recruitment indices were above or near equal to the reference value for all species (Figure 9).

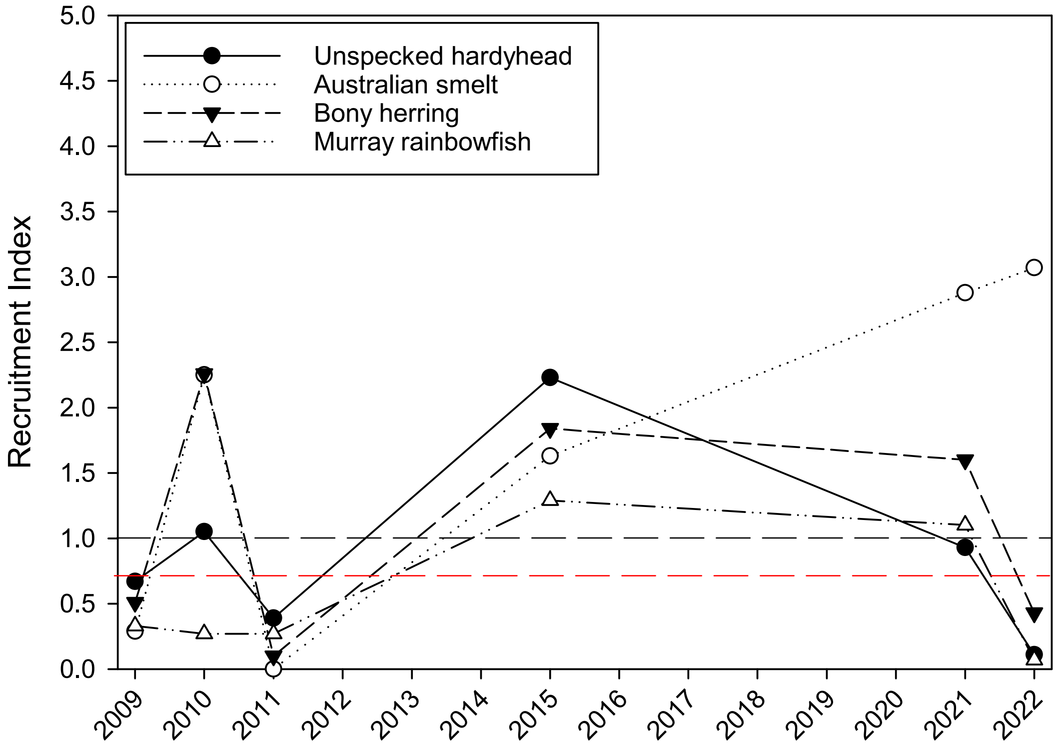

Figure 9. Recruitment Index (*RI*) values for unspecked hardyhead, Murray Rainbowfish, Australian smelt and bony herring from 2009–2022. Dashed black line represents recruitment equal to the reference value and the dashed red line, recruitment 75% of the reference value.

Target 5: Recent recruitment of Murray Cod to YOY and the adult population is evident as displayed by the presence of individuals <200 and 400–600 mm TL, respectively.

The recruitment index for Murray cod ranging from 400–600 mm TL indicated that recruitment to the reproductive adult population was detected in 2009, 2021 and 2022, but not in any other sampling year (Figure 10). Alternatively, for YOY Murray cod (<200 mm TL), recruitment was greater than the reference value in 2010, 2015 and 2021 and absent in 2009, 2011 and 2022 (Figure 10). Only in the sampling year of 2021, did recruitment to YOY and the adult population both occur.

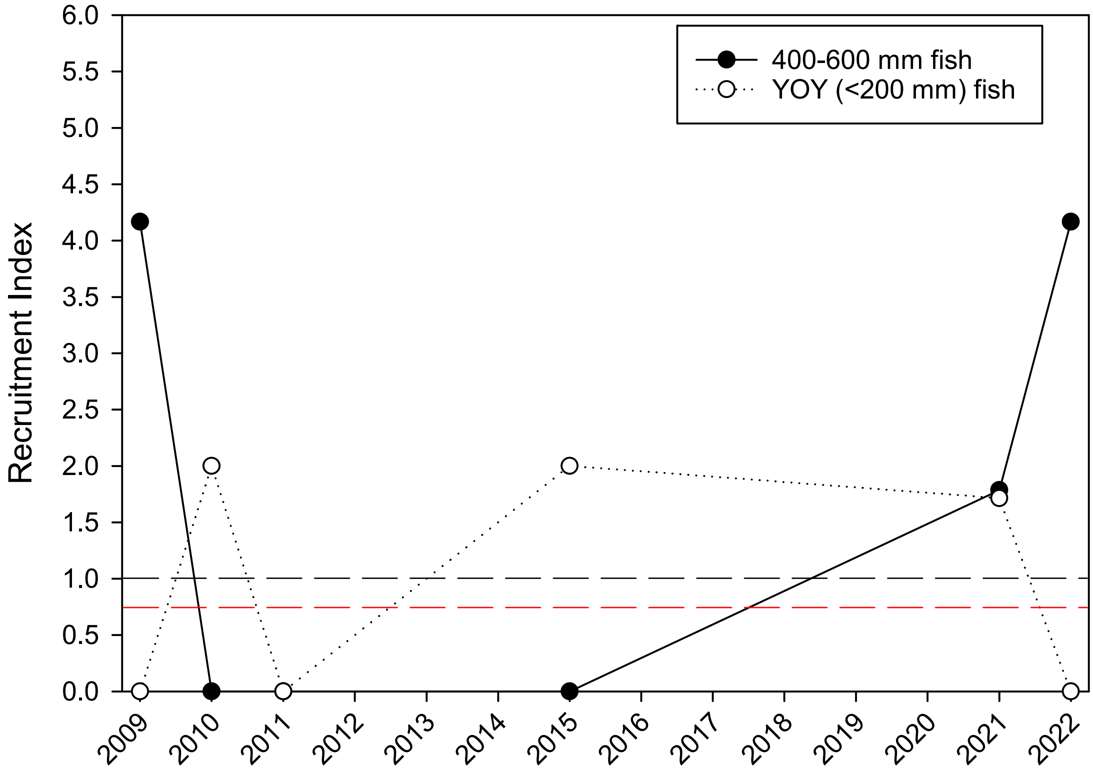

Figure 10. Recruitment Index (*RI*) values for Murray cod ranging 400–600 mm TL (black circles) and YOY (<200 mm TL) Murray cod (open circles) from 2009–2022. Dashed black line represents recruitment equal to the reference value and the dashed red line, recruitment 75% of the reference value.

Target 6: Recruitment events for common carp and goldfish do not occur in the absence of meeting other key targets under managed inundations (e.g. improved condition of long-lived floodplain vegetation)

Recruitment indices for both common carp and goldfish have followed a similar pattern, characterised by temporal variability, albeit with some recruitment to YOY evident in most years (Figure 11). For common carp, recruitment was above the reference in 2011 and 2022, but not in any other year. Goldfish were only above reference in 2011, but a slight increase did occur in 2022, albeit this increase was still below the reference value (Figure 11).

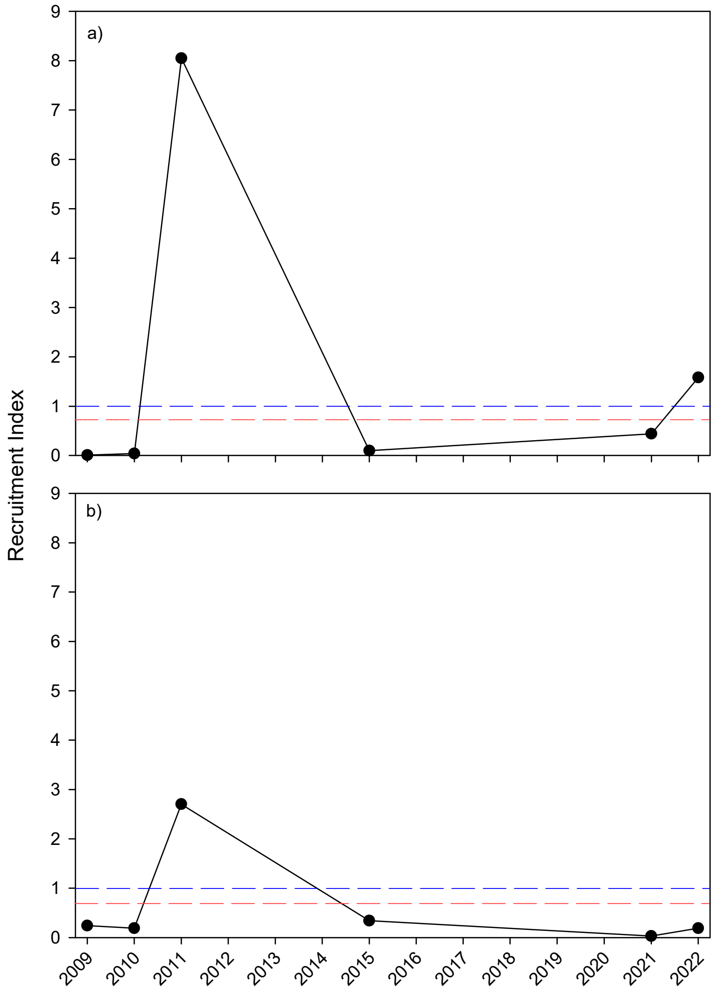

Figure 11. Summary of Recruitment Index (*RI*) values for a) common carp and b) goldfish at the Katarapko Anabranch from 2009–2022. Dashed blue line = reference value, dashed red line = 75% of the reference value.

Summary

Sampling data from 2022 suggests that all six Ecological Targets were achieved or partially achieved (Table 11).

Table 11. Summary of assessment of fish-related Ecological Targets at the Katarapko Anabranch in 2022.

Primary Ecological Objects 1, 2 & 3 (see page 4 above)			**Ecological target**	**2022**
Objective 1	Objective 2		Maintenance or enhanced species diversity	Species diversity index greater than reference value
			Maintenance or enhanced extent of species across the site as indicated by species-specific 'extent index'	Extent maintained or enhanced for 5 of 11 target species
			Abundance (CPUE) of large-bodied native fish exhibits a positive trajectory over a 5-year period from 2020	Murray cod and freshwater catfish abundance currently exhibiting positive trajectory. Whilst golden perch and silver perch abundance are not
	Objective 2		Annual recruitment of foraging generalists is maintained or enhanced relative to historical levels, as indicated by species-specific 'recruitment index'	Only one target species exhibited recruitment indices exceeding reference values
Objective 1			Recent recruitment of Murray Cod to YOY and the adult population is evident as displayed by the presence of individuals <200 and 400–600 mm TL, respectively	Strong recruitment of adult population evident, but recruitment to YOY was absent.
		Objective 3	Relative abundance of common carp and goldfish do not increase in the absence of meeting key targets under managed inundations (e.g. improved condition of long-lived floodplain vegetation)	Recruitment of common carp was elevated relative to the reference value. NOTE: this may be acceptable with achievement of other ecological targets of managed inundation

Not achieved Partially achieved Achieved

4. DISCUSSION

The Katarapko Anabranch system has recently been the focus of substantial environmental rehabilitation efforts under RRP and SARFIIP (completed 2020). Notably, this has included: the upgrade of regulators at Bank J and the Log Crossing to enhance capacity to vary inflow/outflow volumes; the construction of new regulators at Sawmill Creek and the Splash, and associated blocking bank, to facilitate managed inundation of the floodplain; and the construction of fishways on each of the aforementioned structures. In subsequent years, site management will be guided by an Operations Plan that aims to enhance ecological condition and mitigate risks associated with managed inundations. The plan will be supported by a MERI framework to assess ecological condition through time and inform adaptive management. Fish are a key component of the aquatic ecosystem of the Katarapko Anabranch and lower River Murray more broadly, and specific Ecological Objectives and Targets have been developed to assess ongoing condition. The current report presents findings from fish assemblage monitoring in 2022 with comparison to data from previous sampling of fish assemblages (2009–2021) and assessment of Ecological Targets.

4.1. General patterns of abundance and assemblage structure

In 2022, 15 fish species were sampled from 14 sites in the Katarapko Anabranch and adjacent River Murray main channel. The fish assemblage consisted of 11 native and 4 non-native species, with bony herring and common carp the most abundant. The fish assemblage sampled in 2022 differed from a grouping of sampling years that included 2009, 2010, 2015 and 2021, and a single-year grouping from 2011. The years 2009, 2010, 2015 and 2021 were each characterised by predominantly low within-channel flows and minor spring flow pulses of varying magnitude (11,000–18,000 ML.day^{-1}). In 2022, however, sampling was preceded by persistent elevated within-channel flows (up to ~37,500 ML.day^{-1}). In contrast, sampling in 2011 immediately followed a prolonged period of overbank flooding from spring 2010–autumn 2011. These differences in assemblage structure reflect fluctuations in abundance of several small- and medium-bodied generalist species and peak abundance of golden perch and common carp in 2011 in association with variable hydrology.

Patterns of elevated abundance of small- and medium-bodied generalist species including Australian smelt and bony herring are commonly observed in the main channel of the lower River Murray (Zampatti et al. 2011, Bice et al. 2014) and other anabranch habitats (Bice et al. 2015, Fredberg et al. 2021) following prolonged periods of within-channel flow. Causal mechanisms likely relate to the influence of hydraulics on in-stream habitat (e.g. aquatic macrophyte cover) and key life history processes (e.g. survival of early life stages and recruitment). Several of these small-bodied generalist species are typically associated with aquatic macrophytes (Bice *et al.* 2014). Such habitats proliferate in the Katarapko Anabranch, and in the lower River Murray main channel, during periods of regulated low flow and benign hydraulics (as observed in 2009, 2010, 2015 and 2021), but are diminished during and immediately following periods of high flow (as observed in 2011 and 2022) (Bice *et al.* 2014). Overall, flow regulation in the form of altered hydrology and hydraulics (i.e. weir pools) favors generalist small-bodied species that historically may have been more characteristic of wetlands than flowing channel habitats.

The recruitment of large-bodied fishes, notably golden perch, also drove differences among low flow years (2009, 2010, 2015 and 2021) and those characterised by preceding flood (2011) or high within-channel flows (2022). In the lower River Murray, the association of golden perch spawning and recruitment (from local spawning or immigration) with elevated flow is well established (Zampatti et al. 2013a, b). In 2011, the population across the lower Murray was abundant and largely comprised of YOY fish spawned in 2009/10 and 2010/11 in association with high flow in Darling and Murray rivers (Wilson et al 2014, Zampatti et al 2021).

Across sampling years, there were consistent differences in fish assemblages among mesohabitat types and in-turn, associations of certain species with specific mesohabitat types. Specifically, Murray cod, golden perch and Murray rainbowfish characterised River Murray mesohabitats, while Australian smelt, carp gudgeon, redfin perch and eastern gambusia characterised fast flowing mesohabitats. Similar associations with river habitats have been found previously at the Katarapko and Pike anabranches (Bice et al. 2015, 2016; Fredberg and Bice 2022). The association of several small-bodied species with fast flowing mesohabitats was unexpected. This may be a result of changes to the system hydrology to promote lotic habitats following interventions under RRP and SARFIIP in 2020. Furthermore, fast flowing creeks are typically not characterised by uniform high flow velocities, but rather are hydrodynamically diverse, and commonly support high abundances of a range of species, not just iconic large-bodied native fishes (Fredberg et al. 2019).

4.2. Assessment of Ecological Targets

Diversity and extent

The mesohabitat and overall site species diversity indices were stable across years and greater than the reference value, indicating fish species diversity was maintained over the period 2009–2022. The extent of most species has also been maintained or increased, with some notable exceptions. Both dwarf flat-headed gudgeon and flat-headed gudgeon exhibited variable extent across sampling years. Nevertheless, variability was likely due to the generally low abundance of these species in most surveys (e.g. dwarf flat-headed gudgeon 0–1 per year and flat-headed gudgeons 3–23 per year). Electrofishing, whilst efficient in rapidly sampling a diversity of fishes, is not efficient in sampling small, benthic species in turbid waters and as such, caution should be exercised in interpreting fluctuating extent for these species.

In 2022, the extent index for Murray cod was greater than the reference value, and higher than preceding sampling events. The same positive trajectory in extent index was also observed at the Chowilla and Pike Anabranches over the same period (SARDI unpublished data), while increases in abundance and frequency of occurrence were also noted in the lower River Murray main channel (SARDI unpublished data). Positive responses at Katarapko likely reflect broad-scale patterns in the lower River Murray and potentially improved hydrology and hydraulics within the Katarapko system.

Freshwater catfish and silver perch extent were above and just below the reference value in 2022, respectively. Improvement to extent for these species from previous sampling years may indicate initial positive responses to the promotion of lotic habitats at the site since 2020 when in-channel infrastructure works at the anabranch were completed.

Abundance of large-bodied native fish

Similar to the extent index, the standardised abundance of Murray cod increased in 2022. Murray cod were either absent or in low abundance from 2010–2015 in the Katarapko Anabranch and were found in only low abundance in the River Murray main channel (Beyer et al. 2010, Bice et al. 2016, Ye et al. 2016). Increased abundance has since been noted at Chowilla, Pike, Katarapko and in the main channel (Ye et al. 2021; Fredberg et al 2021; Fredberg et al. 2022). For Katarapko, steadily increasing abundance is likely a result of multiple factors, including: improvements to connectivity (e.g. fishway construction); increased extent of lotic habitats under normal operating conditions; and natural recruitment.

Similar to Murray cod, freshwater catfish also exhibited an increasing trajectory in abundance in 2022. Freshwater catfish abundance peaked in 2011 and this pattern was reflected in other regions of the lower Murray and followed increases in abundance following flooding and high flow (Ye et al. 2015). Declines relative to this period or variable abundance have also been noted in other anabranches in recent years (Fredberg et al. 2021; Fredberg et al. 2022). Reasons for increases of freshwater catfish in the Katarapko Anabranch may be similar to those mentioned above for Murray cod. This species has a life history that operates over meso-scales (1–10's km) (Koehn et al. 2020) and in the lower River Murray, is often associated with lotic habitats (Fredberg et al. 2019; Fredberg et al. 2022). As such, recent interventions at Katarapko were predicted to promote the abundance of freshwater catfish.

For golden perch, abundance peaked in 2011 and declined thereafter, albeit there were minor increases in abundance in 2015 and 2022. 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 2013a, 2013b). High abundance in 2011, followed immediately after elevated flow and flooding and widespread recruitment in the lower River Murray (Zampatti et al 2021). From 2014–2021, however, only limited recruitment was observed in anabranch and main-channel habitats (Fredberg et al. 2022; Ye et al. 2021). In 2022, the population of golden perch sampled at the Katarapko Anabranch remained dominated by large individuals (>59% >350 mm TL), but smaller size classes including YOY (<70 mm TL) were present suggesting recent spawning and recruitment. Indeed, YOY golden perch have been collected throughout the lower River Murray in autumn 2022 (SARDI unpublished data). Continued high flow in 2022 will likely see increased dispersal of juvenile golden perch, while a high likelihood of an elevated spring flood may see further spawning and recruitment in 2022/23.

Silver perch abundance was only above the reference value in 2010 and 2011. Higher abundances of this species are associated with periods of elevated within-channel flows (2011), with this pattern also being observed in other anabranch systems in the lower River Murray (Fredberg et al. 2021; Fredberg et al. 2022). In 2022, abundance of silver perch was slightly below the reference value but had increased from the previous year which could be attributed to the combination of elevated flows (up to ~37,500 $ML.day^{-1}$) preceding the sampling period and improvements to connectivity (e.g. fishway construction) and increased extent of lotic habitats under normal operating conditions at the Katarapko Anabranch.

Recruitment of native species

Two approaches were used to assess recruitment of Murray cod: 1) recruitment to YOY (fish <200 mm TL) and 2) recruitment to reproductively mature population (fish 400–600 mm TL). The YOY recruitment index was temporally variable, with the reference value being exceeded in 2015 and 2021 but decreasing to below reference in 2022. In contrast, the index for recruitment to the adult population exceeded the reference value in 2021 and increased further in 2022. This substantial increase in recruitment to the reproductively mature population likely reflects growth of YOY detected in preceding years and immigration of other sub-adult individuals to the region, as improvements to lotic habitats have occurred post SARFIIP works in 2020.

Recruitment indices for the small-bodied Murray rainbowfish, Australian smelt and unspecked hardyhead, and the medium-bodied species bony herring indicate recruitment was variable, but present in all years. Limited to no recruitment for most of the above species was evident in both 2011 and 2022, which coincided with periods of high flow. Australian smelt recruitment, however, was substantially above the reference value in 2022. These small and medium-bodied generalist species are widespread and abundant throughout the lower River Murray (Baumgartner et al. 2008, Bice et al. 2014) and have flexible spawning and recruitment strategies that are not reliant on elevated flow (Baumgartner et al. 2013), and indeed, appear to be enhanced during years of low flow in most circumstances.

Recruitment of non-native species

The greatest level of recruitment of YOY common carp and goldfish in the Katarapko Anabranch was observed in autumn 2011 following extensive and prolonged natural flooding. In 2022, recruitment was lower than 2011 but greater than all other sampling years. The combination of elevated flows preceding sampling in 2022 and a managed inundation event occurring in winter-spring 2021 could be attributed to this increase. Enhanced recruitment of common carp is commonly associated with periods of increased discharge and water levels, either through natural or managed inundations (Bice and Zampatti 2011). A similar response from both species was seen at both the Chowilla and Pike anabranches in Autumn 2022 (SARDI unpublished data).

5. CONCLUSION

Monitoring of fish assemblages at the Katarapko Anabranch in 2022 indicated that all of fish-related Ecological Targets were partially or fully achieved. Importantly, metrics related to Murray cod distribution, abundance and recruitment have generally exhibited positive trajectories. This species is a key target and indicator of success of in-channel management actions at the site (i.e. improved connectivity and hydrodynamics).

The year 2022, represented the second year for application of the newly developed Ecological Targets. The use of these targets for condition assessment brings Katarapko in line with the approach at the Pike and Chowilla Anabranches. The similarity in management of the Katarapko, Pike and Chowilla Anabranches, and approaches to monitoring and reporting on fish condition monitoring, presents an opportunity to better integrate understanding and management of these critical anabranch habitats across the region.

5.1. Future research needs

Monitoring at the Katarapko Anabranch across 2009–2022 has provided valuable information on the ecology of freshwater fish at Katarapko and the lower River Murray. Continued monitoring of fish assemblages post completion of SARFIIP works will be critical to inform responses to changes in management and future adaptive management. Underlying causal mechanisms of observed responses, however, remain speculative and require associated hypothesis-based research. This includes research at the scale of the Katarapko Anabranch and more broadly.

Specific research questions include:

- Investigating factors influencing recruitment variability of Murray cod at the Katarapko Anabranch.
- The influence of site management (e.g. regulator operation) on recruitment and abundance of common carp at Katarapko and contribution to broader regional populations.
- The movement and habitat use of native (e.g. Murray cod) and non-native fish (e.g. common carp) in the Katarapko Anabranch and adjacent River Murray in relation to natural flows and engineered floodplain inundation.
- Response of fish assemblages (diversity and abundance) to altered hydrodynamics at the mesohabitat scale.

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APPENDIX

Appendix 1. Results of similarity or percentages analysis (SIMPER) presenting species that cumulatively contributed >50% to dissimilarity between fish assemblages sampled in year groups at the Katarapko Anabranch, deemed to be significantly different by PERMANOVA. * indicates greater contribution to assemblages from the 'column year', whilst its absence represents greater contribution to assemblages from the 'row year'. *NS* = non-significant comparison.

Year	Year group 1	Year group 2
Year group 2	*C. carpio* *C. auratus* *M. fluviatilis* *N. erebi**	-
Year group 3	*C. carpio* *C. fulvus** *R. semoni* *P. fluviatilis* *N. erebi** *M. fluviatilis*	*C. auratus** *C. carpio** *M. fluviatilis** *M. ambigua** *N. erebi*

Appendix 2. Total number of species captured at each site in 2009.

2009	Site Number														
Species	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Total**
Golden perch	1		6	1		2	9	15	8	8	10	6		3	**69**
Murray cod							2				4			1	**7**
Silver perch						1	1	1			1	1			**5**
Freshwater catfish	1													1	**2**
Bony herring	246	74	59	137	59	53	36	188	235	311	68	26	83	133	**1708**
Australian smelt	32	2	2	7	11	4	8		1	12	3	1	4	23	**110**
Murray rainbowfish	7		2		3	1	8	8	6	19	16	20	1	79	**170**
Unspecked hardyhead	96	10	17	151	13	39	52	10	11	158	118	66	22	113	**876**
Carp gudgeon	12	1	3	1		1			1		1	4	19	2	**45**
Flatheaded gudgeon				1	2					12	2	6			**23**
Dwarf flatheaded gudgeon										1					**1**
Carp	5	15	5	11	25	9	2	16	7	24	14	34	17	16	**200**
Gambusia	8	1	1	13	5	3	1		1	10	2	1	4	2	**52**
Goldfish	7	85	42	38	48	2	1	6	5	3	6	25	50	1	**319**
Redfin perch														1	**1**
Total Species	**10**	**7**	**9**	**9**	**8**	**10**	**10**	**7**	**9**	**10**	**12**	**11**	**8**	**12**	**15**
Total	**415**	**188**	**137**	**360**	**166**	**115**	**120**	**244**	**275**	**558**	**245**	**190**	**200**	**375**	**3588**

Appendix 3. Total number of species captured at each site in 2010.

2010	Site Number																	
Species	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**16**	**18**	**20**	**22**	**Total**
Golden perch	2	1	1	8	7	14	7	14	8	29	9	6		6		2		2	**116**
Murray cod										1	1								**2**
Silver perch				1		1	1	1	2	7	3								**16**
Freshwater catfish	4									1				2				2	**9**
Bony herring	564	80	804	402	498	473	379	824	1155	548	826	422	98	404	247	238	99	628	**8689**
Australian smelt	111		4	63	48	16	21	15	17	99	79	19	10	28	25	18	19	73	**665**
Murray rainbowfish	1	1	3	5	1	7	7	66	55	12	11	19	3	40		1	2	10	**244**
Unspecked hardyhead	277	9	11	67	49	27	59	21	33	195	70	270	43	87	77	6	7	110	**1421**
Carp gudgeon	9			6	3	10		2	2	11	3	2	5		3			20	**76**
Flatheaded gudgeon		1	1	2										2	2				**8**
Carp	5	8	10	18	16	12	8	13	12	20	23	49	9	12	15	23	19	15	**287**
Gambusia	6			4	1	9	8			5		1			6	1		13	**54**
Goldfish	17	47	30	33	41	1	3	13	19	39	4	30	21	17	44	25	54	20	**458**
Redfin perch	1																		**1**
Total Species	**11**	**7**	**8**	**11**	**9**	**10**	**9**	**9**	**9**	**12**	**10**	**9**	**7**	**9**	**8**	**8**	**6**	**10**	**14**
Total	**997**	**147**	**864**	**609**	**664**	**573**	**493**	**969**	**1303**	**967**	**1029**	**818**	**189**	**598**	**419**	**314**	**200**	**893**	**12046**

Appendix 4. Total number of species captured at each site in 2011.

2011	Site Number														
Species	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**16**	**18**	**Total**
Golden perch	29	65	57	17	25	26	57	47	27	54	49	30	54	5	16	**558**
Murray cod										1						**1**
Silver perch			1		2	7	3	4	2	4			3			**26**
Freshwater catfish		1					1		1	1						**4**
Bony herring	55	21	316	42	368	30	30	14	74	41	41	30	18	25	154	**1259**
Australian smelt	4	7	17	51	80	13	18	33	37	36	18	27	39	15	17	**412**
Murray rainbowfish	73	114	147	62	107	92	149	144	99	194	364	171	47	86	86	**1935**
Unspecked hardyhead	120	128	108	36	8	24	21	3	26	35	47	54	5	169	13	**797**
Carp gudgeon	8	3	12	3			7		16	12	8	5	3	3	4	**84**
Flatheaded gudgeon		2	8							1	3	1		1	4	**20**
Dwarf flatheaded gudgeon															1	**1**
Spangled perch										2			2			**4**
Carp	1477	1092	851	1211	1347	535	2738	366	576	377	1009	2189	464	462	1671	**16365**
Gambusia	9	11	35	40	1	7	22	6	1	2	19	11	4	92	18	**278**
Goldfish	191	47	1075	322	392	306	471	103	125	142	339	172	74	267	595	**4621**
Redfin perch					1											**1**
Species Total	**9**	**11**	**11**	**9**	**10**	**9**	**11**	**9**	**11**	**14**	**10**	**10**	**11**	**10**	**11**	**16**
Total	**1966**	**1491**	**2627**	**1784**	**2331**	**1040**	**3517**	**720**	**984**	**902**	**1897**	**2690**	**713**	**1125**	**2579**	**26366**

Appendix 5. Total number of species captured at each site in 2015.

2015	Site Number												
Species	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**9**	**10**	**12**	**13**	**14**	**Total**
Golden perch	4	1	5			10	13	5	25	8	1	6	**78**
Murray cod						1			1			1	**3**
Silver perch	1					2						2	**5**
Freshwater catfish						4							**4**
Bony herring	395	48	20	693	106	348	280	355	830	758	235	402	**4470**
Australian smelt	59	9	2	28	5	39	32	21	129	24	8	38	**394**
Murray rainbowfish	72		26	20		29	15	57	82	58	2	175	**536**
Unspecked hardyhead	162	285	303	517	188	69	29	31	75	126	31	12	**1828**
Carp gudgeon	8		2	1	2	3	1		3	2	3		**25**
Flatheaded gudgeon				2			1						**3**
Spangled perch	1												**1**
Carp	21	14	122	32	14	113	9	1	28	5	8	4	**371**
Gambusia	8	1	5	37	4		6						**61**
Goldfish	42	26	33	73	18	5	1		34		8		**240**
Redfin perch	1			2									**3**
Total Species	**12**	**7**	**9**	**10**	**7**	**11**	**10**	**6**	**9**	**7**	**8**	**8**	**15**
Total	**774**	**384**	**518**	**1405**	**337**	**623**	**387**	**470**	**1207**	**981**	**296**	**640**	**8022**

Appendix 6. Total number of species captured at each site in 2021.

2021	Site Number														
Species	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**9**	**10**	**12**	**13**	**14**	**22**	**24**	**Total**
Golden perch	1		1		1	7	8	4	4	5		7	1		39
Murray cod						1			5				2		8
Freshwater catfish													2		2
Bony herring	93	7	21	166	95	381	217	135	1413	267	263	82	1025	417	4582
Australian smelt	174	29	16	124	19	78	77	12	753	10	51	18	583	85	2029
Murray rainbowfish	27	1	20	10	16	36	37	19	77	47		92	76	4	462
Unspecked hardyhead	29	121	20	11	52	83	29	23	362	69	7	117	229	49	1201
Carp gudgeon	1	1	3	1	4	3	7	3	4	4			9	1	41
Flatheaded gudgeon		2	1				2	1	1	3					10
Carp	31	29	164	51	174	13	25	3	32	63	41	11	57	44	738
Gambusia	4		2	18		2	1		3				4	5	39
Goldfish		1	5	4	6		1	1	3	11	1				33
Redfin perch								1					1		2
Total Species	**8**	**8**	**10**	**8**	**8**	**9**	**10**	**10**	**11**	**9**	**5**	**6**	**11**	**7**	**13**
Total	**360**	**191**	**253**	**385**	**367**	**604**	**404**	**202**	**2657**	**479**	**363**	**327**	**1989**	**605**	**9186**

Appendix 7. Total number of species captured at each site in 2022.

2022	Site Number														
Species	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**9**	**10**	**12**	**13**	**14**	**22**	**24**	**Total**
Golden perch			12	3	2	7	6	7	9	11		16	3		76
Murray cod						2		2	3	3					10
Silver perch				1		2	2			1		1	2		9
Freshwater catfish							1		1			3	1		6
Bony herring	133	110	79	328	236	95	118	186	408	314	100	281	197	215	2800
Australian smelt	27	6	3	68	16	277	305	101	35	24	5	63	96	10	1036
Murray rainbowfish	13	2	19	8	23	44	21	13	11	9		11	75	11	260
Unspecked hardyhead	17	5	2	8	9	6	7	2	21	44	4	17	48	7	197
Carp gudgeon	3		2	1	1	3	1	1		9			2	1	24
Flatheaded gudgeon						1			2						3
Spangled perch				1											1
Carp	135	395	288	205	131	114	131	228	130	489	38	247	127	92	2750
Gambusia	1	1		13	2	2	1		1	1			4		26
Goldfish	2	19	18	43	20	9	2	14	6	133	4	6	3	11	290
Redfin perch	4	1	6	7	4	4	2				1	2	4	4	39
Species Total	**9**	**8**	**9**	**12**	**10**	**13**	**12**	**9**	**11**	**11**	**6**	**10**	**12**	**8**	**15**
Total	**335**	**539**	**429**	**686**	**444**	**566**	**597**	**554**	**627**	**1038**	**152**	**647**	**562**	**351**	**7527**