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Katarapko Fish Assemblage Condition Monitoring 2023

J. Fredberg and C. M. Bice

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SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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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: improving connectivity and extension of lotic habitats under normal operating conditions; and promoting more frequent floodplain inundation than would occur naturally under current conditions, by undertaking 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 April–May 2023, fish condition monitoring was undertaken at the Katarapko Anabranch to assess spatio-temporal variability in fish assemblage structure (i.e., species identity and abundance) relative to results from previous surveys (i.e., 2009–2022) and the current condition of fish assemblages with regard to the above Ecological Objectives and Targets. Standardised boat electrofishing was used to sample fish from the littoral zones of streams across 14 sites; all species captured were identified, enumerated and a sub-sample measured for length.

A total of 21,686 fish were captured from 12 species (8 native and 4 non-native). The most abundant native species were bony herring (30%), Australian smelt (9%) and unspecked hardyhead (5.2%) whilst the remaining native species comprised ~3% of the total catch. The non-native common carp (42.5%) dominated the catch, while goldfish (*Carassius auratus*, 6%) and redfin perch (*Perca fluviatilis,* 3.4%) were also abundant. Two species of conservation significance were sampled, namely Murray cod (*vulnerable* under the *EPBC Act 1999*) and silver perch (*endangered* under the *EPBC Act 1999*).

In 2023, sampling followed a large, basin-wide, flooding event that peaked in the lower River Murray in December 2022 (~185,000 ML.day^{-1}). The fish assemblage sampled in 2023 differed from a grouping of sampling years (2009, 2010, 2015 and 2021) characterised by predominantly low within-channel flows (max annual discharge = 11,000–18,000 ML.day^{-1}), as well as previous years following flood (2011) and high within-channel flow (2022). These differences in assemblage structure in 2023 generally reflect fluctuations in abundance of several small- and medium-bodied generalist species and large-bodied species whose reproduction is associated with high flows and flooding. 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 2023, except target six, related to the abundance of common carp and goldfish abundance. Species diversity exceeded the reference value, whilst extent indices were met for six of eleven target species. The abundance of Murray cod was above the reference, and the recruitment target was met for the adult population but not for young-of-year (YOY) fish. The abundances of freshwater catfish, golden perch and silver perch were below reference values. Recruitment was limited for most common small- and medium-bodied species. Conversely, recruitment of common carp and goldfish was elevated, a commonly observed response to prolonged periods of high flow and flooding in the lower River Murray.

The results highlight potential positive responses (e.g., Murray cod metrics) to improvements in 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, flooding.

1. INTRODUCTION

1.1. Background

The Katarapko Anabranch and Floodplain (hereafter Katarapko, >9,000 ha) is one of three large anabranch systems that bypass Lock and Weir structures on the main channel of the lower River Murray, South Australia (together with Chowilla and Pike). Katarapko 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 from the lower River Murray main channel under regulated conditions (Bice et al. 2017). Subsequently, Katarapko supports a diversity of native aquatic biota including fishes of conservation concern (e.g., Murray cod (*Maccullochella peelii*), freshwater catfish (*Tandanus tandanus*) and silver perch (*Bidyanus bidyanus*)) (Bice et al. 2015). For this reason, the site was declared 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 Katarapko supports significant aquatic and floodplain communities, the ecosystem was considered to be in a degraded state due to the impacts of river regulation. In response 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 Katarapko 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 is being used to: 1) improve connectivity and extension of lotic habitats under regulated conditions; and 2) promote more frequent floodplain inundation than would occur naturally under current conditions, by undertaking managed inundation events. The operation of this infrastructure is 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 system that are likely to be influenced by management. As such, within the Operations Plan, three primary Ecological Objectives were developed for 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*) and goldfish (*Carassius auratus*)).

In association with these Objectives, 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 Katarapko in autumn 2023, 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 nine occasions, namely: 2009, 2010, 2011, 2012, 2013, 2015, 2021, 2022 and 2023 (Leigh *et al.* 2009, 2012, Wilson *et al.* 2012, 2013, Bice *et al.* 2015, Fredberg and Bice 2022a) (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 2023, a total of 14 sites were sampled 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 2009–2023 and used to calculate all indices and reference values for future condition monitoring reporting.

Site no.	Site name	2009	2010	2011	2015	2021	2022	2023	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

^sampled with fyke nets in 2012–2013, but sampled with electrofishing in 2021-2023

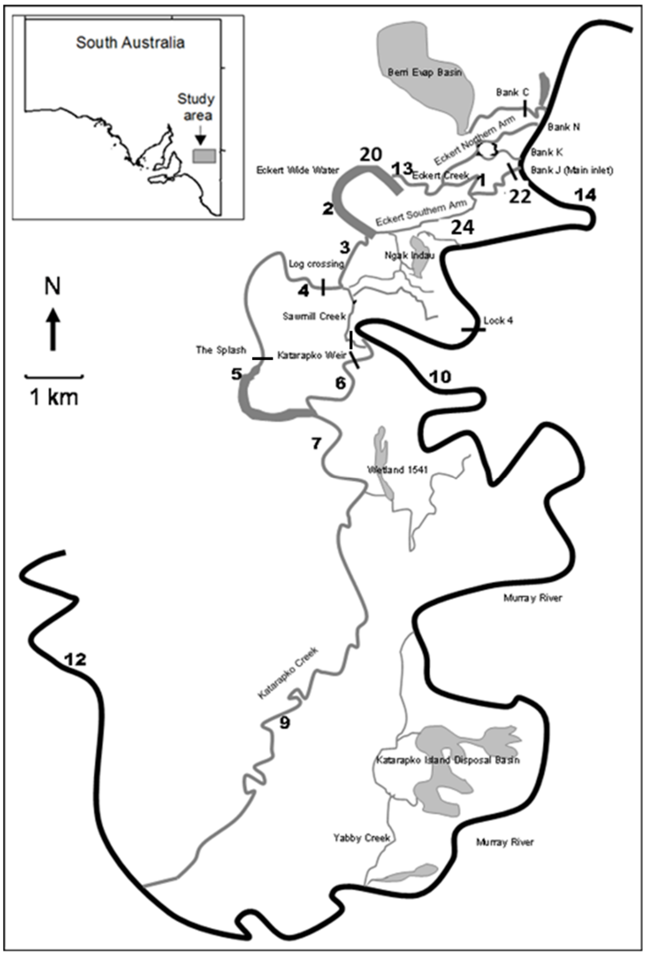

Figure 1. The 15 sites sampled between 2009–2023 as a part of condition monitoring in the Katarapko Anabranch system.

2.2. Data collection

Fish assemblages were sampled from 13 April–5 May 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 (catch per unit effort (CPUE), fish.min^{-1}) of fish sampled between years were analysed using univariate (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) were 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 correction 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}), 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 (year groupings) 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 based on 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 defined 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 (2009–2022).

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

- *MH* = mesohabitat,
- R_{year} = ratio of sites sampled in given year,
- *ER* = expected ratio for each mesohabitat type,
- *EI* = Study Site Extent Index,
- $EI = \text{mean}(MH_1(R_{year}/ER_{MH1}) + MH_2(R_{year}/ER_{MH2}) + MH_3(R_{year}/ER_{MH3}) + MH_4(R_{year}/ER_{MH4}))$,
    - *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 and freshwater catfish. As such, specific targets were developed for these species that propose increasing trajectories of abundance relative to a reference value. Additionally, golden perch and silver perch are also included in Ecological Target 3, as to contribute to data on variability in abundance at the regional scale. However, caution must be taken when interpreting these data as changes in abundance for these two species may not be influenced by local site management. For all species, the reference value 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 size structure (as a proxy for age) 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

From 2007–2023, River Murray discharge to South Australia (QSA) has been highly variable (Figure 2). The period 2007–2010, represented the final years of the Millennium Drought and was characterised by very low within channel flow (<10,000 $ML.day^{-1}$). This was followed by significant flooding in summer-autumn 2010/11 (peak ~93,000 $ML.day^{-1}$), a smaller overbank flood in autumn 2012 (peak ~60,000 $ML.day^{-1}$) and generally elevated discharge throughout much of 2012. Discharge from 2013–2021, was 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 within-channel pulses of 15,000–25,000 $ML.day^{-1}$ in September 2013, August 2014, December 2017, October 2019, and November 2020. In 2021, discharge increased abruptly in August 2021 and was elevated throughout spring, before peaking in early January 2022 at ~37,500 $ML.day^{-1}$. Discharge remained >20,000 $ML.day^{-1}$ through much of autumn before increasing drastically through winter and peaking at ~185,000 $ML.day^{-1}$ in December 2022. This was the largest flood event in the lower River Murray since 1956 (~341,000 $ML.day^{-1}$). Sampling of fish assemblages at the Katarapko Anabranch System has typically occurred during QSA of ≤7,500 $ML.day^{-1}$, with the exception of 2011 (~24,000 $ML.day^{-1}$), 2022 (~22,000 $ML.day^{-1}$) and 2023 (~25,000 $ML.day^{-1}$) (Figure 2).

Prior to completion of the Bank J Regulator on Eckerts Creek (the primary influent creek to the Katarapko Anabranch), and under 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. In 2022, the Bank J Regulator was discharging ~500 $ML.day^{-1}$ when under normal operating conditions.

From 8 September–24 December 2020 and 26 July–28 November 2021, floodplain infrastructure was operated to promote 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. In 2022, however, only a minor operation at the Boyties Lagoon regulator was initiated in early August but was abandoned by early September due to rising flood waters.

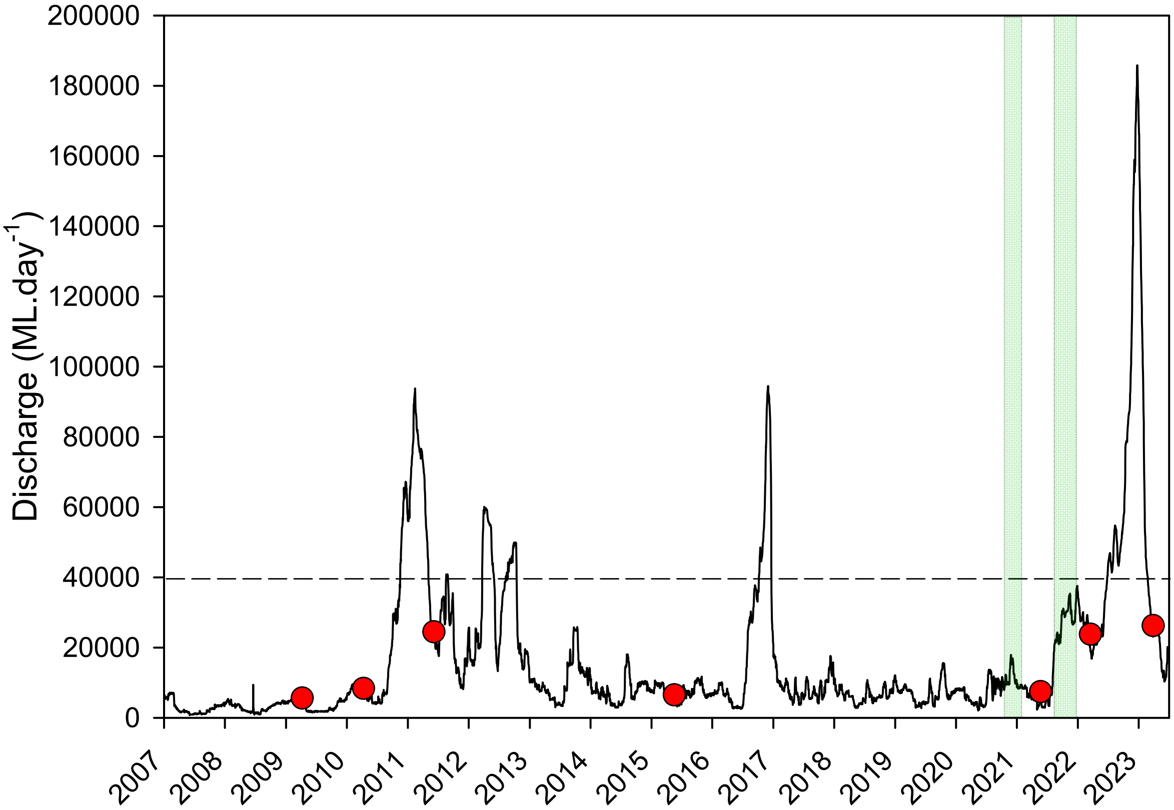

Figure 2. Mean daily discharge (ML.d^{-1}) in the River Murray at the South Australian Border (Site A42610010) January 2009–June 2023 (https://water.data.sa.gov.au/). Red circles indicate sampling events, the dashed line represents approximate bankfull discharge in the vicinity of the Katarapko Anabranch (~40,000 ML.d^{-1}) and the green shaded areas represents managed inundation events at Katarapko in 2020 and 2021.

3.2. Catch summary

In 2023, a total of 21,686 fish were captured from 12 species (8 native and 4 non-native; Table 6). The most abundant native species were bony herring (30%), Australian smelt (9%) and unspecked hardyhead (5.2%) whilst the remaining native species comprised ~3% of the total catch (Table 6). The non-native common carp (42.5%) dominated the catch, while goldfish (6%) and redfin perch were also abundant (3.4%) (Table 6). Two species of conservation significance were sampled, namely: Murray cod (*vulnerable* under the *EPBC Act 1999*); and silver perch (*Endangered* under the *EPBC Act 1999*).

In the seven years that surveyed comparable sites from 2009–2023, a total of 88,571 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 2009–2023.

Species	2009	2010	2011	2015	2021	2022	2023	Grand Total
Golden perch	69	116	558	78	39	76	59	995
(Macquaria ambigua)	4.9	6.4	37.2	6.5	2.8	5.4	4.2	
Murray cod	7	2	1	3	8	10	8	39
(Maccullochella peelii)	0.5	0.1	0.1	0.3	0.6	0.7	0.6	
Silver perch	5	16	26	5	-	9	1	62
(Bidyanus bidyanus)	0.4	0.9	1.7	0.4		0.6	0.10	
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	6502	30146
(Nematalosa erebi)	122.0	490.3	83.9	372.5	327.3	200	464.4	
Australian smelt	110	665	412	394	2029	1036	1960	6620
(Retropinna semoni)	7.9	37.7	27.5	32.8	144.9	74	140.0	
Murray rainbowfish	170	244	1935	536	462	260	606	4213
(Melantaenia fluviatilis)	12.1	13.6	129.0	44.7	33.0	18.6	43.3	
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	1130	7450
(Craterocephalus fulvus)	62.6	78.9	53.1	152.3	85.8	14.1	80.7	
Carp gudgeon spp.	45	76	84	25	41	24	10	305
(Hypseleotris spp.)	3.2	4.2	5.6	2.1	2.9	1.7	0.7	
Spangled perch	-	-	4	1	-	-	-	5
(Leipotherapon unicolour)			0.3	0.1				
Common carp*	200	287	16365	371	738	2750	9234	29945
(Cyprinus carpio)	14.3	15.9	1091.0	30.9	52.7	196.4	659.6	
Gambusia*	52	54	278	61	39	26	140	650
(Gambusia holbrooki)	3.7	3.0	18.5	5.1	2.8	1.9	10.0	
Goldfish*	319	458	4621	240	33	290	1299	7260
(Carassius auratus)	22.8	25.4	308.1	20.0	2.4	20.7	92.8	
Redfin perch*	1	1	1	3	2	39	737	784
(Perca fluviatilis)	0.1	0.1	0.1	0.3	0.1	2.8	52.6	
Total species	**15**	**14**	**16**	**15**	**13**	**15**	**12**	**16**
Total number of sites	**14**	**18**	**15**	**12**	**14**	**14**	**14**	
Total number of fish	**3,588**	**12,064**	**26,366**	**8,022**	**9,186**	**7,527**	**21,686**	**88,571**
Standardised total abundance	**256.3**	**677.6**	**1757.7**	**668.5**	**656.1**	**537.6**	**1549.0**	

3.3. Temporal variation in fish abundance

Between 2009 and 2023, annual total fish abundance (all species combined) varied significantly among years (Figure 3; $Pseudo\text{-}F_{8,\,108} = 16.55$, $p < 0.001$). Pairwise comparisons (B-Y corrected $\alpha = 0.012$) indicated abundance in 2011 and 2023 were significantly greater than all other years, whilst abundance in 2009 was significantly less than all other years, but all other comparisons were non-significant. As a proportion of the total catch, native fish numerically dominated in all years, except for 2011 and 2023 when non-native species comprised ~80% and ~52% of fish sampled, respectively (Figure 3). A relatively high proportion of non-native fish were also sampled in 2022 (~40%).

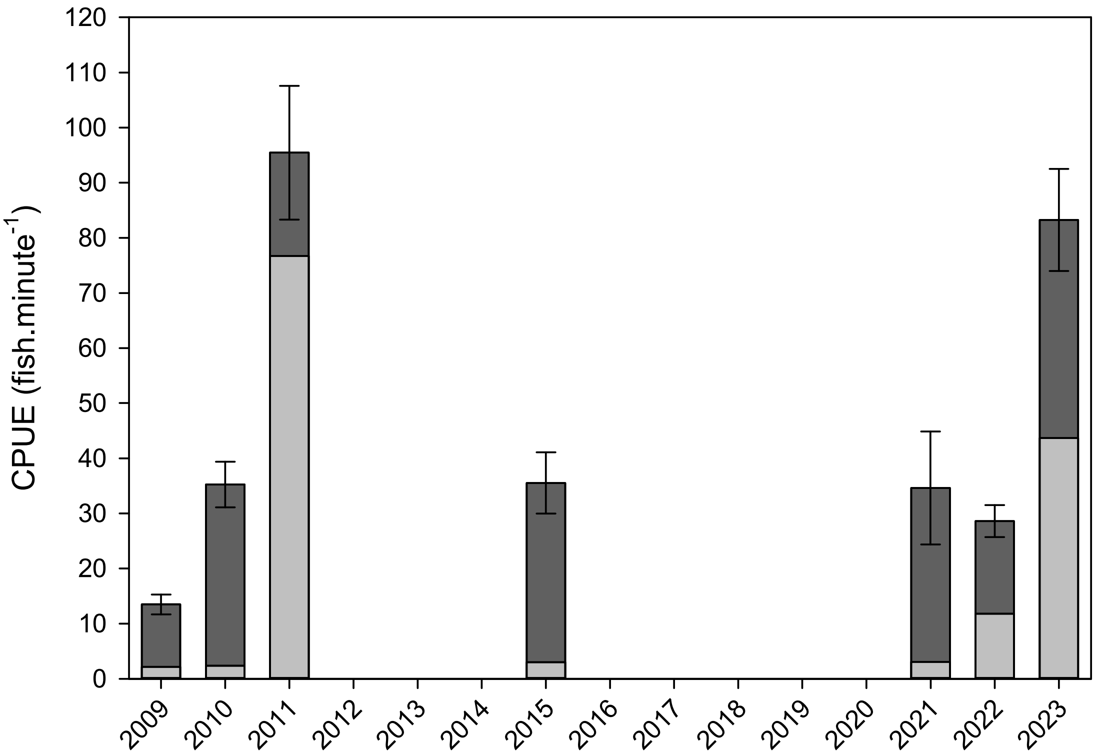

Figure 3. Mean (± SE) catch-per-unit-effort (CPUE) (fish.min^{-1}) of fish (all species combined) collected during standardised boat electrofishing surveys from 2009–2023 in the Katarapko Anabranch system and adjacent River Murray. Dark grey = native species, light grey = non-native species. Note: no sampling was conducted from 2012–2014 or 2016–2020.

3.4. Spatio-temporal differences in fish assemblage structure

Two-factor PERMANOVA, performed on data from 2009–2023, 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 fish species composition and relative abundance among years and mesohabitats between 2009–2023. Significant *p* values are presented in bold.

Factor	*df*	*Pseudo-F*	*p* value
Year	6, 90	10.66	**0.001**
Mesohabitat	3, 90	6.09	**0.001**
Year x mesohabitat	18, 90	1.05	0.344

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 four 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, 2022, and 2023, respectively (Figure 4).

Table 8. PERMANOVA pair-wise comparisons between fish assemblages among different mesohabitats in the Katarapko Anabranch between 2009–2023. Significant values are highlighted in bold (B-Y corrected α = 0.02).

Pairwise comparison		*t*	*p* value
Mesohabitat	Mesohabitat		
Fast	Backwater	2.88	**0.001**
Fast	Slow	2.37	**0.001**
Fast	River	2.28	**0.001**
Backwater	Slow	2.25	**0.001**
Backwater	River	3.53	**0.001**
Slow	River	1.93	**0.005**

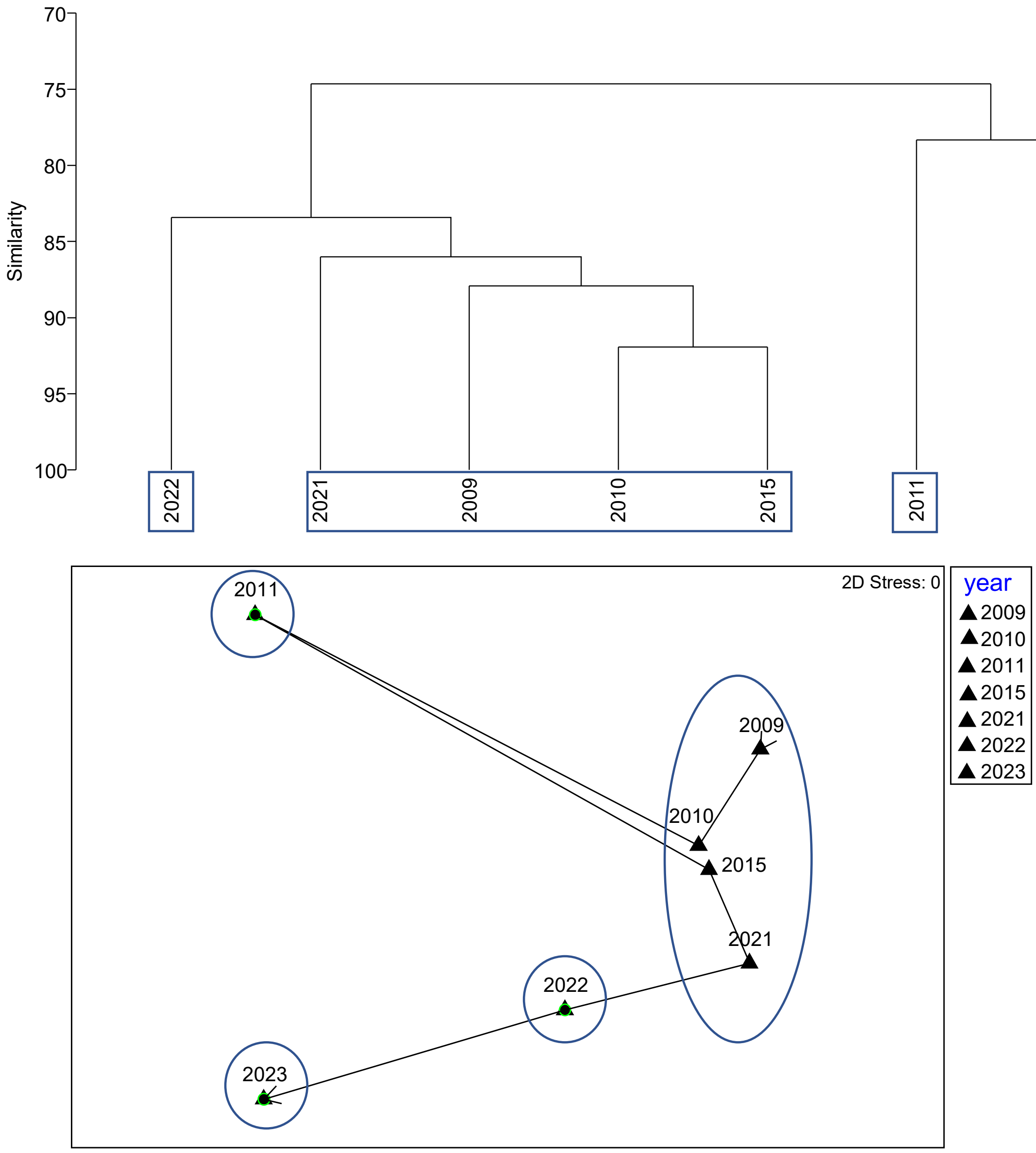

Figure 4. a) Dendrogram indicating fish assemblage clusters between 2009–2023; and b) Non-metric multi-dimensional scaling (MDS) plot of the same data.

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 common carp, goldfish, and 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. The assemblage from 2023 differed from the grouping of 2009, 2010, 2015 and 2021, and the single year grouping for 2022 due to greater abundances of common carp, goldfish, redfin perch and Australian smelt in 2023. Assemblage from 2023 differed from 2011 due to greater abundances of redfin perch, bony herring and Australian smelt in 2023, but greater abundance of goldfish and golden perch in 2011. 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 unspecked hardyhead and bony herring (Table 9). In 2023, fish assemblages were characterised by redfin perch and Australian smelt (Table 9).

Indicator species analysis comparing mesohabitat types suggested fast-flowing mesohabitats were characterised by eastern gambusia, bony herring, Australian smelt and redfin perch (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 2009–2023. (Year group 1 = 2011; Year group 2 = 2009, 2010, 2015, 2021; Year group 3 = 2022; Year 4 group = 2023). 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	24.7	<0.001
Goldfish	1	26.0	<0.001
Gambusia	1	22.9	<0.001
Golden perch	1	25.2	<0.001
Murray rainbowfish	1	22.2	<0.001
Bony Herring	2	17.2	0.012
Unspecked hardyhead	2	17.9	0.018
Australian smelt	4	19.5	<0.001
Redfin perch	4	61.0	<0.001

Table 10. Indicator species analysis comparing the relative abundance of fish in the four aquatic mesohabitats between 2009–2023. 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	Indicator value	*P* - value
Gambusia	Fast	39.4	<0.001
Australian smelt	Fast	30.4	0.012
Redfin perch	Fast	25.7	0.025
Bony herring	Fast	28.1	0.033
Murray cod	River	23.4	0.012
Murray rainbowfish	River	32.1	<0.001
Golden perch	River	34.3	<0.001

3.5. Assessment of Ecological targets

Target 1: Maintenance or enhanced species diversity

In all sampling years, species diversity was greater than the reference value across all mesohabitats (Figure 5a). The mean of mesohabitat diversity indices for each year was calculated to provide an overall site diversity score (Figure 5b); in all years, the site diversity score was greater than the reference value, with 2011, 2022 and 2023 having the highest diversity scores.

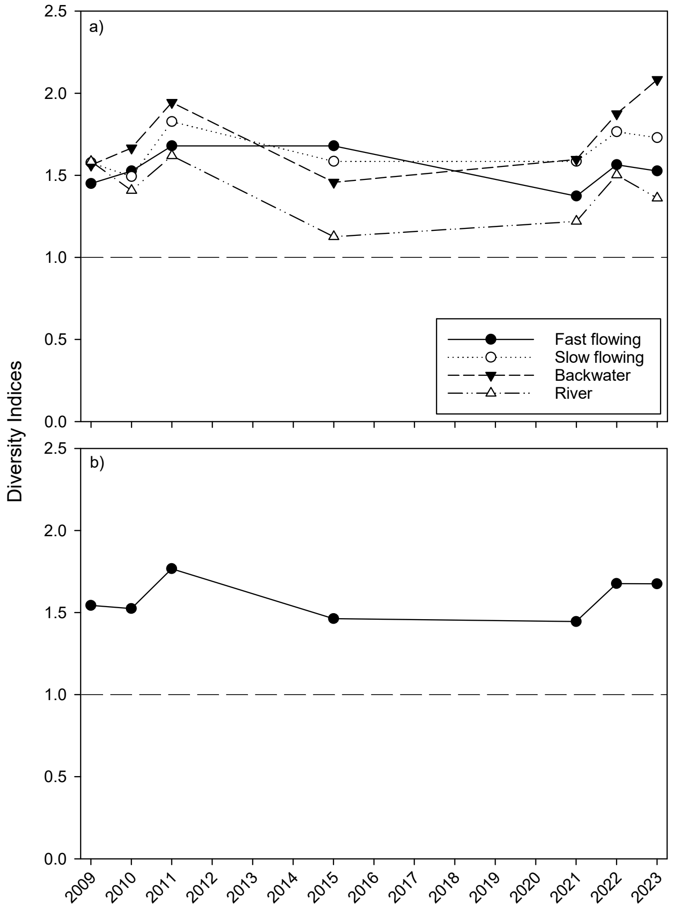

Figure 5. Diversity indices for a) fast-flowing, slow-flowing, backwater and main River channel mesohabitats and b) the calculated Site Diversity Index (DI), at the Katarapko Anabranch from 2009–2023.

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

For large-bodied native fishes, the extent index varied among species (Figure 6a). 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, approximately equal to the reference in 2011, and above the reference in 2022 and 2023. Silver perch, however, only met the reference value in 2011; an increase in extent was recorded in 2022 but was followed by a decline in 2023. Similarly, freshwater catfish extent in 2010–2011 was approximately equivalent to the reference, with extent decreasing in 2015 and 2021. In 2022, however, extent increased substantially to be over the reference value, before 2023, when the species was not detected. 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, including absence of both species from sampling in 2023 (Figure 6b).

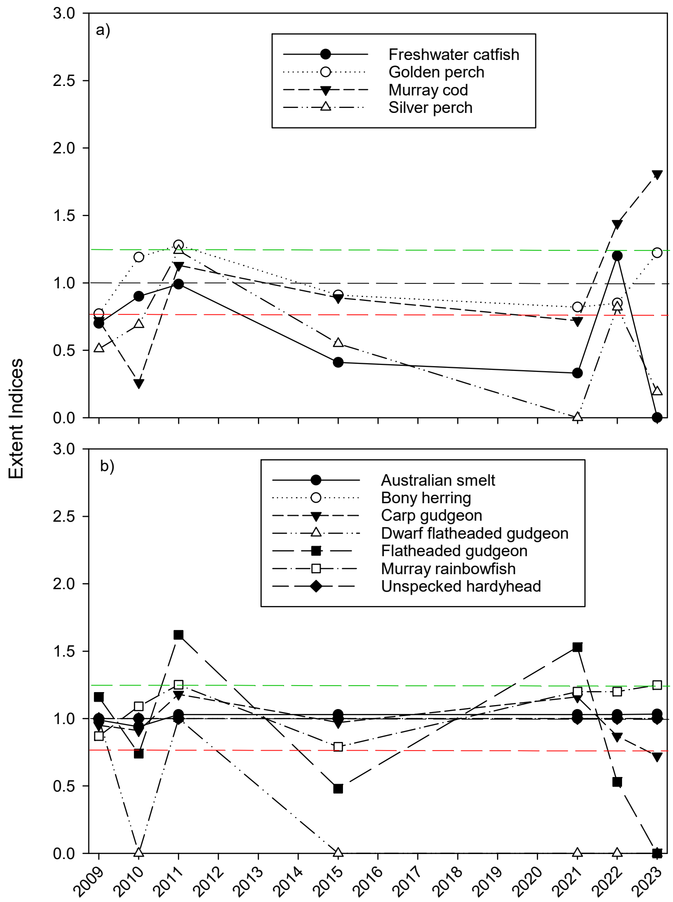

Figure 6. Extent Index (*EI*) scores for a) large-bodied native species and b) small- to medium-bodied native species at the Katarapko Anabranch from 2009–2023. Black dashed line represents extent equal to the reference, green dashed line extent 25% greater than reference and red dashed line extent 25% 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. Murray cod abundance was above the reference in 2009 but the species was absent or in low abundance in 2010 and 2011. From 2015–2023, Murray cod either met or exceeded the reference value (Figure 7a). For freshwater catfish, abundances were above the reference value in 2010, 2015 and 2022, but were absent from sampling in 2023 (Figure 7b). Golden perch abundance peaked in 2011, but has since (2015–2023) been relatively stable at or just below the reference value (Figures 7c). Silver perch abundance was above the reference value between 2010–2011, but from 2012–2023 abundance for this species was below reference (Figure 7d).

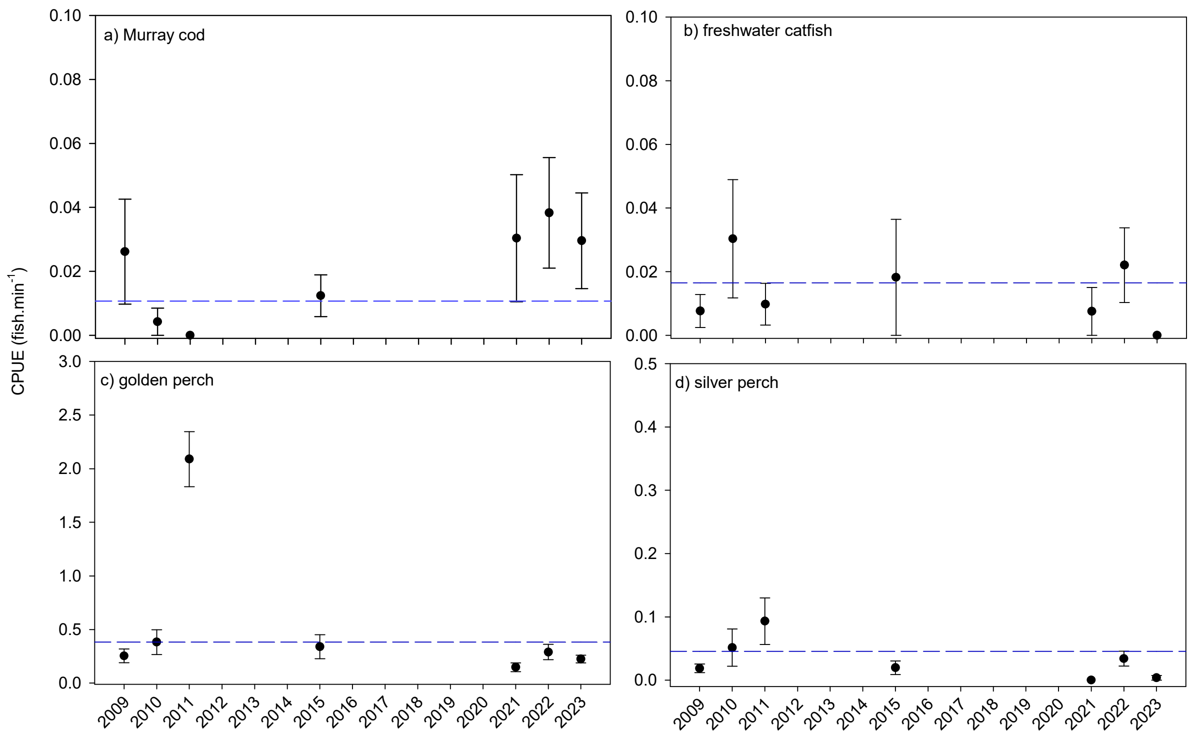

Figure 7. Mean abundance (CPUE; fish.minute electrofishing^{-1}.site^{-1}) ±SE for a) Murray cod, b) freshwater catfish, c) golden perch and d) silver perch at the Katarapko Anabranch between 2009–2023. The blue dashed line represents mean abundance equal to the reference value.

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 (Figure 8). 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 8). In 2023, recruitment indices were above the reference value for all species except for Murray rainbowfish (Figure 9).

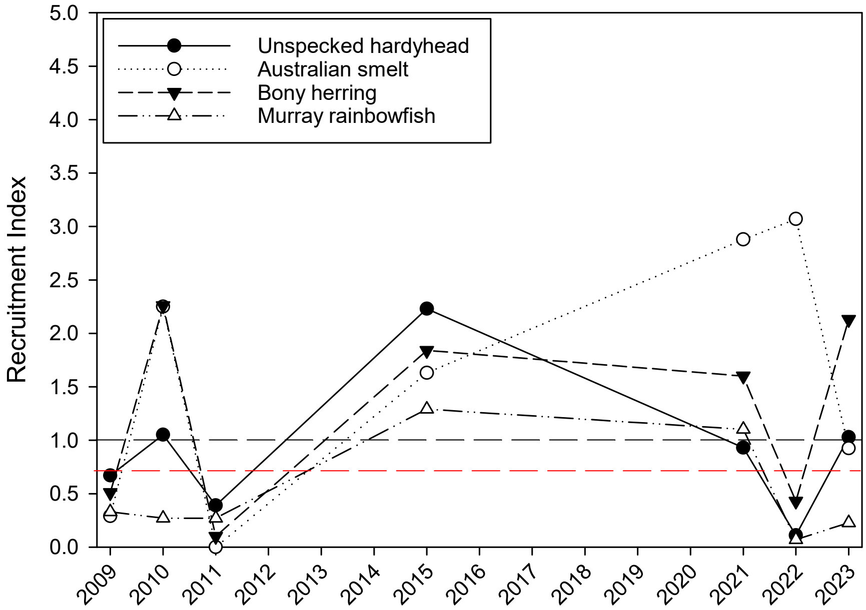

Figure 8. Recruitment Index (*RI*) values for unspecked hardyhead, Murray Rainbowfish, Australian smelt and bony herring from 2009–2023. Dashed black line represents recruitment equal to the reference value and the dashed red line, recruitment 75% of the reference value.

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, 2022 and 2023 but not in any other sampling year (Figure 9). Alternatively, for YOY Murray cod (<200 mm TL), recruitment was greater than the reference value in 2010, 2015 and 2021, slightly below the reference in 2023, and absent in 2009, 2011 and 2022 (Figure 9).

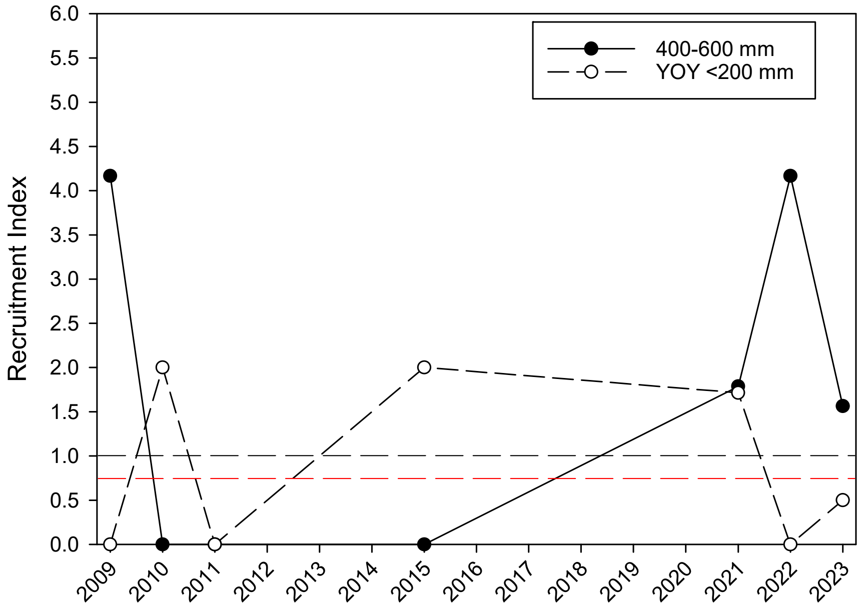

Figure 9. Recruitment Index (*RI*) values for Murray cod ranging 400–600 mm TL (black circles) and YOY (<200 mm TL) Murray cod (open circles) from 2009–2023. Dashed black line represents recruitment equal to the reference value and the dashed red line, recruitment 75% of the reference value.

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 10a & 10b). For common carp, recruitment was above the reference in 2011, 2022 and 2023, but not in any other year (Figure 10a). Goldfish recruitment exceeded the reference in 2011 and was equivalent to reference in 2023, but was below the reference in every other year (Figure 10b).

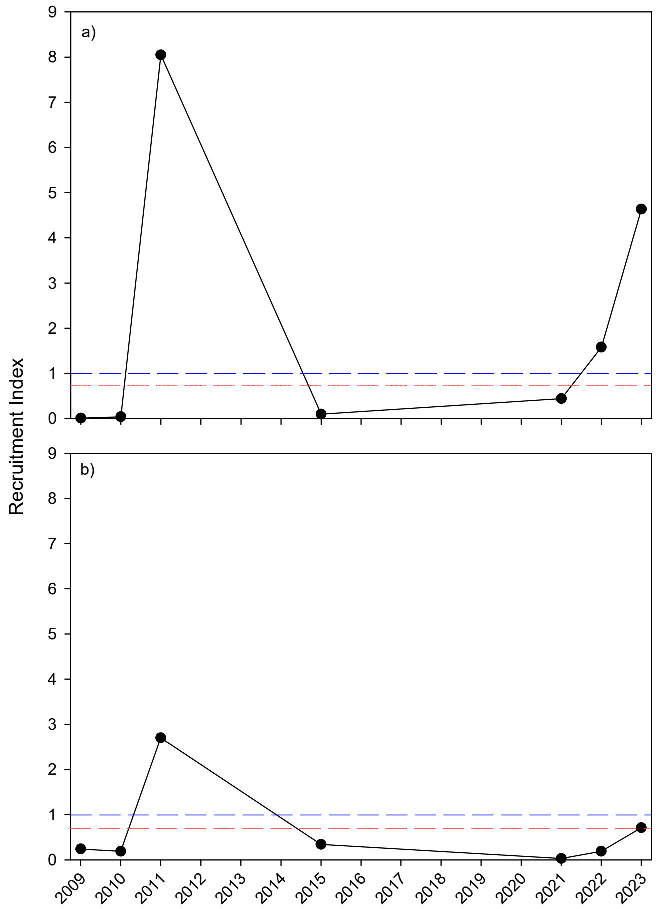

Figure 10. Summary of Recruitment Index (*RI*) values for a) common carp and b) goldfish at the Katarapko Anabranch from 2009–2023. Dashed blue line = reference value, dashed red line = 75% of the reference value.

Summary

Sampling data from 2023 suggests that five of the six Ecological Targets were achieved or partially achieved, the decrease in common carp and goldfish abundance, was not (Table 11).

Table 11. Summary of assessment of fish-related Ecological Targets at the Katarapko Anabranch in 2023.

Primary Ecological Objects 1, 2 & 3 (see page 4 above)			**Ecological target**	**2023**
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 6 of 11 target species (see Figure 6)
			Abundance (CPUE) of large-bodied native fish exhibits a positive trajectory over a 5-year period from 2020	Murray cod exhibiting positive trajectory, whilst freshwater catfish, 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’	Three of four target species exhibited recruitment indices exceeding reference values (see Figure 8)
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 to adult population evident, but recruitment to YOY below reference.
		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 and goldfish were elevated or equivalent to the reference value, but occurred in association with natural flooding and achievement of other ecological targets.

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 these 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 Katarapko 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 2023 with comparison to data from previous sampling of fish assemblages (2009–2022) and assessment of Ecological Targets.

4.1. General patterns of abundance and assemblage structure

In 2023, 12 fish species were sampled from 14 sites in the Katarapko Anabranch and adjacent River Murray main channel. The fish assemblage consisted of 8 native and 4 non-native species, with the non-native common carp and native bony herring the most abundant. In general, the assemblage reflected the extensive and prolonged floodplain inundation through spring-summer 2022/23 that preceded sampling. The fish assemblage sampled in 2023 differed from a grouping of sampling years (2009, 2010, 2015 and 2021) characterised by predominantly low within-channel flows (max annual discharge = 11,000–18,000 ML.day^{-1}), as well as previous years following flood (2011) and high within-channel flow (2022). These differences in assemblage structure in 2023 reflect fluctuations in abundance of several small- and medium-bodied generalist species and large-bodied species whose reproduction is associated with high flows and flooding.

Patterns of elevated abundance of small- and medium-bodied generalist species including unspecked hardyhead, 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 (Bice *et al.* 2014). These patterns were generally consistent following flood and high flow in 2011 and 2022, respectively, but less so in 2023, when unspecked hardyhead, Australian smelt and bony herring maintained relatively high abundances.

The recruitment of large-bodied fishes, notably common carp, and golden perch, also drove differences among low flow years (2009, 2010, 2015 and 2021) and those characterised by preceding flood (2011 and 2023) or high within-channel flows (2022). Spawning and recruitment in common carp is positively associated with flooding and inundation of favored shallow, off-channel nursery habitats (Stuart and Jones 2006, Maitzegui et al. 2019), with peak abundances at Katarapko occurring following flooding in 2011 and 2023. For golden perch in the lower River Murray, spawning and recruitment (from local spawning or immigration) are also associated with elevated flow (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 a & b). 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 species diversity indices were stable across years, and greater than the reference value, indicating fish species diversity was maintained over the period 2009–2023. 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 individuals per year and flat-headed gudgeon = 0–23 individuals 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 2023, Murray cod were sampled from five of fourteen sites and the extent index was substantially greater than the reference value, and higher than all preceding sampling events. The same positive trajectory in extent index was also observed at the Pike Anabranch over the same period (Fredberg and Bice 2022b, SARDI unpublished data). Positive responses at Katarapko likely reflect broad-scale patterns in the lower River Murray and potentially improved hydrology and hydraulics within Katarapko.

Freshwater catfish and silver perch extents were below the reference value in 2023 following 2022 when the indices were similar to reference values for both species. Sampling in 2023, was undertaken during relatively high flow (23,000–27,000 $ML.d^{-1}$), which may have limited sampling efficiency, especially for the benthic freshwater catfish.

Abundance of large-bodied native fish

Over the period 2021–2023, similar to the extent index, the standardised abundance of Murray cod has been above the reference value and substantially greater than the period 2010–2015. Over the same period, increased abundance has also been noted at the Pike Anabranch, where similar interventions have been undertaken (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 recent natural recruitment.

For freshwater catfish, from 2009–2023, total numbers (*n* = 0–9) and standardised abundance have typically been low and variable, and the species was not detected in 2023. 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 are predicted to promote the abundance of freshwater catfish, but such a pattern is not yet evident.

For golden perch, from 2009–2023, annual abundances have been similar, except for a notable peak in 2011. 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 2014–2023, however, recruitment has been observed in anabranch and main-channel habitats in several years (e.g., 2017, 2022, 2023) (Fredberg et al. 2022; Ye et al. 2021), but has not been of a magnitude to promote enhanced abundance at Katarapko. In 2023, the population of golden perch sampled at the Katarapko Anabranch was dominated by individuals 200–300 mm TL (~54%) and a distinct cohort of fish 100–140 mm TL (6%) was also present. While no ageing was conducted for fish from Katarapko, fish of these size ranges in the broader lower River Murray were determined to be +1 and 0+ year old individuals spawned in 2021/22 and 2022/23, respectively (SARDI Unpublished Data).

Silver perch abundance was only above the reference value in 2010 and 2011, and only a single individual was sampled in 2023. This species has a life history that operates over macro-scales (100’s–1000’s km) (Koehn et al. 2020), yet in the lower River Murray, is often associated local-scale lotic habitats (Fredberg et al. 2019; Fredberg et al. 2022). As such, similar to freshwater catfish, recent interventions at Katarapko are predicted to promote abundance of silver perch, but this pattern is not yet evident.

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 the 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 and 2023. Nonetheless, YOY were sampled in 2023. In contrast, the index for recruitment to the adult population exceeded the reference value in 2021, 2022 and 2023. This substantial increase in recruitment to the reproductively mature population likely reflects growth of YOY detected in preceding years and potential immigration of other sub-adult individuals to Katarapko 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 generally present in all years. In 2023, recruitment was greater than the reference for all species except Murray rainbowfish. 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

Common carp and goldfish both exhibited enhanced recruitment in 2023, albeit lower than following flooding in 2011. A similar recruitment response from both species was seen throughout the lower River Murray in 2023 (SARDI unpublished data). Common carp also exhibited enhanced recruitment in 2022 following high within-channel flows and a managed inundation event in spring 2021. Enhanced recruitment of common carp and goldfish is commonly associated with periods of increased discharge and water levels, either through natural or managed inundations (Bice and Zampatti 2011).

5. CONCLUSION

Monitoring of fish assemblages at the Katarapko Anabranch in 2023 indicated that five of the six 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 2023, 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 2009–2023 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 3
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*	-
Year group 4	*C. carpio* *P. fluviatilis* *C. auratus* *R. semoni*	*P. fluviatilis* *N. erebi* *C. auratus** *M. ambigua** *R. semoni*	*P. fluviatilis* *C. carpio* *C. auratus* *R. semoni* *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**

Appendix 8. Total number of species captured at each site in 2023.

2023	Site Number														
Species	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**9**	**10**	**12**	**13**	**14**	**22**	**24**	**Total**
Golden perch	5	2	4	4	5	4	11	2	5	4	1	5	3	5	60
Murray cod	1					1		1	4						7
Silver perch													1		1
Bony herring	1117	189	123	102	191	978	1315	471	358	531	151	224	654	98	6502
Australian smelt	151	91	52	74	9	41	127	257	387	299	79	167	180	46	1960
Murray rainbowfish	13	54	48	9	17	34	25	69	116	127	8	26	40	20	606
Unspecked hardyhead	11	254	38	3	3	11	588	10	135	18	11	25	22	1	1130
Carp gudgeon		1	1		1			1				1	4	1	10
Carp	680	159	1021	613	2143	452	612	397	261	577	540	431	839	509	9234
Gambusia	23	1		7	5	5	9	2	7	2	7	2	69	1	140
Goldfish	55	12	202	215	47	12	2	22	111	59	38	105	267	152	1299
Redfin perch	69	9	162	96	71	54	30	13	15	13	17	36	101	51	737
Species Total	**10**	**10**	**9**	**9**	**10**	**10**	**9**	**11**	**10**	**9**	**9**	**10**	**11**	**10**	
Total	**2125**	**772**	**1651**	**1123**	**2492**	**1592**	**2719**	**1245**	**1399**	**1630**	**852**	**1022**	**2180**	**884**	**21686**