Evaluation of the effectiveness of the Tallowa Dam Fishway

Chris Walsh, Michael Rodgers, Wayne Robinson and Dean Gilligan

NSW Department of Primary Industries
Batemans Bay Fisheries Centre
P.O. Box 17, Batemans Bay, NSW 2536
Australia

July 2014

NSW Department of Primary Industries -
Fisheries Final Report Series
No. 143
ISSN 1837-2112

NSW GOVERNMENT Department of Primary Industries

SYDNEY CATCHMENT AUTHORITY

Evaluation of the effectiveness of the Tallowa Dam Fishway

July 2014

Authors: Chris Walsh, Michael Rodgers, Wayne Robinson and Dean Gilligan
Published By: NSW Department of Primary Industries
Postal Address: Batemans Bay Fisheries Centre
Internet: www.dpi.nsw.gov.au

ISSN 1837-2112

Note: Previous issues of the 'Fisheries Final Report Series' (ISSN 1837-2112) have been published as follows: (i) No.'s 1 – 66: 'NSW Fisheries Final Report Series' (ISSN 1440-3544); (ii) No.'s 67 – 110: 'NSW Department of Primary Industries – Fisheries Final Report Series' (ISSN 1449-9967); (iii) No.'s 111 – 129: 'Industry & Investment NSW – Fisheries Final Report Series' (ISSN 1837-2112).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

We take this opportunity to thank the many people who assisted with this project. In particular, Mick Bettanin, Prue McGuffie, Craig Mercier, Karen Scott, Justin Stanger, Jerom Stocks, Nicholas Thorne and Dylan van der Meulen all helped with field work. Sydney Catchment Authority (SCA) staff, including Jerry Evans and Ken Hansen, provided valuable knowledge and assistance regarding the operation of the fishway, while Tony Paull was exceptional in overseeing the management and budgetary aspects of the project. Furthermore, Ivars Reinfelds (New South Wales Office of Water) provided assistance with the acoustic telemetry section of the project. We are particularly grateful to members of the Southern Bass Fishing Club for passive integrated transponder (PIT) tagging a substantial number of fish throughout the course of the study, and who were instrumental in angling many of the Australian bass used for the acoustic telemetry component. Lee Baumgartner and Meaghan Duncan provided sound advice throughout the course of the project, while Gavin Butler provided valuable comments on the draft manuscript. Funding for this study was provided by SCA under a joint agreement with New South Wales Department of Primary Industries. The collection of all animals was in accordance with the appropriate Animal Care and Ethics Authority (04/02) and a Section 37 research permit in accordance with the *Fisheries Management Act 1994* (NSW).

NON-TECHNICAL SUMMARY

Evaluation of the effectiveness of Tallowa Dam Fishway

PRINCIPAL INVESTIGATORS: Dr Chris Walsh and Dr Dean Gilligan

ADDRESS:
Batemans Bay Fisheries Centre
P.O. Box 17 Batemans Bay, NSW, 2536
Telephone: +61 2 4478 9101 Fax: +61 2 4472 7542
E-mail: chris.walsh@dpi.nsw.gov.au

OBJECTIVES:

To evaluate the performance of the Tallowa Dam Fishway in remediating upstream and downstream passage for fish communities in the Shoalhaven River.

Specifically, to:

1. Determine changes in fish community structure in the Shoalhaven River after fishway construction.

2. Evaluate the effectiveness of the Tallowa Dam fish lift in facilitating upstream fish passage.

3. Assess the mortality, physiological consequences and long-term survival of Australian bass and freshwater mullet migrating downstream over the Tallowa Dam spillway.

During the course of the evaluation, the findings have been used to make research and management recommendations to improve the effectiveness of the Tallowa Dam Fishway.

NON-TECHNICAL SUMMARY:

Since the completion of Tallowa Dam in 1976, the migration of fish within the Shoalhaven catchment has been obstructed. As migratory fish represent 96% of freshwater fish species that potentially occur in the catchment, Tallowa Dam prevents a large proportion of species from using 54% of available habitat within the river channel. Twenty-three years after the construction of the dam no fish species that naturally migrate between freshwater and the sea existed in reaches upstream of the dam, except for those that had been stocked or those capable of climbing (e.g. some gudgeon species and eels) (Gehrke *et al.* 2002). This study conducted by New South Wales Department of Primary Industries (NSW DPI) identified regular accumulations of at least 10 species of migrating fish downstream of the dam. Importantly, more species, numbers and size classes of fish were caught immediately downstream of the dam than at any other site in the system. This demonstrated that Tallowa Dam was a significant barrier within the Shoalhaven catchment and identified the need to remediate fish passage to restore the longitudinal connectivity of habitats for native fish.

In 2009, the Sydney Catchment Authority (SCA) constructed a fish lift, commenced new environmental flows and removed a source of cold water pollution at Tallowa Dam, aimed at enabling native fish to complete upstream migrations. Works were also undertaken to modify the spillway, consisting of an over-shot gate that can be fully retracted to allow for greater control over downstream environmental flow releases and to provide downstream fish passage. Hence, Tallowa Dam Fishway not only needs to be evaluated for its effectiveness in facilitating the upstream passage of fish, but also for its potential to cause mortality to fish undertaking downstream migrations. This report consists of information on seasonal and annual variation in fish distributions and abundance in the Shoalhaven River, an analysis of changes in fish communities resulting from the construction of the Tallowa Dam Fishway, and a series of manipulative experiments to assess the success of upstream and downstream fish passage.

Component 1: Detecting changes in fish community structure after fishway construction

To assess the overall effectiveness of the Tallowa Dam Fishway in restoring longitudinal connectivity of habitats for native fish in the Shoalhaven River, spatial and temporal variation in contemporary fish communities was compared with that from historical and more recent surveys. This involved community-based fish sampling using standardised electrofishing. Fish were sampled twice yearly for 4 years at 12 sites throughout the catchment.

There was reduced species richness upstream of the fishway, including the absence of several catadromous species, while significant accumulations of fish were present directly below the dam. Differences in population structure remained evident for species present above and below the dam, with the majority of fish upstream being larger individuals. Moreover, fish assemblages were significantly different between the upstream riverine reaches and the lacustrine habitats within Lake Yarrunga. Comparing historical, pre-fishway and contemporary fish assemblage abundances confirmed that Tallowa Dam still represents a critical discontinuity in contemporary fish communities. However, small numbers of two previously absent diadromous fish species were captured within Lake Yarrunga—striped gudgeon and empire gudgeon. In addition, several species historically reported to have higher population abundances above the dam compared to those downstream, have now been determined as similar. This component, further detailed in Chapter 2, meets objective 1 (see above).

Component 2: Effectiveness of the Tallowa Dam Fishway in facilitating upstream fish passage

The performance of the fish lift in providing upstream fish passage was evaluated by documenting the species composition, abundance and population structure of fish migrating through the fishway, as well as fish behaviour and environmental conditions relevant to fishway usage. This involved alternate trap/hopper sampling experiments comparing species and size classes of fish that approached the bottom of the fishway with those that successfully ascended and exited. Eighteen paired samples were collected between 2010 and 2013 over several upstream migration periods (spring and autumn). Frequency, timing and diel activity of tagged individuals migrating through the fishway was assessed for the same period using passive integrated transponder (PIT) technology.

The fishway provided successful upstream fish passage for 12 fish species, 11 of which were native, including both small and large-bodied individuals (22–1,110 mm). This included four diadromous fish species formerly considered locally extinct upstream of Tallowa Dam. However, two catadromous fishes (sea mullet and of dwarf flat-headed gudgeon) found downstream of the dam were not detected utilising the fishway. Apart from the greater numbers of Cox's gudgeon exiting the fishway, abundances at the entrance and the exit for all other species were similar. PIT-tag data revealed that approximately 40% of individuals, for the majority of tagged species, detected at the entrance of the attraction chamber continued on their ascent and successfully migrated through the fishway. Tagged fish were mostly recorded using the attraction chamber during the day and through the warmer months of spring and autumn; the timing of which coincides with important life-history strategies. Differences in population size structure were detected between fish entering the attraction chamber and those exiting via the fish lift. Nevertheless, the species richness and successful passage of medium and of small-bodied species suggests that the fishway provides upstream fish passage. This component, further detailed in Chapter 3, meets objective 2 (see above).

Component 3: Effectiveness of the Tallowa Dam spillway in ensuring safe downstream fish passage

The performance of the over-shot gate and spillway in providing safe downstream fish passage was evaluated by assessing the immediate fate and long-term survivability of Australian bass and freshwater mullet migrating over the Tallowa Dam over-shot gate and spillway. Mortality rates and blood physiology of Australian bass passing downstream over the modified spillway were assessed during low-flow and high-flow release conditions. Information on long-term survival and movement behaviour of Australian bass and freshwater mullet migrating downstream over spillway was also derived through the use of acoustic telemetry and PIT tagging.

There were no immediate mortalities of fish entrained over the modified spillway during either low- or high-flow conditions, with all fish (including control fish which were confined as per the treatment fish, but did not pass over the spillway) recorded in similar condition to that prior to entrainment. However, there were significant deaths (up to 25%) across all groups and time periods 24 hours and 72 hours after passing over the spillway. Analysis of blood chemistry immediately after fish were recaptured confirmed high stress levels. Although stress decreased between 24 and 72 hours after the experiment, it remained elevated compared to that of ‘wild’ fish (which had not been confined). As there were no differences in mortality rate or blood physiology between the controls and treatment groups among all time periods, we attributed the deaths of highly stressed individuals to the significant and potentially cumulative influence of two factors—general handling (including angling the fish) and confinement—rather than passage over the spillway. Acoustic and PIT-tag data revealed high long-term survival rates for Australian bass and freshwater mullet (up to 945 days and 340 days, respectively) that had migrated over the spillway (either the original spillway or the newly modified over-shot gate). Moreover, the timing and movement strategy of both species mirrored previously known life-history studies, confirming that stress associated with travelling downstream over the spillway is not likely to interrupt their normal movement patterns and spawning behaviour. This component, further detailed in Chapter 4, meets objective 3 (see above).

Conclusions

This study represents the first stage in assessing the effectiveness of the Tallowa Dam fish lift and associated modified spillway works in providing successful upstream and downstream fish passage in the Shoalhaven River. Encouragingly, results suggest that a broad range of species and size classes are using the fish lift in large numbers and at appropriate times of the year. Short- and long-term survivability of large-bodied fish passing downstream over the Tallowa Dam modified spillway is high and conducive to normal movement patterns and spawning behaviour. Despite this, fish community surveys indicate that the biodiversity of the river system within the Shoalhaven catchment upstream of Tallowa Dam remains depauperate, due to the continued absence of several migratory species. However, this is not surprising considering the flood damage and recurring reliability issues associated with the fish-lift hopper and attraction chamber flows over the first 4 years of operation. Nevertheless, the detection of two fish species formerly extinct upstream of Tallowa Dam (striped gudgeon and empire gudgeon), the trapping of diadromous species in the fish-lift hopper and evidence of equilibration of the size-frequency distribution in formerly disconnected populations of several other species suggests a gradual shift in continuity of fish assemblages above and below Tallowa Dam. These shifts likely represent the first stages of recovery as a result of the construction and operation of the new fishway.

Recommendations

This study has provided a detailed assessment of the fish communities in the Shoalhaven River after fishway construction, including the effectiveness of the fish lift and the modified spillway in facilitating successful upstream and downstream fish passage, respectively. Therefore, recommendations resulting from this study are summarised below:

(i) Once the fish lift is fully and consistently operational, it is recommended that electrofishing surveys on the Shoalhaven River be ‘revisited’ after a period of 3 years to assess if there are any further changes in fish community structure as a result of successful ascension of the Tallowa Dam Fishway.

(ii) To gain further information on the timing and seasonal occurrence of fish species utilising the fish lift, as well as assist SCA in prioritising the functional aspect of fishway operations, more frequent alternate hopper/trap experiments (on a monthly basis) replicated over multiple years is recommended. Note: this aspect is proposed to commence in 2014.

(iii) As the PIT-tag and acoustic telemetry infrastructure is now established in the Shoalhaven River, fish tagging and monitoring should continue to complement existing information on successful upstream and downstream fish passage over Tallowa Dam. In addition, this technology can provide information on fish passage in relation to environmental flows, as well as the behaviour of fish in the lake and their ability to locate riverine habitats upstream of the dam once they have passed through the fishway.

(iv) Further investigation is required into reasons why some fish species may not be using the fish lift.

(v) Further investigation of potential research techniques is needed, including the use of chemical marking, to determine the fate of juvenile and small-bodied species (which are too small for PIT tagging) migrating downstream over the dam wall.

KEYWORDS

Fish passage, migration barrier, acoustic telemetry, downstream mortality, Shoalhaven River, species assemblages, PIT tagging
.

1 GENERAL INTRODUCTION

1.1 Restoring fish passage within the Shoalhaven River

Many fish species inhabit a broad range of freshwater and estuarine habitats throughout their life and need to be able to freely migrate between these habitats. In coastal rivers of south-eastern Australia, it has been estimated that 70% of fish may move between rivers and an estuary at some stage of their life (Harris 1984). These migrations can be for a variety of reasons, including spawning, dispersal of juveniles from nursery grounds or the movement of fish between habitats. These movements also maintain gene flow and support ecological processes essential for maintaining the integrity and resilience to change of native fish assemblages (Harris 1984; Mallen-Cooper and Harris 1990). Moreover, effective fish dispersal in coastal environments is likely to maintain the productivity of estuarine, coastal and marine fisheries (Meynecke *et al.* 2008; Blaber 1980). For many species, these freshwater to estuarine/marine migrations are an obligatory process required for the species to fulfil its life cycle and, if impeded, result in the local extinction of populations upstream of barriers (Bishop and Bell 1978; Brumley 1987; Gehrke *et al.* 2002).

Artificial barriers on rivers, such as dams, weirs and culverts, present significant impediments to these migrations and have detrimental effects on fish populations (Orth and White 1993; Holmquist *et al*. 1998). Because of the declines and localised extinctions of migratory species above anthropogenic barriers, fishways are often the obvious solution. Fishways not only allow for continued utilisation of the water resource, but allow migratory species to access habitats upstream of the fish passage barrier. Wherever upstream fish passage is provided, the capacity for downstream fish passage is equally important. By restoring fish passage and reducing the obstructive effect of dams, fishways constitute a key component of rebuilding riverine ecosystems and restoring degraded fish communities. Notwithstanding the complexities of fishway design and the value of ascending fish as a measure of effectiveness, the ultimate goal of restoring fish passage is to rehabilitate fish communities upstream and downstream of the barrier. Thus, there is a need for more detailed assessment of the effectiveness of fishways in achieving this goal.

Completed in 1976, Tallowa Dam is located at the junction of the Shoalhaven and Kangaroo rivers on the New South Wales (NSW) South Coast. The impounded waters above Tallowa Dam are known as Lake Yarrunga. The 43-metre-high dam and reservoir are an integral part of the Sydney Catchment Authority’s (SCA’s) Shoalhaven Scheme, and are essential to the bulk raw water supply system for Greater Sydney. Since construction, several studies of the fish communities of the Shoalhaven River demonstrated that Tallowa Dam represents a major barrier to fish migration, and has caused a significant loss of biodiversity upstream of the barrier. Importantly, more species and greater numbers and broader ranges of size classes of fish were found downstream of the dam than at any other site in the system (Bishop and Bell 1978; Marsden and Harris 1996; Gehrke *et al.* 2002). Therefore, a need was identified to restore the longitudinal connectivity of habitats for native fish within the river system.

In 2001, the SMEC company was engaged by the SCA to undertake a feasibility study to examine the viability of constructing a high-level fishway at Tallowa Dam to transport the fish from downstream of the dam into Lake Yarrunga. This assessment was done with the involvement of NSW Department of Primary Industries (DPI) and with the assistance of Australian and international experts on fishway design, fish biologists and key stakeholders. The study concluded that the preferred option for Tallowa Dam was a fish lift that could trap migrating fish at the base of the dam and transport them in a hopper over the abutment of the dam and into the impoundment (SMEC 2001). There was also the need for a multi-level offtake to improve the quality of the water released from the dam’s outlet. In 2004, the Hawkesbury–Nepean River Management Forum recommended a new environmental flow regime be instigated for Tallowa Dam releases. In response to this recommendation, the NSW Government directed SCA to fund studies to develop a Shoalhaven environmental flow regime for the Shoalhaven River. Furthermore, in 2007, the NSW Government announced that, together with changes to water transfer rules from Tallowa Dam, SCA would design and implement measures that would: (1) introduce new variable releases of water from Tallowa Dam specifically for the river environment; (2) improve the quality of water released from the dam; and (3) provide fish passage past the dam.

In 2009, a high-dam fish lift was constructed at Tallowa Dam, in association with a revised environmental flow regime, to restore the longitudinal connectivity of habitats for native fish within the Shoalhaven River system. The design of this fishway is such that fish are attracted to the entrance of the fishway by turbulent water, created by a series of perforated pipes and screens. This flow encourages fish to swim along a rectangular concrete channel and into a chamber that contains a stainless-steel hopper at its base. Fish enter the hopper through a cone trap and, on a set cycle, the hopper is then winched up and over the 43-m-high abutment of the dam. The fish are released into the dam through a tilt gate in the hopper floor. For downstream fish passage, the new works improved the range of flows over the spillway by which downstream migration can occur. Previously, downstream fish passage was only possible when a sufficient depth of water flowed over the dam crest. Now, a 1.5-m-deep slot cut into the existing spillway near the left abutment, controlled by a vertical-lift over-shot gate, allows fish to pass downstream over the spillway under a greater range of impoundment water levels. Fish pass over the gate, down the face of the dam and into the new stilling basin below.

1.2 Objectives of the study

To evaluate the performance of the Tallowa Dam Fishway in remediating upstream and downstream passage for fish communities in the Shoalhaven River.

Specifically, to:

1. Identify changes in fish community structure in the Shoalhaven River after fishway construction.

2. Evaluate the effectiveness of the Tallowa Dam fish lift in facilitating upstream fish passage.

3. Assess the mortality, physiological consequences and long-term survival of Australian bass and freshwater mullet migrating downstream over the Tallowa Dam spillway.

During the course of the evaluation, the findings have been used to make research and management recommendations to further evaluate and improve the effectiveness of the Tallowa Dam Fishway.

2 CHANGES IN FISH COMMUNITY STRUCTURE IN THE SHOALHAVEN RIVER AFTER FISHWAY CONSTRUCTION

2.1 Introduction

Movement is integral to the ecology of fishes, often associated with completing their life cycle, enabling them to access resources such as food, shelter and potential mates, and to avoid threats (Koehn and Crook 2013). Among fishes, these movements can be over a range of temporal and spatial scales, from vertical movements over diel cycles within the water column (Jellyman and Tsukamoto 2002) to longitudinal spawning migrations over thousands of kilometres (O'Connor *et al.* 2005). Although the migrations of Australian freshwater fishes may be less conspicuous than the famous spawning runs of Northern Hemisphere salmonids, the smaller-scale migrations they undertake are just as ecologically important to their survival. In the coastal rivers of south-eastern Australia, 70% of fish species exhibit 'diadromy', referring to the migration of fishes between freshwater and marine habitats (Miles *et al.* 2014). Anthropogenic influences on the migratory habits of Australian diadromous fishes have led to 9% of this group being listed as threatened (McDowall 1999). This is considerably less than the rest of the world, however this may reflect the lack of available information on the life cycles and status of these and other Australian fish species (Miles *et al.* 2014).

The natural distributions of many Australian diadromous species are limited by the presence of natural barriers, such as cascades and waterfalls. Artificial barriers on rivers, such as dams, weirs and culverts, create additional and often significant impediments to fish migrations, further limiting their potential distribution and often having detrimental effects on entire populations (Orth and White 1993; Holmquist *et al*. 1998). Barriers disrupt all forms of connectivity between populations, including longitudinal migrations and lateral connections between river and floodplain habitats. In particular, obstructed movements can lead to declines and localised extinctions of migratory species above and below barriers (Bishop and Bell 1978; Brumley 1987; Gehrke *et al.* 2002). Compounding the impacts of a physical migration barrier are the effects of river regulation and thermal pollution. Indeed, many Australian diadromous species are thought to rely heavily on flood events for either the downstream drift of juveniles from freshwater to marine habitats, or as a cue to initiate migratory behaviour (Koehn and O'Connor 1990; O'Connor and Koehn 1998; Pusey *et al.* 2004).

Construction of Tallowa Dam on the Shoalhaven River effectively blocked access to approximately 54% of the freshwater habitat likely to have been historically utilised by the majority of diadromous species in the Shoalhaven catchment (altitude <250 m above sea level, maximum downstream slope <5° and average flow >5 ML/day). Gehrke *et al.* (2002) demonstrated that Tallowa Dam is a major barrier to fish migration and has caused a significant loss of biodiversity in the system. In particular, 10 diadromous species were found to be locally extinct above Tallowa Dam, with more species, numbers and size classes of fish being caught immediately downstream of the dam than at any other site in the system. Recommendations from that study supported the construction of a fishway to provide fish passage at Tallowa Dam with the objective of restoring the longitudinal connectivity of habitats for native fish. Upstream and downstream works to facilitate fish passage were completed in 2009.

The aim of this study was to investigate spatial and temporal variation in contemporary fish communities after fishway construction, and to document changes that have occurred in species distributions since the fishway was constructed. This represents a component of the joint project between the Sydney Catchment Authority (SCA), New South Wales Department of Primary

Industries (NSW DPI) and the former Cooperative Research Centre for Freshwater Ecology, 'Post-construction ecological assessment after fishway construction to assess the effectiveness of the fishway'.

2.2 Methods

2.2.1 Study area

Fish were sampled at the same 12 sites established and sampled prior to fishway construction (Gehrke *et al.* 2002). These included: three sites in the Shoalhaven River downstream of Tallowa Dam; four sites within the impounded waters of Lake Yarrunga; and five sites upstream of the storage. Upstream sites included two sites in each of the Shoalhaven and Kangaroo rivers and one site in the Mongarlowe River in the upland zone of the catchment (Fig. 2.1). Details of the sites and habitat characteristics at each are given in Table 2.1 and Appendices 2.1 and 2.2, respectively.

2.2.2 Sampling strategy

Between 2009 and 2013, all 12 sites were sampled twice a year in both spring and autumn (eight sampling events at each site). The sampling protocol applied during each sampling event was identical to that used during the pre-fishway-construction assessment (see Gehrke *et al.* 2002), allowing a standardised before–after comparison. This comprised single-pass electrofishing using a combination of boat and backpack electrofishing, all undertaken during daylight hours. Each major habitat type present at a site was sampled at least once and then remaining sampling effort occurred in the most abundant habitat types. Boat electrofishing consisted of 15 × 2-minute (elapsed time) electrofishing operations using either a 2.5 kW or 7.5 kW Smith-Root electrofishing unit (depending on the size of the waterway at the site). Boat electrofishing units were generally operated at between 500 and 1,000 V DC, 4–10 amps pulsed at 120 Hz and 20–90% duty cycle. Backpack electrofishing was used at a subset of sites (site numbers: 2, 4, 5, 8, 11 and 12) to sample riffle or backwater habitats too shallow to navigate with a boat electrofisher. Backpack electrofishing effort consisted of 2 × 50 m stretches of river using a Smith-Root LR20 or LR24 backpack electrofisher in addition to the standard boat electrofishing effort.

At the completion of each electrofishing operation, all fish sampled were identified to species level, counted, measured and released alive. Length measurements to the nearest millimetre were taken as fork length for species with forked tails, and total length for all other species. Where large catches of a species occurred, only a sub-sample of 20 individuals of each species was measured per operation. Fish observed during the sampling operations, but not dip-netted from the water, were recorded as observed.

2.2.3 Reconstruction of historical Shoalhaven River fish assemblages

Historical fish distributions (Bishop and Bell 1978; Llewellyn 1983) and species recorded from previous studies at similar elevations in the Shoalhaven and neighbouring river systems (Gehrke and Harris 1996; McDowall 1996) were used to reconstruct fish assemblages before the construction of Tallowa Dam. The resulting binary matrix of species presence/absence at each site served as a model to allow comparison between pre-fishway (Gehrke *et al.* 2002) and present-day assemblages.

Figure 2.1. Study sites sampled above/below Tallowa Dam and within Lake Yarrunga.

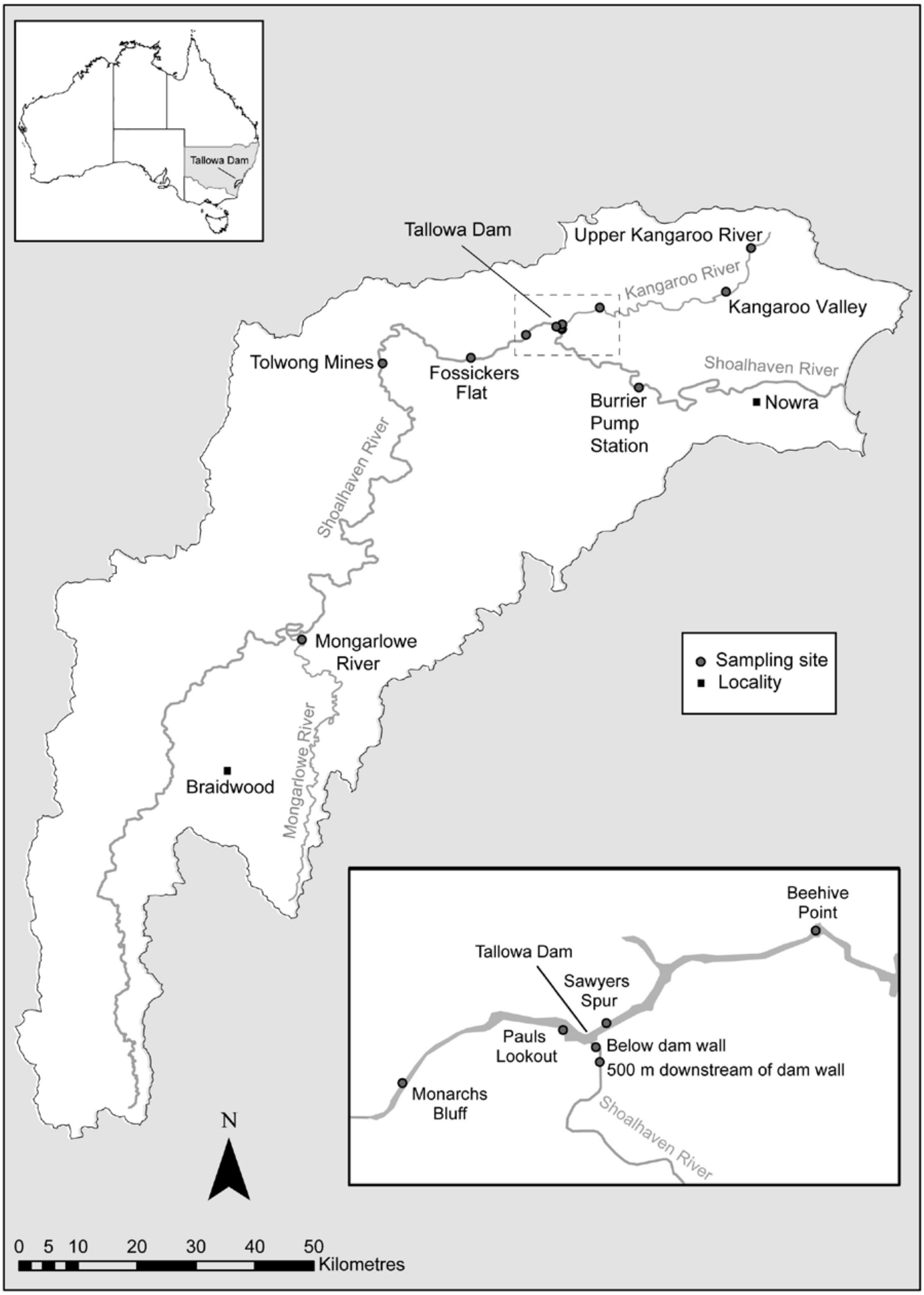


Table 2.1. Details of sites sampled above/below Tallowa Dam and within Lake Yarrunga. Note: sites 1 and 3 were not part of this study.

Site no.	Site name	Zone	Latitude (°S)	Longitude (°E)	Altitude (m)
11	Mongarlowe River	Mongarlowe River	35.2480	149.9187	550
12	Tolwong Mines	Shoalhaven River upstream	34.8321	150.0424	130
2	Fossickers Flat	Shoalhaven River upstream	34.8226	150.1594	70
4	Upper Kangaroo River	Kangaroo River	34.6516	150.6039	140
5	Kangaroo Valley	Kangaroo River	34.7300	150.5246	70
14	Beehive Point	Lake Yarrunga	34.7425	150.3737	65
6	Sawyers Spur	Lake Yarrunga	34.7614	150.3267	65
7	Pauls Lookout	Lake Yarrunga	34.7712	150.3054	65
13	Monarchs Bluff	Lake Yarrunga	34.7872	150.2594	65
8	Below dam wall	Directly below Tallowa Dam	34.7731	150.3144	35
9	500 m downstream of dam wall	Directly below Tallowa Dam	34.7774	150.3152	30
10	Burrier pump station	Burrier	34.8640	150.4333	<10

2.2.4 Analytical methodology

The catch from each electrofishing operation for each sampling event per site was pooled for analysis and standardised to catch per unit effort (CPUE) by dividing by the total number of electrofishing operations. A suite of multivariate analyses of species abundances, univariate assessment of individual species abundances and comparison of population size structures of individual species were undertaken to identify spatial and temporal effects of the new fishway on fish assemblages in the Shoalhaven River.

Multivariate analyses of fish assemblages were done in PRIMER 6.0 (Plymouth Marine Laboratory). For analysis of spatial patterns, species abundances were transformed to the fourth root and similarities between fish assemblages at each site were calculated using the Bray–Curtis similarity measure (Bray and Curtis 1957). Two-dimensional multidimensional scaling (MDS) ordinations were done on similarities among sites to illustrate the affinities of fish assemblages among sites, and the effect of the Tallowa Dam Fishway on the composition of assemblages. One-way analysis of similarity (ANOSIM) comparisons (Clarke 1993) were done to identify differences in fish assemblage composition across six catchment zones (Table 2.1): Burrier; sites below the dam; within Lake Yarrunga; Shoalhaven River upstream; Kangaroo River; and Mongarlowe River. Similarity percentage (SIMPER) analyses were used to identify species contributing most to observed dissimilarities among sites. Temporal analyses were done by comparing contemporary fish assemblages (pre- and post-fishway) with reconstructed natural fish distributions in the Shoalhaven River system before the dam was built. As the reconstructed species distributions could only be expressed as binary data, fish samples from the pre-fishway and present studies were pooled over sampling occasions and converted to binary form. Assemblages for the three time periods were analysed using the Bray–Curtis similarity matrix to generate a two-dimensional MDS of the sites over the three time periods, while a permutational multivariate analysis of variance (PERMANOVA) (Anderson 2001) model was used to test for any significant temporal differences in fish community assemblages.

Univariate analyses of total abundance were done in Statistica (Statsoft). Abundances were $\log_{10}$-transformed to stabilise variances. Spatial and temporal differences in CPUE were analysed using factorial analysis of variance (ANOVA). The spatial analysis used data collected during this study (2009–2013) to compare CPUE across catchment zones. *A priori* comparisons were used to compare total abundance, and the abundance of individual species within the 'Directly below Tallowa Dam' zone with each of the other catchment zones (Table 2.1). The temporal analysis compared abundances of fish captured within each catchment zone during the pre-fishway study (Gehrke *et al*. 2002) and present study using factorial ANOVA.

Size distributions of species above and below the dam were compared using Kolmogorov–Smirnov tests to assess the effect of the dam on contemporary fish populations. This analysis was done for species where the lengths of at least 50 individuals were recorded in each of the following three catchment zones: above Tallowa Dam; in Lake Yarrunga; and below the dam (but excluding Burrier). These species were longfinned eel, common carp, Cox's gudgeon, Australian bass, flat-headed gudgeon and Australian smelt.

2.3 Results

2.3.1 Description of current fish assemblages

Overall, 17,428 individuals representing 26 species were captured during this study. Of these, 16 species and 7,486 individuals were caught from nine sites within and upstream of Lake Yarrunga (Table 2.2, Appendix 2.3) and 21 species and 9,942 fish were sampled from three sites downstream of Tallowa Dam. Species richness (SR) was greater at all sites downstream of Tallowa Dam than at any site upstream (Table 2.2, Fig. 2.2). The Mongarlowe River supported eight species, which is within the range of SR observed at other sites upstream of the dam, with two species unique to this site; mountain galaxias and Macquarie perch. The upper Kangaroo River site had by far the lowest SR (4) despite a lack of any significant fish passage obstructions between that site and the next site downstream at Kangaroo Valley, where the SR was 8. Of the seven diadromous species collected during this study that require passage past Tallowa Dam (excluding the three species that are capable of climbing and those that have been stocked in Lake Yarrunga), two—striped gudgeon and empire gudgeon—were captured upstream of Tallowa Dam in Lake Yarrunga.

There were significant accumulations of fish directly downstream of Tallowa Dam. The mean (± standard error (SE)) total abundance of fish collected per site across all eight sampling events was greater directly below the dam (812 ± 217) and 500 m downstream of the dam (721 ± 286) (Fig. 2.3) than at any other sites either upstream or downstream (minimum 22 ± 5.9 fish per sample from the Mongarlowe River) (ANOVA: $F_{11,80} = 5.61$, $p < 0.0001$). Significant accumulations of individuals below the dam were detected for freshwater herring, common jollytail, Australian bass, sea mullet, freshwater mullet, striped gudgeon and empire gudgeon (ANOVA: $p < 0.05$).

Table 2.2. Summary of fish captured in the Shoalhaven River. Sites upstream of Tallowa Dam are Mongarlowe River (MR), Shoalhaven River upstream (SR), Kangaroo River (KR) and Lake Yarrunga (L); and downstream of the dam are: directly below the dam (DB) and Burrier (B). For site names, see Table 2.1. Catches are pooled results from eight sampling occasions.

Species	**Upstream of Lake Yarrunga**					**Lake Yarrunga**				**Downstream of dam**			Total
	MR	**SR**		**KR**		**L**				**DB**		**B**	
	11	**12**	**2**	**4**	**5**	**14**	**6**	**7**	**13**	**8**	**9**	**10**	
Anguillidae													
Shortfinned eel		1											**1**
Longfinned eel	3	19	17	54	50	16	10	12	4	120	35	14	**354**
Clupeidae													
Freshwater herring										2	38	22	**62**
Galaxiidae													
Common jollytail										37	62	21	**120**
Mountain galaxias	69												**69**
Gerreidae													
Silver biddy												6	**6**
Salmonidae													
Brown trout	1		1										**2**
Retropinnidae													
Australian smelt		153	299	580	354	632	558	989	890	1,144	4,079	314	**9,992**
Cyprinidae													
Goldfish	2								2		1	6	**11**
Common carp	30	47	40		47	14	9	23	35	26	34	22	**327**
Plotosidae													
Freshwater catfish		2	5			13	11	8	4	1	10	6	**60**

continued

Table 2.2. (*continued*) Summary of fish captured in the Shoalhaven River.

Species	Upstream of Lake Yarrunga					Lake Yarrunga				Downstream of dam			Total
	MR	SR		KR		L				DB		B	
	11	12	2	4	5	14	6	7	13	8	9	10	
Poeciliidae													
Eastern gambusia	10				4	22	13	46	5	1			**101**
Scorpaenidae													
Bullrout										3	8	3	**14**
Percichthyidae													
Macquarie perch	2												**2**
Estuary perch												1	**1**
Australian bass		20	43	18	60	37	47	21	19	342	158	124	**889**
Sparidae													
Yellowfin bream												7	**7**
Mugilidae													
Sea mullet										62	93	130	**285**
Freshwater mullet										70	97	122	**289**
Gobiidae													
Striped gudgeon						1			7	74	136	104	**322**
Cox’s gudgeon		9	10	34	7	5	3	3	1	262	199	131	**664**
Empire gudgeon			2					1	1	50	51	158	**263**
Firetail gudgeon										1			**1**
Western carp-gudgeon	56												**56**
Flat-headed gudgeon		61	35		64	573	444	602	68	762	755	13	**3377**
Dwarf flat-headed gudgeon			1		22	53	24	25	3	5	15	5	**153**
Total	**173**	**312**	**453**	**686**	**608**	**1,366**	**1,119**	**1,730**	**1,039**	**2,962**	**5,771**	**1,209**	**17,428**
Species richness	**8**	**8**	**10**	**4**	**8**	**10**	**9**	**10**	**12**	**17**	**16**	**19**	**26**

Figure 2.2. Species richness sampled at each site over eight sampling events between 2009 and 2013: Mongarlowe River (MR); Shoalhaven River upstream (SR); Kangaroo River (KR); Lake Yarrunga (L); directly below Tallowa Dam (DB); and Burrier (B).

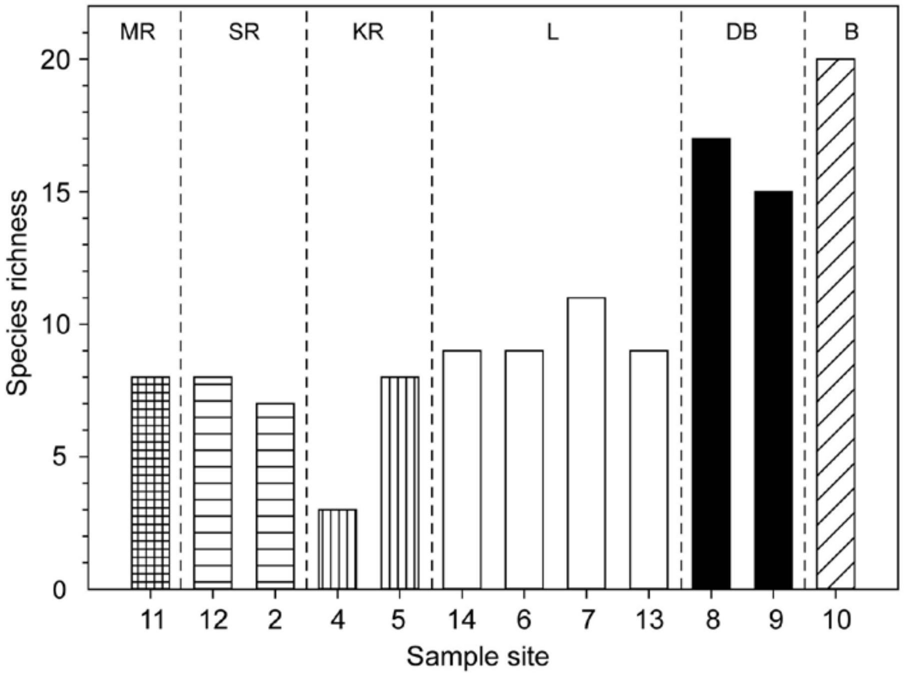
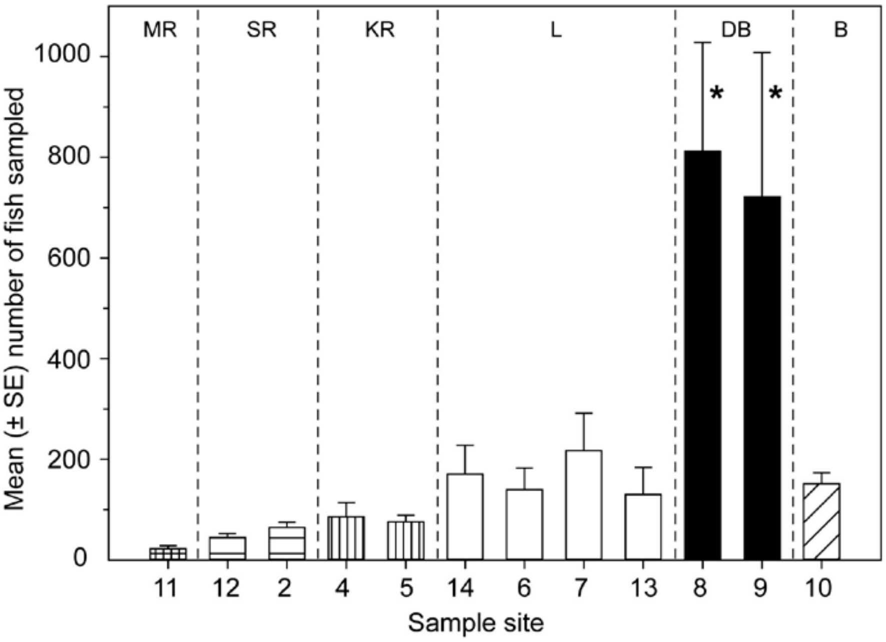


Figure 2.3. Abundance of fish sampled (all species combined) at each site averaged over eight sampling events between 2009 and 2013: Mongarlowe River (MR); Shoalhaven River upstream (SR); Kangaroo River (KR); Lake Yarrunga (L); directly below the dam (DB); and Burrier (B). Note: * denotes significant difference ($p < 0.0001$); numbers of fish sampled were standardised based on electrofishing operations.



2.3.2 Spatial variation among sites

Significant spatial differences were observed between contemporary fish communities within catchment zones (Fig. 2.4) (ANOSIM: $R = 0.635$, $p < 0.001$; Table 2.3). The Mongarlowe River in the upland reaches of the catchment, along with sites directly below the dam and at Burrier, supported the most distinctive fish assemblages ($p < 0.001$). The Mongarlowe River fish assemblage was characterised by the absence of Australian smelt, Australian bass, flat-headed gudgeon and Cox's gudgeon, the occurrence of mountain galaxias and the low abundance of longfinned eel (Table 2.4). Fish communities downstream of Tallowa Dam were characterised by the presence of catadromous freshwater mullet and sea mullet, and relatively higher abundance of striped, Cox's and flat-headed gudgeons. Fish assemblages within the remaining three zones upstream of the dam were less distinctive (Table 2.4); however, there were significant differences between the lacustrine habitats of Lake Yarrunga and the riverine habitats upstream in the Shoalhaven and Kangaroo rivers ($p < 0.002$), with no significant difference found between the two upstream catchment zones ($p = 0.06$). Riverine fish assemblages were characterised by greater abundances of Australian smelt, Cox's gudgeon and common carp, while lacustrine sites had comparatively greater abundances of flat-headed and dwarf flat-headed gudgeon and freshwater catfish (Table 2.4).

Figure 2.4. Multidimensional scaling (MDS) ordinations based on similarities among fish assemblages sampled at 12 sites within 6 catchment zones in the Shoalhaven catchment between 2009 and 2013.

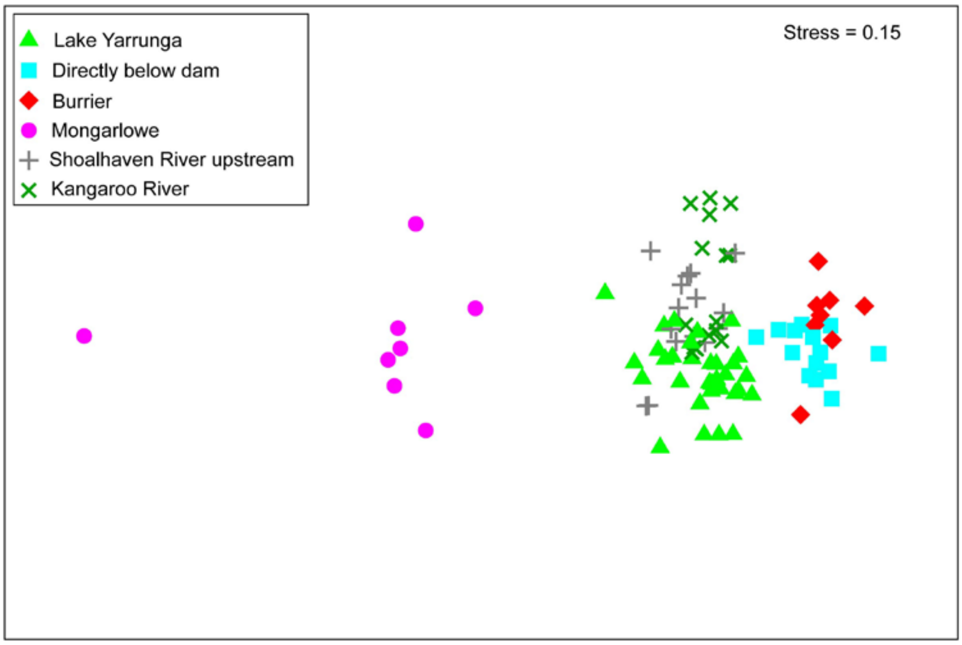


Table 2.3. Analysis of similarity (ANOSIM) results for fish communities in designated reaches of the Shoalhaven River.

Comparisons	***R***	***p***
Among zones	0.635	0.001
Pairwise comparisons		
Lake Yarrunga *v* Burrier	0.912	0.001
Lake Yarrunga *v* Directly below dam	0.788	0.001
Lake Yarrunga *v* Mongarlowe River	0.998	0.001
Lake Yarrunga *v* Shoalhaven River upstream	0.278	0.001
Lake Yarrunga *v* Kangaroo River	0.301	0.002
Burrier *v* Directly below dam	0.395	0.001
Burrier *v* Mongarlowe River	1.000	0.001
Burrier *v* Shoalhaven River upstream	0.885	0.001
Burrier *v* Kangaroo River	0.863	0.001
Directly below the dam *v* Mongarlowe River	1.000	0.001
Directly below the dam *v* Shoalhaven River upstream	0.866	0.001
Directly below the dam *v* Kangaroo River	0.828	0.001
Mongarlowe River *v* Shoalhaven River upstream	0.982	0.001
Mongarlowe River *v* Kangaroo River	0.998	0.001
Shoalhaven River upstream *v* Kangaroo River	0.113	0.060

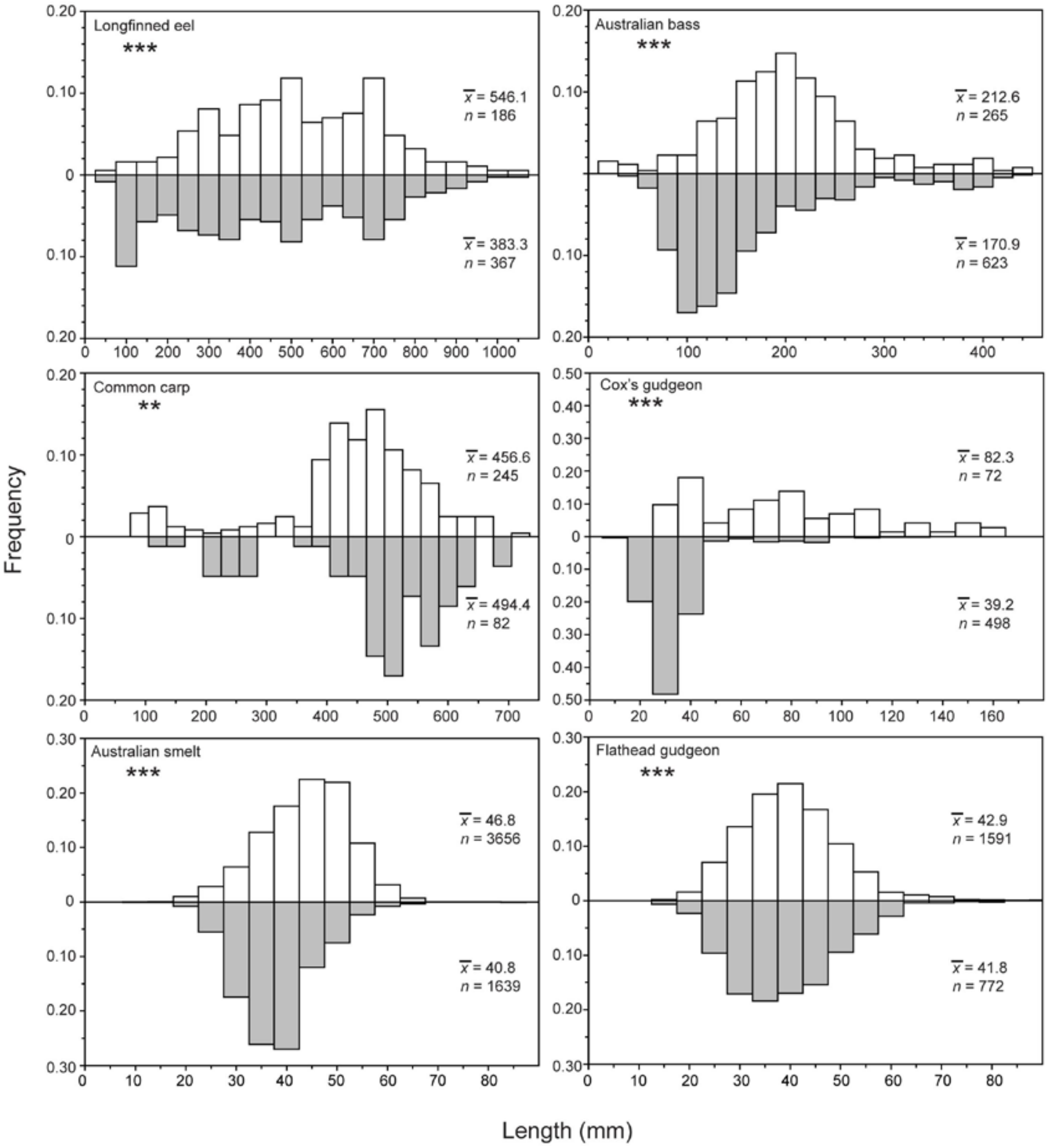
Table 2.4. Contributions of species to the dissimilarity (D) between fish assemblages in different zones within the Shoalhaven catchment.

Species	**Mean abundance**		**Consistency ratio**	**Cumulative %**	***D*%**
Mongarlowe River v *rest of catchment*					**87.41**
	Mongarlowe	Rest			
Australian smelt	2.64	–	15.74	18.00	18.00
Mountain galaxias	–	1.65	10.62	12.15	30.16
Flat-headed gudgeon	1.72	–	9.66	11.05	41.21
Australian bass	1.49	–	8.53	9.76	50.97
Western carp-gudgeon	0.02	1.05	6.12	7.00	57.96
Longfinned eel	1.14	0.28	6.10	6.98	64.94
Below Tallowa Dam v *Riverine*[a]					**54.95**
	Below	Riverine			
Freshwater mullet	–	1.85	6.12	11.14	11.14
Sea mullet	–	1.75	5.67	10.32	21.45
Striped gudgeon	0.04	1.69	5.3	9.64	31.1
Cox's gudgeon	0.47	1.85	4.71	8.57	39.66
Flat-headed gudgeon	1.59	2.11	4.63	8.42	48.09
Eastern gambusia	2.44	3.18	4.62	8.41	56.49
Empire gudgeon	0.05	1.31	4.14	7.54	64.03
Riverine [a] v *lacustrine*[b] *habitats*					**41.37**
	Riverine	Lacustrine			
Flat-headed gudgeon	2.22	0.91	8.2	19.82	19.82
Australian smelt	2.54	2.35	6.41	15.5	35.32
Dwarf flat-headed gudgeon	0.87	0.29	4.22	10.2	45.51
Common carp	1.06	1.13	3.91	9.44	54.96
Freshwater catfish	0.74	0.18	3.77	9.1	64.06
Cox's gudgeon	0.27	0.69	3.76	9.08	73.14

[a] Shoalhaven River upstream and Kangaroo River sites
[b] Lake Yarrunga sites

Of those species that were abundant both upstream and downstream of the dam, all showed a significant difference between size distributions of individuals upstream and downstream (Kolmogorov–Smirnov tests: $p < 0.001$) (Fig. 2.5). Differences in population size structure were highly significant ($p < 0.0001$) for longfinned eels, Australian bass, Cox's gudgeon, Australian smelt and flat-headed gudgeon, with a smaller modal population size downstream of Tallowa Dam (Fig. 2.5). The size structures of common carp were also significantly different ($p < 0.001$), however common carp downstream of the dam had a larger modal size (Fig 2.5). For both Australian bass and common carp, modal patterns showed evidence of recent recruitment. This was particularly evident among Australian bass upstream of Tallowa Dam and both upstream and downstream for common carp.

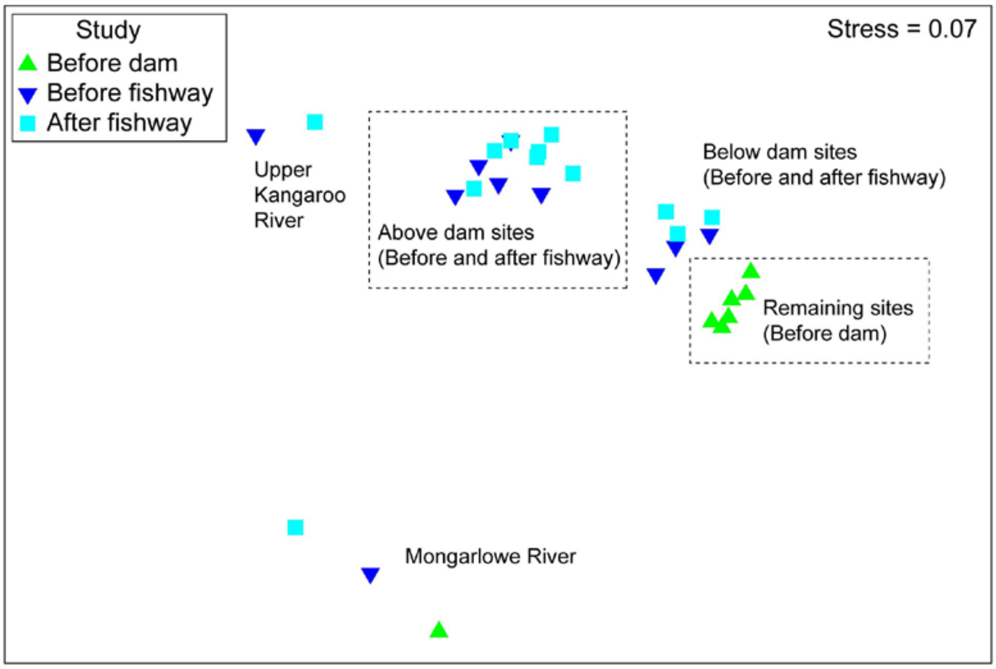
Figure 2.5. Length-frequency distributions of six fish species from sites upstream (white bars) and downstream (grey bars) of Tallowa Dam. Kolmorogorov–Smirnov tests are illustrated. Asterisks denote significant difference (** = $p < 0.\ 001$, *** = $p < 0.0001$.



2.3.3 *Temporal differences between historical and contemporary assemblages*

Temporal comparisons between reconstructed historical (before dam), after dam but pre-fishway (Gehrke *et al.* 2002) and contemporary fish communities, based on binary data matrices, revealed significant changes over the three time periods (PERMANOVA: $p < 0.001$) (Appendix 2.4). The Mongarlowe River continues to display the lowest similarity to sites within other zones across the three time periods. The expected fish community before dam construction showed no evidence of a discontinuity in species distributions across the remaining 11 sites, with all sites demonstrating greater than 90% similarity. In contrast, similarities in species assemblages for both the pre-fishway and present study were less than 50%, with ordination supporting distinctive fish communities found below Tallowa Dam and those in Lake Yarrunga and upstream (excluding upper Kangaroo River which remains unique) (Fig. 2.6). A pair-wise comparison revealed there was no significant difference between pre-fishway and current fish assemblages ($p = 0.855$). A two-factor ANOVA also confirmed higher numbers of individuals were present below Tallowa Dam for both the current study and communities sampled before fishway construction ($F_{11,\ 115} = 4.09$, $p < 0.001$). There was no significant difference in total species abundance between the two time periods ($p > 0.1$).

Figure 2.6. Mulitdimensional scaling (MDS) ordinations of binary matrices from sites in the Shoalhaven River before dam and pre- and post-fishway fish communities.



2.4 Discussion

Over the period 2009 to 2013, following installation of the fish lift on Tallowa Dam, 21 fish species were captured in the Shoalhaven River below Tallowa Dam and the fishway, while 17 species were captured upstream of the dam. Significant accumulations of fish were present directly below the dam (with the lowest abundances at higher elevations in the riverine reaches upstream of Lake Yarrunga) and length–frequency distribution analyses suggest a discontinuity in population size structures of those species present both above and below the dam. Differences in species diversity in catchment zones above and below Tallowa Dam are generally attributable to the absence of several catadromous species upstream of the dam. The biodiversity of the river system within the Shoalhaven catchment upstream of Tallowa Dam remains depauperate due to the continued absence of several migratory species. Even with the fishway in operation since 2009, populations of freshwater mullet, sea mullet, common jollytail, bullrout and freshwater herring were not captured upstream of the dam, and continue to accumulate downstream of the dam wall. However, in contrast to pre-fishway-construction fish assemblage patterns, the abundances of flat-headed gudgeon, longfinned eel and Australian smelt are now similar between upstream and downstream habitats, suggesting the continuity of populations above and below the dam. Although the first two species are capable of climbing barriers (Beumer 1996; Larson and Hoese 1996), sampling of the fishway exit (see Chapter 3) showed significant numbers of these fish and Australian smelt successfully utilising the fishway.

Fish assemblages were not significantly different between the upstream riverine reaches of the Shoalhaven and Kangaroo rivers; however, there was a divergence in community structure between these catchment zones and the lacustrine habitats within Lake Yarrunga. Reasons for impounded lakes developing divergent biological communities to those that originally occurred in the river may include loss of flow (Sheldon and Walker 1997), changes in vegetation within the impoundment and changes in water quality (Cogels *et al*. 1997; Garnier *et al*. 2000). Greater numbers of flat-headed gudgeon, dwarf flat-headed gudgeon and freshwater catfish were captured in Lake Yarrunga than in the upstream riverine habitats. It is possible that the littoral zone of the lake may have increased the amount of spawning habitat for these species, while the upstream riverine habitats are susceptible to episodic torrential flows which may displace individuals venturing upstream (Gehrke *et al.* 2002).

In addition to localised extinction of migratory species and decreases in population abundances upstream of dams (Ribeiro *et al*. 1995; Holmquist *et al*. 1998; Peter 1998), fragmented populations upstream and downstream of dams often develop independent population structures (Almodóvar and Nicola 1999). In this study, differences in population size structure were observed for all of the six species analysed—Cox’s gudgeon, longfinned eel, Australian bass, Australian smelt, common carp and flat-headed gudgeon—all of which have been recorded successfully ascending the fishway (see Chapter 3). This demonstrates that despite allowing fish to move upstream or downstream of a barrier, fishways do not provide a solution to all of the problems that dams create for riverine fish communities. In fact, lentic habitats are an unavoidable by-product of impounding rivers. Moreover, the population of Australian bass only existed in Lake Yarrunga previously because of extensive stocking over the last 20 years. Indeed, recent stockings (i.e. new recruits) upstream of the dam are still being detected as evidenced from multi-modal population size structures. Therefore, this population will continue to differ from the natural population below the dam until there is significant mixing between upstream and downstream populations. Similarly, there was evidence of recent recruitment success in common carp populations above the dam, although this was apparently confined to the upper catchment zones of the Shoalhaven River and is not likely to have resulted from juvenile carp migrating upstream through the fishway.

Comparing historical, pre-fishway and present fish assemblage abundances confirms that Tallowa Dam still represents a critical discontinuity in contemporary fish communities. The overall characteristics of the fish communities of the Shoalhaven River system, some 4 years after Tallowa Dam fishway first commenced operation, have demonstrated minimal change. Consistent with Gehrke *et al.* (2002), there is still evidence of (i) reduced species richness upstream of the dam compared to that of populations below; (ii) accumulations of fish directly below the dam wall; and (iii) divergence of population size structures of species that live upstream and downstream of the dam. Encouragingly, however, during the last two sampling events (spring 2012 and autumn 2013), two diadromous species, the striped gudgeon and empire gudgeon, were detected for the first time within Lake Yarrunga. In addition, several species historically reported to have significantly higher population abundances above the dam, compared to those downstream, have now been determined as similar. The detection of two species that were formerly locally extinct upstream of Tallowa Dam and evidence for equilibration of formerly disconnected populations of several other species suggests a gradual shift in continuity of fish assemblages above and below Tallowa Dam and the first stages of recovery as a result of the construction and operation of the Tallowa Dam Fishway.

3 EFFECTIVENESS OF TALLOWA DAM FISHWAY IN FACILITATING UPSTREAM FISH PASSAGE

3.1 Introduction

The need to ensure fish passage in the rivers of Australia was recognised more than a century ago, and the challenge since has been to facilitate movements over dams, weirs and other structures without compromising their operation (Humphries and Walker 2013). Adapting passage systems to species-specific biological needs and behaviour, as well as providing suitable hydraulic conditions, remain the most critical aspects for fishway effectiveness (Mallen-Cooper and Stuart 2003). Over the last 20 years, substantial research has been undertaken to maximise fish passage success for all species and size classes of migratory fish. These include assessments of self-operating rock ramp, vertical-slot and Denil designs. Mechanical fishway designs, including fish locks and lifts, are still considered highly experimental in Australia, as their ability to pass a significant biomass of fish over a broad range of size classes remains largely unknown (Baumgartner 2005). Currently, there are only two high dam fish lifts operating in Australia; at Paradise Dam in central-eastern Queensland and, more recently, at Tallowa Dam on the Shoalhaven River in New South Wales (NSW).

Fishway evaluation requires appropriate monitoring strategies to ensure integrity of the data and thus a comprehensive understanding of fishway performance (Baumgartner *et al.* 2010). Trapping fish from the fishway entrance and exit is a common method of determining fish movement and passage success of diadromous (Stuart and Berghuis 2002; Morgan and Beatty 2006) and potamodromous species (Mallen-Cooper and Stuart 2003; Stuart *et al.* 2008). Specifically, independent trap catches (exit and entrance) are compared to determine the proportion of fish species and size classes that can successfully ascend. However, fishway trapping does have limitations, and can be biased by fish behaviour or trap avoidance (Sugimoto *et al.* 1996). Often done in conjunction with trapping, electronic monitoring of fishways through the use of passive integrated transponder (PIT) technology provides a cost-effective method of studying the movements of medium- to large-bodied fish over large spatial and temporal scales (Castro-Santos *et al.* 1996; Zydlewski *et al.* 2006). A well-designed system has the potential to correlate behaviour, migration and fishway use with a range of environmental variables such as season, time of day, temperature and river discharge.

A high dam fish lift was constructed at Tallowa Dam in 2009, in association with a revised environmental flow regime to restore the longitudinal connectivity of habitats for native fish within the river system. In addition to an ‘outcomes assessment’ of fish assemblages throughout the catchment before and after fishway construction (Chapter 2), an evaluation of fishway performance in providing upstream fish passage was required. Such evaluation can provide explanations for unexpected results observed during catchment-wide fish assemblage monitoring and identify design issues limiting fishway performance for particular species or size classes of fish. The aim of this study was to combine the use of fishway trapping and PIT-tag technology to: (i) document the species composition, including richness, abundance and population structure of fish migrating through the fishway; and (ii) assess fish behaviour and environmental conditions relevant to fishway usage. This represents a component of the joint project undertaken by the Sydney Catchment Authority (SCA), NSW Department of Primary Industries (DPI) and the former Cooperative Research Centre for Freshwater Ecology, ‘Assessment of fishway effectiveness, and optimisation of operations for fish migrations’.

3.2 Methods

3.2.1 Site and fishway description

Both components of this chapter were carried out at Tallowa Dam on the Shoalhaven River (see Chapter 2, Fig. 2.1), with PIT tagging of fish in the upstream and downstream reaches of the river, including smaller tributaries.

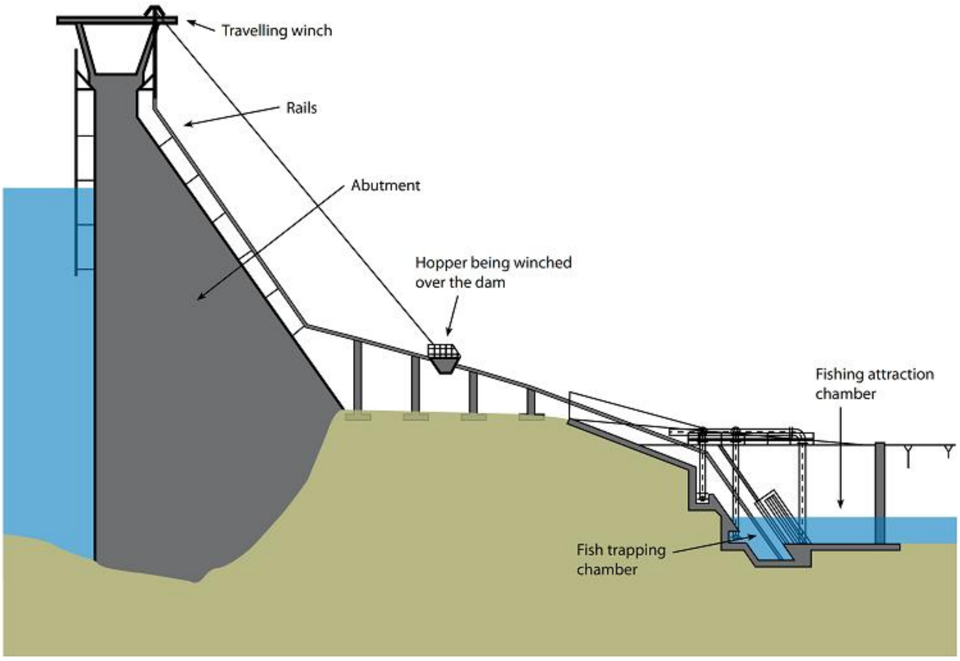
The fish lift is a mechanical system that attracts, captures and then transports upstream-migrating fish from the base of Tallowa Dam into Lake Yarrunga (Fig. 3.1a). The attraction chamber of the fishway is a 3.5-m-wide open-topped channel which fish enter through a 300-mm-wide vertical slot positioned close to the upstream limit of migration at the dam (Fig. 3.1b). An attraction flow is maintained within the attraction chamber at all times, with an entrance slot velocity of approximately 0.8 m/s (favourable for fish passage). Fish entering the attraction chamber must move upstream against the attraction flow for a distance of 50 m to access a cone trap at the entrance to the trapping chamber. The trapping chamber contains a hopper at its base. The stainless-steel hopper is 3.5 m long × 1.5 m wide × 1.0 m deep and holds approximately 3 m^3 of water (Fig. 3.2a). The upper walls and roof of the hopper are constructed from 4-mm screen to prevent fish from leaping out during transportation. The hopper is raised out of the water by a hoisting system and transported over the dam wall. The hopper is then lowered to the surface of the water on the upstream side of the dam and fish are released from the hopper through a hinged flap in the hopper's floor. No fish can remain within the hopper over multiple fishway cycles. The time taken for fish to be transported from the attraction chamber to release is approximately 10 minutes and the cycle is repeated 15 to 20 times each day. Although the fishway's attraction, transport and re-setting phase operations are all fully automated, these operations can be manually overridden and the hopper contains a manual water-release valve allowing inspection of the hopper and the removal of any fish it contains during the transportation phase.

3.2.2 Fishway trapping

Direct trapping in the fishway (Fig. 3.2) was done at two locations: (i) the attraction chamber, 20 m upstream of the entrance slot ('entrance'—representing fish entering the attraction chamber); and (ii) in the fish-lift hopper ('exit'—fish considered to have successfully utilised the fishway to move upstream). Trapping events were stratified so that a paired entrance and exit sample was collected over a 48-hour period, with the hopper and downstream trap set for an alternate 24 hours at each location. During trapping events, the fishway was manually set to 'attraction mode' for the full 48-hour duration and the hopper or trap was left in place for 24 hours, thus providing results comparable between the entrance and exit. The entrance sample was collected using a purpose-built cage trap (3.25 m (H) × 3.40 m (L) × 1.40 m (W)) (Fig 3.2b) constructed from 4-mm bar mesh and with six dual cone-trap entrances. The trap was lowered and set into the attraction chamber. Rubber flanges around the face of the trap ensured fish could not pass between the trap and the attraction chamber floor or walls. The exit sample was collected from the hopper (accessed manually) (Fig. 3.2a) as it was being transported over the crest of the dam wall (Fig. 3.2c) at the completion of the 24-hour sampling period.

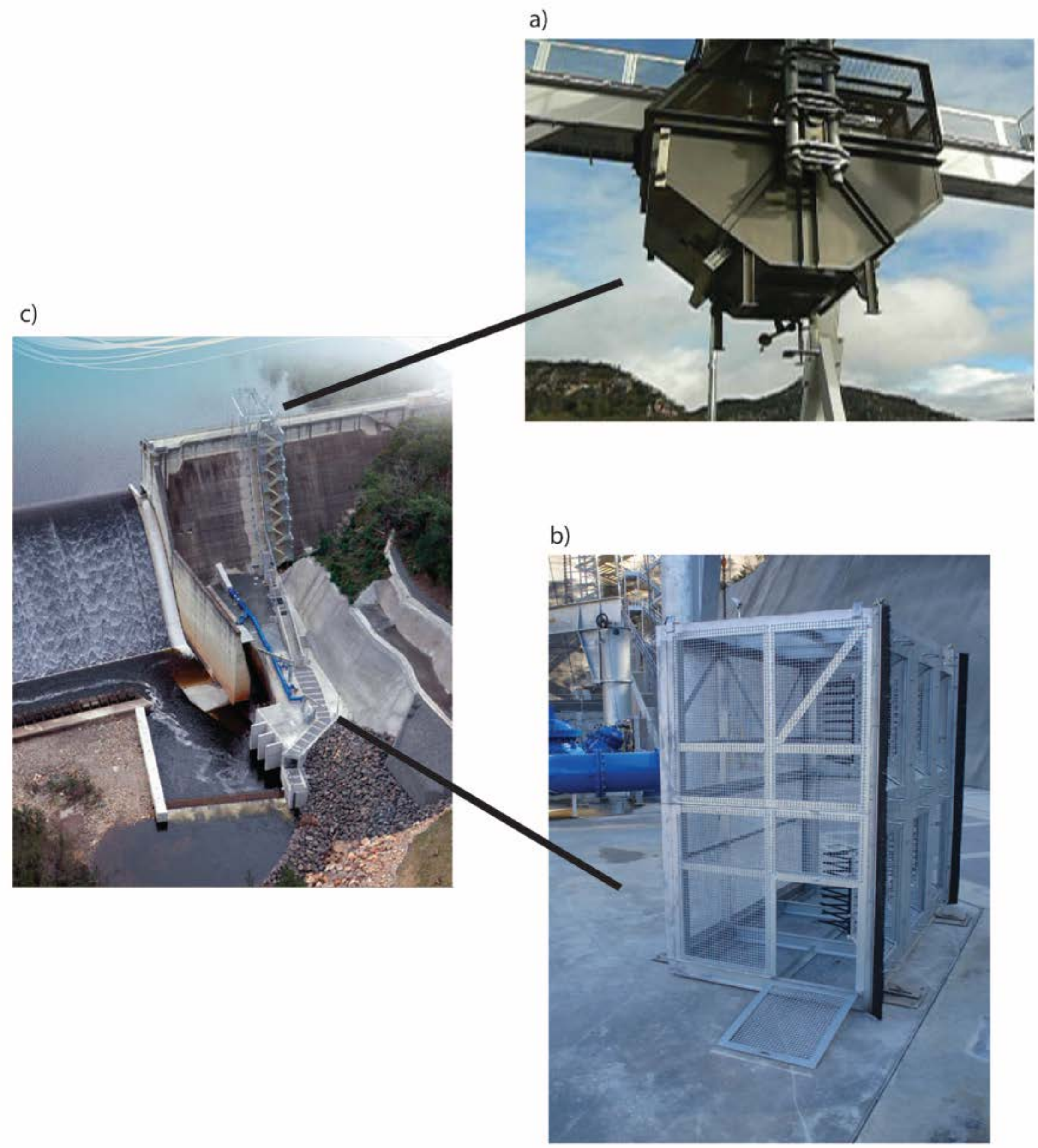
Figure 3.1. Schematic diagram of fishway at Shoalhaven Dam (a) and entrance to attraction chamber where one of the PIT-tag antennae was located (b).

a)



b)

Figure 3.2. Hopper (exit) (a) and trap (entrance) (b) in relation to their location on the crest of the dam and within the fish attraction chamber, respectively (c).



A total of 12 × 48-hour paired trapping events were proposed in each year between 2010 and 2013, with six trapping events in spring and six events in autumn. Trapping times were chosen to coincide with different fish species' migration patterns. Adults of most diadromous species generally migrate between September and November, while juveniles and sub-adults generally move upstream between January and April (McDowall 1996).

All fish were identified, counted, measured and released after capture. Length measurements were to the nearest millimetre and were taken as fork length for species with forked tails, and total length for all other species. Where large catches of a species occurred, a sub-sample of 100 individuals of each species was measured per 24-hour period. Those fish captured in the fish-lift hopper were released into Lake Yarrunga. Water temperature (°C) and daily water discharge outflows from Tallowa Dam were supplied by SCA.

3.2.3 PIT antennae system

To collect data on the fishway ascent success and the migratory behaviour of individual fish, PIT tags (Texas Instruments eco-line glass transponder, half and full duplex, 11 mm and 22 mm, respectively) were implanted in the gut cavity of individual fish of >200 mm in length that were collected during dedicated biannual 'tagging trips', during fishway trapping events, and as part of fish community surveys (Chapter 2) between 2005 and 2013. Smaller-bodied species and small juveniles of large-bodied species were not tagged due to the physical size of the PIT tags used. Suitable fish were anaesthetised with a light sedative (Aquis®, 10 mg/L) before implantation and released at point of capture. Subsequent recapture of PIT-tagged fish indicated that the entry wound healed completely within a few weeks. In total, 3,741 individuals of nine species were PIT tagged. Of these, 1,502 were Australian bass tagged by members of the Southern Bass Fishing Club between 2004 and 2013.

A dual-antennae, fixed PIT-tag reader system (KarlTek KLK5000) was installed within the fish attraction chamber (Fig. 3.1a). The locations of the swim-through antennae included the vertical slot located at the attraction chamber entrance (Fig. 3.1b) and the entrance of the fishway trapping chamber (i.e. the hopper entrance). Any time a tagged fish swam through the antennae, its presence was recorded along with time of day and date. The detection of a tagged fish at the hopper entrance with no subsequent detections would indicate that the fish had successfully utilised the fishway and had migrated over the dam wall. Alternatively, if a fish was not detected at the hopper entrance, or it was last recorded by the attraction chamber entrance antenna, then it had not successfully utilised the fishway. Data were downloaded from the antennae on a bimonthly basis by DPI personnel and collated in a Microsoft Access database.

3.2.4 Data analysis

A suite of multivariate and non-parametric analyses were undertaken to detect spatial and temporal differences in fish assemblages and species abundances, including the comparison of population size structures for those species that were captured in sufficient numbers ascending the fish lift or trapped in the attraction chamber downstream. Spatial and temporal analyses of fish assemblages were done using PRIMER 6.0 (Plymouth Marine Laboratory). Abundances were transformed to the fourth root, with similarities between fish assemblages at each site calculated using the Bray–Curtis similarity measure (Bray and Curtis 1957). A permutational multivariate analysis of variance (PERMANOVA) (Anderson 2001) model was used to test for significant differences in fish community structure between the entrance and the exit among seasons. Individual species abundances at the exit and entrance of the fishway were compared using Wilcoxin's rank sum tests on the raw abundance data. Size distribution data of fish from the entrance and exit were compared using Kolmogorov–Smirnov (KS) two-tailed tests. KS analyses could only be done for those species where >50 individuals were recorded at both the fishway entrance and exit sites; Australian bass, Australian smelt, Cox's gudgeon and flat-headed gudgeon.

For PIT-tag data, size distributions of species tagged and those detected by the PIT-tag antennae were compared using KS two-tailed tests. A generalised linear model determined whether fish species were more likely to use, or be active in, the fish attraction chamber at night or during the day. Detection data were based on a Poisson distribution and because the same fish were used to determine detections at antennae for day and night treatment, individual fish were included in the models as subjects in a repeated measures design using generalised estimating equations (Liang and Zeger 1986).

3.3 Results

3.3.1 Present fish assemblages

In all, 29,091 individuals representing 15 fish species were caught within the Tallowa Dam Fishway over 18 paired trapping events between October 2010 and March 2013 (Table 3.1). Eight of the 10 catadromous native species sampled at the entrance to the fishway were also collected at the exit. The two exceptions were freshwater herring and bullrout. The introduced species, common carp, was also caught at the entrance but not the exit. By far the most common species captured at both the entrance and exit was Cox’s gudgeon, representing 97% and 88% of all fish caught, respectively. There were no significant differences in fish assemblage structure between the fishway entrance and exit or among seasons (PERMANOVA: site, p = 0.81; season, p = 0.328). There were significantly more Cox’s gudgeon (Wilcoxin’s test: p = 0.032) at the exit of the fishway, while there were no significant differences in mean catch rates between the entrance and the exit for Australian bass (p = 0.92), Australian smelt (p = 0.56) and longfinned eel (p = 0.59) (Fig. 3.3). Of the species captured that were abundant at both the entrance and exit, all except flat-headed gudgeon displayed a significant difference in size distributions (KS test: p < 0.001) (Fig. 3.4). Australian bass, Cox’s gudgeon and Australian smelt reaching the exit were all significantly larger than those caught at the entrance.

Australian bass made up the majority (60%) of fish PIT tagged, and comprised approximately 60% of the fish detected swimming through the fish attraction chamber. Recapture rates (i.e. tagged fish captured by DPI personnel, members of Southern Bass Fishing Club and the general public) ranged from <1% for longfinned eels through to 9% for common carp (Table 3.2, Appendix 3.1). Importantly, seven individual fish comprising five Australian bass and two common carp, originally tagged downstream of the fishway were recaptured later above the dam in Lake Yarrunga. With the exception of longfinned eels (22%), similar detection (‘recapture’) rates (1–8%) were also observed for tagged fish within the attraction chamber. Five of the nine tagged fish species were last detected at the hopper, after swimming through the entrance, meaning it was likely these fish ascended the fishway (Table 3.2). For four of these species, at least 40% of individuals were successful. The exception was freshwater mullet (10%), indicating the potential reluctance of this species to enter the fish-lift hopper. The size distribution of Australian bass detected by the PIT antenna within the attraction chamber was significantly larger than the size distribution of the tagged Australian bass population as a whole (KS tests: p < 0.001). For all of the other fish species with sufficient sample sizes to allow comparisons (common carp, longfinned eel and freshwater mullet, Table 3.2), there were no significant differences in the size distributions (KS tests: p > 0.1).

Table 3.1. Summary table of fish species captured in the hopper (exit) and the trap (entrance) of the Tallowa Dam Fishway.

Species	**Hopper**		**Trap**		**Total**
	n	**Length (mm)**	***n***	**Length (mm)**	***n***
Shortfinned eel[a]	2	107–113	6	100–122	8
Longfinned eel[a]	32	110–975	19	65–1,110	51
Goldfish	1	281			1
Common carp			1	432	1
Common jollytail[a]	14	43–47			14
Striped gudgeon[a]	4	37–58	2	48–50	6
Cox's gudgeon[a]	24,295	24–56	3,659	22–89	27,954
Empire gudgeon[a]	20	33–37	21	32–38	41
Australian bass[a]	208	89–435	87	85–448	295
Bullrout[a]			4	67–78	4
Flat-headed gudgeon	237	31– 58	259	17–66	496
Freshwater herring[a]			1	142	1
Australian smelt	140	32–62	72	30–77	212
Freshwater catfish	1	465	4	468–532	5
Freshwater mullet[a]	1	477	1	422	2
Total	**24,955**		**4,136**		**29,091**
Total no. of species caught	**12**		**13**		**15**

[a] Catadromous species

Figure 3.3. Mean catch rates (± SE) of fish per day at the exit and entrance of the Tallowa Dam Fishway. Asterisk denotes a significant difference ($p < 0.05$). Log-scale on y-axis.

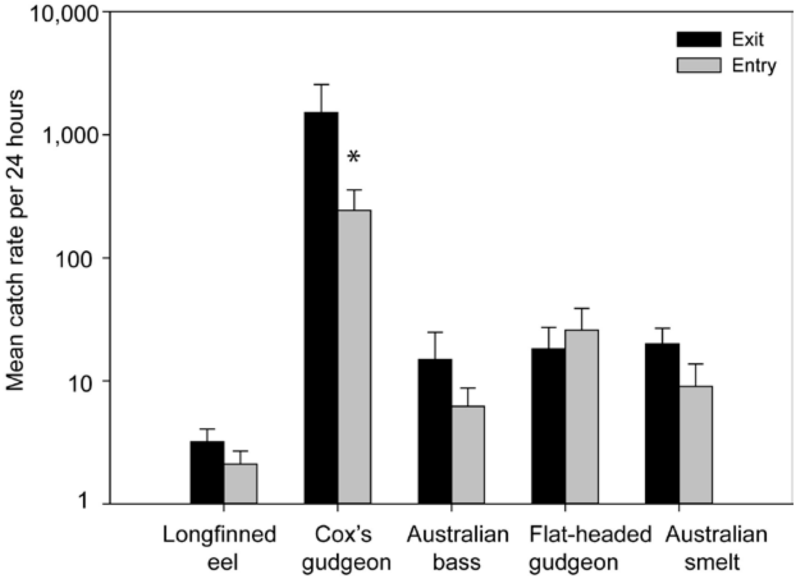


Figure 3.4. Length–frequency distributions of four fish species from the hopper (white bars) and the trap (grey bars). Kolmogorov–Smirnov comparisons are illustrated. Asterisks denote significant difference ($p < 0.0001$).

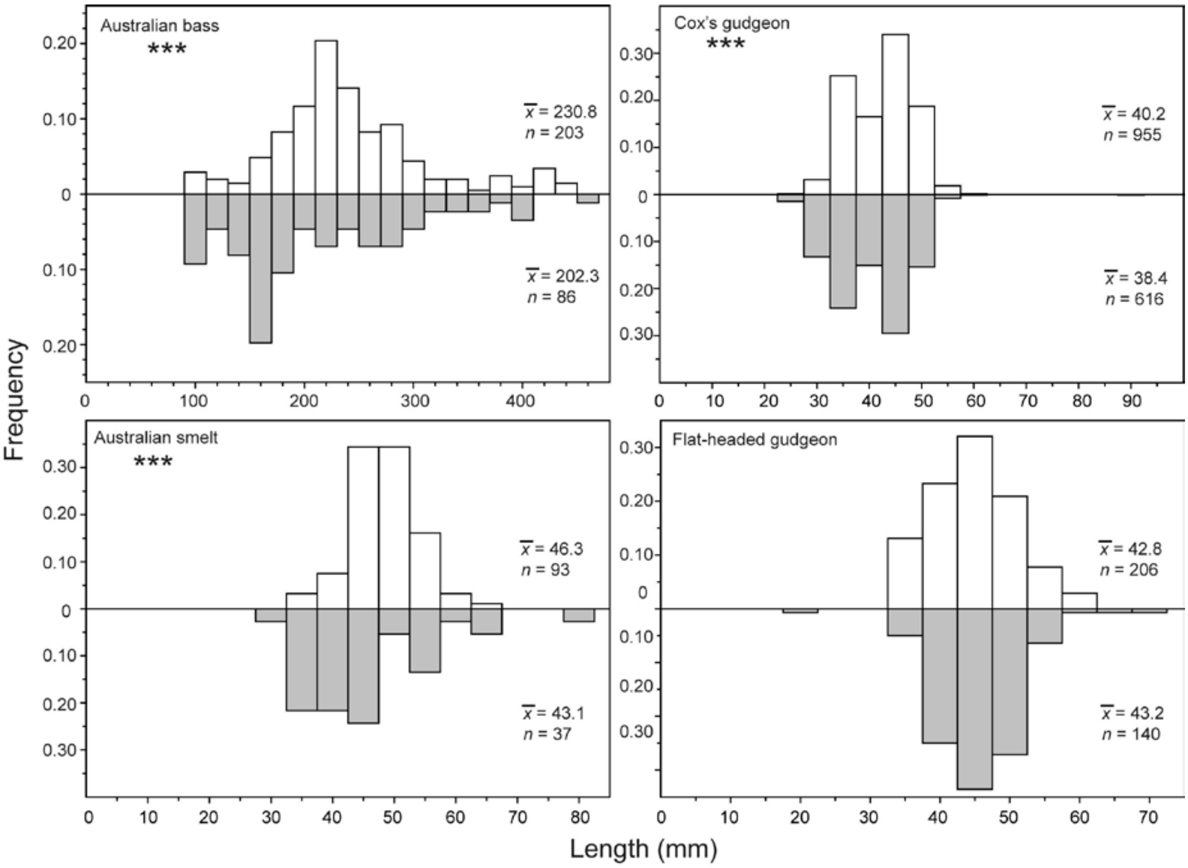


Table 3.2. Summary table of fish species PIT tagged, the number of fish recaptured by Department of Primary Industries personnel and Southern Bass Fishing Club, and number detected by the antennae in the attraction chamber.

Species	No. tagged	size range (mm)	No. of fish recaptured	No. of fish detected	Last detected at reader 3[a]
Longfinned eel	156	400–1,210	1 (<1%)	34 (22%)	17 (50.0%)
Goldfish	8	220–290	0	0	0
Common carp	348	150–810	30 (8.6%)	29 (8%)	12 (41.4%)
Estuary perch	36	210–320	0	0	0
Australian bass	2,253	110–500	107 (4.8%)	135 (6%)	54 (40.0%)
Sea mullet	261	210–490	20 (7.7%)	2 (1%)	0
Freshwater mullet	572	200–500	34 (5.9%)	21 (4%)	2 (9.5%)
Freshwater herring	13	200–260	0	0	0
Freshwater catfish	94	160–530	2 (2.1%)	5 (5%)	2 (40.0%)
Total	**3,741**		**194 (5.1%)**	**226**	**87**

[a] Percentage indicates proportion of number of fish detected by PIT-tag readers

3.3.2 Diel and seasonal variability of upstream fish passage

Significantly higher mean diurnal detections were recorded for Australian bass (X^2= 4.26, df = 1, $p = 0.04$), freshwater mullet (X^2= 113.1, df = 1, $p < 0.0001$) and common carp (X^2= 93.75, df = 1, $p < 0.0001$) (Table 3.3, Fig. 3.5). Although longfinned eel detections were mostly nocturnal, no significance difference was detected for this species. Detections of migrating tagged fish through the fishway were highly seasonal, with peaks in numbers of individuals coinciding with the austral spring (September to November) and late summer to autumn (February to May) periods (Fig. 3.6). Small numbers or no detections were recorded in the fishway during June to August (austral winter). There was no relationship evident between number of tagged individuals of any species visiting the fishway and increased flows (Appendix 3.2).

Table 3.3. Mean percentage and number of individuals (in brackets) detected during the day and the night in the fish attraction chamber. Note: an individual can be detected during both the day and the night.

Species	**No. of fish detected**	**No. of detections**	**Day**	**Night**
Australian bass	135	535,364	70.37% (123)	29.62% (99)
Freshwater mullet	21	4,362	91.37% (20)	8.63% (6)
Common carp	29	22,312	83.49% (29)	16.51% (14)
Longfinned eel	34	432,341	36.72% (29)	63.28% (32)
Freshwater catfish	5	1,986	70.45% (5)	29.55% (3)

Figure 3.5. Mean (± SE) number of detections of tagged fish species recorded in the attraction chamber. Asterisks denote significant difference (* means $p < 0.05$, *** means $p < 0.0001$).

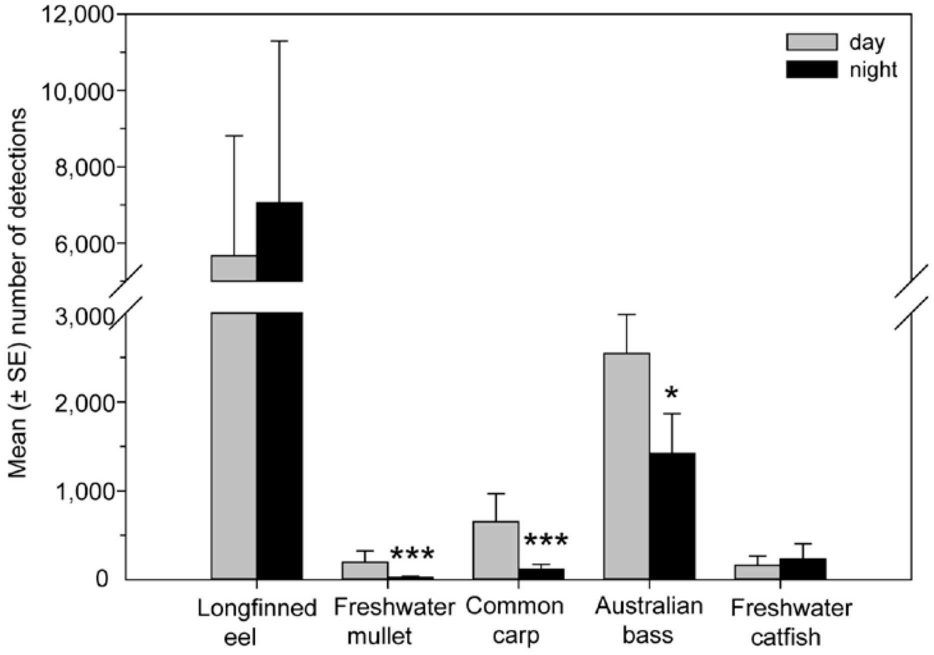
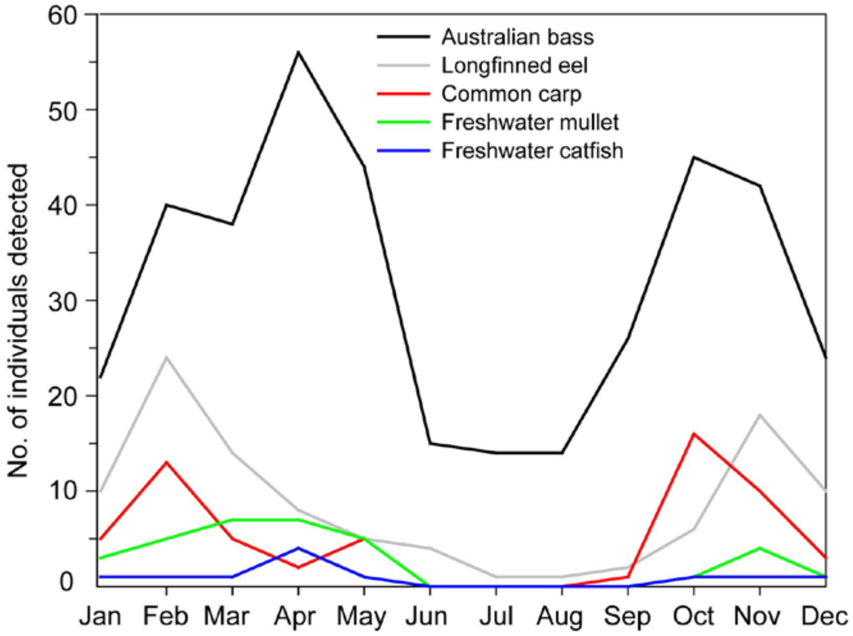


Figure 3.6. Total number of individuals of different species detected within the attraction chamber (readers 1 and 3) each month. Years 2009–2013 were pooled.



3.4 Discussion

The combined use of trapping and PIT-tag technology provided a useful insight into fish behaviour and the effectiveness of the fish lift in providing upstream fish passage. Our results indicate that the Tallowa Dam fish lift provides effective fish passage for the majority of those species that enter the fishway and provides passage for a broad range of size classes of those species. The fishway successfully provided upstream fish passage for 12 fish species, 11 of which were native, including small- to large-bodied fish (22–1,110 mm). However, not all species found below the dam wall (Chapter 2) were represented in the trap and hopper experiments. There was a complete absence of the catadromous species sea mullet, and of dwarf flat-headed gudgeon, as well as an under-representation of other fishes, including freshwater herring, freshwater mullet, common carp and bullrout.

All fish captured in the hopper were observed to be in excellent condition, with no identifiable evidence of trauma. Even though fish numbers were dominated by small-bodied species (<100 mm), the physical size and capacity of the hopper and speed at which fish are transferred into Lake Yarrunga appears to be adequate. During normal operations, the time for the hopper to be lifted from the bottom of the dam and lowered into Lake Yarrunga is relatively short (approximately 10 minutes). Only during peak migration times, when high numbers of adult large-bodied species (e.g. Australian bass) are entering the hopper, would the depletion of dissolved oxygen potentially be an issue. In the initial stages of the monitoring program, large numbers of Cox’s gudgeon were observed stranded outside the mesh on the top of the hopper while in travel mode. The mesh size on the roof of the hopper has since been widened to allow small-bodied fish to drop back into the hopper. Gaps between the mesh and the roof sections of the hopper have also been sealed to minimise any risk of fish escaping from the hopper during transit.

Marginal differences in abundances and size structure were observed between fish populations entering the attraction chamber and those exiting via the fish lift, with discrepancies likely being the result of differences in configurations between the hopper and trap. Other reasons for fish species or smaller-sized individuals not entering the attraction chamber, or migrating successfully through the fishway, are numerous, but have been linked to species-specific biological behaviour, as well as differential flow requirements (Stuart and Mallen-Cooper 1999). Studies on fish behaviour have shown the inhibition of some native species (e.g. silver perch, bony bream and sea mullet) to pass through tunnels and confined spaces (Mallen-Cooper 1996; DEEDI 2012). Based on the absence and low utilisation rates for some species at Tallowa Dam, this ‘shyness’ effect may hold true for the more ‘flighty’ fishes, including freshwater herring and the two mullet species (freshwater and sea mullet). Moreover, homogenous hydrological conditions within fishways have led to a decrease in species diversity and size range of fishes that pass through them (Mallen-Cooper and Stuart 2007; Baumgartner *et al.* 2010). However, the large numbers of Cox’s gudgeon and flat-headed gudgeon captured in the hopper appear to confirm that water velocity in the attraction chamber is suitable for migrating small-bodied species.

Australian bass, common carp and freshwater herring were mostly detected swimming in the fish attraction chamber during the day. Diel habitat preference has been reported among many freshwater and marine fishes, whether it be related to food availability (Pedersen 2000), predator avoidance (Culp 1989) or as a migration strategy (Reichard *et al.* 2002; Walsh *et al.* 2013). Therefore, the unfamiliar environment and low light intensity of the fish attraction chamber may be conducive for these three species to be more active during the day. For fish such as longfinned eels, similar detections were recorded in the attraction chamber for both day and night. Interestingly, 22% of all longfinned eels tagged downstream of the fishway were eventually detected by the PIT antennae, suggesting a preference for upstream habitats. During a number of hopper sampling events, longfinned eels were observed regurgitating partially eaten fish and displayed evidence of full stomachs. It is evident that fishes such as eels may be exploiting the fishway for predation purposes; however, this behaviour is likely linked to the long cycle times (up to 24 hours) used during sampling. Operation of the fishway in a normal frequent-cycling mode should reduce predation within the hopper as well as minimise the fatigue levels of small fish trying to migrate.

Tagged fish species predominantly moved through the fishway during the warmer months of spring and autumn, the timing of which coincides with important life-history strategies, including spawning and juvenile recruitment. Adult Australian bass returning from their winter estuarine spawning grounds (Harris 1986; Walsh *et al.* 2012a; Reinfelds *et al.* 2013) were detected in considerable numbers as water temperatures rose in the spring months, while more juvenile Australian bass were detected migrating during the autumn months. Increased numbers of tagged freshwater mullet returning from late-summer spawning activity (C. Walsh, unpubl. data) also visited during this time. Periods of least activity among species were detected during the winter months, which is understandable considering their life-history strategies and the lack of activity associated with minimal water temperatures. Being ectotherms, the metabolic rate of a fish will decrease as the ambient temperature lowers (Katersky and Carter 2007). Periods of inactivity among fishes suggests that fishway operations may not be required all year round. This effectively would enable routine maintenance to be carried out at certain times without affecting the overall performance of the fishway.

Due to flood damage and reliability issues associated with the fish-lift hopper and attraction chamber flows, only 50% of the trapping events scheduled were completed. This affected the autumn and spring sampling periods in 2012, when no sampling occurred. Furthermore, due to water ingress and power failures, the PIT-tag antennae responsible for detecting tagged fish, were reduced in efficiency, or had failed for approximately 55% of the time (Appendix 3.2). Because medium to large flow events in the Shoalhaven fell within these time periods, the effect of flows on fish migration could not be appropriately investigated. Further replicated alternate trap/hopper experiments throughout the whole year, in conjunction with the PIT-tag data, will provide finer detailed information into the seasonal timing and hydrological requirements for fish migrating through the fishway.

4 EFFECTIVENESS OF TALLOWA DAM SPILLWAY IN FACILITATING DOWNSTREAM FISH PASSAGE

4.1 Introduction

In the coastal rivers of south-eastern Australia, 70% of fish species exhibit ‘diadromy’, undertaking obligatory and regular migrations between freshwater and marine habitats (Miles *et al.* 2014). Artificial barriers on rivers, such as dams, weirs and culverts, are significant impediments to these migrations and have detrimental effects on fish populations (Orth and White 1993; Holmquist *et al*. 1998). Because of the declines and localised extinctions of diadromous species above barriers (Bishop and Bell 1978; Brumley 1987; Gehrke *et al.* 2002), fishways are often constructed, allowing the continued utilisation of the water resource upstream of the fish passage barrier. However, wherever upstream fish passage is provided, the capacity for downstream fish passage is equally important. Providing upstream fish passage at a barrier without provisions for downstream passage would have a perverse negative outcome on fish populations downstream of the barrier, by allowing them to access upstream reaches from which they cannot return safely to reproduce, thus leading to a net loss of reproductive potential within the overall population.

Downstream dispersal during larval/juvenile phases (Humphries *et al*. 1999; Gilligan and Schiller 2003) and downstream adult spawning migrations (Crook *et al.* 2010; Reinfelds *et al.* 2013) are undertaken by several freshwater fish species in south-eastern Australia. Barriers to downstream fish passage have been identified as having negative impacts on survival, behaviour, reproduction and overall fish community structure (O’Connor *et al.* 2003; Schilt 2007; Baumgartner *et al.* 2008). However, there is a paucity of data on the effects of dams, weirs and other physical structures on downstream fish passage; in particular, the survivability of fish migrating over high dam spillways. Although spillway passage is generally considered the most benign way to pass large numbers of fish downstream (Schilt 2007), disadvantages include the release of elevated dissolved oxygen gas downstream which can stress or kill fish (Backman and Evans 2002), as well as reduced swimming performance and resistance to pathogens (Weiland *et al.* 1999).

A high dam fish lift was constructed at Tallowa Dam on the Shoalhaven River (see Chapter 2, Fig. 2.1) in 2009 to restore the longitudinal connectivity of habitats for native fish within the catchment and reverse the significant loss of biodiversity upstream of the dam (Gehrke *et al.* 2002). Downstream fish passage is via a 32-m-high overflow spillway which is 352 m wide, has a maximum slope of 1:0.7 on the downstream face and discharges into a roller bucket energy dissipater. In association with fishway construction, a 2-m-wide × 1.5-m-deep gate-controlled channel was recessed into the eastern extremity of the spillway (Fig. 4.1a). This vertical-lift over-shot gate allows for downstream fish passage and delivery of environmental releases when the water level within the lake is below the spillway crest. When fully lowered and the storage level is at full supply, the over-shot gate is capable of discharging up to 700 ML/day. The spillway face downstream of the gate has been coated with epoxy resin to provide a less abrasive surface. Migrating fish slide over the spillway into the stilling basin that in turn distributes fish to the downstream river channel.

The emergence and use of acoustic telemetry and passive integrated transponder (PIT) tag technology has provided an effective tool for investigating movement biology of many fish species (Koehn 2000). In particular, acoustic telemetry allows individuals to be tracked with high spatial and temporal resolution, by using an array of fixed logging stations that passively and continuously monitor fish movement. As acoustic signals are unaffected by salinity, they are especially useful for species that traverse freshwater, estuarine and marine waters. Several studies using this technology on diadromous fish within the Shoalhaven River in New South Wales (NSW) have examined survivability and home range sizes (Walsh *et al.* 2012a) and spawning behaviour and movement in relation to environmental flows (Reinfelds *et al.* 2013; Walsh et al. 2013; van der Meulen *et al.* 2014).

The aim of this study was to assess the effectiveness of the Tallowa Dam spillway in providing downstream fish passage—specifically, to: (i) assess the mortality and physiological consequences of Australian bass entrained over the modified spillway; and (ii) determine the long-term survivability and timing of Australian bass and freshwater mullet migrating over the dam wall. This represents a component of the joint project undertaken by the Sydney Catchment Authority (SCA), NSW Department of Primary Industries (DPI) and the former Cooperative Research Centre for Freshwater Ecology, ‘Assessment of fishway effectiveness, and optimisation of operations for fish migrations’.

4.2 Methods

4.2.1 Downstream mortality assessment

An experiment was carried out at Tallowa Dam in February 2013 to assess the fate and long-term mortality of Australian bass migrating downstream over the spillway gate and down the spillway. In all, 144 fish, including controls and two flow treatment groups (low flow and high flow) were used. Treatment fish were released over the over-shot gate during either low-flow (50 ML/day) or high-flow (500 ML/day) conditions, and then recaptured in the stilling basin. Control fish were introduced into the stilling basin without going over the dam wall. All control and treatment fish were released in randomised blocks of four (Appendix 4.1) to minimise time spent adjusting to flow conditions, and to maximise recapture and processing efficiency.

Fish were collected by boat electrofishing downstream of the dam wall <48 hours prior to the start of the experiment. Each fish was mildly sedated (10 mg/L AQUIS®) and tagged for identification with an external dart tag (Hallprint®). Fish were then housed in cylindrical floating cages as shown in Fig 4.1b (2.5 m^3, 22 mm knotless mesh) in the impoundment at a density of 10 fish per m^3.

On the day of the experiment, fish were removed from the cages in four equal-sized batches, and transferred to an oxygenated 1,000 L tank for transport to the crest of the dam. Each individual was assigned a treatment, block and recovery cage based on the order in which they were removed from the transport tank (Appendix 4.1). Each fish was tethered to a 100 mm diameter polystyrene float using a 2 m length of 15 kg monofilament fishing line attached to a circle hook through the upper jaw, photographed, placed in a 20 L bucket containing 5 L of water and lowered 10 m to the release position—about 1 m upstream of the vertical over-shot gate (Fig. 4.1a). When the bucket had reached the water surface, it was inverted to release the fish. The direction the fish was facing at release could not be controlled, but it was observed that the ratio of fish facing upstream into the flow, or facing downstream over the gate crest, when they were entrained in the current and swept over the spillway was approximately equal.

Fish assigned as controls were similarly tethered, but not released over the spillway. Instead they were released directly into the spilling basin pool one at a time and then retrieved using the same procedure used to recapture fish in the low-flow and high-flow treatment groups. This ensured that any differences between control and treatment fish in mortality and/or blood physiology would be a direct result of passage through the over-shot gate.

Figure 4.1. Modified spillway (a) and cages (b) used to house the fish following treatment.

a)

b)

The polystyrene float tether was used to retrieve fish from the stilling basin. Recaptured fish were photographed before being placed into one of 12 cages (2.5 m^3, 22 mm knotless mesh) (Fig. 4.1b) for monitoring of mortality and blood physiology over a period of 72 hours. Each cage contained 12 fish (four from each treatment). At each time period—0, 24 and 72 hours—four cages were randomly selected, mortalities counted and live fish released back into the river. Any fish that died during the monitoring period were replaced with an untagged fish to maintain constant fish densities within the cages.

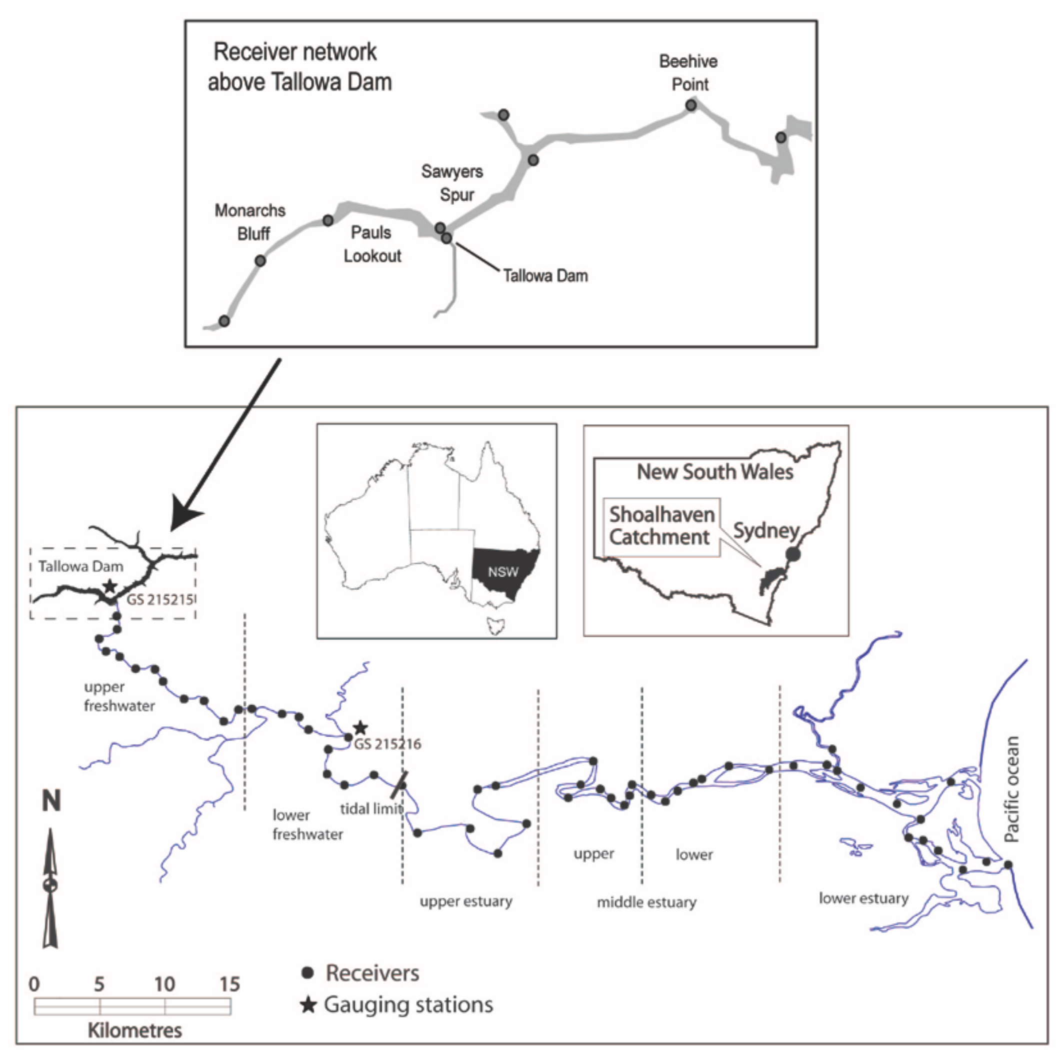
To monitor the relative stress of control and treatment fish, blood was sampled from 12 random fish (three fish from each cage; control, high flow and low flow) at each time period. Three blood chemistry parameters were used to determine sublethal stress levels. Cortisol levels and certain energy metabolites—in particular, glucose and lactate—increase dramatically in response to most types of stressors and are now commonly used as indicators of stress in fish (Barton and Iwama 1991; Butcher *et al.*2011). Within 2 minutes of removal from the cage, each fish was inverted and restrained in a foam block for blood collection via caudal puncture using heparinised syringes (22-gauge needles). Blood was stored on ice and the plasma separated by centrifugation within 6 hours of collection. Plasma was stored at –18 °C until cortisol concentrations were measured by radioimmunoassay using the reagents and protocol of Pankhurst and Sharples (1992) and Broadhurst *et al.* (2005). Whole blood plasma glucose and lactate were measured immediately by handheld meters using Accu-Chek® Advantage II and Accutrend® Plus by Cobas, respectively. Blood was also collected from an additional 12 'wild' Australian bass caught by electrofishing following the methods described by Haddy and Pankhurst (1999). Such an approach is considered the most appropriate for estimating the baseline physiological status of fish (Hanson and Cooke 2009).

4.2.2 Acoustic telemetry and PIT tagging

Movement data generated using acoustic telemetry and PIT tagging were interrogated to assess longer-term survival of downstream-migrating Australian bass and freshwater mullet. In 2011 and 2012, 20 adult Australian bass were captured by angling or electrofishing within Lake Yarrunga and 20 adult freshwater mullet were captured by electrofishing below the Tallowa Dam wall. Fish were placed in an anaesthetic bath containing 50 mg/ L of Aqui-S® solution until their operculum rate became slow and irregular (2–3 minutes). Fish were then weighed (± 1 g), measured (fork length, ± 1 mm) and placed ventral-side up in a V-shaped surgical cradle. During surgery, 25 mg/L of anaesthetic was irrigated over the gills of the fish using a battery-operated pump. A Vemco V13 or V9 acoustic transmitter, with a battery life of 2 years and weighing <2% of the body mass of the fish, was inserted into the peritoneal cavity of each fish via a 20-mm incision on the ventral midline between the pelvic fins and the anus. The incision was closed with two synthetic absorbable sutures (Ethicon Vicryl®) and tied with a double surgeon's knot. All fish were marked with an external T-bar anchor tag (Hallprint®) inserted below the dorsal fin. Fish were allowed to recover in holding tanks until they were able to swim normally, after which they were released into Lake Yarrunga (typically within 1 hour of capture).

A linear array of nine acoustic receivers (Vemco VR2W) was deployed in Lake Yarrunga (Fig. 4.2), building on an existing acoustic array already established in the Shoalhaven River below Tallowa Dam. Methods for deploying the receivers are described in Walsh *et al.* (2012a). Receivers recorded the time, date and identity of the tagged fish that swam within range of a unit. Receivers were single frequency (69 kHz) omni-directional units and had mean detection ranges of 350 m (range of 280–420 m). The location of receivers within the array ensured that there was minimal chance of tagged fish escaping detection when swimming past a receiver. Data from receivers were downloaded bi-monthly and stored in a Microsoft SQL Server database. The mean hourly location of individuals (i.e. distance from sea) was calculated based on the proportion of time spent within the vicinity of a receiver (a proxy for known river distance, Walsh *et al.* 2012b).

Figure 4.2. Location of VR2W receivers within Lake Yarrunga and the lower Shoalhaven River.



In addition to the acoustic telemetry data, 138 Australian bass captured in the hopper during trapping experiments (see Chapter 3) were PIT tagged at the crest of the dam and released immediately above the modified spillway. Re-detection on PIT-tag readers within the fish attraction chamber provided additional information on the long-term survival of Australian bass migrating down over the modified spillway.

4.2.3 Data analysis

All statistical analyses were done with Statistica software (Statsoft 2010) using a significance level of $p < 0.05$. All response variables were assessed for normality and homogeneity of variances prior to analysis. Mortality and blood physiology (cortisol, glucose and lactate) concentrations were $\log_{10}$ transformed to normalise data. Although data for 'wild' controls were included in graphs, they were excluded from statistical analyses because none were captured at similar sample times to those fish from the experiment. Experimental data were analysed by factorial analysis of variance (ANOVA) to test the null hypothesis that there were no differences in mortality and stress levels between control and treatment fish among the three different time periods. Significant F-ratios were investigated with *post-hoc* Tukey's honest significant difference (HSD) means tests. Analysis of acoustic telemetry and PIT-tag data were descriptive with no formal statistical tests used.

4.3 Results

4.3.1 Downstream mortality assessment

In association with 48 controls, 96 Australian bass were released through the low-flow over-shot gate and down the modified spillway during either low-flow or high-flow conditions. All groups had similar size distributions (mean ± SE: controls, 252.7 mm ± 5.5; low flow, 263.8 mm ± 7.3; high flow, 266.6 mm ± 7.5) (Kolmogorov–Smirnov: $p < 0.05$ for all tests). Environmental conditions were similar for all blocks of fish released, as well as for the three monitoring days. During the course of the experiment, several nets developed holes due to cages rubbing up against the concrete abutment, which resulted in the escape of 11 fish.

On recapture (time 0), all fish were observed to be in similar condition to that before the experiment, with some fish across controls and both treatments showing evidence of scale loss due to handling. No immediate mortalities were recorded among the three groups. After 24 hours, significant mortality occurred (27.5%), while at 72 hours the percentage of mortalities in the last batch of cages remained stable (22.5%). There was no significant difference in mortality between the control and the treatment groups (ANOVA: $F_{2, 27} = 2.47$, $p = 0.10$); however, mortality rates at 24 hours and 72 hours were significantly higher than at time 0 (ANOVA: $F_{2, 27} = 1.08$, $p < 0.001$). This pattern was similar among all three groups tested (ANOVA: interaction, $F_{4, 27} = 0.88$, $p = 0.49$).

Table 4.1. Summary table of mortalities, blood sampled and unaccountable fish for each time period post recapture.

Time (hours since recapture)	**Control**			**Low flow**			**High flow**		
	No. dead	**Blood sampled**	**Fish lost**	**No. dead**	**Blood sampled**	**Fish lost**	**No. dead**	**Blood sampled**	**Fish lost**
0	0	4	1	0	3	1	0	4	2
24	5	4	2	3	3	1	3	4	1
72	5	4	1	1	5	0	3	4	2

4.3.2 Blood physiology

Compared to the ‘wild’ individuals (baseline control sample), all low-flow, high-flow and control treatment fish from all time periods had elevated cortisol, glucose and lactate blood concentrations (Fig. 4.3). There were no significant differences (Table 4.2) between the three groups for any blood parameter. All blood parameters for control and treatment fish were significantly higher at time of recapture (0 hour, $p < 0.004$; Table 4.2) than at the other time periods, with no significant differences between treatments after 24 and 72 hours. As with the mortality assessment, changes in control and treatment group blood physiology levels were consistent through time (all interactions, $p > 0.30$).

Figure 4.3. Mean (± SE) cortisol (a) glucose (b) and lactate (c) concentrations in blood samples of Australian bass from each experimental treatment at each sample time.

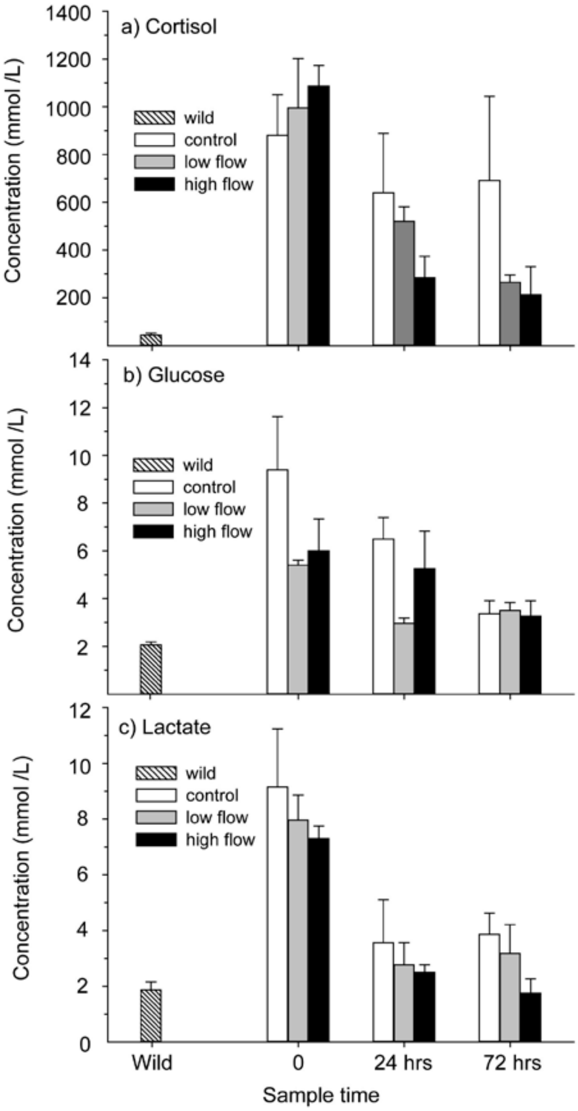


Table 4.2. Summary table results for blood physiology comparisons using factorial analysis of variance (ANOVA)

Blood analysis	Treatment	Time	Treatment × Time
Cortisol	$F_{2,27} = 1.16$, $p = 0.32$	$F_{2,27} = 9.98$, $p < 0.0001$	$F_{4,27} = 1.28$, $p = 0.30$
Lactate	$F_{2,27} = 1.53$, $p = 0.24$	$F_{2,27} = 18.50$, $p < 0.0001$	$F_{4,27} = 0.10$, $p = 0.98$
Glucose	$F_{2,27} = 3.30$, $p = 0.06$	$F_{2,27} = 6.75$, $p = 0.004$	$F_{4,27} = 1.12$, $p = 0.36$

4.3.3 Acoustic telemetry and PIT tagging

Acoustically tagged Australian bass and freshwater mullet were detected within the acoustic array for 495 ± 60 and 235 ± 30 days (mean ± SE), respectively. Nine (45%) of the Australian bass and 17 (85%) of the freshwater mullet migrated downstream over the spillway on at least one occasion (Table 4.3). The remaining individuals of both species were last detected within Lake Yarrunga. Survival rates of both species were high, with 81% of all fish that did pass downstream being re-detected between 105 and 589 days after descending the spillway. Individual movement histories were typical of each species' behaviour, with the majority of fish making large-scale migrations to their estuarine spawning grounds (Appendices 4.2 and 4.3). The timing of downstream migrations over the spillway was highly correlated with spillway flows. The majority of Australian bass migrated down the spillway during variable freshwater inflow pulses. Fourteen of the 17 freshwater mullet descended over the spillway within a 48-hour period during the initial rise of a moderate flow event in February 2013 (Fig. 4.4). The three remaining fish descended on a receding flow 1 week later. Five (of nine) Australian bass and only one (of 17) freshwater mullet made at least one return migration upstream through the fishway.

Of the 138 Australian bass PIT tagged during trapping experiments (Chapter 3) and then released down the modified spillway, 18 were subsequently detected in the fish attraction chamber. Fish were recorded at liberty between 24 and 945 days (395 mean ± 58 SE) after descending the spillway.

4.4 Discussion

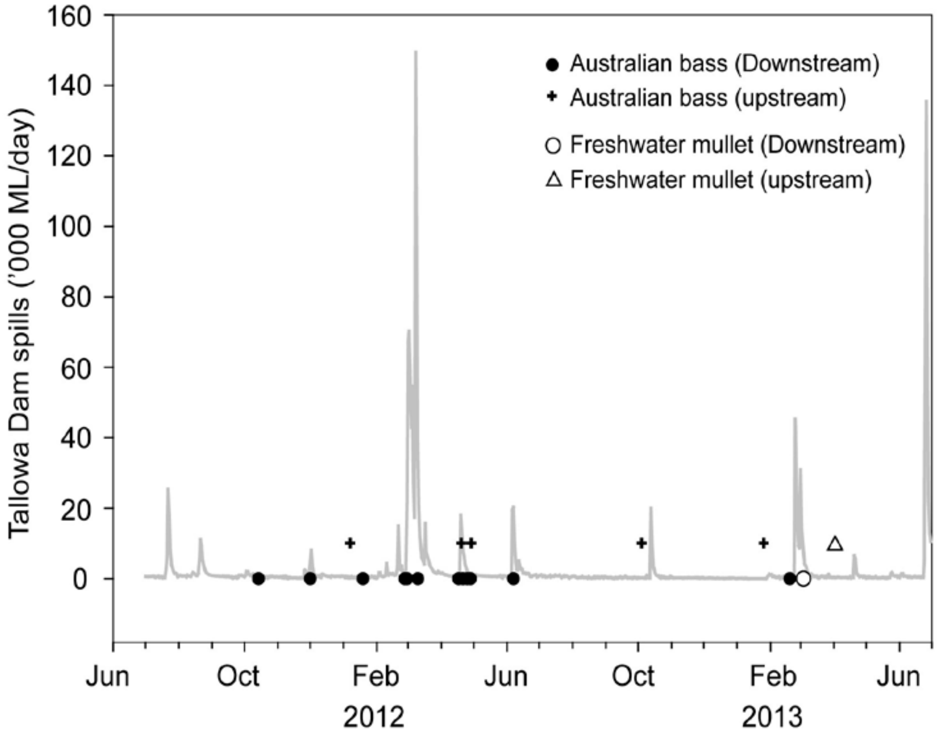
Our controlled and replicated downstream mortality experiment, in conjunction with long-term acoustic telemetry and PIT-tag-derived movement data, demonstrates that the spillway and/or low-flow over-shot gate provide safe downstream fish passage for Australian bass and freshwater mullet at Tallowa Dam. We did not observe any immediate mortality of Australian bass during downstream passage through the low-flow over-shot gate at either low or high discharge rates and we did not observe any obvious external physical injuries or trauma. Despite recording elevated mortality and physiological alterations to blood chemistry consistent with stress during the experiment, the same responses were observed in the control group, suggesting that mortality and stress was in response to handling and the conditions within the cages in which the fish were held. There was no evidence that downstream passage increased the probability of mortality or the physiological responses. The data from tagged fish indicate that most fish that pass downstream do so successfully. There were no data collected during any of the tagging programs that could be interpreted as suggesting that fish died during or after passing downstream over the spillway.

Previous studies assessing the post-release survival of angled Australian bass and other estuarine-dependent species determined short-term mortality rates as low as 0–6%, depending on bait type, hook location and fish size (Hall *et al.* 2009a; Butcher *et al.* 2011). However, Hall *et al.* (2009b) recorded significant delayed mortality (up to 25%) and restricted gonad development in harshly handled Australian bass confined to nets over a 3-week period. Despite their apparent ability to withstand the immediate physical consequences of migrating down the low-flow over-shot gate at Tallowa Dam, Australian bass exhibited significant physiological stress during the experiment. On initial capture among the experimental fish, stress levels peaked across all three groups. Blood cortisol concentrations were around 10 times higher compared with wild angled fish, and more than twice those reported in harshly angled fish (Hall *et al.* 2009a). Although by 24 hours blood cortisol, glucose and lactate levels in control and treated fish significantly dropped (approximately 40%); similar elevated levels across all three groups remained another 48 hours later.

Table 4.3. Summary table of acoustically tagged Australian bass and freshwater mullet, including migration success downstream over the Tallowa Dam spillway and upstream through the fish lift.

Fish ID	Fork length (mm)	Release date	Days at liberty	No. of detections	Fishway success		No. of days since descended spillway
					downstream	upstream	
Australian bass							
1122820	359	12/11/2011	649	5,531			
1122821	324	12/11/2011	109	9,483	1		2
1122822	384	01/12/2011	692	11,888	1		503
1122823	311	12/11/2011	703	10,108			
1122824	406	12/11/2011	703	24,059	1	1	546
1122825	309	12/11/2011	10	1,620			
1122826	346	12/11/2011	698	6,808			
1122827	399	30/11/2011	47	435			
1122828	307	12/11/2011	573	11,746			
1122829	375	12/11/2011	79	161			
1122830	335	12/11/2011	703	23,522			
1122831	311	12/11/2011	703	13,161			
1122832	374	21/11/2011	689	117,924	3	2	589
1122833	353	12/11/2011	6	97			
1122834	301	12/11/2011	594	482			
1122835	370	13/10/2011	558	15,128	1		367
1122836	408	12/11/2011	524	22,773	1		405
1122837	318	12/11/2011	557	16,590	2	1	538
1122838	397	13/10/2011	605	775	1	1	604
Freshwater mullet							
1149295	404	05/12/2012	297	29,545	1		216
1149296	383	05/12/2012	308	31,102	1		228
1149297	415	29/11/2012	210	14,073	1		118
1149298	433	29/11/2012	267	33,322	1		180
1149299	405	29/11/2012	87	2,154	1		1
1149300	367	05/12/2012	242	19,235	1		160
1149301	396	05/12/2012	343	2,425			
1149302	440	29/11/2012	176	8,657	1		84
1149303	412	05/12/2012	286	12,244	1		206
1149304	394	05/12/2012	310	50,558	1		224
1149305	482	29/11/2012	295	11,044	1		208
1149306	426	29/11/2012	315	30,901	1		229
1149307	425	29/11/2012	272	29,063	1		186
1149308	400	05/12/2012	176	1,266			
1149309	422	05/12/2012	186	12,496	1		105
1149310	380	05/12/2012	305	23,616	1		225
1149311	421	29/11/2012	340	1,599	1	1	254
1149312	440	29/11/2012	92	227	1		6
1149313	382	05/12/2012	282	5,174			
1149314	438	05/12/2012	82	195	1		0

Figure 4.4. Timing of Australian bass and freshwater mullet individual downstream migrations over the spillway and upstream migration via the fish lift, relative to river discharge. Note : O = 17 individuals.



This persistent elevation of all blood chemistry variables 72 hours after the experiment commenced suggests that either this species has (i) a comparatively slower rate of recovery from capture-induced stressors or, more than likely, (ii) their confinement was stressful (Butcher *et al.* 2011). Previous research on many fish species indicates that most blood chemistry variables, including cortisol, glucose and lactate, recover to near baseline values within around 120 minutes after angling and handling (Suski *et al.* 2007). It is only when technical or environmental conditions are extreme (e.g. confinement, long angling play times, warm water conditions) that recovery time can become protracted (Cooke and Suski 2005). Hall *et al.* (2009a) found that cortisol concentrations in harshly angled Australian bass that were confined to net cages only returned to pre-treatment levels after 1 week. Because blood physiology variables remained elevated across all three treatment groups, we propose that post-release cumulative stressors—in particular, net confinement—likely contributed to the observed delayed mortality in these fish.

There were no such confounding influences when investigating the long-term survivability of Australian bass and freshwater mullet migrating downstream over the spillway. Both acoustic telemetry and PIT-tag data revealed that Australian bass and freshwater mullet were still being detected after descending the spillway, for up to 945 days and 340 days, respectively. As both species migrated on moderate to large flood events (i.e. when the dam was spilling), this meant that fish had access to the entire spillway, not just the modified section—which is designed to provide passage during low-flow conditions. Hence, long-term survival was not only evident in Australian bass descending down the modified spillway, but also of both species surviving the descent over the original spillway. Tagged freshwater mullet were translocated into Lake Yarrunga from below the dam, and it was not known whether these fish, or resident Australian bass, would possess the innate ability to migrate in response to spawning activity and/or increased flows. In this study, there was a direct relationship between the timing of fish passage downstream and increased freshwater inflows into Lake Yarrunga. In particular, 17 of the 20 freshwater mullet migrated downstream over the spillway on a single moderate flood event in February 2013.

Moreover, Australian bass and freshwater mullet travelled down to the estuary before returning back to freshwater habitats below the dam. Thus, the timing and movement strategy of both species coincides with previously known reproductive biology work (Harris 1986; Humphrey 1980) and, importantly, confirms that stress associated with travelling downstream over the spillway does not appear to interrupt their normal spawning behaviour.

Despite proving that downstream fish passage was safe for adults of two representative large-bodied species, due to methodological constraints (an inability to tether, or implant acoustic or PIT tags in fish under 100-mm fork length), we were unable to experimentally quantify *in situ* survivability of downstream-migrating juvenile or small-bodied species. Previous mitigation studies have shown that survivability of individuals and species is size-selective (Powers *et al.* 1985; Bunt *et al.* 2001). While it may be credible to assume the success of original and modified spillway at Tallowa Dam in ensuring safe downstream fish passage for Australian bass and freshwater mullet is also applicable for species across the entire fish community, the suitable sampling of a wide variety and size range of fishes, including juveniles and smaller bodied species, should also be considered when determining the success of downstream fish passage.

REFERENCES

Almodóvar, A., and Nicola, G.G. (1999). Effects of a small hydropower station upon brown trout *Salmo trutta* L. in the River Hoz Seca (Tagus basin, Spain) one year after regulation. *Regulated Rivers: Research and Management* **15**(5), 477–484.

Anderson, M.J. (2001). A new method for non-parametric multivariate analysis of variance. *Austral Ecology* **26**(1), 32–46.

Backman, T.W.H., and Evans, A.F. (2002). Gas bubble trauma incidence in adult salmonids in the Columbia River Basin. *North American Journal of Fisheries Management* **22**(2), 579–584.

Barton, B.A., and Iwama, G.K. (1991). Physiological changes in fish from stress in aquaculture with emphasis on the response and effects of corticosteroids. *Annual Review of Fish Diseases* **1**, 3–26.

Baumgartner, L.J. (2005). *Effects of Weirs on Fish Movements in the Murray–Darling Basin*. PhD thesis, University of Canberra.

Baumgartner, L.J., Boys, C.A., Stuart, I.G., and Zampatti, B.P. (2010). Evaluating migratory fish behaviour and fishway performance: testing a combined assessment methodology. *Australian Journal of Zoology* **58**(3), 154–164.

Baumgartner, L.J., Stuart, I.G., and Zampatti, B.P. (2008). Determining diel variation in fish assemblages downstream of three weirs in a regulated lowland river. *Journal of Fish Biology* **72**(1), 218–232.

Beumer, J.P. 1996. Freshwater eels. In: McDowall, R.M. (ed.), *Freshwater Fishes of South-eastern Australia*. Reed Books, Chatswood, pp. 39–43.

Bishop, K., and Bell, J. (1978). Observations on the fish fauna below Tallowa Dam (Shoalhaven River, New South Wales) during river flow stoppages. *Marine and Freshwater Research* **29**(4), 543–549.

Blaber, S.J.M., Blaber, T.G., (1980). Factors affecting the distribution of juvenile estuarine and inshore fish. *Journal of Fish Biology* **17**, 143-162.

Bray, J.R., and Curtis, J.T. (1957). An ordination of the upland forest communities of southern Wisconsin. *Ecological Monographs* **27**(4), 325–349.

Broadhurst, M.K., Gray, C.A., Reid, D.D., Wooden, M.E.L., Young, D.J., Haddy, J.A., and Damiano, C. (2005). Mortality of key fish species released by recreational anglers in an Australian estuary. *Journal of Experimental Marine Biology and Ecology* **321**(2), 171–179.

Brumley, A.R. (1987). Past and present distributions of golden perch *Macquaria ambigua* (Pisces: Percichthyidae) in Victoria, with reference to releases of hatchery-produced fry. *Proceedings of the Royal Society of Victoria* **99**, 111–116.

Bunt, C., Van Poorten, B., and Wong, L. (2001). Denil fishway utilization patterns and passage of several warmwater species relative to seasonal, thermal and hydraulic dynamics. *Ecology of Freshwater Fish* **10**(4), 212–219.

Butcher, P.A., Broadhurst, M.K., Hall, K.C., and Cooke, S.J. (2011). Post-release survival and physiology of angled luderick (*Girella tricuspidata*) after confinement in keeper nets in an Australian estuary. *ICES Journal of Marine Science: Journal du Conseil* **68**(3), 572–579.

Castro-Santos, T., Haro, A., and Walk, S. (1996). A passive integrated transponder (PIT) tag system for monitoring fishways. *Fisheries Research* **28**(3), 253–261.

Clarke, K.R. (1993). Nonparametric multivariate analyses of changes in community structure. *Australian Journal of Ecology* **18**(1), 117–143.

Cogels, F.X., Coly, A., and Niang, A. (1997). Impact of dam construction on the hydrological regime and quality of a Sahelian lake in the River Senegal basin. *Regulated Rivers: Research and Management* **13**(1), 27–41.

Cooke, S.J., and Suski, C.D. (2005). Do we need species-specific guidelines for catch-and-release recreational angling to effectively conserve diverse fishery resources? *Biodiversity and Conservation* **14**(5), 1195–1209.

Crook, D.A., Reich, P., Bond, N.R., McMaster, D., Koehn, J.D., and Lake, P.S. (2010). Using biological information to support proactive strategies for managing freshwater fish during drought. *Marine and Freshwater Research* **61**(3), 379–387.

Culp, J.M. (1989). Nocturnally constrained foraging of a lotic minnow (*Rhinichthys cataractae*). *Canadian Journal of Zoology* **67**(8), 2008–2012.

Department of Employment, Economic Development and Innovation (DEEDI) (2012) Paradise Dam Upstream Fishway Monitoring Program, Final Report. June 2012, Queensland Fisheries.

Garnier, J., Billen, G., Sanchez, N., and Leporcq, B. (2000). Ecological functioning of the Marne reservoir (upper Seine basin, France). *Regulated Rivers: Research and Management* **16**(1), 51–71.

Gehrke, P.C., Gilligan, D.M., and Barwick, M. (2002). Changes in fish communities of the Shoalhaven River 20 years after construction of Tallowa Dam, Australia. *River Research and Applications* **18**(3), 265–286.

Gehrke, P.C, and Harris, J.H. (1996). *Fish and Fisheries of the Hawkesbury–Nepean River System: Final Report to the Sydney Water Corporation.* Cronulla Fisheries Research Centre, Cronulla.

Gilligan, D., and Schiller, C. (2003). *Downstream Transport of Larval and Juvenile Fish in the Murray River.* NRMS Project No. R7019. NSW Fisheries Final Report Series No. 50. NSW Fisheries: Cronulla.

Haddy, J., and Pankhurst, N. (1999). Stress-induced changes in concentrations of plasma sex steroids in black bream. *Journal of Fish Biology* **55**(6), 1304–1316.

Hall, K.C., Broadhurst, M.K., Butcher, P.A., and Rowland, S.J. (2009a). Effects of angling on post-release mortality, gonadal development and somatic condition of Australian bass *Macquaria novemaculeata*. *Journal of Fish Biology* **75**(10), 2737–2755.

Hall, K.C., Butcher, P.A., and Broadhurst, M.K. (2009b). Short-term mortality of Australian bass, *Macquaria novemaculeata*, after catch-and-release angling. *Fisheries Management and Ecology* **16**(3), 235–247.

Hanson, K.C., and Cooke, S.J. (2009). Why does size matter? A test of the benefits of female mate choice in a teleost fish based on morphological and physiological indicators of male quality. *Physiological and Biochemical Zoology* **82**(6), 617–624.

Harris J.H. (1984). Impoundment of coastal drainages of south-eastern Australia and a review of its relevance to fish migration*.* *Australian Zoologist* **21***:* 235–250.

Harris, J. (1986). Reproduction of the Australian bass, *Macquaria novemaculeata* (Perciformes: Percichthyidae) in the Sydney Basin. *Marine and Freshwater Research* **37**(2), 209–235.

Holmquist, J.G., Schmidt-Gengenbach, J.M., and Yoshioka, B.B. (1998). High dams and marine-freshwater linkages: effects on native and introduced fauna in the Caribbean. *Conservation Biology* **12**(3), 621–630.

Humphries, P., King, A.J., and Koehn, J.D. (1999). Fish, flows and flood plains: links between freshwater fishes and their environment in the Murray–Darling River system, Australia. *Environmental Biology of Fishes* **56**(1–2), 129–151.

Humphrey, C.L. (1980). Growth and Reproduction of the Freshwater Or Pink-eye Mullet Trachystoma Petardi (Castelnau) in the Macleay River, NSW.Ph.D Thesis. University of New England.

Humphries, P., and Walker, K. (2013). *Ecology of Australian Freshwater Fishes.* CSIRO Publishing, Collingwood.

Jellyman, D., and Tsukamoto, K. (2002). First use of archival transmitters to track migrating freshwater eels *Anguilla dieffenbachii* at sea. *Marine Ecology Progress Series* **233**, 207–215.

Katersky R.S. and Carter, C.G. (2007). A preliminary study on growth and protein sysnthesis of juvenile barramundi, *Lates calcarifer* at different temperatures. *Aquaculture* **267**, 157–164.

Koehn, J. D., et al. (2000). "Why use radio tags to study freshwater fish." Fish movement and migration. Sydney: Australian Society for Fish Biology, 24-32.

Koehn, J.D., and Crook, D.A. (2013). Movements and migration In: Humphries, P., and Walker, K. (eds), *Ecology of Australian Freshwater Fishes*. CSIRO Publishing, Collingwood, pp. 105–128.

Koehn, J.D., and O'Connor, W.G. (1990). *Biological Information for Management of Native Freshwater Fish in Victoria.* Department of Conservation and Environment, Freshwater Fish Management Branch, Arthur Rylah Institute for Environmental Research, Melbourne.

Larson, H., and Hoese, D. (1996). Family Gobiidae, subfamilies Eleotridinae and Butinae: gudgeons. In: McDowall, R.M. (ed.), *Freshwater Fishes of South-eastern Australia*. Reed Books, Chatswood, pp. 200–219.

Liang, K.Y. and Zeger, S.L. (1986). Longitudinal data analysis using generalized linear models. *Biometrika* **73**, 13–22.

Llewellyn, L. (1983). The distribution of fish in New South Wales. Australian Society for Limnology, Sydney.

McDowall, R.M. (1996). *Freshwater Fishes of South-eastern Australia*. Reed Books, Chatswood.

McDowall, R.M. (1999). Different kinds of diadromy: different kinds of conservation problems. *ICES Journal of Marine Science* **56**(4), 410–413.

Mallen-Cooper, M. (1996). *Fishways and Freshwater Fish Migration in South-eastern Australia.* PhD thesis, University of Technology, Sydney.

Mallen-Cooper, M. and J. Harris (1990). *Fishways in mainland south-eastern Australia.* Proceedings of the International Symposium on Fishways '90, 221-229.

Mallen-Cooper, M., and Stuart, I.G. (2003). Age, growth and non-flood recruitment of two potamodromous fishes in a large semi-arid/temperate river system. *River Research and Applications* **19**(7), 697–719.

Mallen-Cooper, M., and Stuart, I.G. (2007). Optimising Denil fishways for passage of small and large fishes. *Freshwater Management and Ecology* **14**, 61–71.

Marsden, T. J. and Harris, J. H. (1996). Tallowa Dam high fishway project. Preliminary report. NSW Fisheries Research Institute, Cronulla.

Meynecke, J.O., Lee, S.Y., and Duke, N.C. (2008) Linking spatial metrics and fish catch reveals the importance of coastal wetland connectivity to inshore fisheries in Queensland, Australia. *Biological Conservation* **141**(4), 981-996.

Miles, N.G., Walsh, C.T., Butler, G., Ueda, H., and West, R.J. (2014). Australian diadromous fishes—challenges and solutions for understanding migrations in the 21st century. *Marine and Freshwater Research* **65**(1), 12–24.

Morgan, D.L., and Beatty, S.J. (2006). Use of a vertical-slot fishway by galaxiids in Western Australia. *Ecology of Freshwater Fish* **15**(4), 500–509.

O'Connor, J., O'Mahony, D. and O'Mahony, J. (2003). Downstream migration of adult Murray-Darling fish species. Arthur Rylah Institute for Environmental Research.

O’Connor, J.P., O’Mahony, D.J., and O’Mahony, J.M. (2005). Movements of *Macquaria ambigua*, in the Murray River, south-eastern Australia. *Journal of Fish Biology* **66**(2), 392–403.

O’Connor, W.G., and Koehn, J.D. (1998). Spawning of the broad-finned galaxias, *Galaxias brevipinnis* Günther (Pisces: Galaxiidae) in coastal streams of southeastern Australia. *Ecology of Freshwater Fish* **7**(2), 95–100.

Orth, D.J., and White, R.J. (1993). Stream habitat management. In: Kohler, C.C., and Hubert, W.A. (eds), *Inland Fisheries Management in North America.* American Fisheries Society, Bethesda, pp. 205–230.

Pankhurst, N., and Sharples, D. (1992). Effects of capture and confinement on plasma cortisol concentrations in the snapper, *Pagrus auratus*. *Marine and Freshwater Research* **43**(2), 345–355.

Pedersen, J. (2000). Food consumption and daily feeding periodicity: comparison between pelagic and demersal whiting in the North Sea. *Journal of Fish Biology* **57**(2), 402–416.

Peter, A. (1998). Interruption of the river continuum by barriers and the consequences for migratory fish. In: Jungwirth, M., Schmutz, S., and Weiss, S. (eds), *Fish Migration and Fish Bypasses.* Fishing News Books, Oxford, pp. 99–112.

Powers, P. and J. Orsborn (1985). "An investigation of the physical and biological conditions affecting fish passage success at culverts and waterfalls." Washington State University report submitted to Bonneville Power Administration. Project (82-14).

Pusey, B., Kennard, M., and Arthington, A. (2004). *Freshwater Fishes of North-eastern Australia.* CSIRO publishing, Collingwood.

Reichard, M., Jurajda, P., and Ondrackova, M. (2002). The effect of light intensity on the drift of young-of-the-year cyprinid fishes. *Journal of Fish Biology* **61**(4), 1063–1066.

Reinfelds, I.V., Walsh, C.T., van der Meulen, D.E., Growns, I.O., and Gray, C.A. (2013). Magnitude, frequency and duration of instream flows to stimulate and facilitate catadromous fish migrations: Australian bass (*Macquaria novemaculeata* Perciformes, Percichthyidae). *River Research and Applications* **29**(4), 512–527.

Ribeiro, M.C., Petrere, M., and Juras, A.A. (1995). Ecological integrity and fisheries ecology of the Araguaia–Tocantins River Basin, Brazil. *Regulated Rivers: Research and Management* **11**(3–4), 325–350.

Schilt, C.R. (2007). Developing fish passage and protection at hydropower dams. *Applied Animal Behaviour Science* **104**(3–4), 295–325.

Sheldon, F., and Walker, K. (1997). Changes in biofilms induced by flow regulation could explain extinctions of aquatic snails in the lower River Murray, Australia. *Hydrobiologia* **347**(1–3), 97–108.

SMEC (2001). *Tallowa Dam High-level Fishway Feasability Study.* SMEC Australia.

Stuart, I.G., and Berghuis, A.P. (2002). Upstream passage of fish through a vertical-slot fishway in an Australian subtropical river. *Fisheries Management and Ecology* **9**(2), 111–122.

Stuart, I.G., and Mallen-Cooper, M. (1999). An assessment of the effectiveness of a vertical-slot fishway for non-salmonid fish at a tidal barrier on a large tropical/subtropical river. *Regulated Rivers: Research and Management* **15**(6), 575–590.

Stuart, I.G., Zampatti, B.P., and Baumgartner, L.J. (2008). Can a low-gradient vertical-slot fishway provide passage for a lowland river fish community? *Marine and Freshwater Research* **59**(4), 332–346.

Sugimoto, Y., Fuwa, S., Ishizaki, M., and Imai, T. (1996). Entrance shape of fish trap and fishing efficiency. *Bulletin of the Japanese Society of Scientific Fisheries* **62**(1), 51-56.

Suski, C.D., Cooke, S.J., Danylchuk, A.J., O’Connor, C.M., Gravel, M.-A., Redpath, T., Hanson, K.C., Gingerich, A.J., Murchie, K.J., and Danylchuk, S.E. (2007). Physiological disturbance and recovery dynamics of bonefish (*Albula vulpes*), a tropical marine fish, in response to variable exercise and exposure to air. *Comparative Biochemistry and Physiology—Part A: Molecular & Integrative Physiology* **148**(3), 664–673.

van der Meulen, D.E., Walsh, C.T., Taylor, M.D., and Gray, C.A. (2014). Habitat requirements and spawning strategy of an estuarine-dependent fish, *Percalates colonorum*. *Marine and Freshwater Research* **65**(3), 218–227.

Walsh, C.T., Reinfelds, I,V., Gray, C.A., West, R.J., van der Meulen, D.E., and Craig, J.R. (2012a). Seasonal residency and movement patterns of two co-occuring catadromous percichthyids within a south-eastern Australian river. *Ecology of Freshwater Fish* **21**(1), 145–159.

Walsh, C.T., Reinfelds, I.V., Ives, M.C., Gray, C.A., West, R.J., and van der Meulen, D.E. (2013). Environmental influences on the spatial ecology and spawning behaviour of an estuarine-resident fish, *Macquaria colonorum*. *Estuarine, Coastal and Shelf Science* **118**, 60–71.

Walsh, C.T., Reinfelds, I.V., West, R.J., Gray, C.A., and van der Meulen, D.E. (2012b). Distribution and movement of catadromous fish: design and implementation of a freshwater-estuarine acoustic telemetry array. In: McKenzie, J., Parsons, B., Seitz, A., Kopf, K., Mesa, M., and Phelps, Q. (eds), *Advances in Fish Tagging and Marking Technology*. American Fisheries Society (Symposium 76), Bethesda, Maryland.

Weiland, L.K., Mesa, M.G., and Maule, A.G. (1999). Influence of infection with *Renibacterium salmoninarum* on susceptibility of juvenile spring chinook salmon to gas bubble trauma. *Journal of Aquatic Animal Health* **11**(2), 123–129.

Zydlewski, G. B., Horton, G., Dubreuil, T. letcher, B., Casey, S., and Zydlewski. J . (2006). "Remote Monitoring of Fish in Small Streams." *Fisheries* **31**(10), 492-50.

APPENDICES

Appendix 2.1. Habitat descriptions at the 12 sites within the Shoalhaven River system

Site	Name	Elev.[a]	Habitat description
11	Mongarlowe River	550	Extreme upper reach site above the confluence the Mongarlowe River and Shoalhaven River. Long pool 1.5 m deep with riffles upstream and downstream. Substratum bedrock, boulders, cobble and sand. Frequent macrophyte beds and timber cover with abundant riparian vegetation.
12	Tolwong Mines	130	Shoalhaven River upstream of Lake Yarrunga. Long pool 3 m deep, bounded by rapids and riffles. Substratum cobble with abundant bedrock and boulders. Frequent macrophyte beds and rushes. Abundant riparian vegetation on one bank, sparse on other bank.
2	Fossickers Flat	70	Shoalhaven River upstream of Lake Yarrunga. Long pool up to 2 m deep, bounded by rapids and riffles. Substratum is a mixture of sand, bedrock and cobble with abundant boulders. Vegetation includes occasional macrophyte beds and native trees and shrubs.
4	Upper Kangaroo River	120	Upper reaches of Kangaroo River. Two short pools up to 2.1 m deep separated by a series of low cascades and bounded by riffles and rapids. Substratum bedrock with abundant boulders and large cobbles. Littoral grasses common. No macrophyte beds and abundant riparian vegetation.
5	Kangaroo Valley	60	Kangaroo River upstream of the weir above Hampden Bridge. Medium-sized pool up to 3 m deep, bounded by riffle downstream and riffles and rapids upstream. Substratum cobble with some sand, bedrock and boulders. Large rock faces exist on both banks. Vegetation is predominantly trees on the banks.
14	Beehive Point	50	Kangaroo River arm within Lake Yarrunga. Average depth 5 m. Substratum mud and silt with frequent boulders and bedrock. Frequent drowned trees. Frequent macrophyte beds and rushes with some riparian vegetation dominated by native trees and shrubs.
6	Sawyers Spur	50	Kangaroo River arm within Lake Yarrunga. Substratum mud and silt with occasional bedrock and boulders. Frequent macrophyte beds and occasional rushes, with the riparian vegetation dominated by native trees.
7	Pauls Lookout	50	Shoalhaven River arm within Lake Yarrunga. Sampled depth up to 3 m. Substratum mud and silt with occasional bedrock and boulders. Occasional macrophyte beds and frequent timber structure. Frequent riparian vegetation.
13	Monarchs Bluff	50	Shoalhaven River arm within Lake Yarrunga. Sampled depth to 5 m. Substratum mud and silt with occasional bedrock and boulders. Frequent drowned trees. Occasional macrophyte beds and rushes with abundant riparian vegetation dominated by native trees and shrubs.
8	Below dam wall	30	Complex of two small pools and interconnecting rapids/riffles. Depth up to 3 m. Includes bottom of fishway. Substratum cobble, boulders with occasional bedrock and gravel. Sparse macrophyte beds. Occasional dense stands of riparian vegetation. Subject to immediate flows released from Tallowa Dam.
9	500 m downstream of dam wall	30	Long pool with maximum depth 3 m. Substratum diverse, including bedrock, boulders, mud and silt. Frequent macrophyte beds and riparian vegetation dominated by native trees and shrubs.
10	Burrier pump station	<10	Long pool 22 km downstream of dam, just upstream of the tidal limit. Maximum depth 3.8 m. Substratum mud, silt and sand with occasional cobbles and boulders. Macrophyte beds common. Riparian vegetation is abundant on one bank and sparse on the other.

[a] Elevation (m above sea level)

Appendix 2.2. Habitat and water quality variables at the 12 sites within the Shoalhaven River system

Site name: **Mongarlowe River** Zone: **Mongarlowe River**

Substratum	% of habitat
Bedrock	35
Cobble	90
Gravel	71
Sand	28
Boulder	41
Mud / Silt	26
Unknown	2
Clay	0

Plants	% of habitat
Native trees	76
Exotic trees	11
Native shrubs	85
Exotic shrubs	28
Terrestrial grass	22
Floating macrophytes	2
Emergent macrophytes	39
Submerged macrophytes	80
Filamentous Algae	10
Biofilms	4

Cover	% of habitat
Rock	75
Undercuts	1
Timber	69
Plant Litter	2

Survey	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Velocity[a]
Spring 2009	20.60	5.62	7.47	0.05	Clear	Slow
Autumn 2010	19.50	8.28	7.20	0.04	Clear	Slow
Spring 2010	22.94	7.00	4.28	0.07	Clear	Slow
Autumn 2011	17.10	11.05	6.77	0.05	–	Slow
Spring 2011	17.00	–	–	–	Low	Slow
Autumn 2012	17.88	9.05	5.89	0.07	Low	Slow
Spring 2012	19.40	7.75	7.40	0.09	Low	Slow
Autumn 2013	17.98	8.04	7.32	0.07	Clear	Slow

[a] Velocity = None, Slow, Moderate or Fast

Site name: **Towlong Mines** Zone: **Shoalhaven River upstream**

Substratum	% of habitat
Bedrock	39
Cobble	45
Gravel	19
Sand	34
Boulder	57
Mud / Silt	61
Unknown	9
Clay	1

Plants	% of habitat
Native trees	84
Exotic trees	0
Native shrubs	41
Exotic shrubs	5
Terrestrial grass	39
Floating macrophytes	2
Emergent macrophytes	14
Submerged macrophytes	39
Filamentous Algae	3
Biofilms	6

Cover	% of habitat
Rock	76
Undercuts	7
Timber	50
Plant Litter	3

Survey	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Velocity[a]
Spring 2009	24.85	7.90	7.81	0.09	High	Slow
Autumn 2010	18.60	7.06	7.04	0.06	Low	Slow
Spring 2010	24.76	10.15	–	0.11	Low	Slow
Autumn 2011	10.40	11.22	4.18	0.06	–	Slow
Spring 2011	21.12	8.78	6.90	0.10	Low	Slow
Autumn 2012	19.97	10.41	6.12	0.11	Moderate	Slow
Spring 2012	21.35	8.34	7.50	0.13	Clear	Slow
Autumn 2013	–	–	–	–	–	Slow

[a] Velocity = None, Slow, Moderate or Fast

Site name: **Fossickers Flat** Zone: **Shoalhaven River upstream**

Substratum	% of habitat
Bedrock	50
Cobble	19
Gravel	10
Sand	49
Boulder	76
Mud / Silt	15
Unknown	11
Clay	0

Plants	% of habitat
Native trees	86
Exotic trees	0
Native shrubs	27
Exotic shrubs	3
Terrestrial grass	25
Floating macrophytes	0
Emergent macrophytes	4
Submerged macrophytes	24
Filamentous Algae	1
Biofilms	0

Cover	% of habitat
Rock	87
Undercuts	0
Timber	25
Plant Litter	0

Survey	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Velocity[a]
Spring 2009	25.70	8.93	8.08	0.10	Moderate	Slow
Autumn 2010	18.60	7.07	7.02	0.06	Low	Slow
Spring 2010	26.06	10.25	4.21	0.11	Moderate	Slow
Autumn 2011	10.43	12.09	8.06	0.07	–	Slow
Spring 2011	21.71	9.49	6.73	0.10	Low	Slow
Autumn 2012	20.68	10.93	6.23	0.13	Low	Slow
Spring 2012	21.75	8.54	7.35	0.13	Low	Slow
Autumn 2013	–	–	–	–	–	Slow

[a] Velocity = None, Slow, Moderate or Fast

Site name: **Upper Kangaroo River** Zone: **Kangaroo River**

Substratum	% of habitat
Bedrock	79
Cobble	46
Gravel	27
Sand	22
Boulder	71
Mud / Silt	6
Unknown	1
Clay	0

Plants	% of habitat
Native trees	88
Exotic trees	0
Native shrubs	68
Exotic shrubs	6
Terrestrial grass	29
Floating macrophytes	0
Emergent macrophytes	11
Submerged macrophytes	0
Filamentous Algae	2
Biofilms	13

Cover	% of habitat
Rock	96
Undercuts	7
Timber	15
Plant Litter	11

Survey	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Velocity[a]
Spring 2009	21.85	8.35	7.95	0.06	Clear	Slow
Autumn 2010	15.20	8.84	7.13	0.04	Clear	Slow
Spring 2010	19.47	8.31	4.44	0.06	Clear	Medium
Autumn 2011	16.99	10.43	6.94	0.06	–	Medium
Spring 2011	16.00	–	–	–	Low	Slow
Autumn 2012	17.24	10.79	5.77	0.07	Low	Medium
Spring 2012	15.04	8.47	3.67	0.08	Low	Slow
Autumn 2013	15.45	9.71	6.69	0.68	Low	Medium

[a] Velocity = None, Slow, Moderate or Fast

Site name: **Kangaroo Valley** Zone: **Kangaroo River**

Substratum	% of habitat
Bedrock	64
Cobble	46
Gravel	14
Sand	36
Boulder	59
Mud / Silt	29
Unknown	8
Clay	1

Plants	% of habitat
Native trees	79
Exotic trees	22
Native shrubs	47
Exotic shrubs	25
Terrestrial grass	14
Floating macrophytes	0
Emergent macrophytes	4
Submerged macrophytes	2
Filamentous Algae	0
Biofilms	3

Cover	% of habitat
Rock	78
Undercuts	13
Timber	41
Plant Litter	3

Survey	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Velocity[a]
Spring 2009	22.80	7.89	7.84	0.07	Low	Slow
Autumn 2010	18.40	9.22	6.80	0.06	Low	Slow
Spring 2010	18.88	8.62	5.57	0.11	Clear	Slow
Autumn 2011	19.17	10.51	7.21	0.10	–	Slow
Spring 2011	19.00	–	–	–	Low	Slow
Autumn 2012	17.62	10.35	6.01	0.11	Low	Slow
Spring 2012	21.45	8.31	6.67	0.11	Low	Slow
Autumn 2013	18.11	9.70	6.58	0.10	Low	Slow

[a] Velocity = None, Slow, Moderate or Fast

Site name: **Beehive Point** Zone: **Lake Yarrunga**

Substratum	% of habitat
Bedrock	62
Cobble	8
Gravel	11
Sand	7
Boulder	38
Mud / Silt	53
Unknown	24
Clay	3

Plants	% of habitat
Native trees	80
Exotic trees	1
Native shrubs	68
Exotic shrubs	1
Terrestrial grass	23
Floating macrophytes	10
Emergent macrophytes	49
Submerged macrophytes	52
Filamentous Algae	3
Biofilms	7

Cover	% of habitat
Rock	66
Undercuts	0
Timber	75
Plant Litter	0

Survey	Depth (m)	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Dam level
Spring 2009	0.2	23.9	8.17	8.07	0.07	Clear	High
Spring 2009	–	–	–	–	–	Clear	High
Autumn 2010	0.2	18.7	4.38	6.61	0.06	Clear	High
Autumn 2010	9.0	18.7	3.85	5.86	0.062	Clear	High
Spring 2010	0.2	21.22	6.85	8.81	0.08	Clear	High
Spring 2010	5.0	18.2	3.29	7.3	0.078	Clear	High
Autumn 2011	0.2	24.85	5.65	7.08	0.09	–	High
Autumn 2011	6.0	22.27	3.72	6.25	0.093	–	High
Spring 2011	0.2	18.16	9.91	7.11	0.10	Low	High
Spring 2011	7.0	16.17	8.54	5.88	0.096	Low	High
Autumn 2012	0.2	18.27	5.92	5.71	0.46	High	High
Autumn 2012	10.0	17.15	5.1	5.1	0.106	High	High
Spring 2012	0.2	21.88	8.40	7.31	0.12	Low	High
Spring 2012	5.0	17.57	6.8	7.41	0.118	Low	High
Autumn 2013	0.2	24.40	9.92	7.48	0.09	Low	High
Autumn 2013	4.0	20.6	1.41	5.9	0.089	Low	High

Site name: **Sawyers Spur** Zone: **Lake Yarrunga**

Substratum	% of habitat
Bedrock	21
Cobble	32
Gravel	45
Sand	18
Boulder	54
Mud / Silt	53
Unknown	17
Clay	8

Plants	% of habitat
Native trees	87
Exotic trees	1
Native shrubs	83
Exotic shrubs	0
Terrestrial grass	11
Floating macrophytes	3
Emergent macrophytes	39
Submerged macrophytes	48
Filamentous Algae	2
Biofilms	2

Cover	% of habitat
Rock	73
Undercuts	0
Timber	83
Plant Litter	8

Survey	Depth (m)	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Dam level
Spring 2009	0.2	24.00	8.99	8.35	0.07	Clear	High
Spring 2009	6.0	18.90	6.12	7.21	0.07	Clear	High
Autumn 2010	0.2	19.25	5.82	7.11	0.06	Low	High
Autumn 2010	9.0	18.40	0.08	5.81	0.06	Low	High
Spring 2010	0.2	19.90	3.92	7.47	0.10	Low	High
Spring 2010	6.0	17.38	3.43	6.80	0.10	Low	High
Autumn 2011	0.2	24.91	6.15	5.95	0.10	–	High
Autumn 2011	8.0	21.99	0.00	6.25	0.10	–	High
Spring 2011	0.2	17.56	9.47	6.10	0.09	Clear	High
Spring 2011	5.0	15.79	8.66	6.03	0.09	Clear	High
Autumn 2012	0.2	18.55	7.59	6.64	0.10	Low	High
Autumn 2012	10.0	16.70	2.92	5.90	0.08	Low	High
Spring 2012	0.2	20.19	8.42	6.84	0.12	Low	High
Spring 2012	6.0	13.78	6.11	5.85	0.12	Low	High
Autumn 2013	0.2	26.51	9.24	7.24	0.11	Low	High
Autumn 2013	2.0	22.82	9.46	6.87	0.10	Low	High

Site name: **Pauls Lookout** Zone: **Lake Yarrunga**

Substratum	% of habitat
Bedrock	12
Cobble	53
Gravel	44
Sand	26
Boulder	27
Mud / Silt	73
Unknown	16
Clay	12

Plants	% of habitat
Native trees	83
Exotic trees	0
Native shrubs	78
Exotic shrubs	1
Terrestrial grass	11
Floating macrophytes	8
Emergent macrophytes	28
Submerged macrophytes	39
Filamentous Algae	0
Biofilms	5

Cover	% of habitat
Rock	60
Undercuts	0
Timber	86
Plant Litter	6

Survey	Depth (m)	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Dam level
Spring 2009	0.2	24.00	8.99	8.35	0.07	Clear	High
Spring 2009	–	–	–	–	–	Clear	High
Autumn 2010	0.2	19.25	5.82	7.11	0.06	Low	High
Autumn 2010	8.0	18.70	4.72	5.76	0.06	Low	High
Spring 2010	0.2	19.90	3.92	7.47	0.10	Low	High
Spring 2010	8.0	17.13	2.30	7.16	0.11	Low	High
Autumn 2011	0.2	24.91	6.15	5.95	0.10	–	High
Autumn 2011	2.0	23.49	5.00	6.66	0.10	–	High
Spring 2011	0.2	17.56	9.47	6.10	0.09	Clear	High
Spring 2011	7.0	14.17	7.13	7.02	0.09	Clear	High
Autumn 2012	0.2	18.55	7.59	6.64	0.10	Low	High
Autumn 2012	10.0	16.73	5.60	6.56	0.10	Low	High
Spring 2012	0.2	20.19	8.42	6.84	0.12	Low	High
Spring 2012	6.0	12.86	6.40	5.51	0.11	Low	High
Autumn 2013	0.2	26.51	9.24	7.24	0.11	Low	High
Autumn 2013	4.0	21.22	6.94	6.85	0.10	Low	High

Site name: **Monarchs Bluff** Zone: **Lake Yarrunga**

Substratum	% of habitat
Bedrock	34
Cobble	8
Gravel	8
Sand	2
Boulder	28
Mud / Silt	60
Unknown	33
Clay	4

Plants	% of habitat
Native trees	73
Exotic trees	3
Native shrubs	59
Exotic shrubs	2
Terrestrial grass	5
Floating macrophytes	0
Emergent macrophytes	22
Submerged macrophytes	22
Filamentous Algae	1
Biofilms	7

Cover	% of habitat
Rock	48
Undercuts	5
Timber	75
Plant Litter	0

Survey	Depth (m)	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Dam level
Spring 2009	0.2	22.10	7.91	7.83	0.08	Clear	High
Spring 2009	0.2	–	–	–	–	Clear	High
Autumn 2010	0.2	17.70	4.20	6.56	0.07	Low	High
Autumn 2010	0.2	–	–	–	–	Low	High
Spring 2010	0.2	19.90	3.00	7.50	0.13	Clear	High
Spring 2010	6.0	15.85	1.56	7.10	0.12	Clear	High
Autumn 2011	0.2	23.44	6.98	6.36	0.10	–	High
Autumn 2011	8.0	20.40	0.00	6.14	0.11	–	High
Spring 2011	0.2	15.81	7.64	6.06	0.08	Low	High
Spring 2011	9.0	13.68	6.13	6.10	0.09	Low	High
Autumn 2012	0.2	16.73	5.48	5.88	0.11	Low	High
Autumn 2012	10.0	16.27	7.42	5.42	0.12	Low	High
Spring 2012	0.2	21.47	8.70	6.70	0.12	Low	High
Spring 2012	4.0	16.31	6.21	5.80	0.12	Low	High
Autumn 2013	0.2	22.32	6.98	7.04	0.10	Moderate	High
Autumn 2013	5.0	19.60	4.93	6.55	0.10	Moderate	High

Site name: **Below dam wall** Zone: **Directly below Tallowa Dam**

Substratum	% of habitat
Bedrock	7
Cobble	97
Gravel	55
Sand	7
Boulder	100
Mud / Silt	0
Unknown	0
Clay	0

Plants	% of habitat
Native trees	78
Exotic trees	1
Native shrubs	15
Exotic shrubs	9
Terrestrial grass	15
Floating macrophytes	0
Emergent macrophytes	0
Submerged macrophytes	19
Filamentous Algae	3
Biofilms	37

Cover	% of habitat
Rock	100
Undercuts	0
Timber	16
Plant Litter	6

Survey	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Velocity[a]
Spring 2009	27.10	7.89	8.64	0.07	Clear	Slow
Autumn 2010	19.50	8.72	7.08	0.06	Clear	Medium
Spring 2010	–	–	–	–	–	–
Autumn 2011	29.59	5.56	7.56	0.09	–	Medium
Spring 2011	24.64	10.46	8.17	0.10	Low	Medium
Autumn 2012	–	–	–	–	–	–
Spring 2012	22.90	9.00	7.24	0.12	Low	Medium
Autumn 2013	22.99	10.07	6.49	0.10	Low	Slow

[a] Velocity = None, Slow, Moderate or Fast

Site name: **500 m downstream of dam wall** Zone: **Directly below Tallowa Dam**

Substratum	% of habitat
Bedrock	27
Cobble	78
Gravel	36
Sand	7
Boulder	73
Mud / Silt	25
Unknown	7
Clay	1

Plants	% of habitat
Native trees	86
Exotic trees	0
Native shrubs	42
Exotic shrubs	2
Terrestrial grass	11
Floating macrophytes	1
Emergent macrophytes	3
Submerged macrophytes	48
Filamentous Algae	3
Biofilms	16

Cover	% of habitat
Rock	87
Undercuts	2
Timber	34
Plant Litter	5

Survey	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Velocity[a]
Spring 2009	23.90	8.54	8.19	0.07	Clear	Slow
Autumn 2010	18.65	8.05	6.80	0.06	Low	Slow
Spring 2010	24.13	4.73	7.54	0.54	Moderate	Medium
Autumn 2011	23.80	5.51	7.07	0.10	–	Slow
Spring 2011	16.34	11.01	6.58	0.08	Low	Slow
Autumn 2012	18.15	9.94	6.75	0.10	Low	Slow
Spring 2012	21.69	10.27	7.15	0.12	Low	Slow
Autumn 2013	23.18	10.72	7.22	0.11	Low	Slow

[a] Velocity = None, Slow, Moderate or Fast

Site name: **Burrier pump station** Zone: **Burrier**

Substratum	% of habitat
Bedrock	24
Cobble	14
Gravel	17
Sand	41
Boulder	34
Mud / Silt	76
Unknown	10
Clay	0

Plants	% of habitat
Native trees	73
Exotic trees	2
Native shrubs	19
Exotic shrubs	22
Terrestrial grass	24
Floating macrophytes	12
Emergent macrophytes	36
Submerged macrophytes	61
Filamentous Algae	3
Biofilms	13

Cover	% of habitat
Rock	43
Undercuts	6
Timber	56
Plant Litter	2

Survey	Temp (°C)	Dissolved oxygen (mg/L)	pH	Conductivity (µS/cm)	Turbidity	Velocity[a]
Spring 2009	23.05	8.05	8.16	0.08	Clear	Slow
Autumn 2010	18.00	7.95	6.96	0.06	Clear	Slow
Spring 2010	24.45	8.60	7.04	0.10	Low	Slow
Autumn 2011	24.33	12.00	7.84	0.11	–	Slow
Spring 2011	17.01	9.81	5.90	0.09	Low	Slow
Autumn 2012	18.95	9.02	7.09	0.11	Low	Slow
Spring 2012	23.79	8.69	6.51	0.12	Low	Slow
Autumn 2013	18.62	8.94	6.78	0.10	Low	Slow

[a] Velocity = None, Slow, Moderate or Fast

Appendix 2.3. Abundances of fish sampled within the Shoalhaven River system. Note: MR = Mongarlowe River; SR = Shoalhaven River upstream; KR = Kangaroo River; L = Lake Yarrunga; DB = directly below Tallowa Dam; B = Burrier; for site names, see Appendix 2.1.

Species	Survey no.	Locality												Total
		MR	SR		KR		L				DB		B	
		11	12	2	4	5	14	6	7	13	8	9	10	
Anguillidae	1	2	0	8	25	4	1	2	1	0	58	7	1	**109**
Longfinned eel	2	0	4	4	5	8	2	1	0	0	7	4	0	**35**
	3	0	2	1	6	8	3	3	2	2	–	4	2	**33**
	4	0	0	1	3	2	2	1	2	0	22	5	2	**40**
	5	1	4	2	4	8	1	2	2	1	6	4	4	**39**
	6	0	1	0	3	6	2	0	1	0	–	8	2	**23**
	7	0	8	1	5	12	2	1	1	1	10	3	3	**47**
	8	0	–	–	3	2	3	0	3	0	17	0	0	**28**
	Total	**3**	**19**	**17**	**54**	**50**	**16**	**10**	**12**	**4**	**120**	**35**	**14**	**354**
Shortfinned eel	1	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	2	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	3	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	4	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	5	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	6	0	1	0	0	0	0	0	0	0	–	0	0	**1**
	7	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	8	0	–	–	0	0	0	0	0	0	0	0	0	**0**
	Total	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
Clupeidae	1	0	0	0	0	0	0	0	0	0	0	5	17	**22**
Freshwater herring	2	0	0	0	0	0	0	0	0	0	0	1	0	**1**
	3	0	0	0	0	0	0	0	0	0	–	10	2	**12**
	4	0	0	0	0	0	0	0	0	0	0	0	1	**1**
	5	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	6	0	0	0	0	0	0	0	0	0	–	0	1	**1**
	7	0	0	0	0	0	0	0	0	0	0	6	0	**6**
	8	0	–	–	0	0	0	0	0	0	2	16	1	**19**
	Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**38**	**22**	**62**

continued

Appendix 2.3. (*continued*) Abundances of fish sampled within the Shoalhaven River system. Note: MR = Mongarlowe River; SR = Shoalhaven River upstream; KR = Kangaroo River; L = Lake Yarrunga; DB = directly below Tallowa Dam; B = Burrier; for site names, see Appendix 2.1.

Species	**Survey no.**	**Locality**												**Total**
		MR	**SR**		**KR**		**L**				**DB**		**B**	
		11	**12**	**2**	**4**	**5**	**14**	**6**	**7**	**13**	**8**	**9**	**10**	
Galaxiidae	1	0	0	0	0	0	0	0	0	0	12	0	0	**12**
Common jollytail	2	0	0	0	0	0	0	0	0	0	0	1	0	**1**
	3	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	4	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	5	0	0	0	0	0	0	0	0	0	2	0	0	**2**
	6	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	7	0	0	0	0	0	0	0	0	0	17	60	21	**98**
	8	0	–	–	0	0	0	0	0	0	6	1	0	**7**
	Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**37**	**62**	**21**	**120**
Mountain galaxias	1	16	0	0	0	0	0	0	0	0	0	0	0	**16**
	2	2	0	0	0	0	0	0	0	0	0	0	0	**2**
	3	14	0	0	0	0	0	0	0	0	–	0	0	**14**
	4	6	0	0	0	0	0	0	0	0	0	0	0	**6**
	5	5	0	0	0	0	0	0	0	0	0	0	0	**5**
	6	5	0	0	0	0	0	0	0	0	–	0	0	**5**
	7	15	0	0	0	0	0	0	0	0	0	0	0	**15**
	8	6	–	–	0	0	0	0	0	0	0	0	0	**6**
	Total	**69**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**69**
Gerreidae	**1**	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Silver biddy	**2**	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	3	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	4	0	0	0	0	0	0	0	0	0	0	0	6	**6**
	5	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	6	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	7	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	8	0	–	–	0	0	0	0	0	0	0	0	0	**0**
	Total	0	0	0	0	0	0	0	0	0	0	0	6	**6**

continued

Appendix 2.3. (*continued*) Abundances of fish sampled within the Shoalhaven River system. Note: MR = Mongarlowe River; SR = Shoalhaven River upstream; KR = Kangaroo River; L = Lake Yarrunga; DB = directly below Tallowa Dam; B = Burrier; for site names, see Appendix 2.1.

Species	**Survey no.**	**Locality**												**Total**
		MR	**SR**		**KR**		**L**				**DB**		**B**	
		11	**12**	**2**	**4**	**5**	**14**	**6**	**7**	**13**	**8**	**9**	**10**	
Gobiidae	1	0	0	0	0	0	0	0	0	0	52	4	10	**66**
Striped gudgeon	2	0	0	0	0	0	0	0	0	0	1	28	2	**31**
	3	0	0	0	0	0	0	0	0	0	–	18	6	**24**
	4	0	0	0	0	0	0	0	0	0	3	31	8	**42**
	5	0	0	0	0	0	0	0	0	0	0	3	2	**5**
	6	0	0	0	0	0	0	0	0	0	–	4	7	**11**
	7	0	0	0	0	0	0	0	0	0	1	20	66	**87**
	8	0	–	–	0	0	1	0	0	7	17	28	3	**56**
	Total	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**7**	**74**	**136**	**104**	**322**
Cox’s gudgeon	1	0	0	3	3	0	0	0	1	0	27	5	1	**40**
	2	0	0	0	0	0	0	0	0	0	7	6	0	**13**
	3	0	0	1	0	1	1	1	0	0	–	9	90	**103**
	4	0	0	0	0	0	0	0	0	0	47	7	5	**59**
	5	0	0	2	2	0	0	0	0	0	31	0	2	**37**
	6	0	5	3	6	1	1	0	0	0	–	9	22	**47**
	7	0	4	1	3	2	0	0	0	0	110	161	7	**288**
	8	0	–	–	20	3	3	2	2	1	40	2	4	**77**
	Total	**0**	**9**	**10**	**34**	**7**	**5**	**3**	**3**	**1**	**262**	**199**	**131**	**664**
Empire gudgeon	1	0	0	0	0	0	0	0	0	0	0	1	36	**37**
	2	0	0	0	0	0	0	0	1	0	0	2	8	**11**
	3	0	0	2	0	0	0	0	0	0	–	0	9	**11**
	4	0	0	0	0	0	0	0	0	0	0	12	24	**36**
	5	0	0	0	0	0	0	0	0	0	0	0	8	**8**
	6	0	0	0	0	0	0	0	0	0	–	3	31	**34**
	7	0	0	0	0	0	0	0	0	0	0	7	29	**36**
	8	0	–	–	0	0	0	0	0	1	50	26	13	**90**
	Total	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**1**	**1**	**50**	**51**	**158**	**263**

continued

Appendix 2.3. (*continued*) Abundances of fish sampled within the Shoalhaven River system. Note: MR = Mongarlowe River; SR = Shoalhaven River upstream; KR = Kangaroo River; L = Lake Yarrunga; DB = directly below Tallowa Dam; B = Burrier; for site names, see Appendix 2.1.

Species	**Survey no.**	**Locality**												**Total**
		MR	**SR**		**KR**		**L**				**DB**		**B**	
		11	**12**	**2**	**4**	**5**	**14**	**6**	**7**	**13**	**8**	**9**	**10**	
Gobiidae (*continued*)	1	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Firetail gudgeon	2	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	3	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	4	0	0	0	0	0	0	0	0	0	1	0	0	**1**
	5	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	6	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	7	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	8	0	–	–	0	0	0	0	0	0	0	0	0	**0**
	Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**
Western carp-gudgeon	1	35	0	0	0	0	0	0	0	0	0	0	0	**35**
	2	10	0	0	0	0	0	0	0	0	0	0	0	**10**
	3	4	0	0	0	0	0	0	0	0	–	0	0	**4**
	4	4	0	0	0	0	0	0	0	0	0	0	0	**4**
	5	3	0	0	0	0	0	0	0	0	0	0	0	**3**
	6	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	7	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	8	0	–	–	0	0	0	0	0	0	0	0	0	**0**
	Total	**56**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**56**
Flat-headed gudgeon	1	0	8	14	0	11	6	21	37	18	35	3	0	**153**
	2	0	25	15	0	4	75	12	48	17	66	348	2	**612**
	3	0	20	6	0	12	142	235	370	6	–	71	1	**863**
	4	0	3	0	0	9	111	51	71	2	42	104	2	**395**
	5	0	5	0	0	3	4	0	8	1	36	8	0	**65**
	6	0	0	0	0	4	10	51	1	2	–	22	5	**95**
	7	0	0	0	0	16	204	39	39	7	20	24	3	**352**
	8	0	–	–	0	5	21	35	28	15	563	175	0	**842**
	Total	**0**	**61**	**35**	**0**	**64**	**573**	**444**	**602**	**68**	**762**	**755**	**13**	**3,377**

continued

Appendix 2.3. (*continued*) Abundances of fish sampled within the Shoalhaven River system. Note: MR = Mongarlowe River; SR = Shoalhaven River upstream; KR = Kangaroo River; L = Lake Yarrunga; DB = directly below Tallowa Dam; B = Burrier; for site names, see Appendix 2.1.

Species	**Survey no.**	**Locality**												**Total**
		MR	**SR**		**KR**		**L**				**DB**		**B**	
		11	**12**	**2**	**4**	**5**	**14**	**6**	**7**	**13**	**8**	**9**	**10**	
Gobiidae (*continued*)	1	0	0	0	0	2	1	1	0	0	2	0	0	**6**
Dwarf flat-headed gudgeon	2	0	0	0	0	6	13	1	1	0	0	2	2	**25**
	3	0	0	0	0	2	6	4	4	0	–	0	0	**16**
	4	0	0	1	0	1	24	11	11	0	3	8	3	**62**
	5	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	6	0	0	0	0	1	0	2	1	0	–	1	0	**5**
	7	0	0	0	0	0	4	2	3	0	0	2	0	**11**
	8	0	–	–	0	10	5	3	5	3	0	2	0	**28**
	Total	**0**	**0**	**1**	**0**	**22**	**53**	**24**	**25**	**3**	**5**	**15**	**5**	**153**
Mugilidae	1	0	0	0	0	0	0	0	0	0	12	16	17	**45**
Sea mullet	2	0	0	0	0	0	0	0	0	0	30	16	4	**50**
	3	0	0	0	0	0	0	0	0	0	–	22	37	**59**
	4	0	0	0	0	0	0	0	0	0	10	15	15	**40**
	5	0	0	0	0	0	0	0	0	0	0	0	25	**25**
	6	0	0	0	0	0	0	0	0	0	–	6	8	**14**
	7	0	0	0	0	0	0	0	0	0	8	7	20	**35**
	8	0	–	–	0	0	0	0	0	0	2	11	4	**17**
	Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**62**	**93**	**130**	**285**
Freshwater mullet	1	0	0	0	0	0	0	0	0	0	9	30	4	**43**
	2	0	0	0	0	0	0	0	0	0	5	9	51	**65**
	3	0	0	0	0	0	0	0	0	0	–	18	2	**20**
	4	0	0	0	0	0	0	0	0	0	4	2	17	**23**
	5	0	0	0	0	0	0	0	0	0	9	12	2	**23**
	6	0	0	0	0	0	0	0	0	0	–	17	15	**32**
	7	0	0	0	0	0	0	0	0	0	26	6	13	**45**
	8	0	–	–	0	0	0	0	0	0	17	3	18	**38**
	Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**70**	**97**	**122**	**289**

continued

Appendix 2.3. (*continued*) Abundances of fish sampled within the Shoalhaven River system. Note: MR = Mongarlowe River; SR = Shoalhaven River upstream; KR = Kangaroo River; L = Lake Yarrunga; DB = directly below Tallowa Dam; B = Burrier; for site names, see Appendix 2.1.

Species	**Survey no.**	**Locality**												**Total**
		MR	**SR**		**KR**		**L**				**DB**		**B**	
		11	**12**	**2**	**4**	**5**	**14**	**6**	**7**	**13**	**8**	**9**	**10**	
Percichthyidae	1	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Macquarie perch	2	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	3	1	0	0	0	0	0	0	0	0	–	0	0	**1**
	4	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	5	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	6	1	0	0	0	0	0	0	0	0	–	0	0	**1**
	7	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	8	0	–	–	0	0	0	0	0	0	0	0	0	**0**
	Total	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**
Australian bass	1	0	0	4	0	9	5	10	2	0	67	64	24	**185**
	2	0	4	8	0	3	9	7	0	4	112	23	24	**194**
	3	0	2	18	0	6	2	1	2	5	–	4	33	**73**
	4	0	0	3	2	1	12	5	5	3	101	27	15	**174**
	5	0	7	5	1	10	1	4	2	1	15	6	3	**55**
	6	0	4	2	4	8	1	4	1	2	–	12	3	**41**
	7	0	3	3	5	14	3	0	2	2	15	10	12	**69**
	8	0	–	–	6	9	4	16	7	2	32	12	10	**98**
	Total	**0**	**20**	**43**	**18**	**60**	**37**	**47**	**21**	**19**	**342**	**158**	**124**	**889**
Estuary perch	1	0	0	0	0	0	0	0	0	0	0	0	1	**1**
	2	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	3	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	4	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	5	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	6	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	7	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	8	0	–	–	0	0	0	0	0	0	0	0	0	**0**
	Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**

continued

Appendix 2.3. (*continued*) Abundances of fish sampled within the Shoalhaven River system. Note: MR = Mongarlowe River; SR = Shoalhaven River upstream; KR = Kangaroo River; L = Lake Yarrunga; DB = directly below Tallowa Dam; B = Burrier; for site names, see Appendix 2.1.

		Locality												
Species	**Survey**	**MR**	**SR**		**KR**		**L**				**DB**		**B**	**Total**
	no.	**11**	**12**	**2**	**4**	**5**	**14**	**6**	**7**	**13**	**8**	**9**	**10**	
Plotosidae	1	0	0	1	0	0	2	0	1	2	0	1	2	**9**
Freshwater catfish	2	0	0	3	0	0	1	1	1	0	0	1	1	**8**
	3	0	0	0	0	0	3	2	0	0	–	0	0	**5**
	4	0	1	0	0	0	0	3	2	0	1	3	0	**10**
	5	0	0	0	0	0	3	2	1	0	0	1	0	**7**
	6	0	0	0	0	0	0	0	1	0	–	1	2	**4**
	7	0	1	1	0	0	2	2	0	1	0	2	0	**9**
	8	0	–	–	0	0	2	1	2	1	0	1	1	**8**
	Total	**0**	**2**	**5**	**0**	**0**	**13**	**11**	**8**	**4**	**1**	**10**	**6**	**60**
Retropinnidae	1	0	40	66	30	15	26	5	42	10	42	3	3	**282**
Australian smelt	2	0	27	51	270	29	329	257	172	461	77	34	28	**1,735**
	3	0	7	39	53	6	201	111	154	146	–	60	41	**818**
	4	0	24	40	53	55	29	57	219	101	421	1,612	104	**2,715**
	5	0	2	6	2	14	2	0	0	14	271	8	28	**347**
	6	0	53	61	65	101	3	29	6	9	–	3	19	**349**
	7	0	0	36	47	42	11	13	1	49	135	562	53	**949**
	8	0	–	–	60	92	31	86	395	100	198	1797	38	**2,797**
	Total	**0**	**153**	**299**	**580**	**354**	**632**	**558**	**989**	**890**	**1,144**	**4,079**	**314**	**9,992**
Scorpaenidae	1	0	0	0	0	0	0	0	0	0	2	1	1	**4**
Bullrout	2	0	0	0	0	0	0	0	0	0	0	4	0	**4**
	3	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	4	0	0	0	0	0	0	0	0	0	0	1	2	**3**
	5	0	0	0	0	0	0	0	0	0	0	1	0	**1**
	6	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	7	0	0	0	0	0	0	0	0	0	0	1	0	**1**
	8	0	–	–	0	0	0	0	0	0	1	0	0	**1**
	Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3**	**8**	**3**	**14**

continued

Appendix 2.3. (*continued*) Abundances of fish sampled within the Shoalhaven River system. Note: MR = Mongarlowe River; SR = Shoalhaven River upstream; KR = Kangaroo River; L = Lake Yarrunga; DB = directly below Tallowa Dam; B = Burrier; for site names, see Appendix 2.1.

Species	**Survey no.**	**Locality**												**Total**
		MR	**SR**		**KR**		**L**				**DB**		**B**	
		11	**12**	**2**	**4**	**5**	**14**	**6**	**7**	**13**	**8**	**9**	**10**	
Sparidae	1	0	0	0	0	0	0	0	0	0	0	0	1	**1**
Yellowfin bream	2	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	3	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	4	0	0	0	0	0	0	0	0	0	0	0	5	**5**
	5	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	6	0	0	0	0	0	0	0	0	0	–	0	1	**1**
	7	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	8	0	–	–	0	0	0	0	0	0	0	0	0	**0**
	Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**7**	**7**
Cyprinidae	1	0	0	0	0	0	0	0	0	2	0	0	1	**3**
Goldfish	2	1	0	0	0	0	0	0	0	0	0	0	5	**6**
	3	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	4	1	0	0	0	0	0	0	0	0	0	1	0	**2**
	5	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	6	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	7	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	8	0	–	–	0	0	0	0	0	0	0	0	0	**0**
	Total	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**1**	**6**	**11**
Common carp	1	0	12	5	0	9	0	2	0	1	2	1	4	**36**
	2	11	6	4	0	4	4	1	2	0	6	3	4	**45**
	3	8	7	10	0	4	3	0	2	3	–	1	2	**40**
	4	2	10	3	0	4	2	2	7	12	7	2	2	**53**
	5	5	4	6	0	7	2	2	2	3	5	4	0	**40**
	6	0	6	5	0	6	1	1	4	2	–	6	3	**34**
	7	3	2	7	0	7	1	0	2	7	6	13	4	**52**
	8	1	–	–	0	6	1	1	4	7	0	4	3	**27**
	Total	**30**	**47**	**40**	**0**	**47**	**14**	**9**	**23**	**35**	**26**	**34**	**22**	**327**

continued

Appendix 2.3. (*continued*) Abundances of fish sampled within the Shoalhaven River system. Note: MR = Mongarlowe River; SR = Shoalhaven River upstream; KR = Kangaroo River; L = Lake Yarrunga; DB = directly below Tallowa Dam; B = Burrier; for site names, see Appendix 2.1.

Species	**Survey no.**	**Locality**												**Total**
		MR	**SR**		**KR**		**L**				**DB**		**B**	
		11	**12**	**2**	**4**	**5**	**14**	**6**	**7**	**13**	**8**	**9**	**10**	
Poeciliidae	1	2	0	0	0	0	0	0	0	0	0	0	0	**2**
Eastern gambusia	2	8	0	0	0	1	0	0	0	0	0	0	0	**9**
	3	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	4	0	0	0	0	0	16	7	22	0	0	0	0	**45**
	5	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	6	0	0	0	0	0	1	1	0	2	–	0	0	**4**
	7	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	8	0	–	–	0	3	5	5	24	3	1	0	0	**41**
	Total	**10**	**0**	**0**	**0**	**4**	**22**	**13**	**46**	**5**	**1**	**0**	**0**	**101**
Salmonidae	1	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Brown trout	2	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	3	0	0	1	0	0	0	0	0	0	–	0	0	**1**
	4	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	5	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	6	0	0	0	0	0	0	0	0	0	–	0	0	**0**
	7	1	0	0	0	0	0	0	0	0	0	0	0	**1**
	8	0	–	–	0	0	0	0	0	0	0	0	0	**0**
	Total	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**
Total no. of fish		**173**	**312**	**453**	**686**	**608**	**1,366**	**1,119**	**1,730**	**1,039**	**2,962**	**5,771**	**1,209**	**17,428**
Total no. of species		**8**	**8**	**10**	**4**	**8**	**11**	**9**	**10**	**12**	**17**	**16**	**19**	

Appendix 2.4. Migratory status and occurrence of fish species in each reach: Mongarlowe River (MR); Shoalhaven River upstream (SR); Kangaroo River (KR); Lake Yarrunga (L); directly below Tallowa Dam (DB); and Burrier (B).

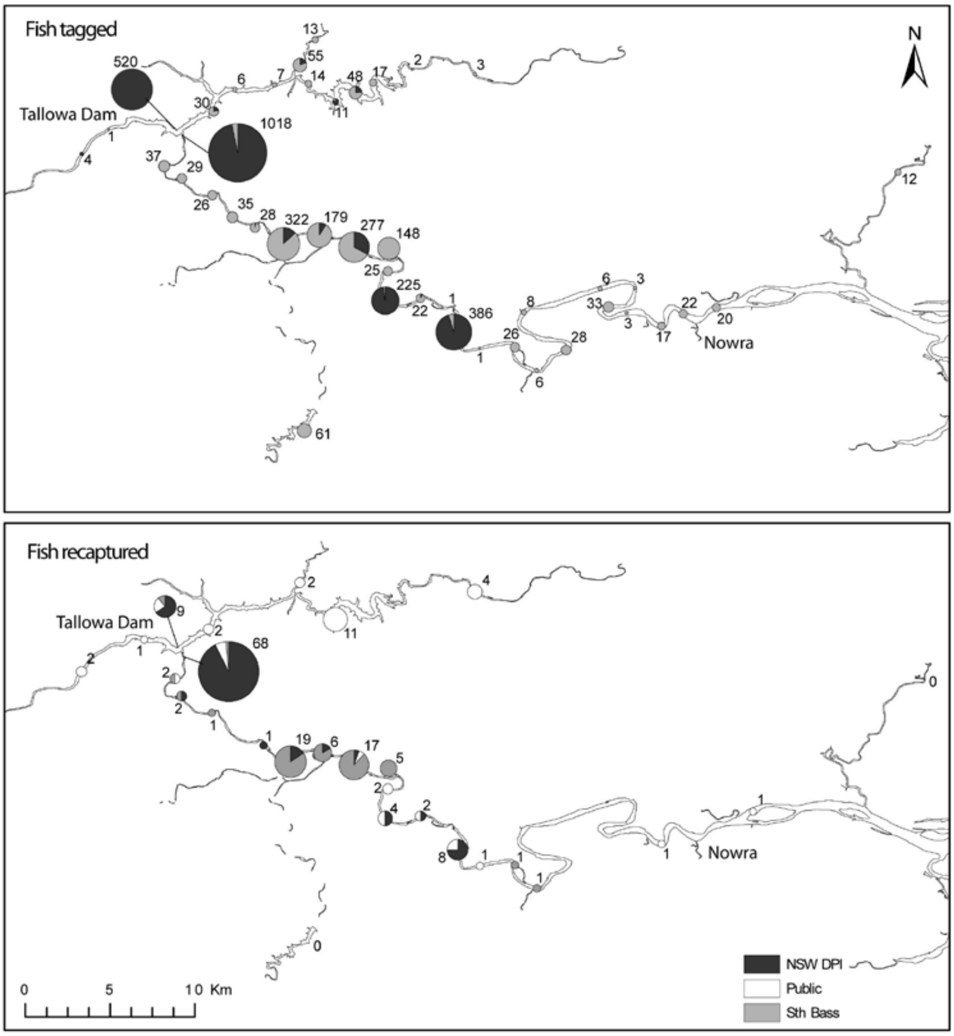
Behaviour type	Species	MR	SR	KR	L	DB	B
Catadromous	Shortfinned eel	*‡	*‡●	*‡	*‡	*‡	*‡
	Longfinned eel	*‡●	*‡●	*‡●	*‡●	*‡●	*‡●
	Common jollytail		*	*	*	*‡●	*‡●
	Striped gudgeon		*	*	*●	*‡●	*‡●
	Empire gudgeon		*	*	*●	*‡●	*‡●
	Sea mullet		*	*	*	*‡●	*‡●
	Bullrout		*	*	*	*‡●	*‡●
	Estuary perch						*‡●
	Australian bass		*‡●	*‡●	*‡●	*‡●	*‡●
	Freshwater herring		*	*	*	*‡●	*‡●
	Freshwater mullet		*	*	*	*‡●	*‡●
	Cox’s gudgeon		*‡●	*‡●	*‡●	*‡●	*‡●
Undefined migratory behaviour	Goldfish	*●		‡	*	*‡●	*‡●
	Eastern gambusia	‡●	‡	*●	‡●	●	
	Western carp-gudgeon	‡●	●		‡		
	Flat-headed gudgeon		*‡●	*‡●	*‡●	*‡●	*‡●
	Dwarf flat-headed gudgeon		*●	*‡●	*‡●	*‡●	*‡●
	Freshwater catfish		●		‡●	‡●	‡●
	Southern blue-eye						*
Potamodromus	Common carp	●	‡●	‡●	‡●	‡●	*‡●
	Mountain galaxias	*●					
	Firetail gudgeon	‡				●	
	Macquarie perch	*●‡	*	*	*	*	
	Australian smelt		*‡●	*‡●	*‡●	*‡●	*‡●
	Brown trout	‡●	‡●			‡	
Amphidromus	Climbing galaxias	*‡	*	*			
	Australian grayling		*	*	*	*	*
Marine estuarine	Silver biddy						●
	Yellowfin bream						*●
Anadromous	Lamprey		*	*	*	*	*‡

* Reconstructed historical fish distribution (Bishop and Bell 1978; Llewellyn 1983; Gehrke and Harris 1996; McDowall 1996)

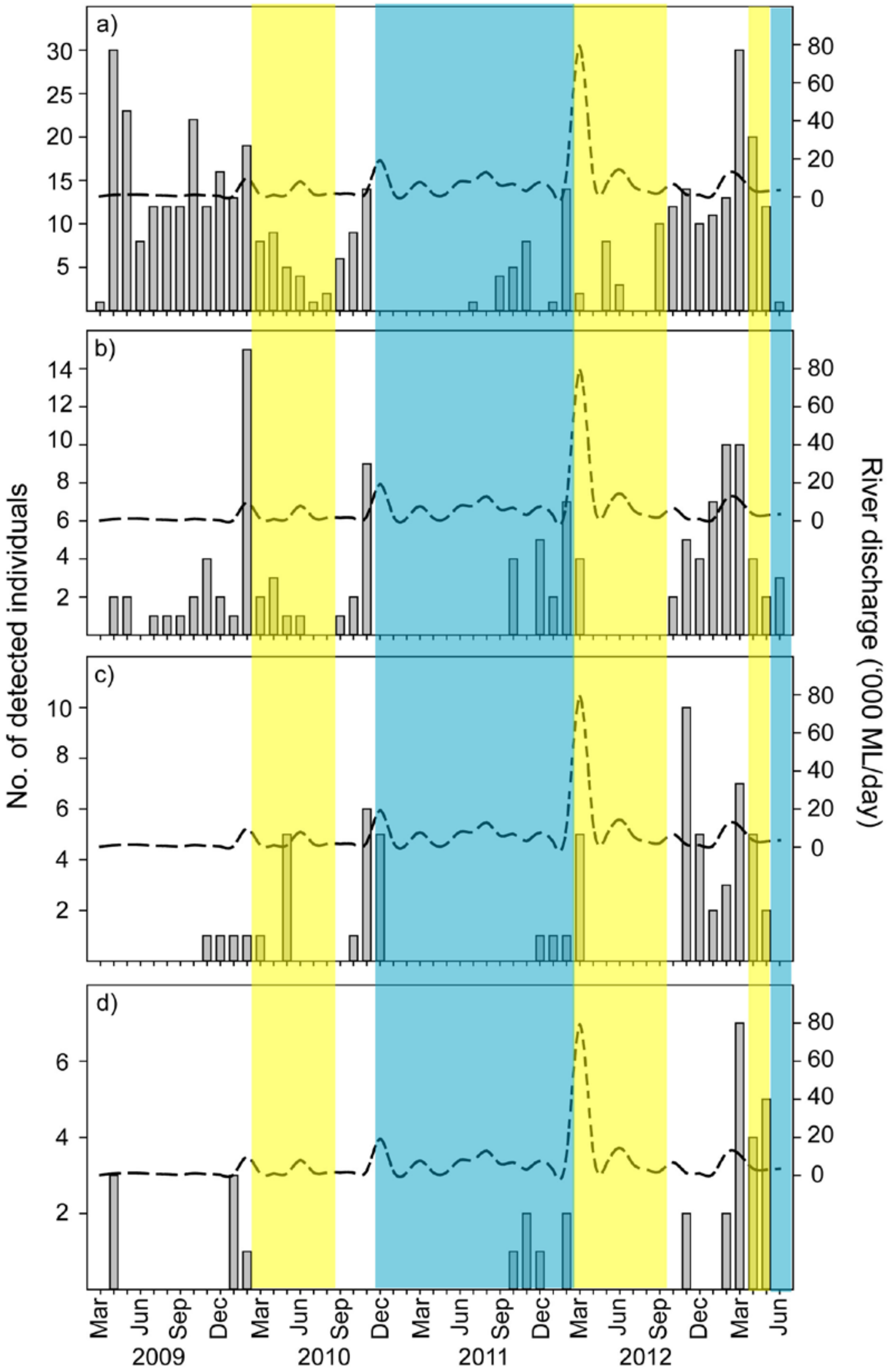
‡ Caught in pre-fishway survey (Gehrke *et al.* 2002)

● Caught in present survey

Appendix 3.1. Location, number and proportion of fish PIT tagged and recaptured by New South Wales Department of Primary Industries (NSW DPI), Southern Bass Fishing Club and the general public.



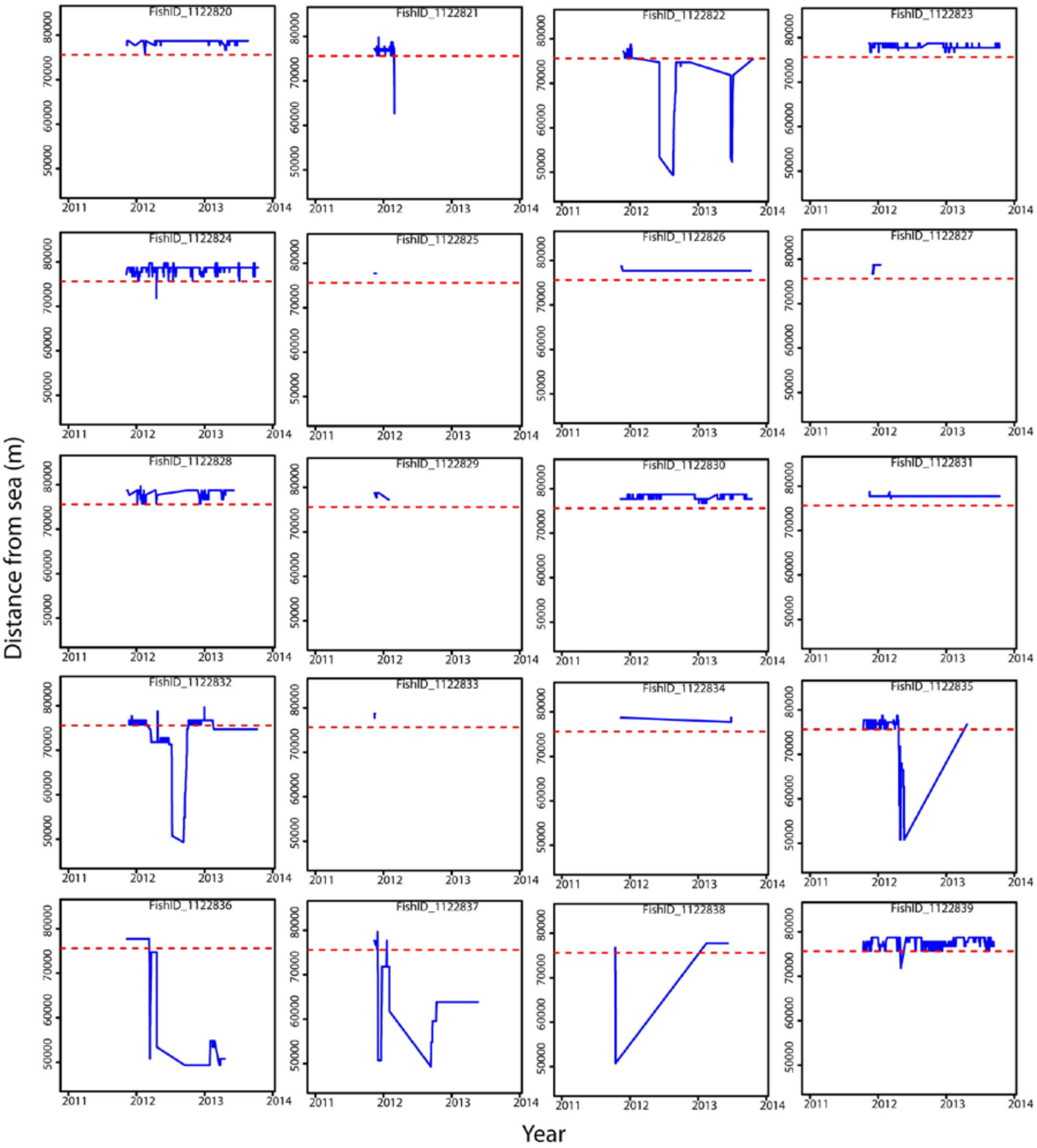
Appendix 3.2. Number of PIT-tagged Australian bass (a); longfinned eel (b); common carp (c) and freshwater mullet (d) individuals detected each month in relation to river discharge. Yellow and blue bars indicate periods where one and both PIT-tag antennae, respectively, were not operational.



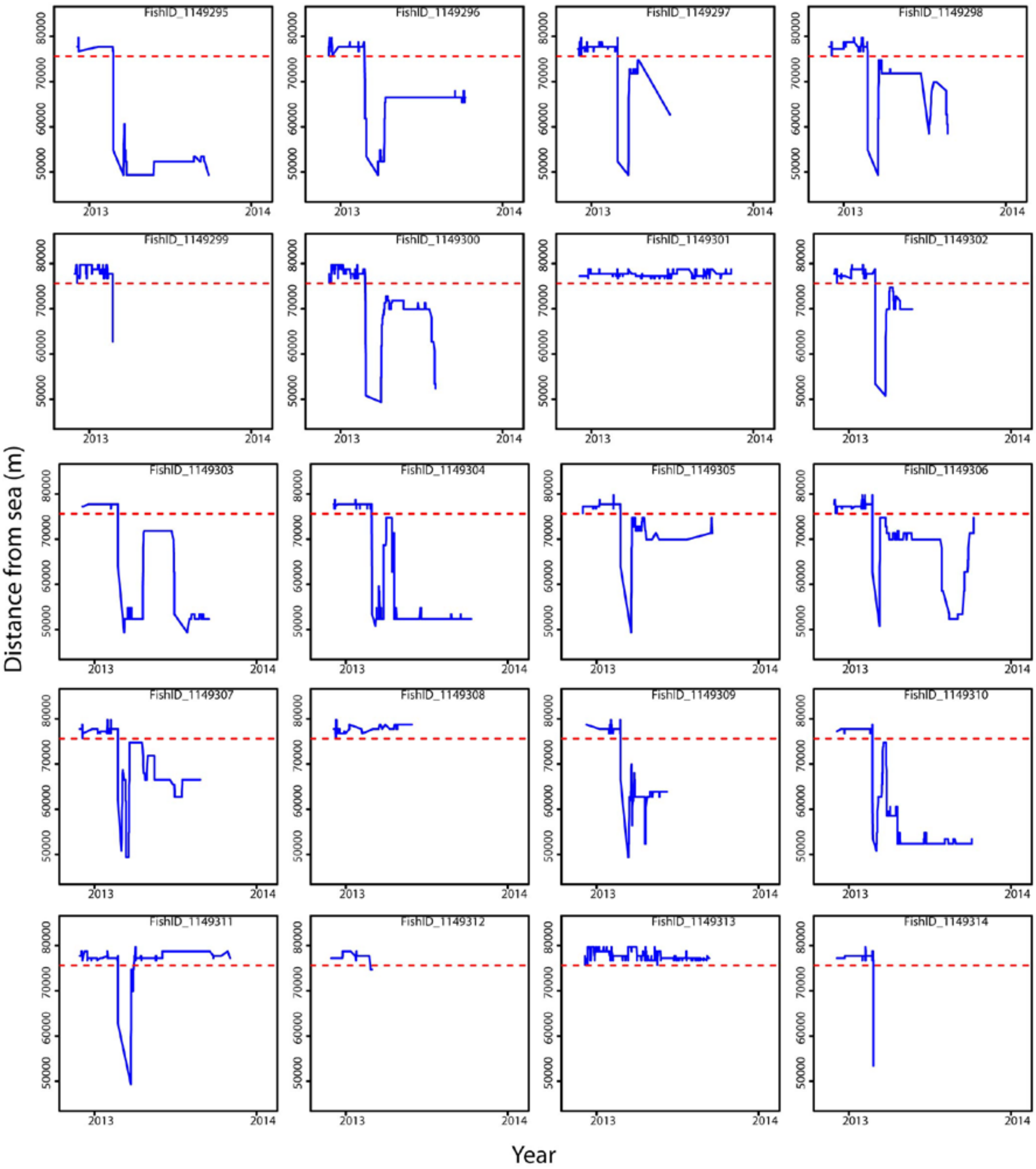
Appendix 4.1. Experimental design for downstream mortality assessment.

Fish	Flow	Cage	Block
1	low	2	1
2	low	10	1
3	low	1	1
4	low	6	1
5	low	6	2
6	low	3	2
7	low	12	2
8	low	11	2
9	control	8	3
10	control	7	3
11	control	11	3
12	control	1	3
13	high	9	4
14	high	12	4
15	high	3	4
16	high	6	4
17	control	6	5
18	control	7	5
19	control	10	5
20	control	2	5
21	high	6	6
22	high	10	6
23	high	7	6
24	high	3	6
25	high	12	7
26	high	6	7
27	high	2	7
28	high	3	7
29	high	1	8
30	high	4	8
31	high	9	8
32	high	8	8
33	control	4	9
34	control	11	9
35	control	8	9
36	control	12	9
37	low	3	10
38	low	5	10
39	low	7	10
40	low	2	10
41	control	5	11
42	control	9	11
43	control	3	11
44	control	6	11
45	low	10	12
46	low	1	12
47	low	12	12
48	low	9	12
49	high	9	13
50	high	8	13
51	high	10	13
52	high	2	13
53	high	7	14
54	high	12	14
55	high	5	14
56	high	3	14
57	control	4	15
58	control	10	15
59	control	9	15
60	control	2	15
61	low	8	16
62	low	8	16
63	low	11	16
64	low	4	16
65	control	3	17
66	control	10	17
67	control	1	17
68	control	6	17
69	low	11	18
70	low	2	18
71	low	10	18
72	low	5	18
73	high	7	19
74	high	5	19
75	high	6	19
76	high	11	19
77	control	5	20
78	control	7	20
79	control	9	20
80	control	2	20
81	high	1	21
82	high	2	21
83	high	8	21
84	high	11	21
85	control	2	22
86	control	9	22
87	control	4	22
88	control	10	22
89	low	8	23
90	low	3	23
91	low	9	23
92	low	6	23
93	low	7	24
94	low	4	24
95	low	5	24
96	low	1	24
97	low	7	25
98	low	9	25
99	low	11	25
100	low	4	25
101	control	8	26
102	control	1	26
103	control	11	26
104	control	5	26
105	low	1	27
106	low	8	27
107	low	5	27
108	low	12	27
109	control	1	28
110	control	7	28
111	control	8	28
112	control	12	28
113	high	2	29
114	high	5	29
115	high	7	29
116	high	11	29
117	high	9	30
118	high	4	30
119	high	12	30
120	high	10	30
121	low	10	31
122	low	9	31
123	low	2	31
124	low	4	31
125	control	3	32
126	control	12	32
127	control	5	32
128	control	6	32
129	low	12	33
130	low	3	33
131	low	6	33
132	low	7	33
133	control	3	34
134	control	4	34
135	control	12	34
136	control	11	34
137	high	11	35
138	high	4	35
139	high	5	35
140	high	1	35
141	high	10	36
142	high	4	36
143	high	8	36
144	high	1	36

Appendix 4.2. Mean daily river location of tagged Australian bass individuals at liberty between 2011 and 2013 (transmitter number noted in each plot). The red dashed line represents the position of Tallowa Dam.



Appendix 4.3. Mean daily river location of tagged freshwater mullet individuals at liberty between 2011 and 2013 (transmitter number noted in each plot). The red dashed line represents the position of Tallowa Dam.



Other titles in this series:

ISSN 1440-3544 (NSW Fisheries Final Report Series)

No. 1 Andrew, N.L., Graham, K.J., Hodgson, K.E. and Gordon, G.N.G., 1998. Changes after 20 years in relative abundance and size composition of commercial fishes caught during fishery independent surveys on SEF trawl grounds.

No. 2 Virgona, J.L., Deguara, K.L., Sullings, D.J., Halliday, I. and Kelly, K., 1998. Assessment of the stocks of sea mullet in New South Wales and Queensland waters.

No. 3 Stewart, J., Ferrell, D.J. and Andrew, N.L., 1998. Ageing Yellowtail (*Trachurus novaezelandiae*) and Blue Mackerel (*Scomber australasicus*) in New South Wales.

No. 4 Pethebridge, R., Lugg, A. and Harris, J., 1998. Obstructions to fish passage in New South Wales South Coast streams. 70pp.

No. 5 Kennelly, S.J. and Broadhurst, M.K., 1998. Development of by-catch reducing prawn-trawls and fishing practices in NSW's prawn-trawl fisheries (and incorporating an assessment of the effect of increasing mesh size in fish trawl gear). 18pp + appendices.

No. 6 Allan, G.L. and Rowland, S.J., 1998. Fish meal replacement in aquaculture feeds for silver perch. 237pp + appendices.

No. 7 Allan, G.L., 1998. Fish meal replacement in aquaculture feeds: subprogram administration. 54pp + appendices.

No. 8 Heasman, M.P., O'Connor, W.A. and O'Connor, S.J., 1998. Enhancement and farming of scallops in NSW using hatchery produced seedstock. 146pp.

No. 9 Nell, J.A., McMahon, G.A. and Hand, R.E., 1998. Tetraploidy induction in Sydney rock oysters. 25pp.

No. 10 Nell, J.A. and Maguire, G.B., 1998. Commercialisation of triploid Sydney rock and Pacific oysters. Part 1: Sydney rock oysters. 122pp.

No. 11 Watford, F.A. and Williams, R.J., 1998. Inventory of estuarine vegetation in Botany Bay, with special reference to changes in the distribution of seagrass. 51pp.

No. 12 Andrew, N.L., Worthington D.G., Brett, P.A. and Bentley N., 1998. Interactions between the abalone fishery and sea urchins in New South Wales.

No. 13 Jackson, K.L. and Ogburn, D.M., 1999. Review of depuration and its role in shellfish quality assurance. 77pp.

No. 14 Fielder, D.S., Bardsley, W.J. and Allan, G.L., 1999. Enhancement of Mulloway (*Argyrosomus japonicus*) in intermittently opening lagoons. 50pp + appendices.

No. 15 Otway, N.M. and Macbeth, W.G., 1999. The physical effects of hauling on seagrass beds. 86pp.

No. 16 Gibbs, P., McVea, T. and Louden, B., 1999. Utilisation of restored wetlands by fish and invertebrates. 142pp.

No. 17 Ogburn, D. and Ruello, N., 1999. Waterproof labelling and identification systems suitable for shellfish and other seafood and aquaculture products. Whose oyster is that? 50pp.

No. 18 Gray, C.A., Pease, B.C., Stringfellow, S.L., Raines, L.P. and Walford, T.R., 2000. Sampling estuarine fish species for stock assessment. Includes appendices by D.J. Ferrell, B.C. Pease, T.R. Walford, G.N.G. Gordon, C.A. Gray and G.W. Liggins. 194pp.

No. 19 Otway, N.M. and Parker, P.C., 2000. The biology, ecology, distribution, abundance and identification of marine protected areas for the conservation of threatened Grey Nurse Sharks in south east Australian waters. 101pp.

No. 20 Allan, G.L. and Rowland, S.J., 2000. Consumer sensory evaluation of silver perch cultured in ponds on meat meal based diets. 21pp + appendices.

No. 21 Kennelly, S.J. and Scandol, J. P., 2000. Relative abundances of spanner crabs and the development of a population model for managing the NSW spanner crab fishery. 43pp + appendices.

No. 22 Williams, R.J., Watford, F.A. and Balashov, V., 2000. Kooragang Wetland Rehabilitation Project: History of changes to estuarine wetlands of the lower Hunter River. 82pp.

No. 23 Survey Development Working Group, 2000. Development of the National Recreational and Indigenous Fishing Survey. Final Report to Fisheries Research and Development Corporation. (Volume 1 – 36pp + Volume 2 – attachments).

No.24 Rowling, K.R and Raines, L.P., 2000. Description of the biology and an assessment of the fishery of Silver Trevally *Pseudocaranx dentex* off New South Wales. 69pp.

No. 25 Allan, G.L., Jantrarotai, W., Rowland, S., Kosuturak, P. and Booth, M., 2000. Replacing fishmeal in aquaculture diets. 13pp.

No. 26 Gehrke, P.C., Gilligan, D.M. and Barwick, M., 2001. Fish communities and migration in the Shoalhaven River – Before construction of a fishway. 126pp.

No. 27 Rowling, K.R. and Makin, D.L., 2001. Monitoring of the fishery for Gemfish *Rexea solandri*, 1996 to 2000. 44pp.

No. 28 Otway, N.M., 1999. Identification of candidate sites for declaration of aquatic reserves for the conservation of rocky intertidal communities in the Hawkesbury Shelf and Batemans Shelf Bioregions. 88pp.

No. 29 Heasman, M.P., Goard, L., Diemar, J. and Callinan, R., 2000. Improved Early Survival of Molluscs: Sydney Rock Oyster (*Saccostrea glomerata*). 63pp.

No. 30 Allan, G.L., Dignam, A and Fielder, S., 2001. Developing Commercial Inland Saline Aquaculture in Australia: Part 1. R&D Plan.

No. 31 Allan, G.L., Banens, B. and Fielder, S., 2001. Developing Commercial Inland Saline Aquaculture in Australia: Part 2. Resource Inventory and Assessment. 33pp.

No. 32 Bruce, A., Growns, I. and Gehrke, P., 2001. Woronora River Macquarie Perch Survey. 116pp.

No. 33 Morris, S.A., Pollard, D.A., Gehrke, P.C. and Pogonoski, J.J., 2001. Threatened and Potentially Threatened Freshwater Fishes of Coastal New South Wales and the Murray-Darling Basin. 177pp.

No. 34 Heasman, M.P., Sushames, T.M., Diemar, J.A., O'Connor, W.A. and Foulkes, L.A., 2001. Production of Micro-algal Concentrates for Aquaculture Part 2: Development and Evaluation of Harvesting, Preservation, Storage and Feeding Technology. 150pp + appendices.

No. 35 Stewart, J. and Ferrell, D.J., 2001. Mesh selectivity in the NSW demersal trap fishery. 86pp.

No. 36 Stewart, J., Ferrell, D.J., van der Walt, B., Johnson, D. and Lowry, M., 2001. Assessment of length and age composition of commercial kingfish landings. 49pp.

No. 37 Gray, C.A. and Kennelly, S.J., 2001. Development of discard-reducing gears and practices in the estuarine prawn and fish haul fisheries of NSW. 151pp.

No. 38 Murphy, J.J., Lowry, M.B., Henry, G.W. and Chapman, D., 2002. The Gamefish Tournament Monitoring Program – 1993 to 2000. 93pp.

No. 39 Kennelly, S.J. and McVea, T.A. (Ed), 2002. Scientific reports on the recovery of the Richmond and Macleay Rivers following fish kills in February and March 2001. 325pp.

No. 40 Pollard, D.A. and Pethebridge, R.L., 2002. Report on Port of Botany Bay Introduced Marine Pest Species Survey. 69pp.

No. 41 Pollard, D.A. and Pethebridge, R.L., 2002. Report on Port Kembla Introduced Marine Pest Species Survey. 72pp.

No. 42 O'Connor, W.A, Lawler, N.F. and Heasman, M.P., 2003. Trial farming the akoya pearl oyster, *Pinctada imbricata*, in Port Stephens, NSW. 170pp.

No. 43 Fielder, D.S. and Allan, G.L., 2003. Improving fingerling production and evaluating inland saline water culture of snapper, *Pagrus auratus*. 62pp.

No. 44 Astles, K.L., Winstanley, R.K., Harris, J.H. and Gehrke, P.C., 2003. Experimental study of the effects of cold water pollution on native fish. 55pp.

No. 45 Gilligan, D.M., Harris, J.H. and Mallen-Cooper, M., 2003. Monitoring changes in the Crawford River fish community following replacement of an effective fishway with a vertical-slot fishway design: Results of an eight year monitoring program. 80pp.

No. 46 Pollard, D.A. and Rankin, B.K., 2003. Port of Eden Introduced Marine Pest Species Survey. 67pp.

No. 47 Otway, N.M., Burke, A.L., Morrison, NS. and Parker, P.C., 2003. Monitoring and identification of NSW Critical Habitat Sites for conservation of Grey Nurse Sharks. 62pp.

No. 48 Henry, G.W. and Lyle, J.M. (Ed), 2003. The National Recreational and Indigenous Fishing Survey. 188 pp.

No. 49 Nell, J.A., 2003. Selective breeding for disease resistance and fast growth in Sydney rock oysters. 44pp. (Also available – a CD-Rom published in March 2004 containing a collection of selected manuscripts published over the last decade in peer-reviewed journals).

No. 50 Gilligan, D. and Schiller, S., 2003. Downstream transport of larval and juvenile fish. 66pp.

No. 51 Liggins, G.W., Scandol, J.P. and Kennelly, S.J., 2003. Recruitment of Population Dynamacist. 44pp.

No. 52 Steffe, A.S. and Chapman, J.P., 2003. A survey of daytime recreational fishing during the annual period, March 1999 to February 2000, in Lake Macquarie, New South Wales. 124pp.

No. 53 Barker, D. and Otway, N., 2003. Environmental assessment of zinc coated wire mesh sea cages in Botany Bay NSW. 36pp.

No. 54 Growns, I., Astles, A. and Gehrke, P., 2003. Spatial and temporal variation in composition of riverine fish communities. 24pp.

No. 55 Gray, C. A., Johnson, D.D., Young, D.J. and Broadhurst, M. K., 2003. Bycatch assessment of the Estuarine Commercial Gill Net Fishery in NSW. 58pp.

No. 56 Worthington, D.G. and Blount, C., 2003. Research to develop and manage the sea urchin fisheries of NSW and eastern Victoria. 182pp.

No. 57 Baumgartner, L.J., 2003. Fish passage through a Deelder lock on the Murrumbidgee River, Australia. 34pp.

No. 58 Allan, G.L., Booth, M.A., David A.J. Stone, D.A.J. and Anderson, A.J., 2004. Aquaculture Diet Development Subprogram: Ingredient Evaluation. 171pp.

No. 59 Smith, D.M., Allan, G.L. and Booth, M.A., 2004. Aquaculture Diet Development Subprogram: Nutrient Requirements of Aquaculture Species. 220pp.

No. 60 Barlow, C.G., Allan, G.L., Williams, K.C., Rowland, S.J. and Smith, D.M., 2004. Aquaculture Diet Development Subprogram: Diet Validation and Feeding Strategies. 197pp.

No. 61 Heasman, M.H., 2004. Sydney Rock Oyster Hatchery Workshop 8 – 9 August 2002, Port Stephens, NSW. 115pp.

No. 62 Heasman, M., Chick, R., Savva, N., Worthington, D., Brand, C., Gibson, P. and Diemar, J., 2004. Enhancement of populations of abalone in NSW using hatchery-produced seed. 269pp.

No. 63 Otway, N.M. and Burke, A.L., 2004. Mark-recapture population estimate and movements of Grey Nurse Sharks. 53pp.

No. 64 Creese, R.G., Davis, A.R. and Glasby, T.M., 2004. Eradicating and preventing the spread of the invasive alga *Caulerpa taxifolia* in NSW. 110pp.

No. 65 Baumgartner, L.J., 2004. The effects of Balranald Weir on spatial and temporal distributions of lower Murrumbidgee River fish assemblages. 30pp.

No. 66 Heasman, M., Diggles, B.K., Hurwood, D., Mather, P., Pirozzi, I. and Dworjanyn, S., 2004. Paving the way for continued rapid development of the flat (angasi) oyster (*Ostrea angasi*) farming in New South Wales. 40pp.

ISSN 1449-9967 (NSW Department of Primary Industries – Fisheries Final Report Series)

No. 67 Kroon, F.J., Bruce, A.M., Housefield, G.P. and Creese, R.G., 2004. Coastal floodplain management in eastern Australia: barriers to fish and invertebrate recruitment in acid sulphate soil catchments. 212pp.

No. 68 Walsh, S., Copeland, C. and Westlake, M., 2004. Major fish kills in the northern rivers of NSW in 2001: Causes, Impacts & Responses. 55pp.

No. 69 Pease, B.C. (Ed), 2004. Description of the biology and an assessment of the fishery for adult longfinned eels in NSW. 168pp.

No. 70 West, G., Williams, R.J. and Laird, R., 2004. Distribution of estuarine vegetation in the Parramatta River and Sydney Harbour, 2000. 37pp.

No. 71 Broadhurst, M.K., Macbeth, W.G. and Wooden, M.E.L., 2005. Reducing the discarding of small prawns in NSW's commercial and recreational prawn fisheries. 202pp.

No. 72. Graham, K.J., Lowry, M.B. and Walford, T.R., 2005. Carp in NSW: Assessment of distribution, fishery and fishing methods. 88pp.

No. 73 Stewart, J., Hughes, J.M., Gray, C.A. and Walsh, C., 2005. Life history, reproductive biology, habitat use and fishery status of eastern sea garfish (*Hyporhamphus australis*) and river garfish (*H. regularis ardelio*) in NSW waters. 180pp.

No. 74 Growns, I. and Gehrke, P., 2005. Integrated Monitoring of Environmental Flows: Assessment of predictive modelling for river flows and fish. 33pp.

No. 75 Gilligan, D., 2005. Fish communities of the Murrumbidgee catchment: Status and trends. 138pp.

No. 76 Ferrell, D.J., 2005. Biological information for appropriate management of endemic fish species at Lord Howe Island. 18 pp.

No. 77 Gilligan, D., Gehrke, P. and Schiller, C., 2005. Testing methods and ecological consequences of large-scale removal of common carp. 46pp.

No. 78 Boys, C.A., Esslemont, G. and Thoms, M.C., 2005. Fish habitat and protection in the Barwon-Darling and Paroo Rivers. 118pp.

No. 79 Steffe, A.S., Murphy, J.J., Chapman, D.J. and Gray, C.C., 2005. An assessment of changes in the daytime recreational fishery of Lake Macquarie following the establishment of a ‘Recreational Fishing Haven’. 103pp.

No. 80 Gannassin, C. and Gibbs, P., 2005. Broad-Scale Interactions Between Fishing and Mammals, Reptiles and Birds in NSW Marine Waters. 171pp.

No. 81 Steffe, A.S., Murphy, J.J., Chapman, D.J., Barrett, G.P. and Gray, C.A., 2005. An assessment of changes in the daytime, boat-based, recreational fishery of the Tuross Lake estuary following the establishment of a 'Recreational Fishing Haven'. 70pp.

No. 82 Silberschnieder, V. and Gray, C.A., 2005. Arresting the decline of the commercial and recreational fisheries for mulloway (*Argyrosomus japonicus*). 71pp.

No. 83 Gilligan, D., 2005. Fish communities of the Lower Murray-Darling catchment: Status and trends. 106pp.

No. 84 Baumgartner, L.J., Reynoldson, N., Cameron, L. and Stanger, J., 2006. Assessment of a Dual-frequency Identification Sonar (DIDSON) for application in fish migration studies. 33pp.

No. 85 Park, T., 2006. FishCare Volunteer Program Angling Survey: Summary of data collected and recommendations. 41pp.

No. 86 Baumgartner, T., 2006. A preliminary assessment of fish passage through a Denil fishway on the Edward River, Australia. 23pp.

No. 87 Stewart, J., 2007. Observer study in the Estuary General sea garfish haul net fishery in NSW. 23pp.

No. 88 Faragher, R.A., Pogonoski, J.J., Cameron, L., Baumgartner, L. and van der Walt, B., 2007. Assessment of a stocking program: Findings and recommendations for the Snowy Lakes Trout Strategy. 46pp.

No. 89 Gilligan, D., Rolls, R., Merrick, J., Lintermans, M., Duncan, P. and Kohen, J., 2007. Scoping knowledge requirements for Murray crayfish (*Euastacus armatus*). Final report to the Murray Darling Basin Commission for Project No. 05/1066 NSW 103pp.

No. 90 Kelleway, J., Williams. R.J. and Allen, C.B., 2007. An assessment of the saltmarsh of the Parramatta River and Sydney Harbour. 100pp.

No. 91 Williams, R.J. and Thiebaud, I., 2007. An analysis of changes to aquatic habitats and adjacent land-use in the downstream portion of the Hawkesbury Nepean River over the past sixty years. 97pp.

No. 92 Baumgartner, L., Reynoldson, N., Cameron, L. and Stanger, J. The effects of selected irrigation practices on fish of the Murray-Darling Basin. 90pp.

No. 93 Rowland, S.J., Landos, M., Callinan, R.B., Allan, G.L., Read, P., Mifsud, C., Nixon, M., Boyd, P. and Tally, P., 2007. Development of a health management strategy for the Silver Perch Aquaculture Industry. 219pp.

No. 94 Park, T., 2007. NSW Gamefish Tournament Monitoring – Angling Research Monitoring Program. Final report to the NSW Recreational Fishing Trust. 142pp.

No. 95 Heasman, M.P., Liu, W., Goodsell, P.J., Hurwood D.A. and Allan, G.L., 2007. Development and delivery of technology for production, enhancement and aquaculture of blacklip abalone (*Haliotis rubra*) in New South Wales. 226pp.

No. 96 Ganassin, C. and Gibbs, P.J., 2007. A review of seagrass planting as a means of habitat compensation following loss of seagrass meadow. 41pp.

No. 97 Stewart, J. and Hughes, J., 2008. Determining appropriate harvest size at harvest for species shared by the commercial trap and recreational fisheries in New South Wales. 282pp.

No. 98 West, G. and Williams, R.J., 2008. A preliminary assessment of the historical, current and future cover of seagrass in the estuary of the Parramatta River. 61pp.

No. 99 Williams, D.L. and Scandol, J.P., 2008. Review of NSW recreational fishing tournament-based monitoring methods and datasets. 83pp.

No. 100 Allan, G.L., Heasman, H. and Bennison, S., 2008. Development of industrial-scale inland saline aquaculture: Coordination and communication of R&D in Australia. 245pp.

No. 101 Gray, C.A and Barnes, L.M., 2008. Reproduction and growth of dusky flathead (*Platycephalus fuscus*) in NSW estuaries. 26pp.

No. 102 Graham, K.J., 2008. The Sydney inshore trawl-whiting fishery: codend selectivity and fishery characteristics. 153pp.

No. 103 Macbeth, W.G., Johnson, D.D. and Gray, C.A., 2008. Assessment of a 35-mm square-mesh codend and composite square-mesh panel configuration in the ocean prawn-trawl fishery of northern New South Wales. 104pp.

No. 104 O'Connor, W.A., Dove, M. and Finn, B., 2008. Sydney rock oysters: Overcoming constraints to commercial scale hatchery and nursery production. 119pp.

No. 105 Glasby, T.M. and Lobb, K., 2008. Assessing the likelihoods of marine pest introductions in Sydney estuaries: A transport vector approach. 84pp.

No. 106 Rotherham, D., Gray, C.A., Underwood, A.J., Chapman, M.G. and Johnson, D.D., 2008. Developing fishery-independent surveys for the adaptive management of NSW's estuarine fisheries. 135pp.

No. 107 Broadhurst, M., 2008. Maximising the survival of bycatch discarded from commercial estuarine fishing gears in NSW. 192pp.

No. 108 Gilligan, D., McLean, A. and Lugg, A., 2009. Murray Wetlands and Water Recovery Initiatives: Rapid assessment of fisheries values of wetlands prioritised for water recovery. 69pp.

No. 109 Williams, R.J. and Thiebaud, I., 2009. Occurrence of freshwater macrophytes in the catchments of the Parramatta River, Lane Cove River and Middle Harbour Creek, 2007 – 2008. 75pp.

No. 110 Gilligan, D., Vey, A. and Asmus, M., 2009. Identifying drought refuges in the Wakool system and assessing status of fish populations and water quality before, during and after the provision of environmental, stock and domestic flows. 56pp.

ISSN 1837-2112 (Industry & Investment NSW – Fisheries Final Report Series)

No. 111 Gray, C.A., Scandol. J.P., Steffe, A.S. and Ferrell, D.J., 2009. Australian Society for Fish Biology Annual Conference & Workshop 2008: Assessing Recreational Fisheries; Current and Future Challenges. 54pp.

No. 112 Otway, N.M. Storrie, M.T., Louden, B.M. and Gilligan, J.J., 2009. Documentation of depth-related migratory movements, localised movements at critical habitat sites and the effects of scuba diving for the east coast grey nurse shark population. 90pp.

No. 113 Creese, R.G., Glasby, T.M., West, G. and Gallen, C., 2009. Mapping the habitats of NSW estuaries. 95pp.

No. 114 Macbeth, W.G., Geraghty, P.T., Peddemors, V.M. and Gray, C.A., 2009. Observer-based study of targeted commercial fishing for large shark species in waters off northern New South Wales. 82pp.

No. 115 Scandol, J.P., Ives, M.C. and Lockett, M.M., 2009. Development of national guidelines to improve the application of risk-based methods in the scope, implementation and interpretation of stock assessments for data-poor species. 186pp.

No. 116 Baumgartner, L., Bettanin, M., McPherson, J., Jones, M., Zampatti, B. and Kathleen Beyer., 2009. Assessment of an infrared fish counter (Vaki Riverwatcher) to quantify fish migrations in the Murray-Darling Basin. 47pp.

No. 117 Astles, K., West, G., and Creese, R.G., 2010. Estuarine habitat mapping and geomorphic characterisation of the Lower Hawkesbury river and Pittwater estuaries. 229pp.

No. 118 Gilligan, D., Jess, L., McLean, G., Asmus, M., Wooden, I., Hartwell, D., McGregor, C., Stuart, I., Vey, A., Jefferies, M., Lewis, B. and Bell, K., 2010. Identifying and implementing targeted carp control options for the Lower Lachlan Catchment. 126pp.

No. 119 Montgomery, S.S., Walsh, C.T., Kesby, C.L and Johnson, D.D., 2010. Studies on the growth and mortality of school prawns. 90pp.

No. 120 Liggins, G.W. and Upston, J., 2010. Investigating and managing the *Perkinsus*-related mortality of blacklip abalone in NSW. 182pp.

No. 121 Knight, J., 2010. The feasibility of excluding alien redfin perch from Macquarie perch habitat in the Hawkesbury-Nepean Catchment. 53pp.

No. 122 Ghosn, D., Steffe, A., Murphy, J., 2010. An assessment of the effort and catch of shore and boat-based recreational fishers in the Sydney Harbour estuary over the 2007/08 summer period. 60pp.

No. 123 Rourke, M. and Gilligan, D., 2010. Population genetic structure of freshwater catfish (*Tandanus tandanus*) in the Murray-Darling Basin and coastal catchments of New South Wales: Implications for future re-stocking programs. 74pp.

No. 124 Tynan, R., Bunter, K. and O'Connor, W., 2010. Industry Management and Commercialisation of the Sydney Rock Oyster Breeding Program. 21pp.

No. 125 Lowry, M., Folpp, H., Gregson, M. and McKenzie, R., 2010. Assessment of artificial reefs in Lake Macquarie NSW. 47pp.

No. 126 Howell, T. and Creese, R., 2010. Freshwater fish communities of the Hunter, Manning, Karuah and Macquarie-Tuggerah catchments: a 2004 status report. 93pp.

No. 127 Gilligan, D., Rodgers, M., McGarry, T., Asmus, M. and Pearce, L., 2010. The distribution and abundance of two endangered fish species in the NSW Upper Murray Catchment. 34pp.

No. 128 Gilligan, D., McGarry, T. and Carter, S., 2010. A scientific approach to developing habitat rehabilitation strategies in aquatic environments: A case study on the endangered Macquarie perch (*Macquaria australasica*) in the Lachlan catchment. 61pp.

No. 129 Stewart, J., Hughes, J., McAllister, J., Lyle, J. and MacDonald, M., 2011. Australian salmon (*Arripis trutta*): Population structure, reproduction, diet and composition of commercial and recreational catches. 257 pp.

ISSN 1837-2112 (Fisheries Final Report Series)

No. 130 Boys, C., Glasby, T., Kroon, F., Baumgartner, L., Wilkinson, K., Reilly, G. and Fowler, T., 2011. Case studies in restoring connectivity of coastal aquatic habitats: floodgates, box culvert and rock-ramp fishway. 75pp.

No. 131 Steffe, A.S. and Murphy, J.J., 2011. Recreational fishing surveys in the Greater Sydney Region. 122pp.

No. 132 Robbins, W.D., Peddemors, V.M. and Kennelly, S.J., 2012. Assessment of shark sighting rates by aerial beach patrols. 38pp.

No. 133 Boys, C.A. and Williams, R.J., 2012. Fish and decapod assemblages in Kooragang Wetlands: the impact of tidal restriction and responses to culvert removal. 80pp.

No. 134 Boys, C.A, Baumgartner,L., Rampano, B., Alexander, T., Reilly, G., Roswell, M., Fowler, T and Lowry. M. 2012. Development of fish screening criteria for water diversions in the Murray-Darling Basin. 62pp.

No. 135 Boys, C.A, Southwell, M., Thoms, M., Fowler, T, Thiebaud, I., Alexander, T. and Reilly, G. 2012. Evaluation of aquatic rehabilitation in the Bourke to Brewarrina Demonstration Reach, Barwon-Darling River, Australia. 133pp

No. 136 Baumgartner, L., McPherson, B., Doyle, J., Cory, J., Cinotti, N. and Hutchison, J. 2013. Quantifying and mitigating the impacts of weirs on downstream passage of native fish in the Murray-Darling Basin. 79pp.

No. 137 Boys, C.A, Baumgartner, B., Miller, B., Deng, Z., Brown, R. and Pflugrath, B. 2013. Protecting downstream migrating fish at mini hydropower and other river infrastructure. 93pp.

No. 138 Hughes, J.M. and Stewart, J. 2013. Assessment of barotrauma and its mitigation measures on the behaviour and survival of snapper and mulloway. 152pp.

No. 139 Ochwada-Doyle, F.A., McLeod, J., Barrett, G., Clarke, G. and Gray, C.A., 2014. Assessment of recreational fishing in three recreational fishing havens in New South Wales. 29pp.

No. 140 Walsh, C. T., Rodgers, M. P., Thorne, N. J. and Robinson, W. A., 2013. Thermoshock Fish Mortality Investigation. 32pp.

No. 141 Boys, C.A., Navarro, A., Robinson, W., Fowler, T., Chilcott, S., Miller, B., Pflugrath, B., Baumgartner, L.J., McPherson, J., Brown, R. and Deng, Z., 2014. Downstream fish passage criteria for hydropower and irrigation infrastructure in the Murray-Darling Basin. 119pp.

No. 142 Cameron, L., Baumgartner, L. and Miners, B., 2012. Assessment of Australian bass restocking in the upper Snowy River. 102pp.

No. 143 Walsh, C., Rodgers, M., Robinson, W. and Gilligan, D., 2014. Evaluation of the effectiveness of the Tallowa Dam Fishway. 81pp.