Quantifying and mitigating the impacts of weirs on downstream passage of native fish in the Murray-Darling Basin

Lee Baumgartner, Bronson McPherson, Jonathon Doyle, Frances Cory, Nestor Cinotti and Jamie Hutchison

Industry and Investment NSW
Narrandera Fisheries Centre
PO Box 182
Narrandera NSW 2700

February 2013

NSW Department of Primary Industries
Fisheries Final Report Series No. 136

ISSN 1837-2112

Quantifying and mitigating the impacts of weirs on downstream passage of native fish in the Murray-Darling Basin

February 2013

Authors: Lee Baumgartner, Bronson McPherson, Jonathon Doyle, Frances Cory, Nestor Cinotti and Jamie Hutchison
Published By: NSW Department of Industry and Investment
Postal Address: PO Box 180, Narrandera, NSW, 2230
Internet: www.dpi.nsw.gov.au

© NSW Department of Primary Industries and Murray-Darling Basin Authority

This work is copyright. Graphical and textual information in the work (with the exception of photographs and departmental logos) may be stored, retrieved and reproduced in whole or in part, provided the information is not sold or used for commercial benefit and its source (*Quantifying and mitigating the impacts of weirs on downstream passage of native fish in the Murray-Darling Basin*) is acknowledged. Such reproduction includes fair dealing for the purpose of private study, research, criticism or review as permitted under the Copyright Act 1968. Reproduction for other purposes is prohibited without prior permission of the Murray-Darling Basin Authority, NSW Department of Industry and Investment or the individual photographers and artists with whom copyright applies.

DISCLAIMER

The publishers do not warrant that the information in this report is free from errors or omissions. The publishers do not accept any form of liability, be it contractual, tortuous or otherwise, for the contents of this report for any consequences arising from its use or any reliance placed on it. To the extent permitted by law, the copyright holders (including its employees and consultants) exclude all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this report (in part or in whole) and any information or material contained in it.

ISSN 1449-9967

ACKNOWLEDGEMENTS

This report was completed as part of the funding requirements of the Murray-Darling Basin Commission project, ‘the Downstream Mortality of Native Fish’; as part of the Native Fish Strategy

A steering committee comprising Adam Vey, Brenton Zampatti, Brian Cooper, Heath Robinson, Martin Mallen-Cooper, Matt Barwick, Jocelyn Karsten, Tom Davy and Janet Pritchard provided guidance throughout the project and during the preparation of this document.

Technical staff contributing to fieldwork included Justin Stanger, Mick Bettanin, Chris Smith, Jarrod McPherson, Duncan McLay and Garry Graf. The authors would also like to thank Erol Bradbury for constructing experimental equipment. Les Rava and Stewart Watters are gratefully thanked for transporting fish to and from the study site.

Bruce Malcolm (Uarah Fish Hatchery) and Ian Charles (Silverwater Fish Hatchery) provided adult Murray cod and Silver perch for experiments. Norm Boyd and Danny Bourke from Lock 10 (Murray River) assisted with the collection of golden perch for use in adult fish trials. David Sly and John McNeil assisted with the collection of small-bodied native fish from Lock 8 (Murray River).

Finally, we would like to thank Drs Craig Boys, Bob Creese and Janet Pritchard for their useful comments on initial drafts.

All work reported in this document was undertaken in accordance with Animal Care and Ethics Permit (ACEC 04/08).

1. EXECUTIVE SUMMARY

An estimated 10,000 dams and weirs are currently installed throughout the Murray-Darling Basin. Weirs were previously thought to only impair movements of upstream moving fish attempting to spawn or recolonise new habitat. The constructions of these structures have been widely implicated in widespread declines of native fish. Recently, studies also demonstrated that weirs represent barriers to downstream movement and could be responsible for large-scale fragmentation of native fish communities.

Two major weir designs, undershot and overshot, are constructed on Australian waterways. Undershot weirs are usually characterised by steel gates where water is released underneath the weir. Overshot weirs usually contain concrete or wooden dropboards and water cascades over the weir crest. Many weirs that were constructed in the early 1900’s were of overshot design but are currently being upgraded to undershot designs to comply with safety requirements and to minimise maintenance. Each weir delivers water in a substantially different way. Undershot weirs are characterised by high velocity, turbulence and sudden pressure changes. Overshot weirs have more gentle flow, but water can accelerate to high velocities when falling from a great height. Fish attempting to pass either type of weir could be subjected to a range of different hydraulic forces. This study sought to quantify whether these presented any welfare concerns for native fish in the Murray-Darling Basin.

A controlled field study sought to determine the impacts of downstream passage of each weir type into low and high tailwater conditions under a range of simulated discharges. Experiments were replicated over different life history stages of seven native fish species commonly recorded in the Murray-Darling Basin. Passage through the more traditional overshot weirs was associated with substantially greater survival in all species. Few fish died and the main welfare issues arose when overshot weirs discharged into shallow water. Under these conditions fish were physically injured when impacting with the downstream weir apron. These results indicate that the construction of overshot weirs with deep plunge pools would provide safe conditions for many fish species and sizes moving downstream.

Large proportions of golden perch (>90%) and silver perch (> 90%) larvae died during undershot weir passage. Murray cod larvae (> 50% mortality) were also substantially impacted. Small-bodied native fish such as Australian smelt and unspecked hardyhead displayed extremely high mortality (>90%) when passing through undershot weirs. Adult life stages of large-bodied species were also affected by undershot weirs but to a much lesser degree, with adult golden perch (82%, n=100), silver perch (70%, n=100) and Murray cod (32%, n=100) suffering minor injuries when passing through small gate openings. Computational Fluid Dynamics determined that undershot weirs were characterised by higher values of shear, turbulence and pressure changes. Hydraulic modifiers were subsequently retrofitted to undershot gates to try and reduce biological impacts. Unfortunately none of the trials successfully mitigated effects.

The findings of this new study are particularly relevant for the Basin given that over 80% of main channel weirs in most inland rivers now use automated undershot weirs as the primary water delivery mechanism. Continuing upgrades to undershot weir structures in smaller creeks and tributaries will certainly improve water delivery efficiency, but may substantially increase incidences of injury and mortality of native fish over a large spatial scale. Options to design and retrofit undershot weirs with ‘fish friendly’ hydraulic modifiers should be explored to minimise these threats to native fish. Alternatively, assessing the applicability of stationary screens may represent a useful mechanism to prevent fish entrainment and subsequent injuries. It is important that any such structure could protect all life history stages and have applicability over a large spatial scale. A long-term and large scale mitigation program could then provide substantial improvements to fish throughout the Murray-Darling Basin.

2. GENERAL INTRODUCTION

The Murray-Darling Basin

The Murray-Darling Basin is Australia's largest catchment covering over one million square kilometres and draining water from five separate states and territories. Its main constituent is the Murray River (2,560 km), which rises in the alpine regions of Southern NSW and meets the sea at the Coorong estuary in South Australia (Walker, 1985). The Darling River is the second largest drainage system in the Basin and rises as the Condamine River in Queensland and joins the Murray near Wentworth, approximately 700 km from the sea. Although the Darling River is greater in length (2,740 km), in most years it contributes much less total discharge than the Murray River (Walker, 1985).

Most of the Murray-Darling Basin represents a typical dryland river system. Much of the catchment is located in semi-arid to arid climatic zones and receives low mean annual rainfall (430 mm) with high evaporation (King, 2002). Ninety-eight percent of the catchment contributes little or no run-off, and subsequently, the system has a relatively small annual discharge (12,200 GL) (Crabb, 1997). Despite such relatively low discharge, the Murray-Darling Basin supports at least 40% of Australia's agricultural production (MDBC, 2003) and a population of over 2 million people (Jacobs, 1990). It is therefore an extremely important natural resource in Australia.

Since European settlement, increased river regulation has fundamentally changed the nature of flows within the Murray-Darling Basin. Flow peaks historically occurred in winter and spring (Walker, 1985) but now more frequently occur in summer, coinciding with increased irrigation demand. These flows are regulated by over 100 storages that have been constructed along the Murray and its tributaries, including a series of barrages at the tidal limit. Seventeen of these weirs were constructed on the main channel of the Murray River to increase navigability for boats and other recreational users. Consequently, the main channel of the Murray River is now characterised by a series of large fragmented weir pools with suppressed flow peaks and disrupted longitudinal connectivity (Walker, 1985).

To meet the increasing demands of both a growing population and a developing agricultural industry, individual state agencies began (in the late 1800s) to divert and store water from major rivers and their associated tributaries (Jacobs, 1990). However, Australian river catchments have low annual rainfall and highly variable flow. To subsequently ensure that required volumes of water were constantly available, at least 144 large dams were constructed on various rivers between 1900 and 1995 (Kingsford, 2000). In addition, numerous smaller regulatory structures were also constructed for diversion and storage purposes (Kingsford, 2000). It is likely that such a degree of development has had a substantial impact on the abundance and distribution of aquatic fauna.

Several reviews have identified a number of factors associated with river regulation that could adversely affect aquatic fauna, including obstructions to migration, modification of flow regimes, alteration of habitat and the extraction of larvae and recruits (Kingsford, 2000). Furthermore, many scientists have identified that aquatic communities in unregulated rivers of the Basin are generally characterised by greater levels of species richness and diversity than regulated rivers (Gehrke *et al.*, 1999; Gehrke and Harris, 2000; Gehrke and Harris, 2001). However, few researchers have specifically identified which ecological processes, interrupted by river regulation, contribute to these observed discrepancies. There are subsequently few data to assist the development of management strategies aimed at reducing the potential impacts of these irrigation practices on aquatic ecosystems.

Dams and weirs in the Murray-Darling Basin

Fish communities of the Murray-Darling Basin are highly migratory, exhibiting movements in both upstream (Reynolds, 1983; Mallen-Cooper and Brand, 2007) and downstream (Humphries *et al.*, 1999; Humphries *et al.*, 2002; Gilligan and Schiller, 2004; O'Connor *et al.*, 2004) directions. Until recently, fish migration studies within the Murray-Darling Basin focused primarily on species of recreational or commercial importance (Reynolds, 1983; Mallen-Cooper, 1996; Thorncraft and Harris, 2000). However, recent studies have also demonstrated that larval native fish also undertake substantial downstream movements (Humphries *et al.*, 1999; Humphries and Lake, 2000; Humphries *et al.*, 2002; Gilligan and Schiller, 2004; O'Connor *et al.*, 2005) and that many small-bodied species are also migratory (Stuart and Mallen-Cooper, 1999; Baumgartner and Harris, 2007; Stuart *et al.*, 2008). Therefore, the development of suitable measures to mitigate potential hazards to downstream movements of fish are required to enhance recruitment potential for native species in the Murray-Darling Basin.

The presence of dams and weirs has had a profound effect on both the abundance and diversity of Australia's inland fish communities (Walker, 1985; Mallen-Cooper, 1996; Mallen-Cooper and Copeland, 1997; Kingsford, 2000; Thorncraft and Harris, 2000). These structures create physical barriers that can prevent important spawning and recolonisation migrations (Lucas and Baras, 2001). In extreme cases, these can result in the extinction of species from upstream habitat (Pelicice and Agostinho, 2008). At Euston Weir on the Murray River, important recreational angling species such as Murray cod, golden perch and silver perch have declined in abundance by 96%, 51% and 94% respectively since weir construction (Mallen-Cooper, 1996). Previously, all migration of Australian freshwater fish was thought to be in an upstream direction and related directly to spawning. Subsequently, fishways were constructed to provide upstream passage. It is now apparent, however, that significant numbers of adult fish, in addition to eggs and larvae also undertake large-scale downstream movements {O'Connor, 2004; O'Connor, 2005}. With any type of migration, it is essential that fish are able to negotiate any barriers without delay or injury.

Two major weir designs, undershot and overshot, are constructed on Australian waterways. Undershot weirs are usually operated via steel gates and water is released underneath the weir. Overshot weirs are usually constructed from concrete or wood and water cascades over the weir crest. Undershot gates are operationally convenient and are widely-constructed on water development projects, particularly in tropical systems (Marttin and De Graaf, 2002). When operated to regulate floodplain inundation, large mortality rates are observed in cyprinid species in Bangladesh (Marttin and De Graaf, 2002). It has been suggested that increased use is partially contributing to declines of fish in floodplain habitats (Halls *et al.*, 1999). The impact of hydroelectric turbines on downstream survival of juveniles is well-accepted, but the impacts of other water delivery structures are unknown in many riverine systems. Studies of downstream losses also rarely investigate passage of larval fish or small-bodied adult fish. The most commonly-documented impacts on downstream passage are known for salmon smolt where losses through hydroelectric turbines are reportedly as high as 9-21% for Chinook salmon on the Columbia River (Mathur *et al.*, 1996). Mortality is often directly related to body size, with smaller fish exhibiting greater survival (Heisey *et al.*, 1996). These observations suggest that a combination of physical and hydraulic effects could be influencing fish which encounter obstructions during downstream migrations.

In Australia, many weirs that were constructed in the early 1900's were of overshot design and are currently being upgraded to undershot designs to comply with safety requirements and to reduce the need for maintenance. A series of recent small scale experiment on a low-level weir determined that undershot weirs contributed to high mortality of golden perch *Macquaria ambigua* (up to 95%) and Murray cod *Maccullochella peelii* (up to 52%) larvae which drifted through the structure (Baumgartner *et al.*, 2006). Mortality due to overshot weirs was substantially lower (1.5%) (Baumgartner *et al.*, 2006). These results demonstrate potentially catastrophic effects of undershot weirs on native fish populations but further research is needed to determine if such mortalities are equal across all species and size classes of native fish.

Sources of injury and mortality

The initial experiments suggested that some hydraulic or physical mechanism is responsible for the observed injuries, but this could not be identified. Studies on hydroelectric facilities have determined three major hydraulic characteristics which can adversely impact fish; pressure changes, physical strike and shear stress (Figure 1.1). All of these factors are relevant to work on low-level weirs but spatial variation in hydrology and weir design criteria suggest that critical values could vary substantially at individual sites. Changes in water delivery method, weir design, river hydrology and target fish species can create a complex series of interacting factors which could facilitate injuries but are difficult to isolate.

Pressure changes

The magnitude of pressure change experienced during downstream passage through a weir is highly dependent on both mode of operation (undershot and overshot) and structure height. Pressure linearly increases by one atmosphere with every 10 m increment in depth (Arlinghaus *et al.*, 2007; Deng *et al.*, 2007). For example, at four metres depth, you would experience a pressure of 1.4 atmospheres, at eight metres this would be 1.8 atmospheres. Weir height is therefore a factor which would hugely dictate expected pressure changes on fish migrating downstream. The impact of pressure changes on fish will also depend on the overall physiology of the target species (Arlinghaus *et al.*, 2007). Many species of fish contain swim bladders, which are gas filled structures necessary to control buoyancy. Rapid changes in pressure can alter swim bladder size in a relatively short amount of time leading to disorientation, loss of motor control or internal injury (Schreer *et al.*, 2009). The seriousness of these responses is largely determined by the physiological response to this rapid pressure change (Nichol and Chilton, 2006).

Passage via spillways is commonly associated with gas bubble trauma. This condition arises from super saturation of water with air and occurs when supersaturated gas dissolves into the tissues of the fish and form bubbles. These bubbles can restrict oxygen supply to tissues and also impair buoyancy in extreme cases. These values are critical when saturation exceeds 100%, which is common at the tailraces of high head dams (Weitkamp *et al.*, 2003). Both of these may not contribute to immediate mortality, but death can occur at a later stage if the situation does not correct.

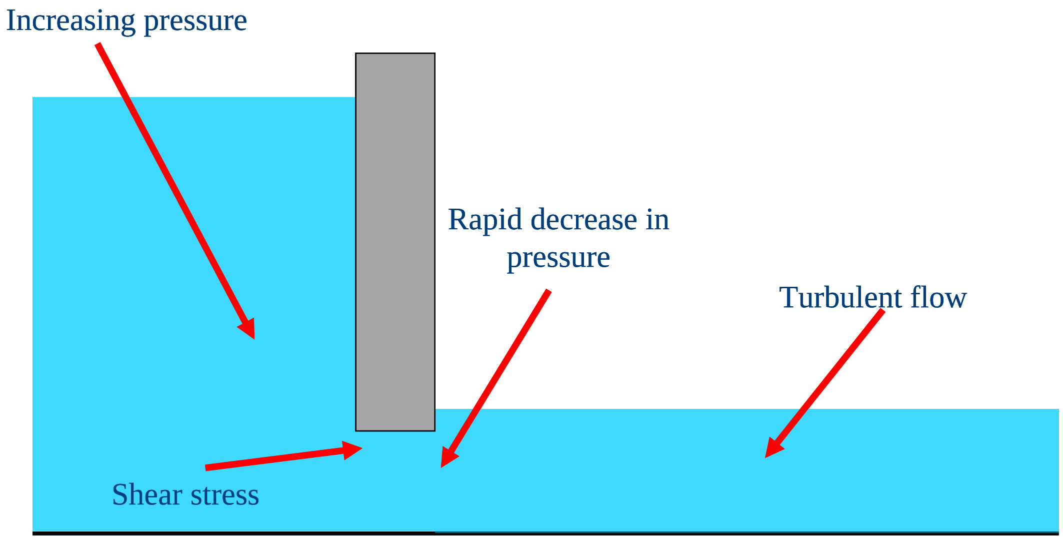


Figure 1.1. Simplified cross section of an undershot weir demonstrating areas where different hydraulic characteristics may impact fish migrating downstream.

Bony fish (teleosts) can be largely divided into two broad groups; physoclists and physostomes (Schreer *et al.*, 2009). Physostomous fish can be simply described as fish which have a physical connection between the swim bladder and intestinal tract. These fish have the advantage of being able to vent excessive swim bladder gas through a pneumatic duct which connects the swim bladder to the oesophagus (Fange, 1966). Physostomes, therefore, actively regulate the size of the swim bladder through ingestion and expulsion of air. This form of physiological regulation is therefore common in pelagic fish or those which inhabit relatively shallow habitats.

Physoclistous fish differ from physostomes by regulating swim bladder size physiologically (Fange, 1966). The pneumatic duct is present in the early stages of development but disappears as the fish grows. Gases regulating buoyancy are then retrieved from the bloodstream through specialised organs known as the gas gland and rete mirabile. These organs detect changes in the size of the swim bladder and exchange gases (either into or out of the swim bladder) through a network of capillaries on the posterior wall. When a fish changes depth, the swim bladder either inflates (in response to decreased external pressure) or deflates (in response to increased external pressure). The entire process takes a period of hours in response to even a relatively small pressure change.

In terms of weir design, the expected responses of physoclistous and physostomous fish to changing are expected to be different. Fish that can physically expel air through a pneumatic duct could theoretically expel any excess air resulting from rapid pressure changes whilst fish that cannot may experience barotrauma (Figure 1.2). Barotrauma is caused by the rapid and unregulated expansion of gas and fluid filled structures within the fish (Gravel and Cooke, 2008). Extreme cases of barotrauma include haemorrhaging or swim bladder distension which can often be fatal (Feathers and Knable, 1983; Hannah and Matteson, 2007). The maximum change in pressure, for undershot weirs, would be directly under the gates. At this point a fish would experience a change from maximum pressure (which is dependent on weirpool height) to a lower pressure which is dependent on tailwater depth. Fish could experience barotrauma-related injuries if these changes are severe.

Figure 1.2. A golden perch (*Macquaria ambigua*) affected by barotrauma. Note the distended abdomen and everted eyes. These injuries arise following a rapid transition from a high to low pressure area (Photo courtesy of Dr Karina Hall, I&I NSW).

Shear Stress

Shear is a natural phenomenon which commonly occurs in rivers and streams throughout the world (Cada, 2001). Shear stress occurs when two water masses of different velocities intersect or are adjacent to each other (Cada *et al.*, 1999). This most commonly occurs when masses of water collide, such as in a waterfall or rapid. Fish will often encounter shear stress many times but, in most incidences, changes are too small to cause problems (Cada *et al.*, 2007). It is only when shear stress is elevated above tolerable levels becomes a substantial problem for fish (Guensch *et al.*, 2002).

The viscosity of water is the major contributing factor to injuries on fish in areas of high shear (Cada *et al.*, 1999). A fish caught between two intersecting masses experiences a force, the size of which is determined by water velocity and weight. If the combined force exceeds the critical threshold that the fish can withstand, it will almost certainly be injured. The critical limits for fish vary considerably among and within species. For example, smaller fish may have a lower tolerance for certain values of shear stress than large fish. A fish could therefore have different thresholds for shear stress over its life and these potential differences create challenges when attempting to determine potential impacts over a range of species and size classes.

The effects of shear stress are most comprehensively understood for passage through hydro facilities. Estimates of injury and mortality are determined either by directly passing fish through a turbine or performing laboratory experiments in jet flumes. Direct passage through Kaplan-style turbines contributes to a maximum 5% mortality of fish under high shear conditions (Cada *et al.*, 2007). Jet experiments identify that exposure to extreme shear stress (with masses interacting at over 20 m.s^{-1}) contributed to gill damage and internal injuries in 0+ rainbow trout (*Onchorhynchus mykiss*) (Guensch *et al.*, 2002). In some instances, fish were initially only injured and mortality was delayed (Deng *et al.*, 2005).

Extreme values of shear could be expected downstream of undershot weirs, where large volumes of water are released at a high velocity. High shear stresses could be expected at the upstream edge of the undershot gate but magnitude would depend on weir height and gate opening dimensions. Higher weirs with large gate openings may be characterised by increased localised shear at the gate edge. Susceptibility to injury for downstream migrants would be largely determined by the proximity of passage to this critical area. Fish that pass closely are likely to exhibit high shear stresses and could be injured. Few studies have effectively quantified shear values for undershot gates. The magnitude of resultant forces and the potential to create injury are therefore largely unknown for many species and size classes of freshwater fish.

Physical Strike

Many instances of fish injury during downstream passage arise from physical strike. Physical strike basically refers to situations where a fish comes into contact with an object such as a turbine blade, weir wall, dissipation sill or spillway. The probability of sustaining an injury from blade strike is dependent on many factors. Disorientation is a major contributor and fish can lose mobility control during downstream passage in high velocity or turbulence conditions. Jet propulsion studies conducted under laboratory conditions have identified this as a common occurrence for salmon smolts (Guensch *et al.*, 2002). During disorientation, fish can come in contact with the weir apron, or other downstream obstacles. Injuries occur if this impact occurs at a high velocity or with increased force.

Injury associated with passage through overshot and undershot weirs is a likely artefact of weir design and operation. Discharge into low tailwater environments could be associated with increased impact injuries arising from direct contact with the downstream apron or dissipater sills. Weirs with high discharges, and increased velocities, could increase the potential for impact with the weir crest or gate. The severity of injuries would be dependent on fish size and discharge volume. There are few data on operating scenarios which contribute to injuries or mortality arising from physical strike at low-head installations and this presently precludes the development of suitable mitigation options.

The purpose of this study

Previous work identified potential adverse impacts arising from downstream passage through undershot weirs, but this work was limited to two species from a single life history stage at a very low head installation (Baumgartner *et al.*, 2006). A major knowledge gap was whether similar situations existed at higher head installations, for other fish species or for different life history stages. The purpose of this study was to obtain data that could be generalised over a larger scale to identify if injuries associated with downstream passage through low-level weirs present a substantial fish welfare issue in the Murray-Darling Basin. A key aspect of this project was to use computational fluid dynamics (CFD) modelling to investigate potential sources of injury. Modelling parameters such as pressure differentials, shear stresses, velocity and turbulence may help to link observed fish injuries with environmental parameters. Acquiring this information could help to inform the development of appropriate mitigation measures. Finally, if low-level weirs were found to substantially impair the welfare of native fish, and CFD modelling helped to identify sources, then field assessments of potential mitigation techniques would be required. The present study therefore sought to develop and field-validate several retrofit options which, if successful, could be considered for wider application throughout the Murray-Darling Basin.

2. GENERAL METHODS

Study Site

The Murrumbidgee River is a highly regulated stream incorporating eight weirs (Ebsary, 1992) and draining 86,467 km^2 (Harris and Gehrke, 1997) from its source to its confluence with the Murray River. The weirs were constructed for domestic water supply, stock water supply, irrigation, re-diversion to irrigation areas and effluent streams. Balranald Weir is the most downstream barrier on the Murrumbidgee River. It is located approximately 6 km west of the Balranald township (Figure 2.1) and is a drop-board regulated structure measuring 40 m long and 3.7 m high. The weir is primarily used for stock and domestic water supply and presents a barrier to fish passage at flows up to 4,500 ML.day^{-1}. Once flows exceed this level, all drop-boards are removed and free passage is restored.

The weir incorporates a Deelder fishlock (Baumgartner and Harris, 2007). The Balranald fishlock is 14 m long x 1.5 m wide x 3 m deep and includes low-flow and high-flow entrance gates and one exit gate, each of which is 400 mm wide (Figure 2.2). A primary entrance gate (the low-flow gate, Gate 1) is 3 m downstream of the high-flow gate and is operated when Murrumbidgee River flow is less than 1,200 ML.day^{-1}. A secondary entrance gate (Gate 2) is 5m upstream toward the weir crest and is used under high-tailwater conditions (flow greater than 1,200 Ml.day^{-1}) until the weir is drowned out. The exit gate (Gate 3) is located at the most upstream point in the lock chamber and can be adjusted vertically to control flow through the exit gates.

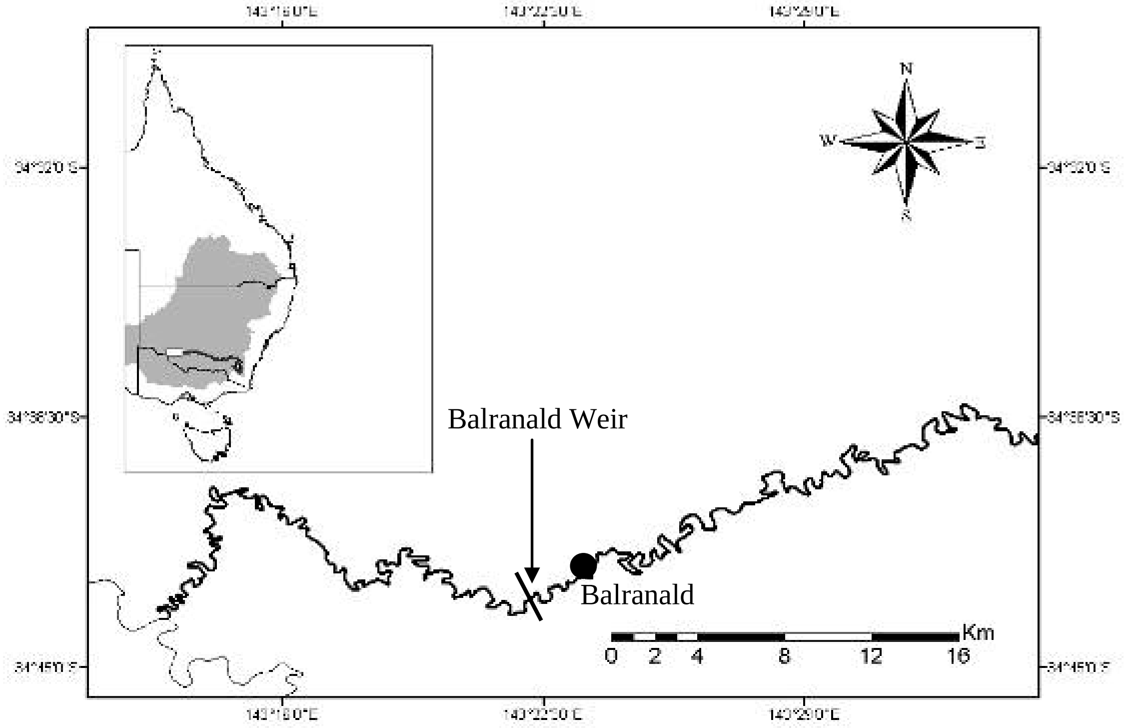


Figure 2.1. Map of the Murrumbidgee River showing the location of the Balranald study site

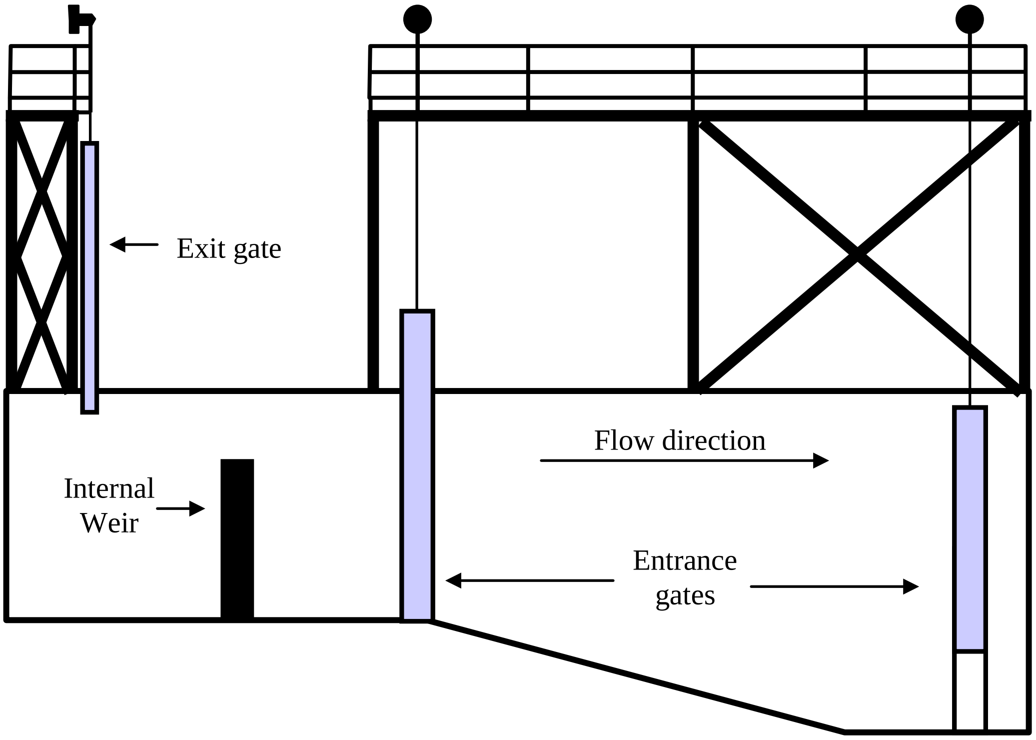


Figure 2.2. Cross sectional representation of the fishlock at Balranald Weir.

Users can switch the fishlock to manual operation and have full control over gate openings and internal water levels. An adjustable internal weir within the lock chamber was also available for manual operation by the project team (Figure 2.2). The weir was constructed out of wooden drop boards and adjustable up to a height of 2.8 m. The use of wooden boards allowed the weir to be operated in either undershot or overshot configuration. Gate openings and flows over the crest could therefore be manipulated in a controlled environment.

Weir Experiments

Experiments were conducted between September 2006 and April 2010. Work was performed during warmer months (December to April) to control for any potential effect of low water temperature on fish welfare. Seven species were used in the trials and work focused on fish that are widely distributed throughout the Murray-Darling Basin. Three species, golden perch *Macquaria ambigua*, Murray cod *Maccullochella peelii* and silver perch were investigated at three different life history stages (adult, juvenile and larvae). The remaining four species were Australian smelt *Retropinna semoni*, Murray-Darling Rainbowfish *Melanotaenia fluviatilis,* Unspecked hardyhead *Craterocephalus stercusmucarum* and carp gudgeon *Hypseleotris* spp. Experiments were only undertaken on adult specimens for these species.

Fish could not be obtained from a single supplier and were sourced from three main locations. Large-bodied adults were obtained from either private hatcheries (silver perch and Murray cod) or vertical slot fishways at Lock 7, 9, and 10 on the Murray River (golden perch). Small-bodied adult fish were collected from a vertical slot fishway located at Lock 8 on the Murray River. Juvenile fish and larvae were sourced from the native fish hatchery located at Narrandera Fisheries Centre. Prior to experimentation, fish were transported to the experimental site in specialised fish transport tanks (800 L) which were aerated and filled with river water. Fish were housed in rearing troughs (larval, juvenile and small-bodied adults) or holding nets (large-bodied adults) and given 24 hours to acclimatise prior to experimentation. Prior to experimentation fish were checked for signs of stress or injury arising from handling and transport. Only visibly healthy fish were used in the trials.

The required experimental setup was configured and fish were then moved to the experimental facility. Fish were introduced upstream of the internal weir and a large fyke net (7 m long x 1.5 m wide x 1.5 m high; 6 mm mesh or 500 um mesh) was installed on the downstream side to collect all experimental fish. After five minutes, all flow through the structure was stopped, the net retrieved and all fish were removed. Surviving fish were placed into the original housing whilst dead fish were measured, weighed and preserved for later analysis in the laboratory. Each treatment required 5 replicates, using 50 fish from each species. The only exception was adult Murray cod, golden perch and silver perch where only 20 fish were used per replicate.

Overshot experiments

Overshot experiments involved replicated tests assessing the impact of head on weir and tailwater depth on successful downstream passage. Experiments sought to determine the precise sources of injury or mortality to influence the future design of overshot-style weirs. In overshot weir situations, injuries can occur from two sources, (1) through physical contact with the weir during passage or (2) via hydraulic processes acting downstream (i.e. shear stress or turbulence). Two experimental factors were considered for subsequent assessment, head on the weir (as this influences the probability of physical strike on the weir crest) and tailwater depth (as this influences the "cushioning" effect of water as it falls from the crest). To determine the full effect of these factors on fish mortality, four experimental treatments were assessed (Table 2.1). The influence of weir head was assessed at heights of 50 mm and 200 mm to determine if increasing water level at the crest influenced survival. Tailwater depth was assessed at two depths (100 mm and 500 mm) to assess any potential improvements to the rate of injury and mortality.

Undershot experiments

Experiments of a similar nature were performed for undershot gate configurations to determine sources of mortality. For undershot gates, injury can occur either during passage through the gates (i.e. where fish are subjected to shear and pressure changes) or on the downstream side when fish are subjected to turbulence and may physically strike the downstream apron or dissipation sills. Undershot gates were assessed using a combination of two different gate openings (200 mm or 50 mm). Each gate opening was assessed under two different tailwater depths (500 mm and 100 mm). These depths were chosen as representations of commonly-used openings at installations throughout the Murray-Darling Basin.

Post Processing

At the conclusion of each experimental treatment, dead fish were immediately placed on ice and later autopsied to identify the probable cause of death. All surviving fish were inspected for obvious signs of external injury then transferred to one of two holding locations. Small-bodied fish and larvae were held in larval rearing troughs (80 L) which were supplied with fresh river water. Large-bodied fish were held in holding cages within the adjacent Balranald weirpool. Fish from each treatment were individually held for a maximum of 2 hours post experimentation. After this period all fish were pooled within a common holding net for a period of up to 5 five days. These fish were then transferred to a vehicle and transported back to Narrandera Fisheries Centre. No fish were re-used in any further experiments.

Table 2.1. A summary of experimental design for both undershot and overshot experiments. This design was repeated for all seven species. Murray cod, golden perch and silver perch were assessed (5 replicates) at adult, juvenile and larval stages but other species (Murray rainbowfish, Australian smelt, unspecked hardyhead and carp gudgeon) were only assessed at an adult stage.

Overshot	High head on weir (200 mm)	Low head on weir (50 mm)
High Tailwater (500 mm)	5 replicates	5 replicates
Low Tailwater (100 mm)	5 replicates	5 replicates

Undershot	High gate opening (200 mm)	Low gate opening (50 mm)
High Tailwater (500 mm)	5 replicates	5 replicates
Low Tailwater (100 mm)	5 replicates	5 replicates

It was impossible to ensure that any batch of fish used in the experiments were of identical size. However, size of the fish may have a substantial influence on its ability to survive downstream passage. Prior to experimentation, a sub-sample of 100 fish from each batch were measured and weighed to determine the length and weight statistics of the sample population. After each experiment was completed, all injured and dead fish were also measured and weighed. This approach enabled a comparison of injured fish with the initial sub-sample to statistically determine any significant size-related effects.

Hydraulic Improvement experiments

Previous investigations suggested that shear and turbulence could be major contributors to injury and mortality. These observations were based on initial studies where large numbers of fish were decapitated when recaptured after passing through undershot weirs (Baumgartner *et al.*, 2006). Decapitation could have arisen from two sources, operating together or independently. Firstly, high amounts of shear at the interface between the weirpool and undershot gate could have been sufficient to injure fish at this critical point. Secondly, increased shear and directional changes experienced in the tailwater region could have created critical forces on fish.

Experiments were undertaken to determine the influence of modifying the hydraulics of undershot weirs to reduce injuries and mortality. This work involved retrofitting hydraulic modifiers to an undershot gate and the downstream apron. The first solution was a hydraulic streamliner. The streamliner was a semicircular half pipe which was fitted on the weirpool side of the gate. The purpose of the streamliner was to reduce shear stress at the weirpool and gate interface. By removing the sharp edge, it was intended to produce a more laminar flow under the gate.

The second solution was an attempt at removing turbulent flow on the downstream side. A flow deflector was retrofitted to the base of the apron (900 mm long; 1:3 slope). The idea was to create laminar flow in the tailwater immediately downstream of the weir. This would have the benefit of reducing shear and also creating laminar flows in the tailwater which would remove potential sources of stress on fish during downstream passage.

Experiments were undertaken to determine the relative success of these hydraulic modifiers. Four experimental treatments were performed on juvenile silver perch and golden perch sourced from the Narrandera Native Fish Hatchery (Figure 2.3). An initial treatment involved establishing the experimental facility with neither the streamliner nor deflector present to establish a baseline understanding of injury and mortality processes. Treatments were established with only the streamliner present, and then with only the deflector present to assess the relative effectiveness of each modifier (Figure 2.4). Finally, a treatment was established with both the streamliner and deflector present, to determine the combined impact of retrofitting both at once.

Each treatment was replicated five times with 50 fish from each species. Fish were released immediately upstream of the undershot gate and recaptured downstream in a large fine-mesh fyke net (10 m long X 6 mm mesh). Fish were given five minutes to pass through the structure and were then collected and transferred to holding troughs where assessments of injury and mortality were completed. All fish were measured, weighed and any dead fish were preserved for an autopsy at a later date. Fish were monitored for a total of six hours post experimentation and were then transferred to a large holding tank for transportation back to the Narrandera Fish Hatchery.

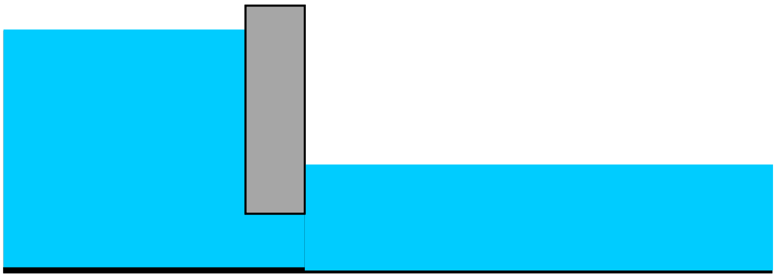
Computational Fluid Dynamics Modelling

Software

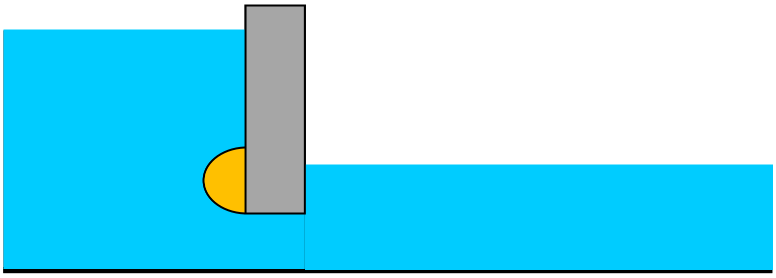
ANSYS-CFX was used to simulate the undershot and overshot weirs hydraulic characteristic. ANSYS-CFX is used extensively in aerodynamic, hydrodynamic and many other industrial applications. The software has been extensively tested and good results have been obtained where comparisons have been made between physical data, theoretical test cases and other software packages. ANSYS-CFX is capable of simulating large, highly complex models with a large number of physics interactions. Such interactions include structures and mechanical devices, radiation and chemical reactions, multiphase flow, selection of numerous turbulence models and the specification of various boundary conditions.

This software solves the required governing equations in three dimensions on an irregular/unstructured mesh as well as on a regular/structured mesh. The selection of an unstructured and/or structured mesh depends on the need to resolve geometrical detail as required without increasing the manual intervention to resolve such detail, which coupled with the use of high resolution numerics allows the solution of rapidly varying dynamics with good accuracy.

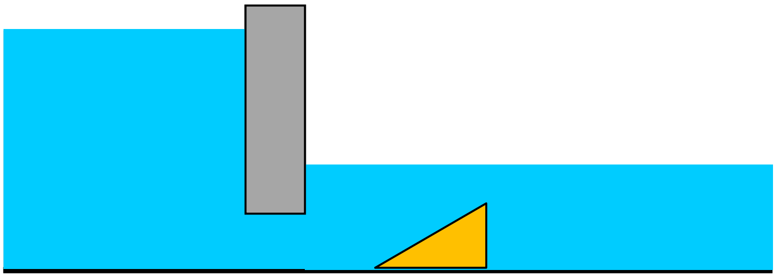
CFX v-12 was used to investigate the hydraulic characteristics of the various weir configurations including additional features such as flow streamliner and flow deflector.



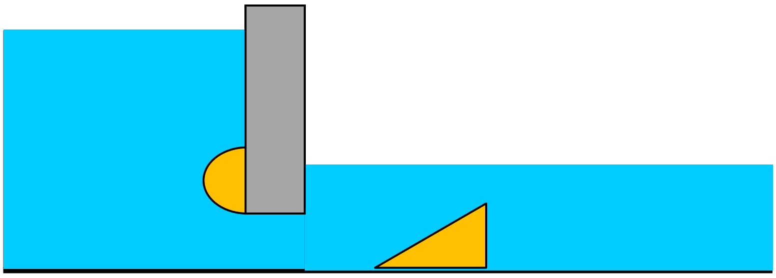
No streamliner / No deflector



Streamliner / No Deflector



No Streamliner / Deflector



Streamliner / Deflector

Figure 2.3. Diagrammatic representation of the experimental treatments used to assess the success of a hydraulic bumper and dissipater sill for reducing injury and mortality associated with downstream passage (specific dimension criteria are given in Appendix 1).

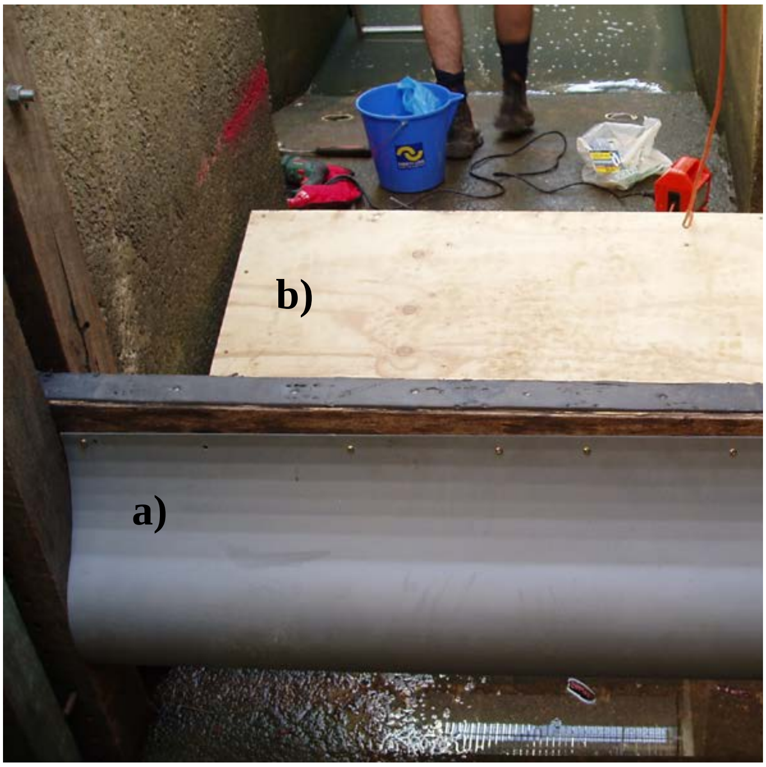


Figure 2.4. Photo showing the actual retrofitting locations of the streamliner (a) and flow deflector (b) used in the mitigation trials within the fishlock at Balranald Weir.

Table 2.2 Analysis Configuration and Boundary Conditions of the Weirs

Flow Case	Gate/Weir Type	Gate Opening/ Weir Height [O] (mm)	Depth over Crest at Upstream Edge [d_c] (mm)	Headwater Depth [d_h] (mm)	Tailwater Depth [d_t] (mm)
1	Undershot	50	-	2700	100
2	Undershot	200	-	2700	100
3	Undershot	50	-	2700	500
4	Undershot	200	-	2700	500
5	Undershot with U/S flow streamliner	200	-	2700	100
6	Undershot with D/S flow deflector	200	-	2700	100
7	Undershot with U/S flow streamliner and D/S flow deflector	200	-	2700	100
8	Overshot	2650	50	2700	100
9	Overshot	2500	200	2700	100
10	Overshot	2650	50	2700	500
11	Overshot	2500	200	2700	500

Velocities and pressures are calculated in selected locations of interest. Streamlines, flow patterns, shear strain rate profile, and general hydraulic behaviour in the immediate areas upstream and downstream of the gate/weir are also shown graphically. The results obtained are based on various experimental configurations of the experimental weir setup (Table 2.2). Inlet and outlet boundaries were extended further from the design specification to improve numerical stability.

Meshing

Meshing is an integral part of the computational fluid dynamics process. In order to solve the partial differential equations that govern fluid flow, the volumetric flow region is split into smaller volumes. Each of these small volumes is known as an element or cell, and the collection of all elements is known as a mesh or grid. Greater detail was focused in the vicinity of the gate opening, flow streamliner and flow deflector, and impact region for the overshot weir where the presence of high velocities could affect the flow behaviour. Away from the weir/gate, velocities are relatively slow and flow behaviour relatively straightforward so less mesh resolution was required. Additional resolution was used across the interphase between the air and the water to maximise the efficiency of the numerical simulation, as the mesh resolution influences the accuracy, convergence and speed of the solution. In addition to the standard program of flow cases, some additional scenarios were run with a finer mesh around the weir/gate opening, flow streamliner and flow deflector. This study was performed with the intention of investigating the sensitivity of the solution in relation to the mesh resolution. It was determined that as the mesh was further refined, the solution was relatively unchanged.

Fluid, air and water properties

The Eulerian-Eulerian multiphase free-surface model was used to resolve the air and water interphase. The non-homogeneous multiphase option was set to resolve any air entrainment of one phase within another phase that occurs when the flow passes the weir for the overshot configuration and possibly to resolve a hydraulic jump when a low gate opening/high tailwater condition is present. The air phase component of the free surface model was modelled as air STP at 25°C with a constant pressure of 1 atmosphere. Water was the main fluid of interest in this study and it was modelled at 25°C with a density of 997.0 kg/m^3 and dynamic viscosity of $8.899e^{-4}$ kg/m.s.

Turbulence Model

Turbulence consists of fluctuations in the flow field in time and space when inertial forces in the fluid become significant compared to viscous forces. To predict this complex unsteady fluctuation of the fluid flow process, turbulence models are used. In this study, the two equation Shear Stress Transport (SST) turbulence model was used. The SST model has proven to be stable and numerically robust for a well established regime of predictive capability.

Inflow, Outflow and Symmetry

An opening hydrostatic boundary was used at the entrance of the lock fishway with a specified headwater depth of 2.7 m. Water could enter and leave the domain freely to maintain the correct dynamic balance. In order to correctly develop a free surface, the air above the water surface was maintained at one atmosphere. To do this an opening boundary was used to allowed free passage of air in and out of the domain. An opening hydrostatic boundary was used at the exit of the lock fishway using a specified tailwater depth following the different flow scenarios. Symmetry boundary condition was used to simulate only a section of the lock fishway geometry. The symmetry plane boundary condition imposes constraints that ‘mirror’ the flow on either side of it, setting the velocity component and scalar variable gradients normal to the boundary plane to be zero.

Model Verification

The purpose of verification tests is to guarantee that the physical model and the numerical implementation of the CFD analysis were performed correctly. The verification procedure normally involves the comparison of the numerical results against analytical and/or experimental solutions for the exact studied case or similar case configuration.

Undershot Gate/Sluice Gate

The formula used to calculate the discharge coefficient (Cd) through a sluice gate was based on results of previous research (Kim 2007, Table 2.3a).

Table 2.3a. Sluice Gate Formulas

Discharge Coefficient (Cd)	$Cd = Q/(a*b*(2*g*h_1)^{1/2})$	Cd: discharge coefficient a: gate opening h_1: approach flow depth b: width (0.5m)

The selected geometrical configuration and the value of the discharge coefficient was obtained from the analysis performed by Kim (2007; Table 2.3b). Kim (2007) also reported various discharge coefficients obtained by previous experimental and theoretical investigations.

Table 2.3b. Geometrical Configuration and Discharge Coefficient

a (m)	**h_1 (m)**	**a/h_1**	**Cd**
0.05	0.5	0.1	0.598

The discharge coefficient value, Cd, computed in this test was 0.601. This value is in close agreement with the reported Cd value by Kim, and Rajaratnam et al. (1967) (Table 2.3b).

Overshot Gate/Thin Plate Weir

The verification for the overshot gate is based on theoretical values from the Australian Standard (1991; Table 2.4). The formulas include contraction coefficient (Ce), effective head (h_e) and discharge coefficient (Cd) through a thin plate weir.

Table 2.4. Thin Plate Formulas from the Australian Standard (1991)

Contraction Coefficient (Ce)	$Ce = 0.602+0.083*(h/p)$	h: measured head, in metres p: height of crest relative to the floor, in metres
Effective Head (h_e)	$h_e = h+0.0012$	h: measured head, in metres
Discharge Coefficient (Cd)	$Ce = Q/((2/3)*(2*g)^{1/2}*b_e*(h_e)^{3/2})$	Ce: coefficient of discharge b_e: effective width (0.5m) h_e: effective head Q: Discharge

The computed value of discharge coefficient (Cd) obtained from the numerical simulation were compared against a calculated theoretical value of Cd following the formulas from section 9.7.1 of the Australian Standard (1991; Table 2.5).

Table 2.5. Computed Values from Numerical Simulation

h (m)	**p (m)**	**Q (m^3/s)**	**h_e (m)**	**Cd**
0.2	2.5	0.092	0.2012	0.6957

The calculated theoretical value is 0.6086. The discrepancy in the discharge coefficient value is explained by the difference in the geometrical configuration for the weir crest. The Australian Standard uses a 1 mm to 2 mm width crest, while the weir used in this study is a square notch with a 75 mm width crest. Therefore, another analysis was performed following the dimensions of the thin weir crest from the Australian Standards (1991), and the computed value of discharge coefficient (Ce) (Table 2.6). The new computed Ce value is in close agreement with the calculated theoretical value from the Australian Standard (1991).

Table 2.6 Computed Values Using the Geometry from the Australian Standard (1991)

h (m)	**p (m)**	**Q (m^3/s)**	**h_e (m)**	**Ce**
0.2	2.5	0.081	0.2012	0.611

Data Analysis

Data were analysed using S-PLUS (Insightful Corporation, 2000). Significant differences in mortality rates among treatments were investigated using Analysis of Variance (ANOVA) models. A four-Way design was used to investigate differences in mortality rates arising from passage through undershot and overshot weirs for the three large bodied species investigated (silver perch, golden perch and Murray cod). Factors used included weir configuration (undershot or overshot), gate/crest height (200mm opening or 50mm opening), tailwater depth (100 mm or 500 mm) and life history stage (larval, juvenile or adult). A three-way design was adopted to investigate mortality of small-bodied native fish (Murray rainbowfish, unspecked hardyhead, Australian smelt and carp gudgeon). Tests sought to identify differences in mortality rate arising from weir configuration (undershot or overshot), gate/crest height (20 0mm opening or 50 mm opening), tailwater depth (100 mm or 500 mm). Differences in mortality rate arising from use of hydraulic modifiers were also examined using three-way ANOVA. Factors investigated were treatment (deflector and streamliner; no deflector no streamliner; no deflector and streamliner, no deflector and streamliner), gate depth (200 mm or 5 0mm) and tailwater depth (500 mm or 100 mm). Cochran's tests identified homogenous variances but Quantile-Quantile plots suggested non normality within the data. All tests were subsequently performed on log (x+1) transformed data.

Two-tailed Kolmogorov-Smirnov tests (Sokal and Rohlf, 2001) were used to compare lengths of fish with mortal injuries with actual lengths of fish used in the trials. For the purpose of the present study, length-frequency analysis revealed whether the empirical distribution functions for dead and surviving fish were relatively similar. All statistical tests were considered significant at $p < 0.05$.

3. RESULTS

Murray cod, silver perch and golden perch

Large bodied fish trials were successfully completed on golden perch, silver perch and Murray cod. There was little variation in mean length and weight of species used in these trials (Table 3.1). Golden perch used in overshot trials were slightly larger than those used for undershot trials. Silver perch and golden perch were most affected during downstream passage. Adults displayed higher short-term survival but sustained some injuries (Figure 3.1). Mortality increased in juvenile life history stages but was greatest for larvae (Figure 3.1). Murray cod demonstrated an overall resilience to the effects of downstream passage through weirs. Relative to other species, mortality was generally low for both weir configurations but was manifest during early life history stages (Figure 3.1). A significant interaction between weir type and gate/crest depth largely arose from increased larval mortality during passage into shallow tailwater (Table 3.2).

Significant differences in mortality rate for each species were significantly influenced by weir design, gate/weir crest depth, tailwater level and life history stage (Table 3.2). For all three species, mortality was substantially greater from undershot weir configurations. However, significant interactions suggest that responses were inconsistent among factors largely because responses differed among life history stages. For instance, adult-related mortality associated with passage through either weir configuration was relatively low for all species (Figure 3.1). The highest mortality was observed in golden perch during passage through overshot weir treatments. No overshot mortality was observed in Murray cod or silver perch and undershot mortality was less than 5%. Only one treatment, high undershot gate discharges into low tailwater, was associated with no mortality from any of the three species.

The majority of welfare issues for adult fish arose largely from injuries associated with downstream passage through undershot weirs. Larger proportions of golden perch (82% and 77%) and silver perch (70% and 72%) were injured when passing through undershot gates with small openings regardless of tailwater level (Table 3.3). Injuries predominantly arose from damage to the body/operculum or by a combination of several injury types (Table 3.3). Injuries ranged from small cuts or minor bruising to large lacerations with visible haemorrhaging. Downstream passage through low opening undershot gates also contributed to injuries sustained by Murray cod (32% and 40%) although to a lesser degree. Substantially fewer injuries were observed from all three species during overshot operation. The most injuries were observed during high discharges into low tailwater. Under this mode of operation, silver perch (57% injured) were most affected. Murray cod sustained more injuries when higher discharges were released through the weir (Figure 3.1).

Autopsies were carried out on 42 adult large-bodied fish (Golden perch n = 37; Silver perch n = 3; Murray cod n = 2) to determine any obvious mortal injuries. Most dead golden perch were retrieved from undershot (n = 21) treatments. In these cases the most obvious injury was internal bleeding, which appeared due to rupture of the dorsal aorta. There were also instances of severe bruising (n = 6) and damage to major organs (n = 2). Golden perch injured through overshot passage displayed bleeding into the abdominal cavity (n = 7) and also bruising in the dorsal musculature (n = 6). A small number of fish (n = 3) also displayed some degree of organ damage. All silver perch and Murray cod died during undershot passage. Silver perch experienced a dorsal aorta rupture (n = 1) and spinal damage (n = 2). The two dead Murray cod had severe internal bruising.

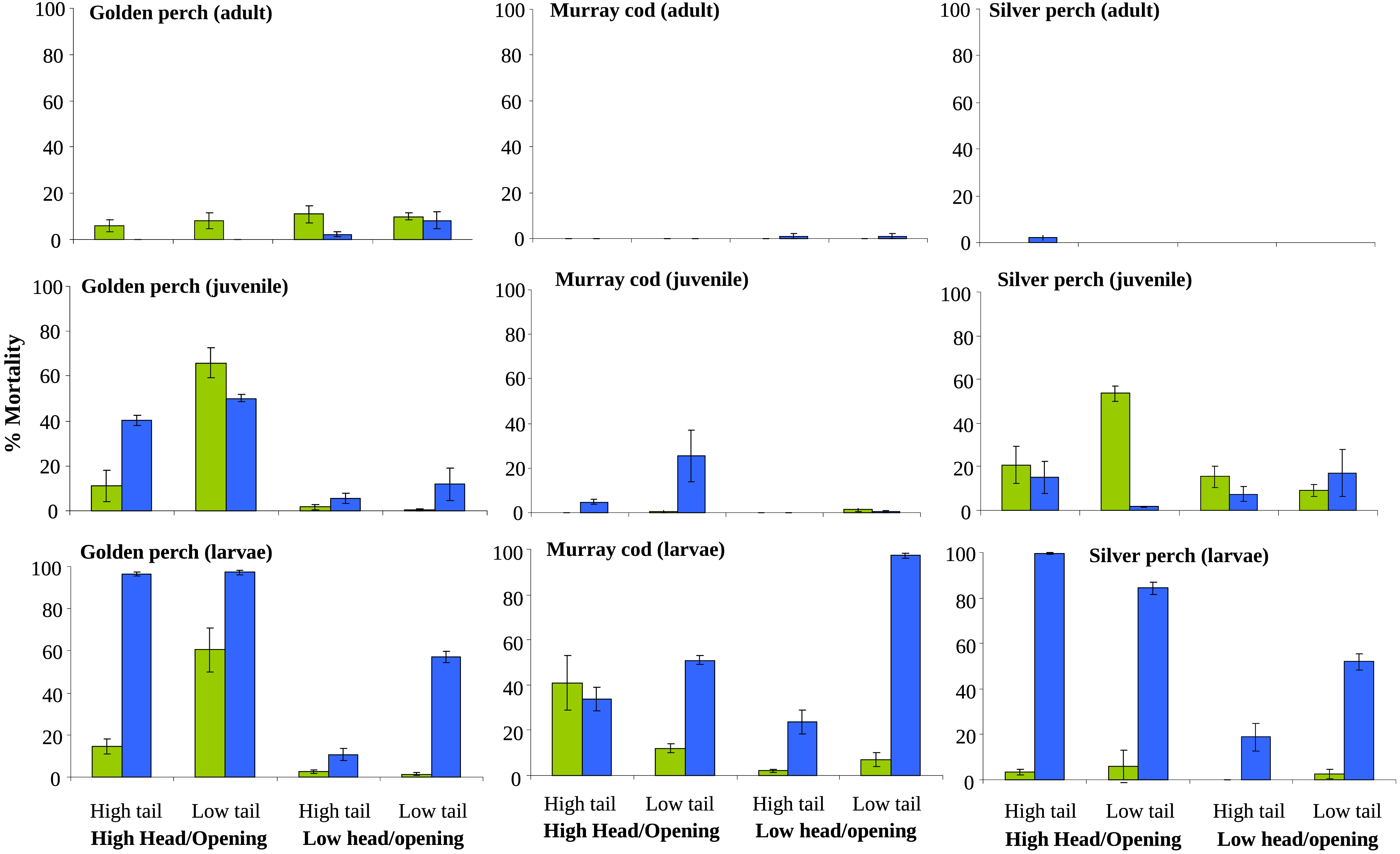
Table. 3.1. Summary of length and weight statistics for adult Murray cod, golden perch and silver perch used in experimental weir trials. * Asterisks denote where fish used to generate the sample statistic were drawn from the same hatchery population.

Species	**Mean Length (mm) ± SD**	**Min (mm)**	**Max (mm)**	**Mean Weight (g) ± SD**	**Min (g)**	**Max (g)**
Overshot						
Golden perch	412 ± 52	246	565	1144 ± 499.00	192.00	3208.00
Murray cod*	351 ± 20	304	456	511.36±128.00	190.00	787.00
Silver perch	296 ± 27	250	440	408.52± 109.58	236.00	1017.00
Undershot						
Golden perch	392 ± 42	319	526	904.85± 397.12	329.00	2662.00
Murray cod*	351 ± 20	304	456	511.36± 128.00	190.00	787.00
Silver perch	293 ± 24	242	415	401.09± 104.03	228.00	1049.00

Table 3.2. Outcomes of a 4-factor analysis of variance investigating differences in mean mortality of silver perch, golden perch and Murray cod explained by weir configuration (W; undershot or overshot), gate/crest depth (GC; 200mm or 50mm), Tailwater depth (T; 500mm or 100mm), Life history (LH; larval, juvenile or adult). Only F values are given and results are interpreted as * = p < 0.05, ** = p < 0.01, *** = p < 0.001. Non significant results are shown as ns. .

Treatment	**df**	**Silver perch**	**Golden perch**	**Murray cod**
W	1	15.68***	10.37***	79.69***
GC	1	30.59***	31.11***	47.60***
T	1	6.72**	11.34***	6.99***
LH	2	169.82***	60.65***	232.92***
W * GC	1	8.31***	15.07***	4.09*
W * T	1	11.86***	4.96*	2.98ns
GC * T	1	0.04ns	1.42ns	0.64ns
W * LH	2	68.34***	44.12***	20.72***
GC * LH	2	14.75***	53.06***	21.46***
T * LH	2	12.70***	1.11ns	1.83ns
W * GC * T	1	24.67***	7.16***	4.90*
W * GC * LH	2	4.96***	4.20*	13.56***
W * T * LH	2	1.53ns	5.56***	1.54ns
GC * T * LH	2	0.80ns	8.93***	0.16ns
W * GC * T * LH	2	3.16*	4.41*	12.58***
Residuals	96			
Sum of Squares	9.42			
Mean Sq	0.09			

Figure 3.1. Average mortality rate (± one standard error) of adult, juvenile and larval fish passing through undershot and overshot configurations of the experimental weir. Overshot samples are green, undershot samples are blue.



Responses of juvenile fish were largely species specific. Although some similarities existed between golden perch and silver perch, there was no consistent pattern to observed mortality rates among species. The most obvious similarity was that mortality associated with small head openings and crest depths was relatively low for all species (Figure 3.1). A small increase was observed during discharges into low tailwater conditions. In general, the highest degree of mortality for all species was associated with passage during large gate openings and crest depths. Under this scenario, mortality was greatest during overshot operation into shallow tailwater. Golden perch, however, also exhibited relatively high mortality during passage through undershot configurations.

Highest levels of mortality were observed in passage of larval golden perch and silver perch particularly at undershot gates (Figure 3.1). Passage through an undershot weir with a large opening, regardless of tailwater depth, had the greatest impact and higher mortality. Passage through undershot weirs, with small openings into shallow tailwater, was also associated with increased injuries in all three species (Figure 3.1). Overshot survival was relatively high in all treatments except during discharges into low tailwater where Murray cod larvae were particularly susceptible to injuries. There was no significant effect of gate/crest discharge or tailwater depth for any species (ANOVA Table 3.2). Observed mortality for these three species therefore appears to be more closely-related to weir design or life history stage rather than to specific gate openings. Effects of tailwater depth and life history stage were only observed in silver perch, largely due to increased mortality under low tailwater conditions, especially during larval and juvenile phases.

Small-bodied natives

There was little variation in lengths or weights of small bodied fish. However, mean lengths and weights of Australian smelt and unspecked hardyhead were slightly higher in undershot experiments (Table 3.4). Although a wide size range of fish was used, no individuals used in the trials were smaller than 20mm. The minimum weight across all species was 0.06 g.

All four small-bodied species were extremely susceptible to injury and mortality during passage through large opening undershot weirs (ANOVA: Table 3.5; Figure 3.2). Unspecked hardyhead and Australian smelt were most susceptible (Figure 3.2; > 85% mortality). Passage through undershot weirs with small gate openings was much lower although both unspecked hardyhead and Australian smelt demonstrated some intolerance to shallow tailwater levels (ANOVA: Table 3.5; Figure 3.2).

Mortality during passage through overshot weirs was substantially smaller among all species. Highest mortality occurred during passage over a deep crest depth (Figure 3.2). Australian smelt and unspecked hardyhead exhibited the greatest impact, with high mortality occurring during passage through undershot weirs with large gate openings (< 60%; Figure 3.2) Passage through small opening undershot weirs was associated with substantially reduced mortality in all species (Figure 3.2).

Survival was much higher during passage through overshot weirs and low opening undershot weirs regardless of tailwater level. Australian smelt and unspecked hardyhead displayed high mortality during passage through increased crest depths (Figure 3.2). Mortality rates associated with all other overshot treatments were substantially reduced in all species (<5%).

Table 3.3 Summary of fish health characteristics associated with passage through all configurations of the experimental weir. Specific injuries relate to fin damage (FD), scale loss (SL), wounds on body or operculum (BO) or combinations of these injuries (MI). The total number that died (DD) and fish which displayed no injury (NI) are also shown.

Species	**FD**	**SL**	**BO**	**MI**	**DD**	**NI**	**% Dead**	**% Injured**	**% No injury**
Undershot - Low Opening, Low Tailwater									
Golden perch	3	4	30	45	11	7	11	82	7
Murray cod	6	7	13	6	0	68	0	32	68
Silver perch	0	9	35	26	0	30	0	70	30
Total	**9**	**20**	**78**	**77**	**11**	**105**	**3.67**	**61.33**	**35.00**
Undershot - Low Opening, High Tailwater									
Golden perch	0	26	27	24	1	22	1	77	22
Murray cod	2	12	14	12	2	58	2	40	58
Silver perch	1	7	27	37	0	28	0	72	28
Total	**3**	**21**	**41**	**49**	**2**	**184**	**0.67**	**38.00**	**61.33**
Undershot - High Opening, Low Tailwater									
Golden perch	2	30	5	1	0	62	0	38	62
Murray cod	1	0	10	1	0	88	0	12	88
Silver perch	4	3	36	10	0	47	0	53	47
Total	**7**	**5**	**53**	**11**	**0**	**224**	**0.00**	**25.33**	**74.67**
Undershot - High Opening, High Tailwater									
Golden perch	0	7	3	1	0	89	0	11	89
Murray cod	0	0	3	0	0	97	0	3	97
Silver perch	0	2	40	4	2	52	2	46	52
Total	**0**	**3**	**50**	**4**	**2**	**241**	**0.67**	**19.00**	**80.33**
Overshot – Shallow Crest, Low Tailwater									
Golden perch	2	1	12	3	10	72	10	18	72
Murray cod	0	3	3	0	0	94	0	6	94
Silver perch	1	3	19	0	0	77	0	23	77
Total	**3**	**7**	**34**	**3**	**10**	**243**	**3.33**	**15.67**	**81.00**
Overshot – Shallow Crest, High Tailwater									
Golden perch	5		16	0	11	68	11	21	68
Murray cod	3	2	1	0	0	94	0	6	94
Silver perch		2	21	0	0	77	0	23	77
Total	**8**	**5**	**38**	**0**	**11**	**270**	**3.31**	**15.36**	**81.33**
Overshot -Deep crest, Low Tailwater									
Golden perch	7	1	17	3	8	64	8	28	64
Murray cod		2	11	1		86	0	14	86
Silver perch	2	19	20	16		43	0	57	43
Total	**9**	**22**	**48**	**20**	**8**	**224**	**2.42**	**29.91**	**67.67**
Overshot- Deep Crest, High Tailwater									
Golden perch	3	2	6	1	6	82	6	12	82
Murray cod	1	8	6	1		84	0	16	84
Silver perch		1	17	2		80	0	20	80
Total	**4**	**11**	**29**	**4**	**6**	**253**	**1.95**	**15.64**	**82.41**

Table 3.4. Length and weight statistics for adult small-bodied fish used in experimental trials.

Species	Ave Length (mm)	Min Length (mm)	Max Length (mm)	Mean weight (g)	Min (g)	Max (g)
Overshot						
Australian smelt	34 ± 4	25	47	0.19 ± 0.07	0.08	0.41
Murray rainbowfish	47 ± 8	35	84	1.06 ± 0.74	0.40	6.10
Unspecked hardyhead	27 ± 6	20	47	0.19 ± 0.16	0.06	0.98
Carp gudgeon	35 ± 6	26	50	0.42 ± 0.19	0.14	0.87
Undershot						
Australian smelt	39 ± 3	29	49	0.27 ± 0.06	0.16	0.50
Murray rainbowfish	47 ± 8	35	84	1.06 ± 0.74	0.40	6.10
Unspecked hardyhead	30 ± 4	23	54	0.21 ± 0.10	0.11	0.90
Carp gudgeon	35 ± 6	26	50	0.42 ± 0.19	0.14	0.87

Table 3.5. Outcomes of a 3-factor analysis of variance investigating differences in mean mortality of silver perch, golden perch and Murray cod explained by weir configuration (W; undershot or overshot), gate/crest depth (GC; 200 mm or 50 mm), Tailwater depth (T; 500 mm or 100 mm). Only F values are given and results are interpreted as * = p < 0.05, ** = p < 0.01, *** = p < 0.001. Non significant results are shaded.

Treatment	df	Unspecked hardyhead	Carp gudgeon	Murray rainbowfish	Australian smelt
W	1	5.81*	53.27***	15.65***	4.82*
GC	1	57.46***	76.22***	124.56***	151.30***
T	1	1.49ns	0.02ns	0.98ns	31.11***
W * GC	1	9.14***	31.25***	17.83***	3.70ns
W * T	1	0.81ns	0.01ns	1.51ns	0.15ns
GC * T	1	0.48ns	3.31ns	0.10ns	21.07***
W * GC * T	1	2.31ns	0.06ns	0.37ns	1.71ns
Residuals	32				
Sum of Squares	4.41				
Mean Sq	0.13				

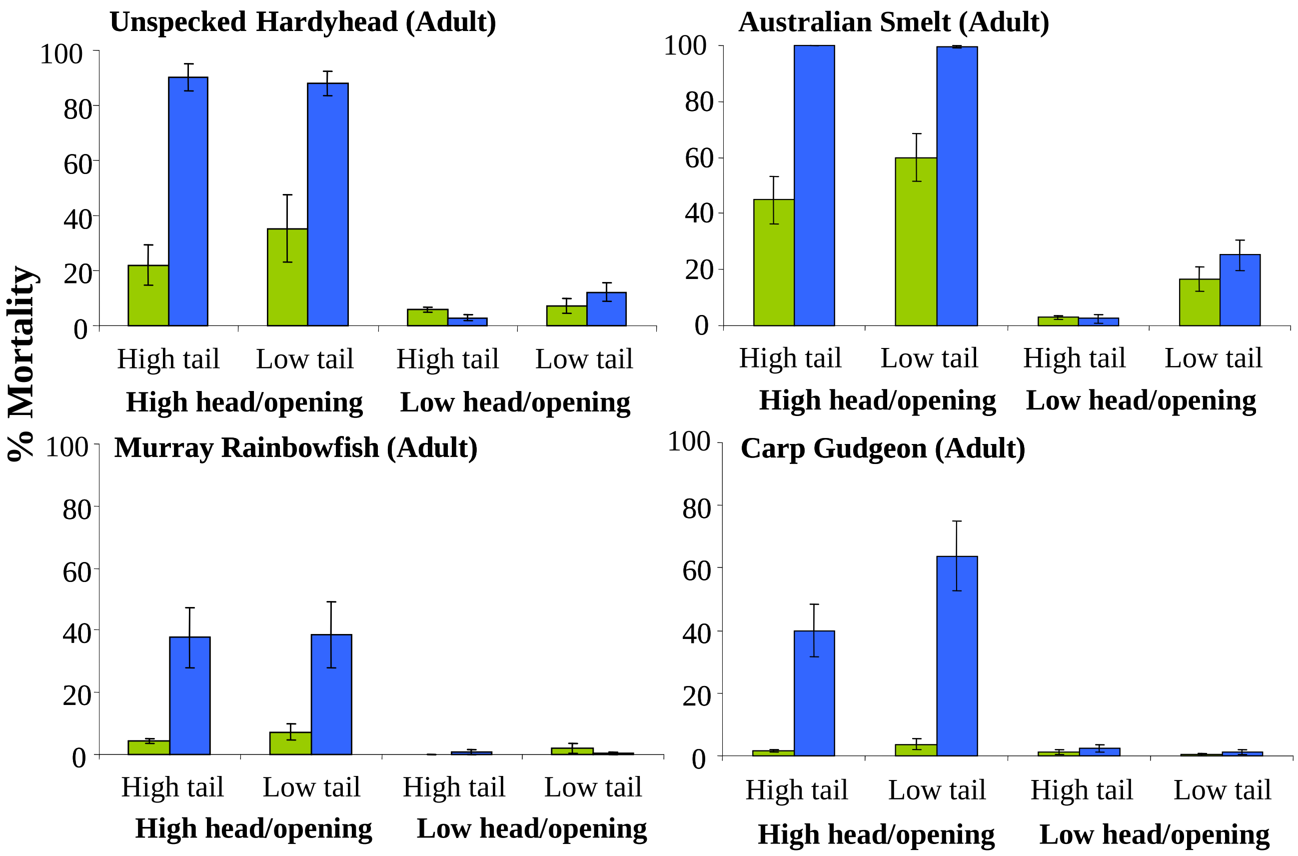


Figure 3.2 Average mortality rate (± one standard error) of larval fish (< 60mm) passing through undershot and overshot configurations of the experimental weir. Overshot samples are green, undershot samples are blue.

Table 3.6. Outcomes of a 3-factor analysis of variance investigating differences in mean mortality of silver perch and golden perch during hydraulic modifier trials. Factors are treatment (DS; deflector and streamliner; no deflector no streamliner; no deflector and streamliner, no deflector and streamliner), gate depth (G; 200 mm or 50 mm), Tailwater depth (T; 500 mm or 100 mm). Only F values are given and results are interpreted as * = p < 0.05, ** = p < 0.01, *** = p < 0.001. Non significant results are shaded.

Treatment	**df**	**Silver perch**	**Golden perch**
DS	3	39.03***	10.11***
G	1	14.40***	88.33***
T	1	3.34ns	4.41**
DS * G	3	6.12***	1.53ns
DS * T	3	2.95*	.45**
G * T	1	10.92**	2.84ns
DS * G * T	3	0.44ns	3.00***
Residuals	64		
Sum of Squares	9.42		
Mean Sq	0.09		

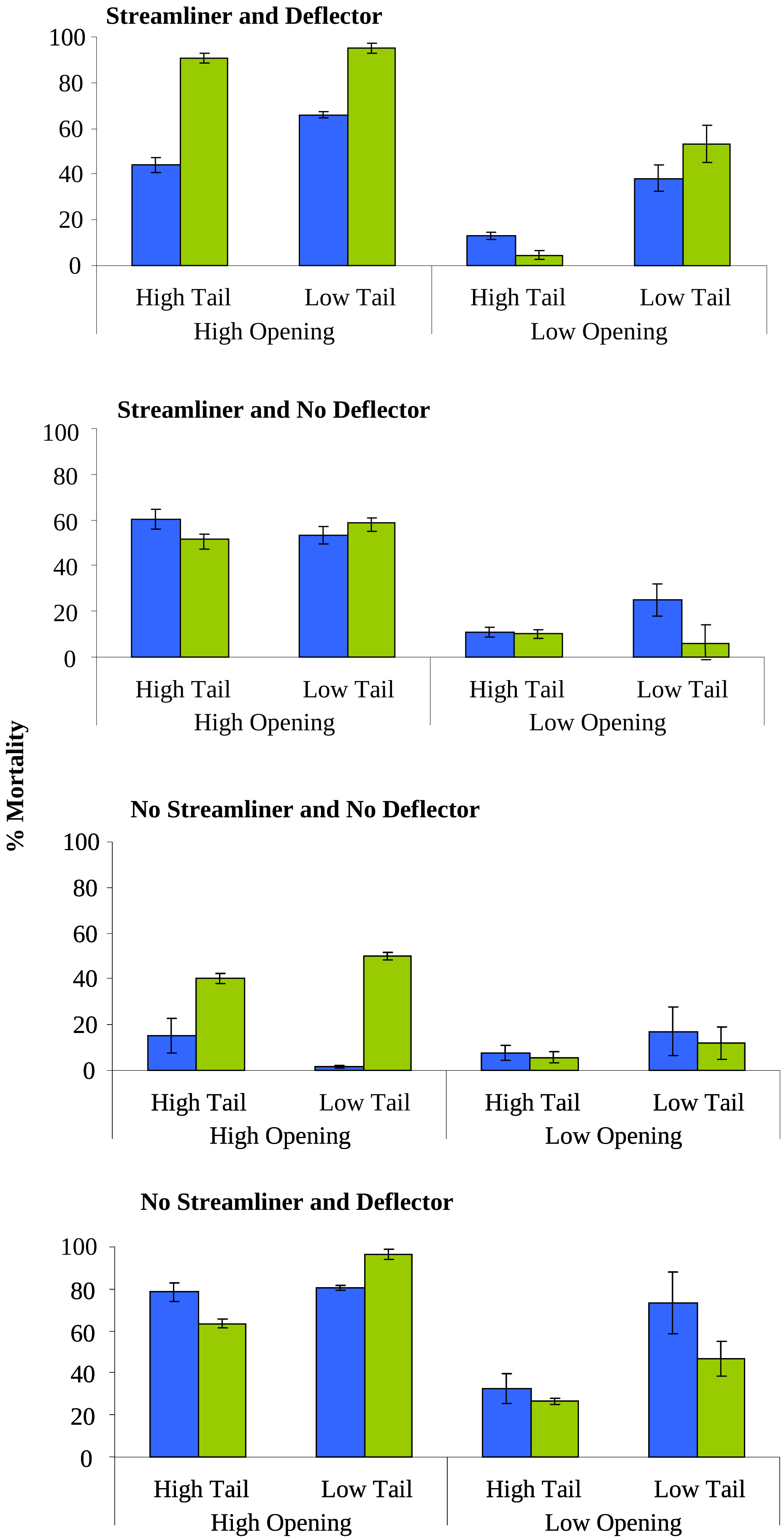
Hydraulic Modifiers

Golden perch and silver perch exhibited similar responses to hydraulic improvements to undershot gates. The most obvious observation was that the introduction of hydraulic modifiers failed to substantially reduce mortality rates. In some instances, mortality actually increased (Figure 3.3). The four treatments yielded relatively similar responses in both silver perch and golden perch, although golden perch were generally more sensitive to changes. Mortality rate significantly differed among treatment types in both silver perch and golden perch (3-way ANOVA; Table 3.6). The magnitude of mortality differed substantially among treatments but was greatest when the streamliner was removed and the deflector was present. Significant differences were associated with gate opening distance in both species (3-way ANOVA; Table 3.6). Values were substantially greater during downstream passage through high gate openings but observed responses were not consistent among treatments. Significant interactions between treatment type and gate opening arose because mortality of both species was significantly greater when the flow deflector was present and stayed high whether or not the streamliner was installed or removed (Figure 3.3).

Tailwater depth had a significant impact on survival of golden perch but not silver perch (3-way ANOVA; Table 3.6). In general, mortality increased as tailwater depth decreased. Significant interaction terms suggested that tailwater did influence survival of silver perch but only during certain gate openings (3-way ANOVA, Table 3.6). When no streamliner was present, mortality substantially increased under low tailwater conditions (Figure 3.3). These observations demonstrate that observed mortality is not easily explained by a single factor. There are often complex interactions under different hydraulic conditions which can greatly influence the survival of native fish. These can be better understood by specifically investigating changes in mortality rates for each of the different experimental treatments.

Control conditions, with no deflector and no streamliner, identified substantial impacts of high opening undershot gates on golden perch. Both silver perch and golden perch also displayed increased mortality with low gate openings into low tailwater conditions. Installing both the streamliner and deflector increased mortality in all treatments. High gate openings were associated with substantial mortality in both species although golden perch was most affected. Mortality also increased when low gate openings were discharged into low tailwater, but was largely unchanged in high tailwater situations. These responses were observed across all size classes in each species and there were no observed differences in the length of dead or surviving fish (Silver perch, KS = 0.113; $p > 0.05$; Figure 3.4; Golden perch KS = 0.189; $p > 0.05$; Figure 3.5).

Mortality substantially increased when the streamliner was removed and the deflector installed. Both species exhibited substantial increases in mortality especially in response to high gate openings. Low gate openings into low tailwater created increased mortality. This effect was partly mitigated under elevated tailwater conditions. This treatment facilitated increased mortality in smaller individuals in silver perch (KS = 0.238, $P < 0.001$) but no size-specific effect was observed in golden perch (KS = 0.346, $P < 0.001$). Experiments with the streamliner present, but deflector absent, lead to increased survival in both species relative to the other treatments. However, survival was still much lower than in control treatments. High gate openings again impacted upon the welfare of both species. Lower tailwater levels exhibited reduced mortality in golden perch, but still facilitated mortality in silver perch. Reduced survival of smaller silver perch (KS = 0.321, $P < 0.001$) were also observed but no size differences in golden perch were detected.



Streamliner and Deflector

Streamliner and No Deflector

No Streamliner and No Deflector

No Streamliner and Deflector

Figure 3.3. Interaction plots of mortality associated with gate opening distance and tailwater level for each of the four experimental treatments. Results are given for golden perch (blue) and silver perch (green).

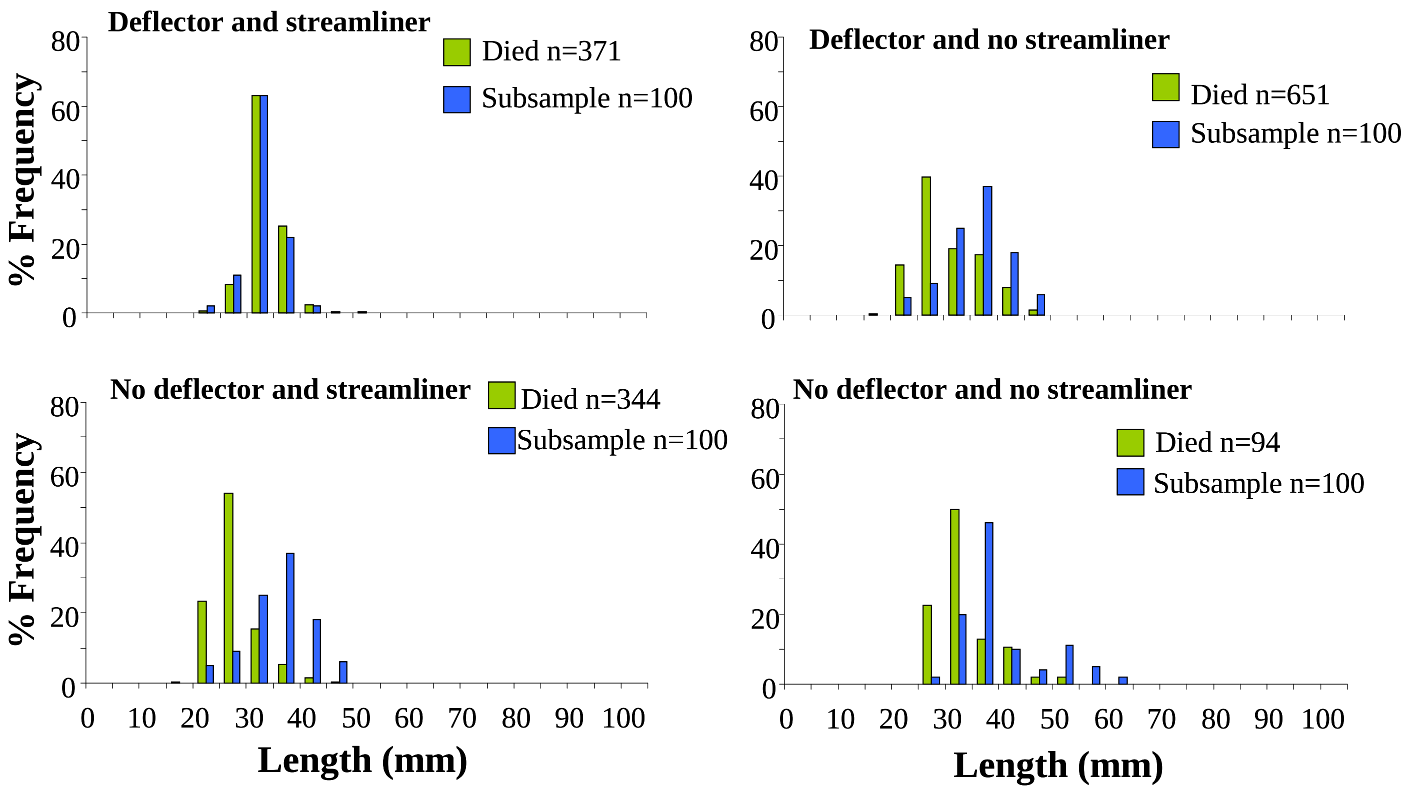


Figure 3.4. Length frequency statistics for silver perch that died during passage through each of the four hydraulic improvement trials compared to a subsample of surviving fish.

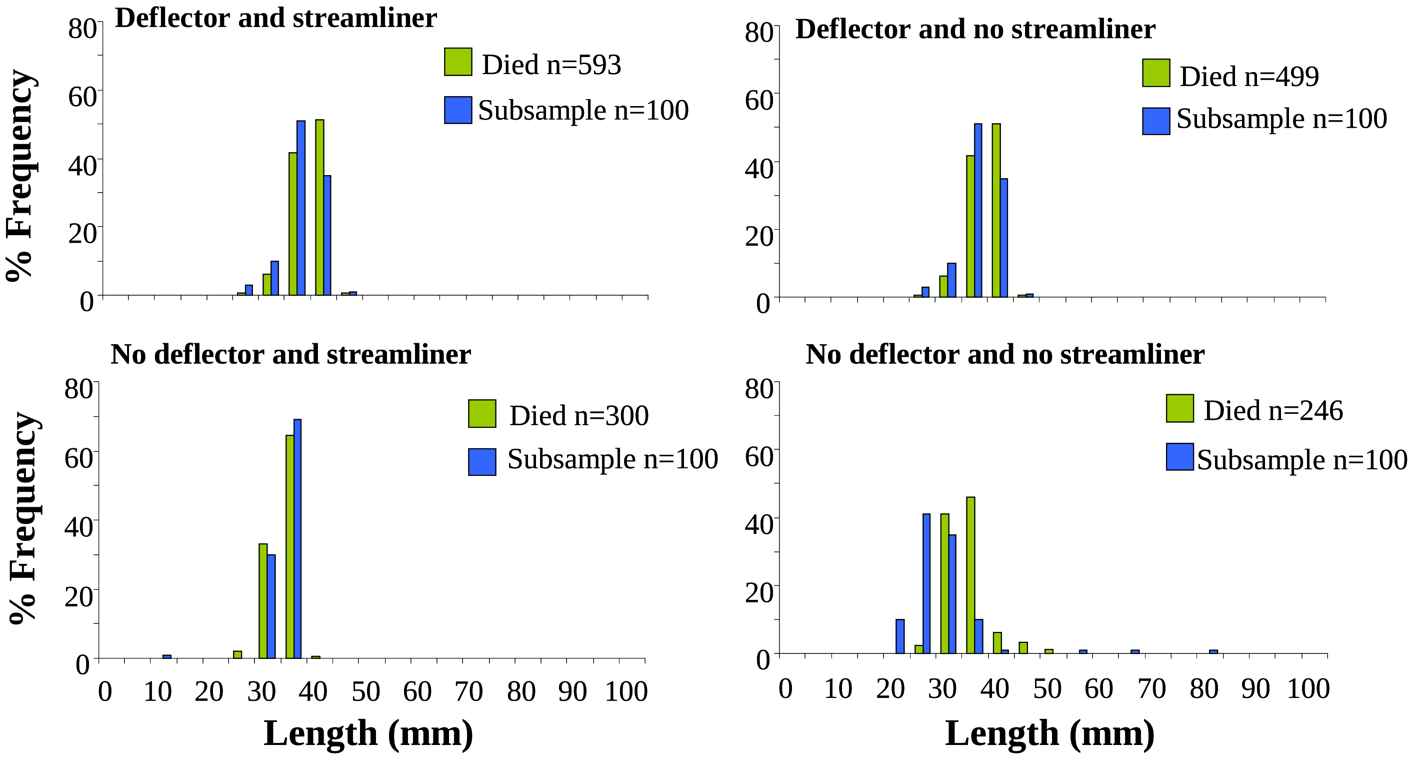


Figure 3.5. Length frequency statistics for golden perch that died during passage through each of the four hydraulic improvement trials compared to a subsample of surviving fish.

CFD Modelling

Modelled flow values varied substantially among the different treatments and were greatest when undershot weirs were retrofitted with downstream flow deflectors. Under these scenarios overshot weirs had the lowest flow rates, although the high crest depth exhibited flows comparable to low opening undershot weirs (Table 3.7).

Undershot Gate/Sluice Gate Flow

The hydraulic characteristic of the undershot gate system was investigated for two gate openings, 50 mm and 200 mm respectively. Headwater depth of 2.7 m was maintained constant, while the tailwater depth was set at two different values, 100 mm and 500 mm. Seven streamlines at different elevations starting from 50 mm up to 2600 mm representing the flow path throughout the length of the undershot gate system were used to calculate pressure, velocity and shear strain rate profiles. Information on flow patterns, velocities, pressure and shear strain rate were calculated through the system. Figures presenting more detailed information of the hydraulic characteristic of undershot gate systems can be found in Appendix A.

Gate Opening of 50 mm

A pressure change from 27 kPa to 0 kPa occurs from upstream to downstream of the gate as water passes through the gate opening (Figure 3.6). The system also experiences an increase in velocity levels from 0-1 m/s upstream of the gate with a rapid increase of velocity as the flow crosses through the gate opening (up to 8.5 m/s). The flow then gradually experiences a drop in velocity as it flows downstream (Figure 3.8). Shear strain rate around the gate opening depicts a 2600 mm elevation streamline flow path (SL at 600 mm). There is a large size area of shear strain (400 to 450 s^{-1}) close to the upstream bottom front edge corner of the gate and inside the gate opening. At 2600 mm elevation the shear strain is reported at 420 s^{-1} (Figure 3.10)

Table 3.7 Flow Results for Different Gate Openings/Weir Heights

Flow Case	Gate/Weir Type	Flow Rate per Width (ML/day/m)	Flow Rate per Width (m^3/s/m)
1	Undershot (50mm opening)	20.74	0.24
2	Undershot (200mm opening)	76.04	0.88
3	Undershot (50mm opening)	20.74	0.24
4	Undershot (200mm opening)	76.04	0.88
5	Undershot with flow streamliner	116.64	1.35
6	Undershot with flow deflector	76.04	0.88
7	Undershot with flow streamliner and deflector	111.46	1.29
8	Overshot (50mm crest depth)	1.73	0.02
9	Overshot (200mm crest depth)	16.42	0.19
10	Overshot (50mm crest depth)	1.73	0.02
11	Overshot (200mm crest depth)	16.42	0.19

Gate Opening of 200 mm

Longitudinal variation in pressure and velocity profile varied greatly for undershot gates. For this gate opening, the pressure change from upstream to downstream of the gate goes from 27 kPa down to 2 kPa as the flow crosses through the opening (Figure 3.7). The system also experiences an increase in velocity levels from 0-1 m/s upstream of the gate with rapid increase of velocity as the flow crosses through the gate opening, recording a velocity value around 7.1 m/s. The flow maintains a steady velocity level as it moves downstream of the gate (Figure 3.9). There is a small to medium sized area of shear strain approaching the bottom front edge corner of the gate (150 to 250s^{-1}), following a rapid change of shear with a value of 500s^{-1} located at the upstream bottom edge of the gate (Figure 3.11). The 2600 mm elevation streamline flow path travels close to this high shear strain region reporting a value around 310s^{-1}.

Overshot Gate/Thin Plate Weir

Headwater depth of 2.7 m was maintained constant, while the tailwater depth was set at two different values, 100 mm and 500 mm. Seven streamlines at different elevations starting from 50 mm up to 2600 mm representing a flow path throughout the length of the overshot gate system were used to calculate pressure, velocity and shear strain rate profiles. Information on flow patterns, velocities, pressure, landing impact pressure and shear strain rate were calculated through the system.

200 mm crest depth with tailwater of 100 mm

The impact pressure underneath the plunging point excluding the hydrostatic pressure from the 100 mm tailwater is about 8 kPa (Figure 3.12a) and the terminal plunging velocity is about 4.5 m/s (Figure 3.13a). There is a dominant medium sized area of shear strain on the left-hand side and underneath the plunging point with values around 130 to 150s^{-1}. Downstream water level is biased towards the left-hand side of the plunging point with an elevation difference of roughly 3.5 times.

200 mm crest depth with tailwater of 500 mm

The impact pressure underneath the plunging point excluding the hydrostatic pressure from the 500 mm tailwater is about 3.1 kPa (Figure 3.12b) and the terminal plunging velocity is about 3.8 m/s (Figure 3.13b). There is a similar very small sized area of shear strain on the left and right-hand side of the plunging point with values around 60s^{-1}. Downstream water level is more or less identical on both sides of the plunging point.

50 mm crest depth with tailwater of 100 mm

The impact pressure underneath the plunging point excluding the hydrostatic pressure from the 100 mm tailwater is about 3 kPa (Figure 3.12c) and the terminal plunging velocity is about 1.7 m/s (Figure 3.13c). There is a dominant small sized area of shear strain on the left-hand side of the plunging point with values between 150 and 250s^{-1}.

50 mm crest depth with tailwater of 500 mm

The impact pressure underneath the plunging point excluding the hydrostatic pressure from the 500 mm tailwater is about 0.11 kPa (Figure 3.12d) and the terminal plunging velocity is about 1.5 m/s (Figure 3.13d). There is an equal small sized area of shear strain on the left and right-hand side of the plunging point with values around 100 s^{-1}.

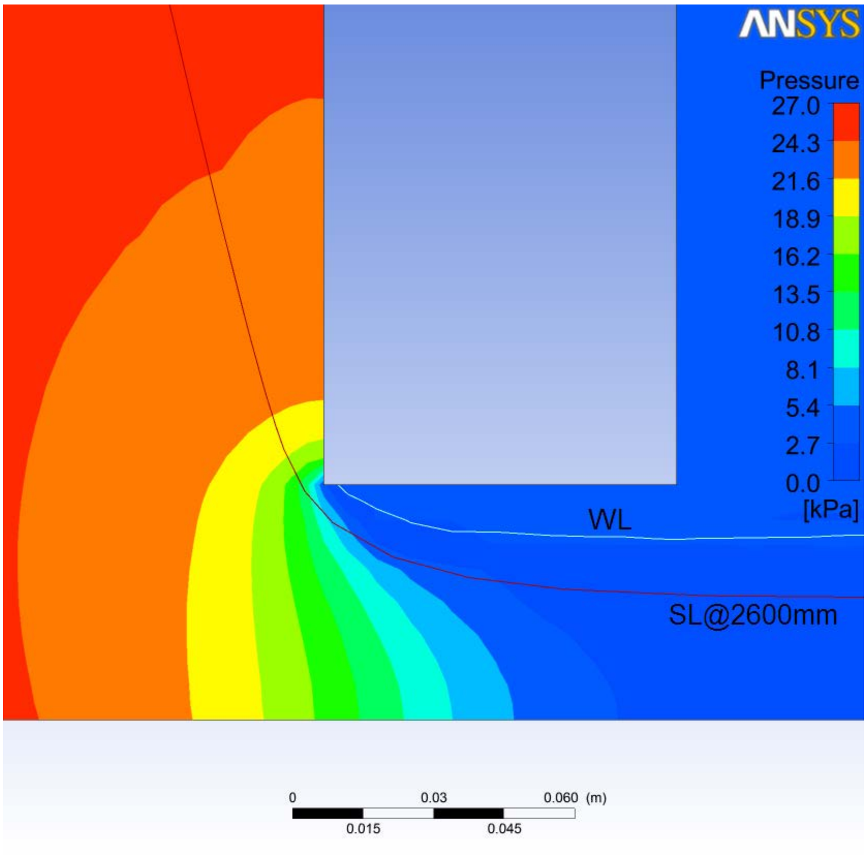


Figure 3.6 Pressure contours for water passing through a low undershot gate (50mm opening)

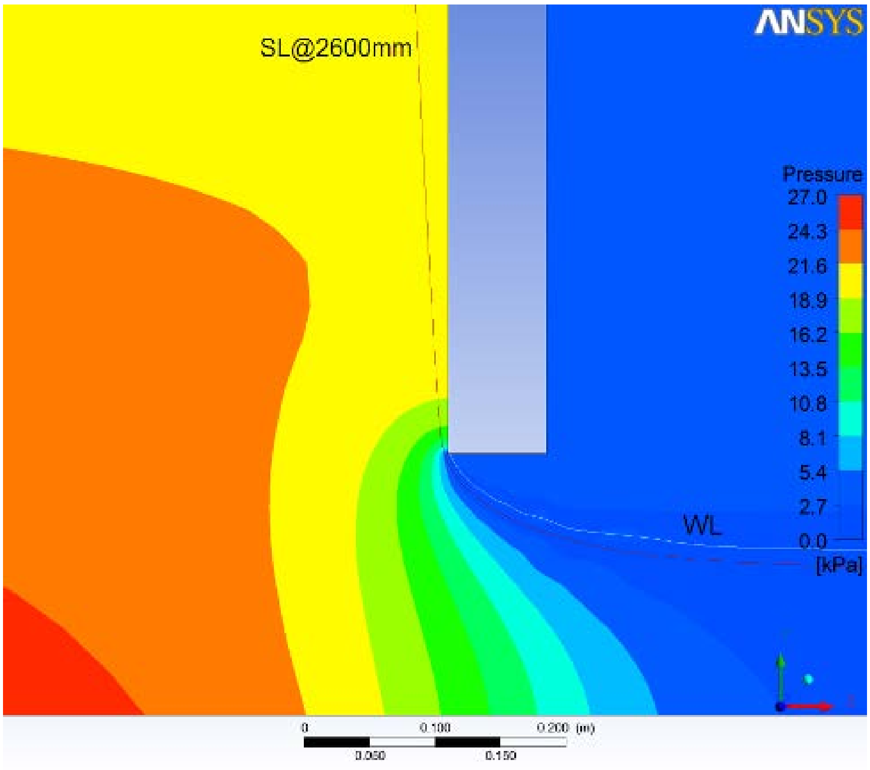


Figure 3.7 Pressure contours for water passing through a high undershot gate (200 mm opening)

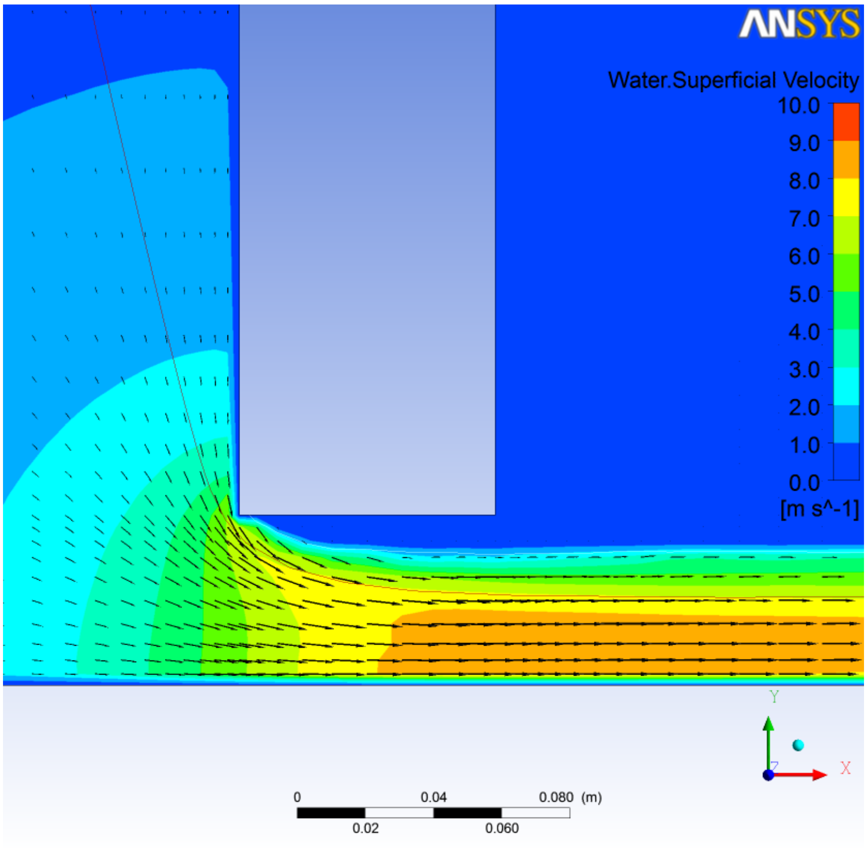


Figure 3.8 Velocity contours and vectors for water passing through a low undershot gate (50 mm opening).

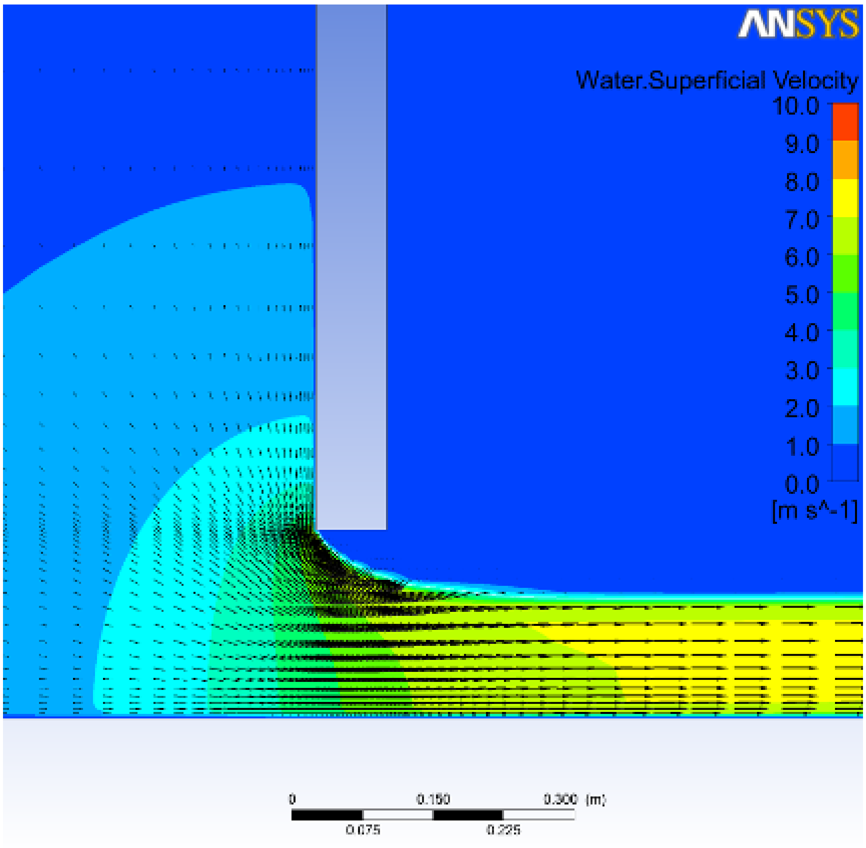


Figure 3.9 Velocity contours and vector plots for water passing through a high undershot gate (200mm opening).

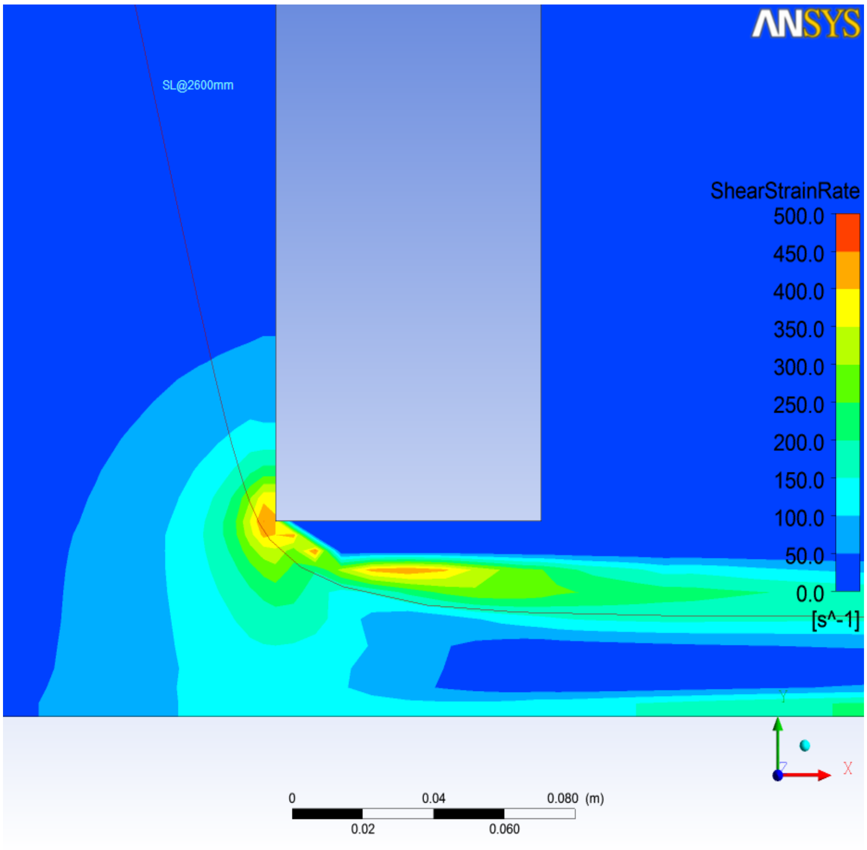


Figure 3.10 Shear stress contours for water passing through an low undershot gate (50mm opening).

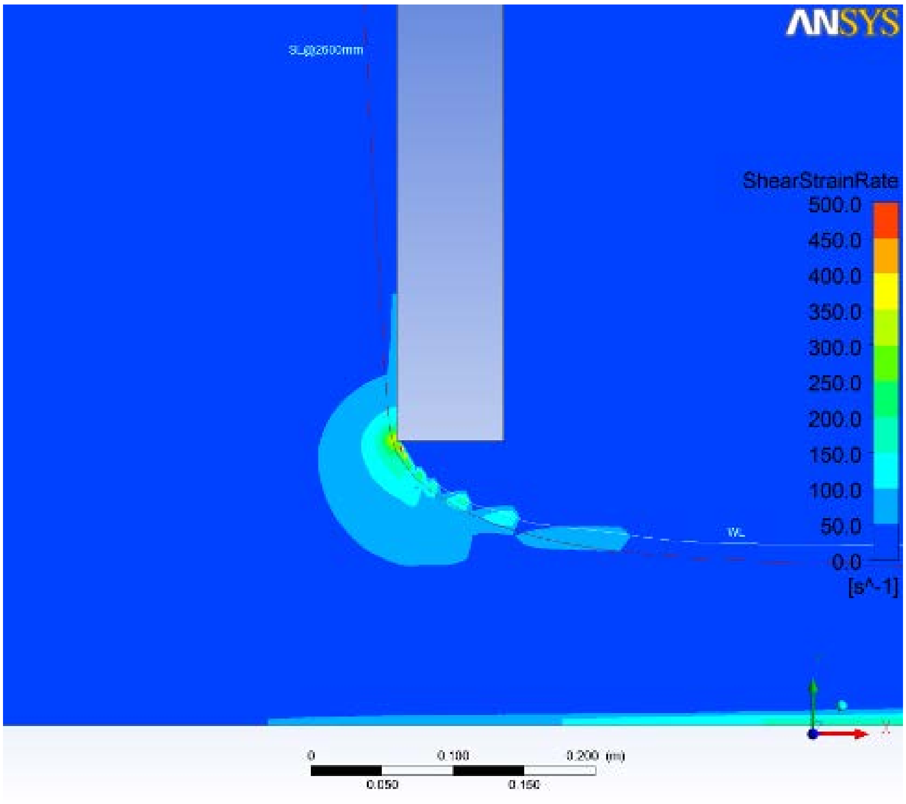


Figure 3.11 Shear stress contours for water passing through an high undershot gate (200mm opening).

Figure 3.12. Plan view of overshot weirs demonstrating downstream changes in pressure profiles in a) low depth into low tailwater, b) high crest depth into high tailwater, c) low crest depth into low tailwater and d) low crest depth into high tailwater

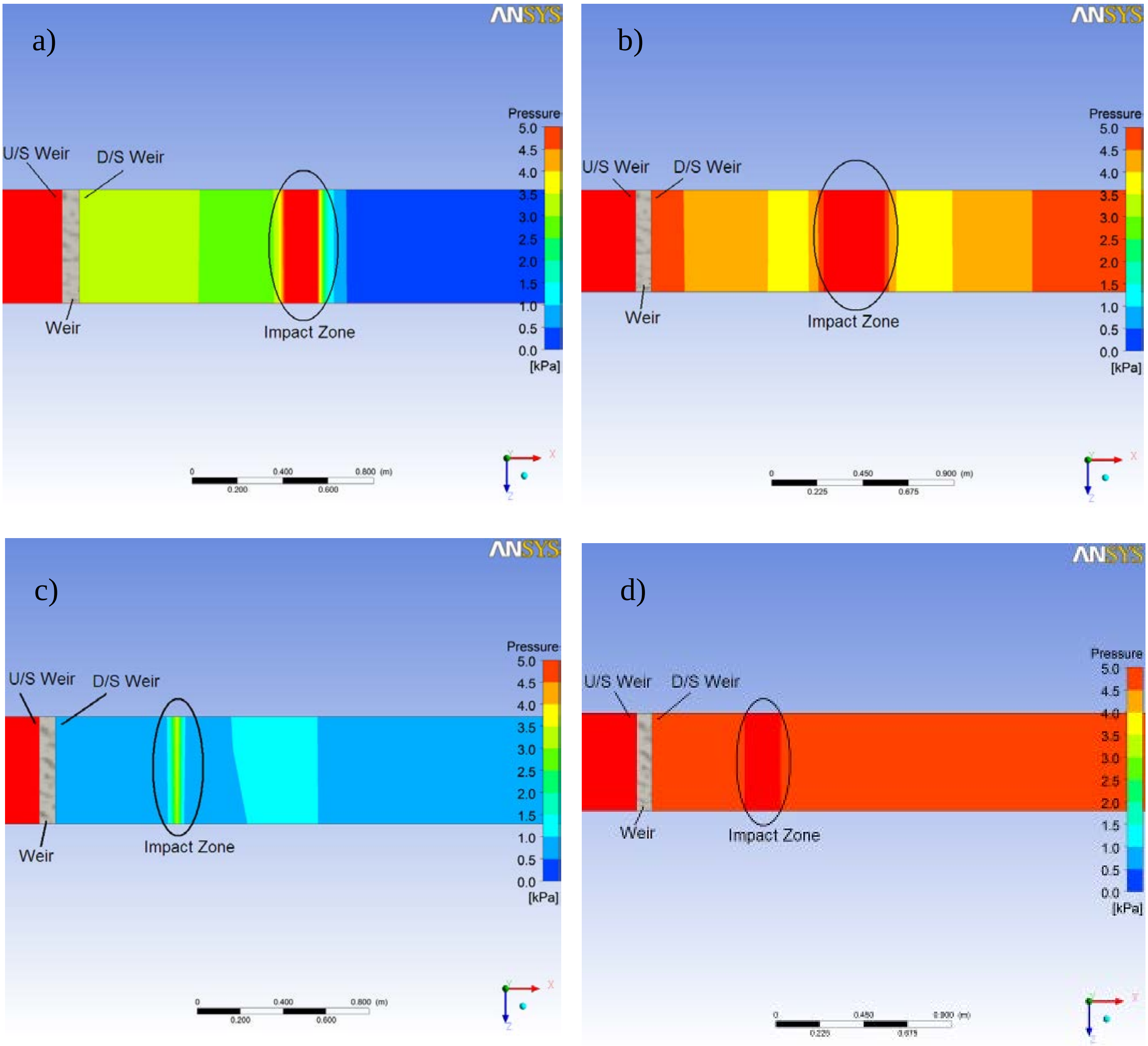
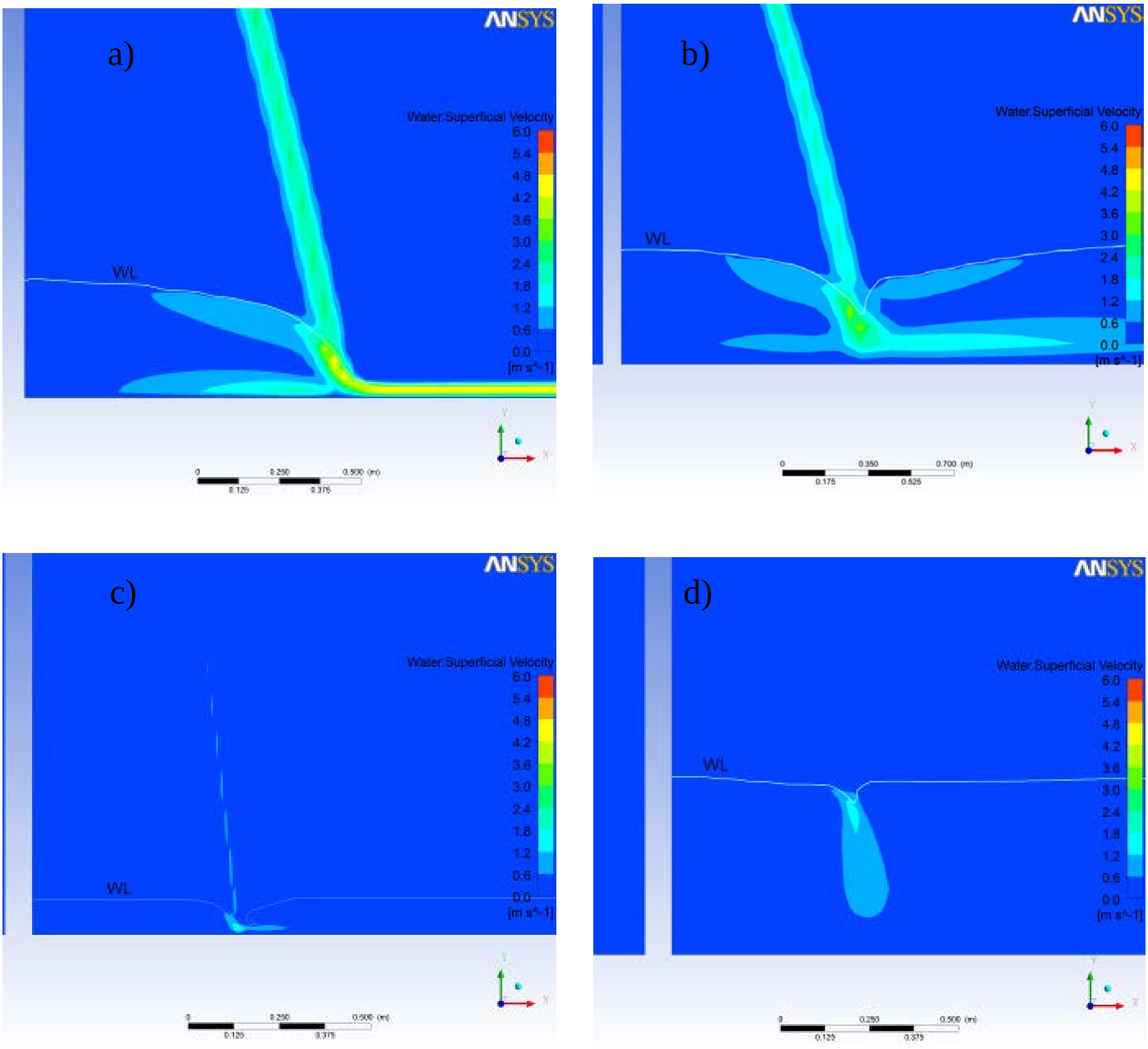


Figure 3.13. Plan view of overshot weirs demonstrating downstream changes in pressure profiles in a) high cest depth into low tailwater, b) high crest depth into deep tailwater, c) low crest depth into low tailwater and d) low crest depth into high tailwater.



Undershot Gate with Flow Streamliner and Flow Deflector

Modifications to the undershot gate were performed by adding a flow streamliner, a flow deflector, and a combination of both to assess their effect on the undershot gate performance and flow characteristics. Headwater depth was maintained constant at 2.7 m and the gate opening was set constant at 200 mm, while the tailwater depth was maintained at 100 mm. Seven streamlines at different elevations starting from 50 mm up to 2600 mm representing a flow path throughout the length of the undershot gate system were used to calculate pressure, velocity and shear strain rate profiles.

Upstream Flow Streamliner Only

The flow streamliner produces a negative pressure as the flow moves closer to the flow streamliner surface with a value of -14 kPa providing a better adjustment of the flow as it crosses through the gate opening (Figure 3.14b). The flow streamliner also improves the flow pattern of the incoming flow through the gate conditioning the flow to a more even velocity distribution immediately after the gate opening with an average velocity magnitude of 6.5 m/s as the flow passes the gate (Figure 3.15b). The nose of the streamliner has an area of shear strain with values of 100 to 150s^{-1} (Figure 3.16b) There is a small area concentrating a rapid change of shear strain located underneath the flow streamliner's bottom edge with a value of 500s^{-1}.

Downstream Flow Deflector Only

The flow deflector shifted the region where the pressure drops from upstream of the gate to downstream of the gate, widening the pressure drop as it crosses through the opening (Figure 3.14c). The flow deflector also creates a water jump as the flow exits the ramp, introducing a second pressure region due to the landing of the flow into the downstream water pool. The re-entering pressure magnitude is around 5 kPa. The flow deflector reduces the flow velocity as the flow crosses the gate opening and increases the flow speed as it moves through the ramp. The re-entering velocity from the water jump into the water pool is about 6.0 m/s inside the core of the water jetstream (Figure 3.15c). There is a small to medium sized area of shear at the bottom edge of the gate with values between 100 and 250 s^{-1}, with an increase of shear strain as the flow approaches the upstream bottom edge of the gate (Figure 3.16c).

Upstream Flow Streamliner and Downstream Flow Deflector

The flow streamliner produces a negative pressure as the flow moves closer to the flow streamliner, providing a better adjustment of the flow as it crosses through the gate opening (Figure 3.14d). The addition of the flow deflector contributes to the extension of the region of pressure drop across the gate opening. The insertion of the flow streamliner drowns the water jump formed from the flow deflector behind the ramp. The flow streamliner improves the flow pattern of the incoming flow through the gate, conditioning the flow to a more even velocity distribution immediately after the gate opening, while the flow deflector reduces the flow speed as it crosses the gate opening and increases the flow speed as it moves through the ramp (Figure 3.14d). The re-entering velocity from the drowned water jump is about 6.5 m/s inside the core of the water jetstream with flow recirculation behind the ramp. The nose of the streamliner has an area of shear strain with values of 100 to 150s^{-1} (Figure 3.15d). The presence of the flow deflector pushes the flow against the gate creating a small thin region concentrating a rapid change of shear strain extending it from the nose of the flow streamliner towards the bottom edge of the gate with a value of 500s^{-1}.

Figure 3.14 Pressure contours for water passing through a 200 mm opening undershot gate with a) no streamliner or deflector; b) streamliner but no deflector c) no streamliner and deflector, d) both a streamliner and deflector present

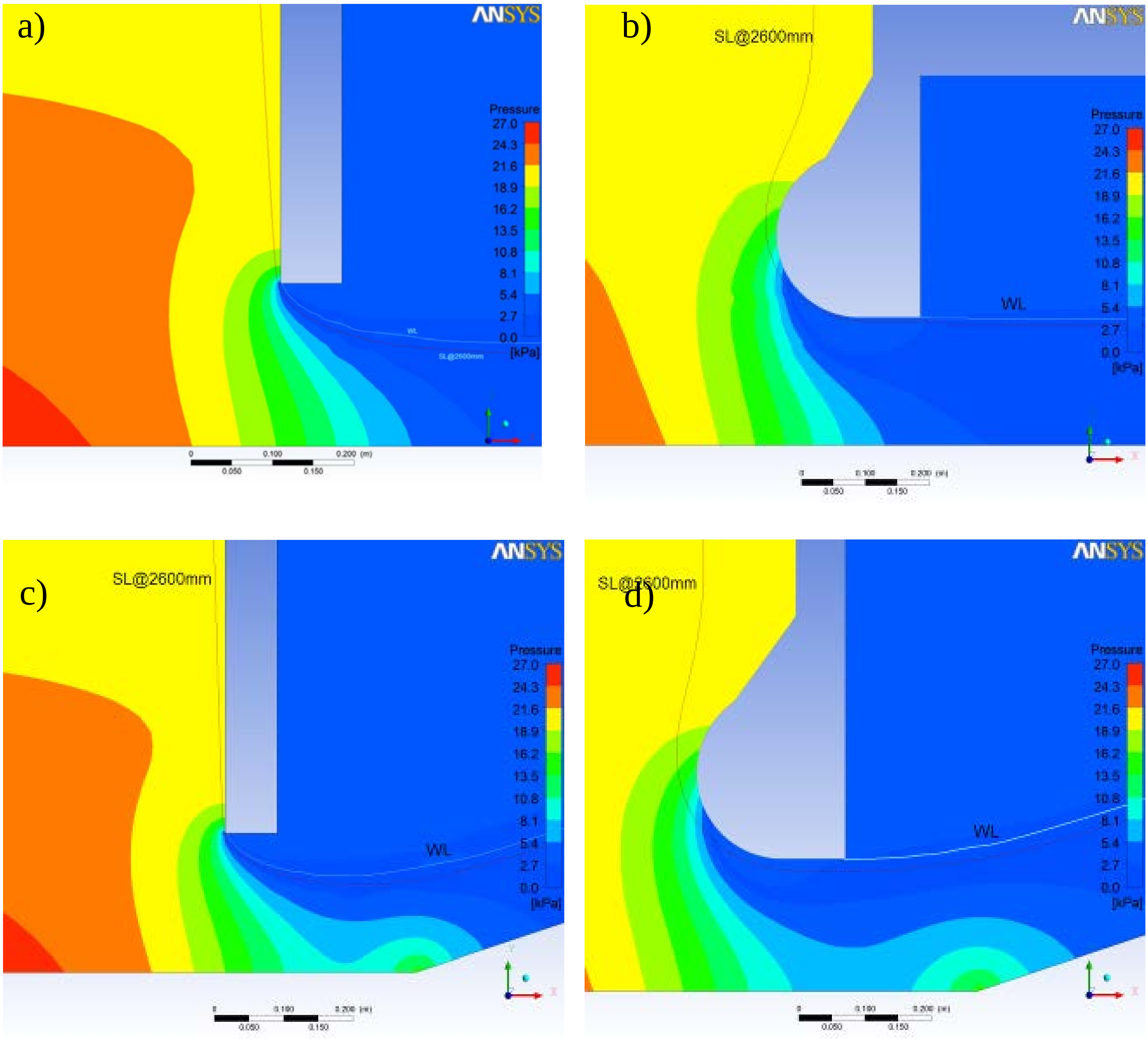


Figure 3.15 Velocity contours for water passing through a 200 mm opening undershot gate with a) no streamliner or deflector; b) streamliner but no deflector c) no streamliner and deflector, d) both a streamliner and deflector present

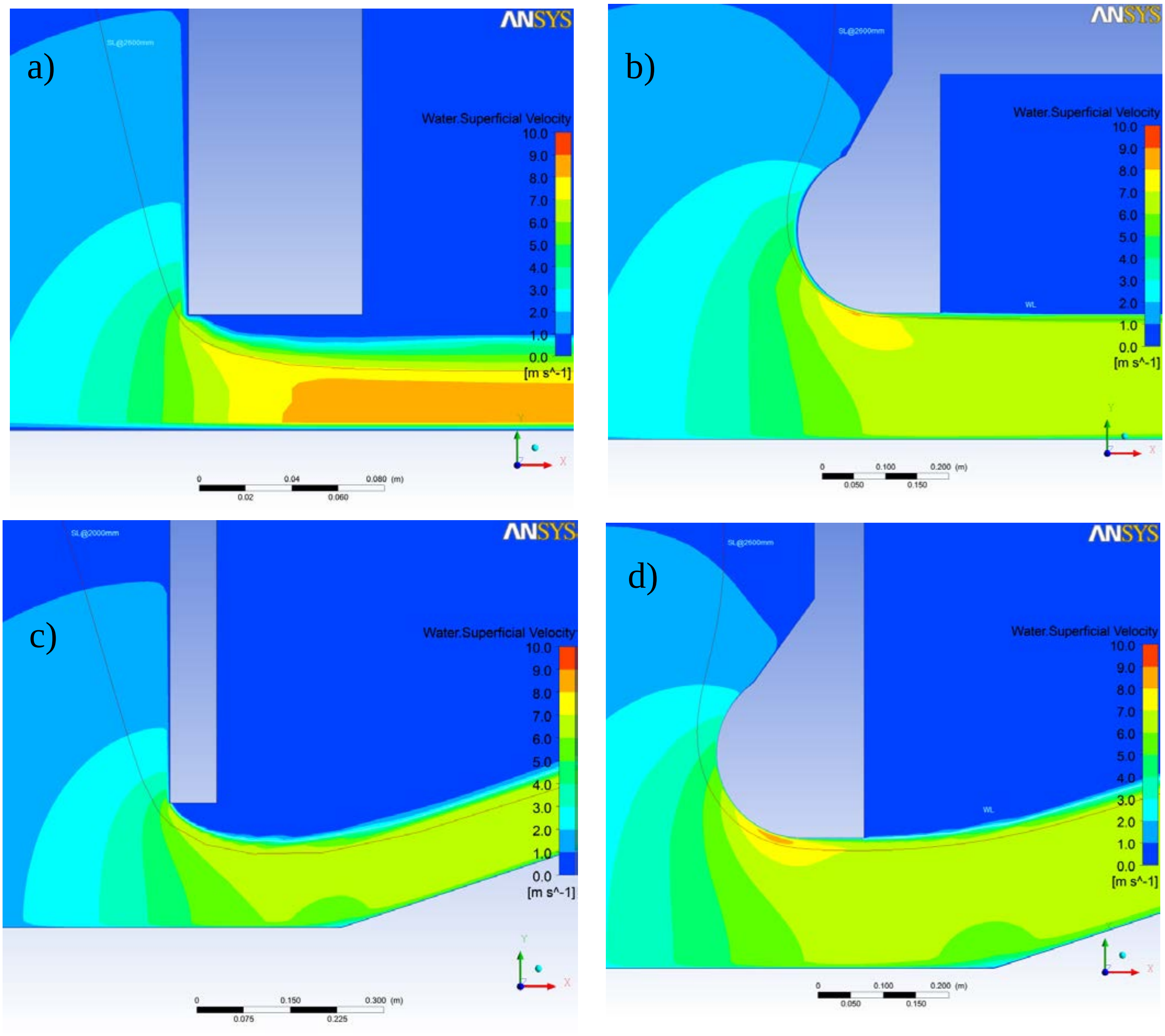
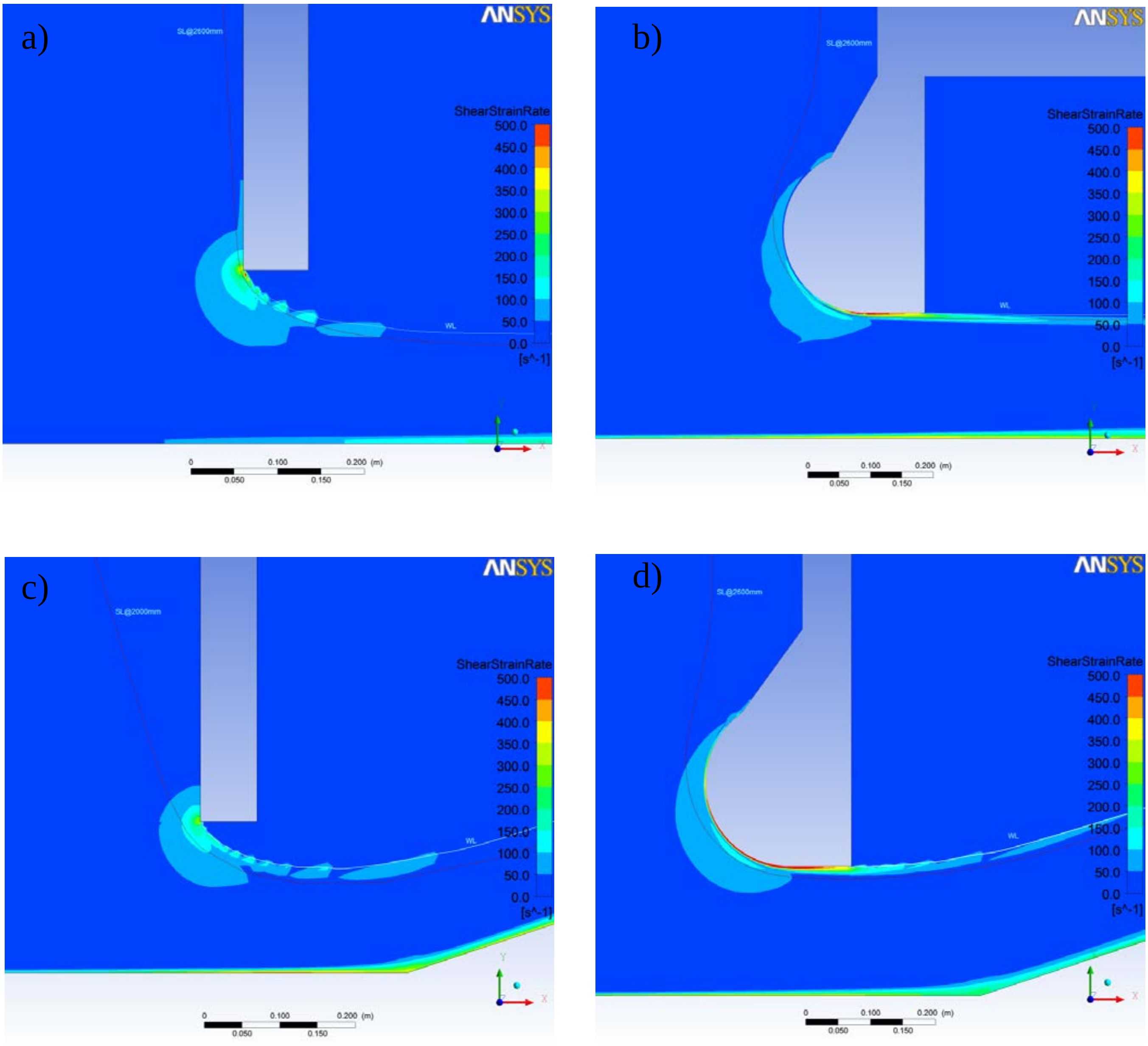


Figure 3.16 Shear stress contours for water passing through a 200 mm opening undershot gate with a) no streamliner or deflector; b) streamliner but no deflector c) no streamliner and deflector, d) both a streamliner and deflector present



4. DISCUSSION

Impacts on native fish

Welfare impacts were extremely specific to life history stage but, in general, all fish were most affected by undershot weirs. Impacts varied greatly among species, body size and physiology. Large-bodied species were greatly affected at juvenile and larval stages but adult small-bodied species also exhibited high mortality. Whilst mortality varied among species and size classes, it also varied among experimental treatments. Undershot weirs were associated with high mortality, but the impact was directly related to tailwater depths. These series of observations suggest that hydraulics of weir design and resultant biological interactions are extremely complex. Hydraulic characteristics varied greatly among treatments. Work was largely standardised so that the experimental treatments aimed to replicate actual operating scenarios. In this regard, experimental manipulations of gate opening and tailwater depth aimed to mimic real-world operational situations. This resulted in experimental treatments that had largely varying discharges. Factors such as turbulence and shear are known to fluctuate with changing discharge (Čada *et al.*, 2006). Controlling operational requirements, rather than hydraulic conditions therefore created a challenging task to interpret observed biological effects. In many instances, the nature of injuries sustained by fish provided additional evidence to suggest the causal factor. Whether these could be directly attributed to a single hydraulic factor, or a combination, warrants further investigation.

Adult fish displayed few immediate impacts other than acquiring injuries (Figure 4.1). These were most common from overshot treatments (Figure 4.2), especially during discharges into shallow tailwater. The overall low degree of injury and mortality may suggest that downstream movements of large fish are largely unaffected by weirs. This study, however, only investigated physical impacts of downstream passage but the presence of a weir may elicit behavioural responses in large fish. For instance, fish exhibiting large scale downstream movements often display migratory delays when confronted by a dam or weir (Barry and Kynard, 1986; Wertheimer, 2007). Delays can persist for a number of days and result in large upstream accumulations of fish in the reservoir (Bell, 1982). These factors were poorly understood for Australian species until radio telemetry helped demonstrate that Murray cod and golden perch were unwilling to move downstream over low-levels weirs despite frequent attempts (O'Connor *et al.*, 2005). Whilst observed mortality associated with downstream passage may be low, the cumulative behavioural aspects of obstructed passage may be enough to limit large-scale movements on a reach or catchment scale.

A further limitation of the adult fish trials was that fish were observed for only short periods post experimentation. This enabled the quantification of any immediate mortality, but delayed mortality is unknown. Many fish exhibited a range of internal injuries such as bruising or bleeding which might have been determined as fatal had a longer post-experimental monitoring period been possible (Figure 4.3). Migrations of salmon smolt through hydroelectric turbines exhibit 46-70% delayed mortality (Ferguson *et al.*, 2006). Observations at hydro facilities also indicate that injured fish often survive initially but become consumed by predators present in the tailrace (Temple, 1987). Large-bodied Australian native fish are known to congregate in areas of high prey abundance. For instance, predatory fish have been observed to take station inside fishways and specifically target small migratory prey (Berghuis, 2008). During periods of peak foraging activity, fish that are injured during downstream passage could easily fall victim to predatory birds or fish that accumulate downstream of weirs.

Figure 4.1. Example of a gill injury from a Murray cod which survived passage through an undershot weir. Although the fish survived initially, the longer term effects of such an injury were not determined as part of this study.

Figure 4.2. Example of an injured golden perch that survived passage through an overshot weir. The longer term effects of this type of injury are also unknown.

Figure 4.3. Example of internal organ rupture from a Murray cod which died during passage through an undershot gate.

Juveniles golden perch and silver perch experienced high mortality during passage through high opening undershot weirs. Sources of mortality largely arose from fatal wounds to the head and tail. In many instances decapitation was the most obvious cause of death. These types of injuries could have occurred from two major sources. Firstly, high velocities beneath the gates would have resulted in loss of control which would have increased the probability of impact with the downstream apron. Secondly, extremely high shear stress was detected at the weirpool and gate interface. It is therefore also possible that fish were injured somewhere in the region of interaction between upstream and downstream water masses. Mortality among juvenile fish was, however, strongly associated with low tailwater levels. The probability of physical contact with the substrate would be substantially higher in shallow water due to reduced energy dissipation. Any shear-related mortality should have been equal among both tailwater treatments because CFD modelling identified little difference in shear distribution in the vicinity of weirpool and gate. Assuming physical strike was the main reason for increased mortality, the provision of deep downstream plunge pools may represent a suitable mechanism to increase survival. Further understanding of the hydraulic characteristics of undershot weirs is essential to help identify mechanisms driving the observed high levels of injury and mortality in juvenile fish.

Only fish between 14 and 30 days old were used in larval trials. This provided standardisation of mortality rates to a known drifting period for each of these species (Gilligan and Schiller, 2004). It also prevented the introduction of size specific bias into the data. It is difficult to ascertain a critical size at which fish become susceptible to downstream passage injuries without assessing a wider range of ages and size classes. Mortality rates for juvenile fish were much lower than larval stages, so presumably fish become more resilient to the effects of downstream passage during development. Hydraulic streamliner experiments identified that surviving silver perch were dominated by larger size classes (> 30mm). Identifying the critical size of susceptible fish would be useful from a management perspective because many fish within the Murray-Darling Basin have restricted spawning periods (Humphries *et al.*, 2002; Gilligan and Schiller, 2004). Adopting ‘fish friendly’ operating protocols during periods of expected larval drift could subsequently contribute to increased survival at many sites within the Murray-Darling Basin.

Mortality could have been facilitated by excessive fish handling or through adverse interactions with collection nets. Inappropriate mesh sizes or handling techniques are widely known to facilitate injuries and mortality in many species (Chopin and Arimoto, 1995; Barthel *et al.*, 2003). Understanding mechanisms of gear-induced mortality is therefore an important factor in experimental design (Davis, 2002). To control for potential gear effects different net types were used in this study. Fine mesh (500 um) was used to collect larvae, juvenile and small-bodied species in order to minimise potential for external wounds. Larger mesh was used for adult fish and designs were adopted from other studies which failed to report any gear-related mortality (Gehrke and Harris, 2000; Gehrke and Harris, 2001; Baumgartner and Harris, 2007). High mortality could also have been expected across all treatments if gear was facilitating most of the observed injuries. Mortality varied among species and size classes and there was no clear evidence of gear-related injuries from any treatment group. It is therefore likely that observed injuries resulted from changed hydraulic conditions rather than gear-related effects.

CFD Modelling

The flow characteristics of the undershot gate system for both gate openings were similar. The pressure drop from upstream to downstream of the gate followed the same trend for both gate openings with a difference in pressure change through the 200 mm gate opening being less abrupt as the flow crosses through the gate opening. The flow also experiences acceleration as it passes through the gate opening having higher velocity values for the 50 mm gate opening and dropping steadily as the flow moves downstream. The 200 mm gate opening has a lower velocity as the flow passes under the gate but the flow maintains its overall velocity level for a longer period as the flow moves downstream of the gate. Observed velocity values ($<10 \mathrm{m.s}^{-1}$) are well within critical values previously determined for juvenile salmonids where higher values (12-16 $\mathrm{m.s}^{-1}$) contributed to bruising and loss of equilibrium (Deng *et al.*, 2005). Velocity was unlikely to have had dramatic impacts on adult large-bodied Australian fish, but is a potential causative factor of increased mortality in juveniles, larvae and small-bodied adults.

Both gate openings present similar shear strain rate profiles but both were lower than critical values ($517\mathrm{s}^{-1}$) known to facilitate injuries in juvenile salmonids and cluepeids (Cada *et al.*, 2007). Whether this critical value can be extrapolated to other species and life history stages is currently unknown. The 50 mm gate opening has a larger sized area of shear strain located close to the upstream bottom front edge corner of the gate, inside the gate opening and bottom floor surface. The 200 mm gate opening has a smaller sized area of shear strain as the gate opening is bigger and the flow has a wider section to travel. In spite of this, the 200 mm gate opening has a higher shear strain value and it is concentrated around a smaller size area providing a more rapid change of shear strain per area than the 50 mm gap. Many juvenile and small-bodied fish died as a result of decapitation. Fish following a streamline which would result in movement though these increased areas of shear stress could easily account for injuries of this nature. However, decapitation injuries were equally reported from both high and low shear situations and this suggests that physical strike may be a more likely factor.

A flow streamliner, flow deflector and the combination of both were added to attempt to improve the hydraulics of high opening undershot gates. When only the flow streamliner was present, a suction effect was created (negative pressure) as the flow travels around the system. This suction effect forced water upwards as it travelled through the gate opening. This suction effect also improves the flow pattern immediately after the gate opening. A fish passing through this region would experience some degree of de-pressurisation, negative pressure then a sharp re-pressurisation to atmospheric levels. Salmonids, a physostomous group of fish, exposed to similar changes in pressure exhibited relatively low mortality (Abernethy *et al.*, 2002). In contrast, the physoclistous species bluegill (*Lepomis macrochirus*), displayed a much greater rate of instantaneous mortality and also haemorrhaging and gill damage (Abernethy *et al.*, 2002). The ability for physostomous fish to manually regulate swim bladder volume likely assists with this regulation and contributes to increased survival. Interestingly, golden perch (physoclist), generally exhibited greater mortality than silver perch (physostome) during hydraulic modifier trials. Sudden pressure changes could therefore have accounted for some of the mortality observed during hydraulic modifier trials.

The flow deflector also creates a water jump at the exit of the ramp, introducing a secondary pressure region as the water lands into the downstream water pool. Finally, when the flow streamliner and flow deflector are both in place, the suction effect around the bottom edge of the gate is still present due to the flow streamliner and the wider pressure profile across the gate opening is also present. The main change when both features are together is drowning of the water jump behind the ramp created by the flow deflector. This jump creates an area of increased pressure where water strikes the downstream apron. Physical strike can create both injuries and mortality even when fish experience moderate velocities (16 $m.s^{-1}$) (Bell and DeLacey, 1972). Any fish subsequently contained within a hydraulic jump would therefore have an increased risk of physical strike especially during low tailwater conditions.

The shear strain rate changed when the flow streamliner and flow deflector were used. When the flow streamliner is placed, the shear strain starts at the nose of the streamliner, concentrating a small area with a rapid change of shear located underneath the flow streamliner bottom edge. When the flow streamliner is removed and the flow deflector is placed, the shear region shifts towards the bottom front edge corner of the gate, and there is a small shear region developed where the water jump lands into the downstream water pool. Despite these changes in shear associated with streamliner placement, mortality rates changed more dramatically when the flow deflector was present. This observation provides further evidence that injuries are likely to have arisen from physical strike than changes in shear.

Mortality was low during most overshot operations and only increased during low tailwater conditions. During overshot operation, the main feature of the weir height system is the landing of the water jet for different tailwater depths. When the tailwater depth was kept to 100 mm, the plunging velocity for the 2.5 m weir height was around 2.5 times higher than for the 2.65 m weir. Juvenile fish falling from heights are know to be susceptible to injury when reaching high free fall velocities (Bell and DeLacey, 1972). Presumably any effects arising from free fall velocity would be dependent on fish weight and the overall drop height. Both of these factors are critical in determining the impact force which may cause injuries.

The pressure impact zone for the high crest overshot weir was also about 2.5 times higher than for the low crest discharge. The water level downstream of the high crest overshot weir at the impact zone had a back-up of water in the direction towards the weir with a difference in the water surface level of 3.5 times. Shear strain was higher around the impact zone for the 2.65 m weir due to water impingement into a shallow tailwater. The uneven plunging pool water level for the 2.5 m weir reduced the shear strain at the impact zone. When the tailwater depth was raised to 500 mm, the plunging velocity, impact pressure, and shear strain for both weir heights dropped. The tailwater effectively created a buffering effect which essentially dissipated energy of the free-falling water. These observations suggest that provision of an increased tailwater substantially reduce the probability of fish striking the downstream apron.

Combining modelled flow data with biological information failed to isolate a single causal factor for increased mortality in fish. The major advantage of modelled data was an increased understanding of changes in hydraulic characteristics arising from structural changes to undershot weirs. Sources of injury arising from downstream fish passage are commonly divided into pressure, shear or physical effects (Bell and DeLacey, 1972; Clay, 1995; Čada *et al.,* 2006). Combining biological data with hydraulic data will provide insights into likely mechanisms, but only if a reductionist approach is adopted. The treatments assessed as part of this study were far too hydraulically variable to enable specific identification of causal factors. Developing engineering solutions to enable improved weir construction would benefit greatly from such an approach. Performing controlled targeted experiments for each of these factors, replicated over a range of species, would help facilitate this process.

Basin-wide management issues

Native fish experienced a range of impacts associated with downstream passage through a low-level weir. Weirs were previously thought to only impact upon upstream moving fish. Obstructions to upstream migrations have caused large scale declines arising from decreases in spawning and recolonisation opportunities (Mallen-Cooper, 1993). Impacts of dams and weirs are now known to extend well beyond issues of connectivity. High dams are known to change flow regimes, sediment loads, water quality and substantially alter riverine habitat (Bayley, 1995; Kingsford, 2000; Lu and Siew, 2006; Poulet, 2007; Pelicice and Agostinho, 2008). Studies in North America have demonstrated that some degree of mortality or delay can be expected during downstream migrations of anadromous species (Bell, 1982; Cada, 2001; Čada *et al.*, 2006; Ferguson *et al.*, 2006). The present study has now further determined that welfare of potamodromous fish can also be compromised during downstream passage. Furthermore, impacts vary greatly among species, life history stages and weir designs.

An estimated 10,000 dams and weirs are currently installed within the Murray-Darling Basin (Baumgartner, 2005). Many of these were constructed in the period between the late 1800's and early 1960's and most exist on smaller streams and tributaries of main rivers (Baumgartner, 2005). The early construction of these structures generally involved the adoption of overshot designs, as automated undershot gates are a recent technological advance. Most structures use wooden drop boards, are constructed out of aging structural concrete and require substantial refurbishment to maintain functionality. Overshot weirs largely require manual operation, so upgrades to automated undershot weirs are common due to anticipated cost savings, safety improvements and operational efficiency. Preliminary surveys of structures in New South Wales have identified that most main channel structures are already upgraded to undershot weirs (Figure 4.1). Over 80% of main channel weirs in the Murrumbidgee, Macquarie, Namoi and Gwydir Rivers now use automated undershot weirs as the primary water delivery mechanism (NSW Department of Primary Industries, 2006). The further adoption of these structures to offstream habitats (i.e. smaller creeks and tributaries) will certainly improve water delivery efficiency but may increase incidences of injury and mortality of native fish over a large spatial scale.

The major implication of such a construction program would be potential impacts on native fish recruitment. Australian native fish larvae can potentially drift extremely long distances, especially during high flow events (Gilligan and Schiller, 2004). Fish spawned in main channels would therefore have a high probability of encountering an undershot weir during early life history stages. Drifting rates can vary, but it is common for abundances to exceed

1000 fish.ML^{-1} (King *et al.*, 2009). Drifting rates of such magnitude could substantially limit recruitment events if a large proportion of fish are adversely impacted by undershot weirs. Quantifying the expected impacts on fish recruitment over reach or catchment scales could help to develop operating protocols to increase recruitment on a catchment-wide scale.

Small-bodied fish were only studied at adult stages and exhibited high mortality during passage through high-opening undershot weirs. Based on these observed impacts it could be expected that these species should experience large-scale declines in the region. These four species, however, are among the most widespread and abundant throughout the Murray-Darling Basin (Gehrke and Harris, 2001). The results of the present study therefore need to be considered in the context of larger-scale ecological processes to determine large scale impacts. For instance, it is unknown whether historical distributions of native fish were greater or less than now. Previous studies have not identified obligate drifting phases and spawning is known to occur on wide spatial and temporal scales (Humphries and Lake, 2000). The need for downstream movements in these species is therefore poorly defined and may not be an essential life history process. These issues warrant further investigation when considering the potentially larger impacts of dams and weirs on these species.

Quantification of the cumulative effects of the construction of weirs would also inform fisheries management. Larger scale monitoring programs should be undertaken on a reach-based scale. The overall impact of a weir on downstream movement would depend largely on structure size, position in the system, operational regime and the status of local fish communities. Weirs in areas of low conservation significance such as irrigation canals or degraded off-river habitat could be considered low prioritises for remedial work. Mitigation efforts would be best directed to known spawning sites or areas containing threatened species. Several key sites for works in NSW can be identified based on existing ecological knowledge (Table 4.1).

Table 4.1. Top 10 priority structures requiring mitigation throughout NSW based on location in the system, local ecology and proximity to threatened species. Species at risk are TC: Trout cod, SP: Silver perch, MC: Murray cod, SM: Small-bodied species, OP: Olive perchlet; FC : Freshwater catfish. This prioritisation has been developed against a series of criteria that can be applied across all undershot weirs in NSW. Site specific factors such as the individual hydraulics and operating regimes of particular structures may have a significant influence on mortality. As such, individual site assessments would be required to refine state or Basin-wide priorities.

Barrier Name	**Waterway**	**Nearby Town**	**Approx Weir Height (m)**	**Species at risk**
Torrumbarry Weir	Murray River	Echuca	6	TC, SP, MC
Stephens Weir	Edward River	Deniliquin	5	TC, SP, MC
Edward River offtake	Edward River	Mathoura	2	TC, SP, MC
Redbank Weir	Murrumbidgee River	Balranald	5	SP, MC, SM
Gogeldrie Weir	Murrumbidgee River	Darlington Point	5	TC, MC, SP
Boggabilla Weir	Macintyre River	Boggabilla	5	SP, MC
Tareelaroi Weir	Gwydir River	Moree	4	SM, MC, FC
Lake Brewster Outlet	Lachlan River	Hillston	8	MC, SM, OP
Yanco Weir	Murrumbidgee River	Narrandera	5	MC, TC, SP
Mollee Weir	Namoi River	Wee Waa	4	MC, SM

Weirs in lowland regions near reaches of increased fish biodiversity should be considered for further field studies determining the impact of these regulators on downstream movements. If impacts are deemed significant then options for potential remedial works could be considered. Initial work should focus on Torrumbarry Weir (Murray River). This is an undershot structure that was constructed at the confluence of the last two self sustaining populations of trout cod (*Maccullochella macquariensis*) and silver perch. The site contains high flows for the majority of the spawning season for both species and could be influencing recruitment in this river reach. Site characteristics are well suited for field tests of an Eicher screen (See Figure 4.6) because it would be relatively straightforward to construct and divert flows through a bypass channel at this site. Operational improvements could also be considered although the site is required to deliver quite large flows during the irrigation season which may limit flexibility.

To provide information to inform fisheries management and policy, a reductionist approach may be required. Initially, the overall impact of key structures within a river system could be modelled based on existing knowledge. Weirs with design and operational protocols likely to have substantial impacts on native fish could be identified. Modelling site hydrology (i.e. total discharge and tailwater ratings) would then be needed to determine critical periods where weir operation is likely to substantially impact fish communities. Consideration of this information in the context of wider river ecology may then help to identify potential impacts. The presentation of this information to fisheries managers and river operators may help to identify suitable operational and engineering solutions which can be prioritised and presented to funding bodies. The process need not be exhaustive as a range of potential mitigation options are already available based on previous work.

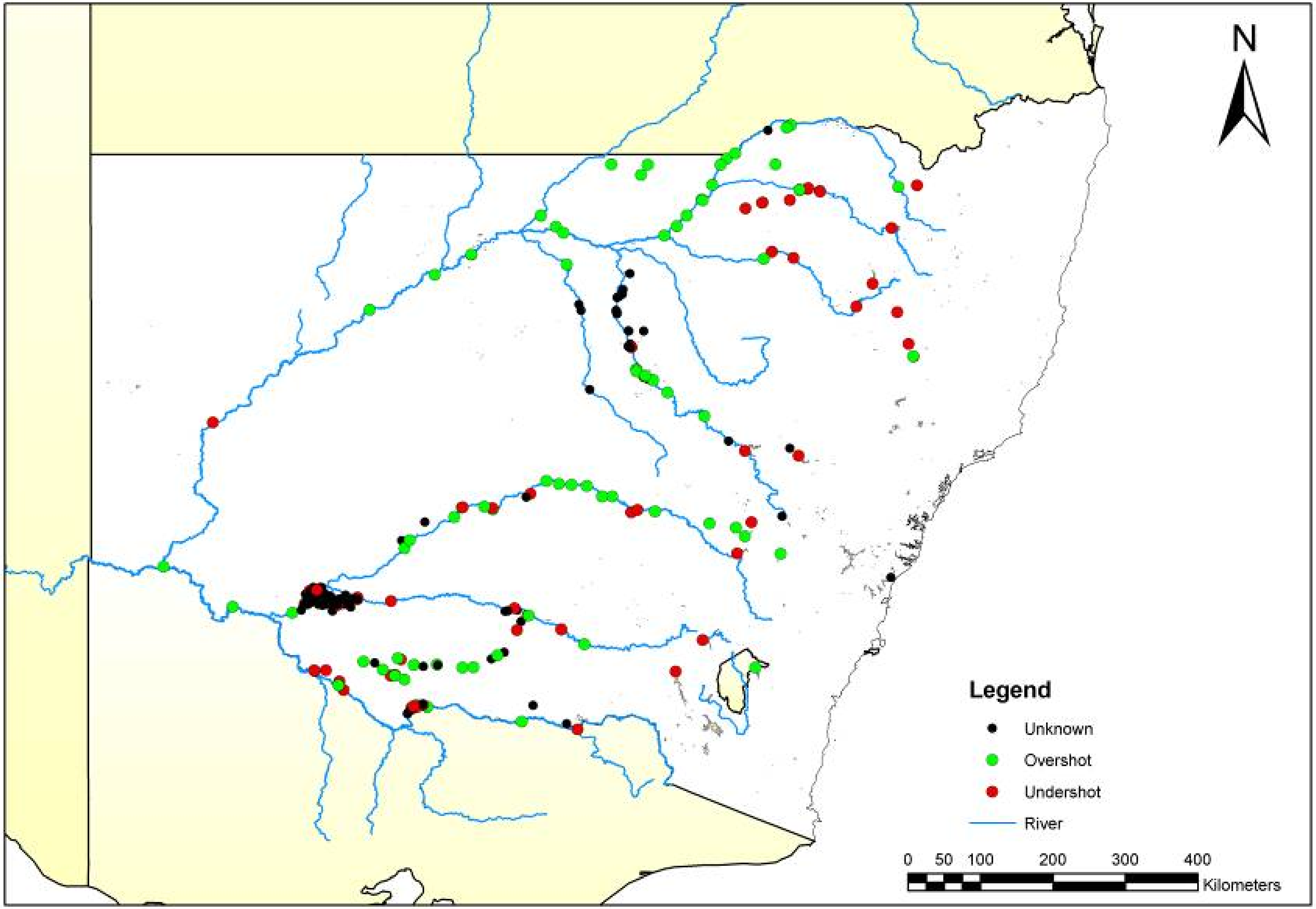
Potential mitigation options

Operational improvements to existing structures

A number of operational improvements could improve the welfare of native fish at weirs. The most obvious areas for improvement are through manipulation of gate openings and crest depth and through monitoring of tailwater level. Modification of gate openings has the effect of increasing discharge through the system. Increasing discharge led to higher velocities and also generated increased shear stress at the gate and weirpool interface. These factors likely contributed, either solely or in combination, to observed mortality. Mortality was much lower when discharges were small. Low gate openings (undershot) and shallow crest depths (overshot) generally produced good survival especially when discharging into high tailwater. This observation suggests that operating low-level weirs to have reduced discharges could provide a substantial benefit for the welfare of native fish. This situation would be relatively easy to control under low flow conditions when demand for water delivery is low. Most existing weirs could be easily operated to ensure gate and crest depths do not exceed the critical values identified in this study.

High discharge situations are more complex. High discharges need to be delivered from large gate openings. The only situation where this may be acceptable for native fish would be during instances where gates are fully removed. This would eliminate most mechanically-induced sources of shear stress as water would flow directly through the gate opening. This situation would create continuity with the tailwater and facilitate a more laminar flow regime. This reduction in shear and turbulence, combined with a lack of pressure change, should provide conditions well-suited to native fish passage.

Figure 4.4. An inventory of weirs in inland New South Wales showing both undershot and overshot designs. This table refers to main channel sites with former government ownership but many private and unclassified structures have not been included (Source: Industry and Investment NSW).



Discharging into low tailwater increased injuries and mortality across most species. Presumably, low tailwater increases the probability of physical strike with the apron. In large fish, this often led to bone fractures and other internal injuries. Two potential mitigation options exist. Firstly, operating weirs during periods of naturally-elevated tailwater levels would greatly reduce the risk of injury. Secondly, the provision of a downstream plunge-pool could effectively simulate high tailwater levels. The ideal depth would be largely dependent on discharge and weir height, because water gains momentum as it falls under gravity. CFD modelling demonstrated that low tailwater was insufficient to effectively dissipate energy from water falling from the crest of high discharge overshot weirs. An increase in tailwater mitigated this effect and the tailwater dissipated the upstream discharge before it contacted the apron. A plunge-pool to simulate a high tailwater would be a useful mechanism to reduce physical strike and could easily be incorporated into the design of future regulators.

Engineering solutions at existing and new structures

Acceptable resolution of fish passage issues usually requires close consultation between biologists and engineers to develop appropriate solutions (Clay, 1995). Developing these close collaborations would ensure that water delivery requirements are maintained in a manner that provides sustainable outcomes for all species and life history stages of fish. The most obvious engineering solution to improve the welfare of native fish would be to cease the construction of undershot weirs. Although the exact mechanisms for injury and mortality could not be confidently determined by this study, mortality through undershot weirs was substantially higher than for overshot weirs for the operational regimes that were assessed.

Recent advances in gate design could also provide substantial benefits for native fish. The application of a combo-gate would provide both operational flexibility and effective water delivery control. A combo gate is a dual-gate system which provides the opportunity to be operated as either an overshot or undershot regulator. If overshot operation is desired, the upper gate can be lowered below the weirpool level so that all discharge can be directed over the weir. During undershot operation, the gate is lifted and flow is directed under the gate. Such a system could have clear benefits for native fish. For example, under most flow situations, the gate could be operated in overshot mode to direct all fish and flow over the top of the weir. The gate could be designed for this operating mode up until drownout at which state the gate could be fully removed for unregulated flow.

A similar solution would involve the construction of automatic hydraulic tilt gates (Figure 4.5). Undershot gates generally operate by moving gates up and down via a spindle. An alternative solution could be to use hydraulics to essentially pivot the gate forward to simulate an overshot weir. Under high discharge requirements, the gate would simply be pivoted at a greater angle. Similarly, the gate could simply be raised during periods when low discharges are needed. This gate design, when used in conjunction with a downstream plunge-pool, would create hydraulic conditions suited to most species and size classes of fish in the Murray-Darling Basin. The main design disadvantage of this system would be a requirement to have sufficient downstream tilting space to accommodate the gate.

Figure 4.5. Example of a hydraulic tilt gate used to simulate overshot flow (Photo Courtesy of Waterpower Engineering, UK).

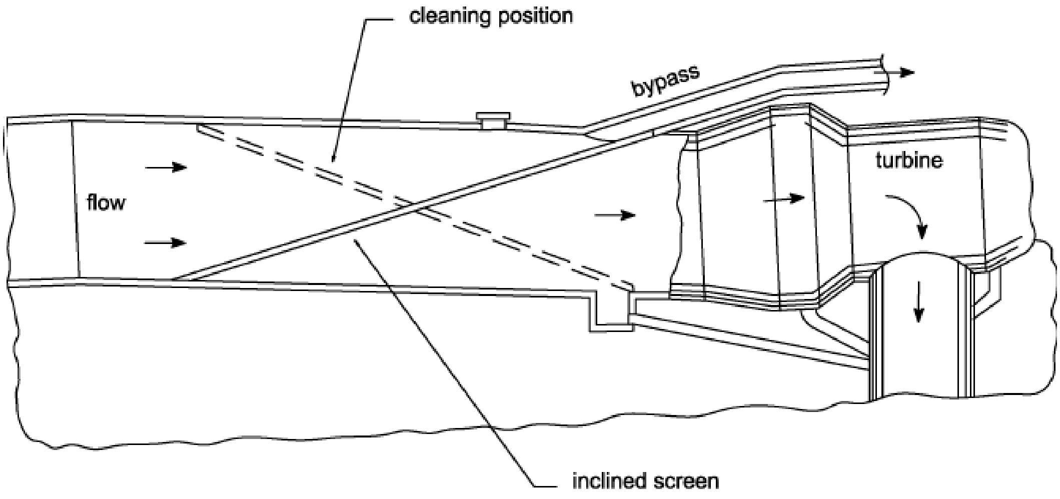


Figure 4.6. Conceptual layout of an Eicher Screen used to divert small-bodied fish at hydroelectric installations (Larinier and Travade, 2002).

Screening facilities are commonly used in North America and Europe to prevent fish entrainment. Screens can be constructed to a range of mesh sizes and are commonly fitted to trash racks or water intakes (Aitken *et al.*, 1966). Screens are usually fixed, but moving self-cleaning screens are also considered at sites where high levels of debris accumulation are likely (Larinier and Travade, 2002). Screen length and mesh size are largely dependent on the target species and site hydrology. Requirements to deliver specified flow volumes often preclude the use of fine mesh screens at many sites (Larinier and Travade, 2002). This creates a difficult paradox for the use of screens in the Murray-Darling Basin. Highest levels of mortality were observed during larval drifting phases which would necessitate the use of extremely fine mesh screens. Large debris loads and increased river flows during peak spawning periods would effectively negate the use of most screens at many sites.

Skimming (or Eicher) screens are shallow angle screens (2 mm x 2 mm mesh) which extend over the full width of a river and slope gently upwards from the riverbed to a spillway or weir crest (Figure 4.6). A screen of this design would provide conditions suitable for the passage of larvae and would be relatively self-cleaning (Larinier and Travade, 2002). The screen would, however, require some adaptation for use in the Murray-Darling Basin because most weirs are either exclusively undershot or overshot design. An Eicher screen works best when fish can be diverted to a spillway or bypass channel. It could not be directly fitted to an undershot weir because of the lack of an appropriate diversion facility. If undershot weirs could be fitted with at least one overshot bay or a diversion spillway, then an Eicher screen could be used to divert fish away from gates to these areas.

Fish passage facilities incorporating downstream transport facilities are recent innovations that have been trialed in Australia. A fishlock recently constructed on the Burnett River (Queensland), specifically contains a downstream migration lock to facilitate the safe passage of fish. Fish are diverted into a transfer chamber via a series of vertical bars (20 mm spacing) with an attraction flow of 0.3 $m.s^{-1}$.(Martin Mallen-Cooper, *pers. comm*). Fish move along the screen and enter the transfer chamber via a 400 mm slot. Fish enter the slot via a downstream spilling overshot gate. Once inside the chamber, the downstream facility operates in a similar manner to a navigation lock for boats but fish are moved in a downstream direction, rather than upstream. An added benefit of this lock-based system is that flows into and within the chamber can be controlled via the use of gates which can help to ensure values of shear and turbulence are maintained within critical tolerances. Installations of this nature have great potential to provide passage for large numbers of fish but require substantial engineering design and have a high capital cost. Application would therefore be limited to a small-number of sites.

5. CONCLUSIONS

This study greatly enhanced understanding of both the hydraulic and biological characteristics of low-level weirs. The work reinforced previous observations that undershot gates substantially impact upon the welfare of native fish. Results now indicate that effects can be extended to more species and size classes than previously thought. Gate opening and tailwater depth had a substantial influence for most species. Higher gate openings appeared to contribute to increased mortality. This increased in magnitude if the weir was discharging into shallow tailwater. These trends were quite consistent among larvae and small-bodied natives, but effects diminished in juveniles and adults of large-bodied species. Larger-scale impacts are therefore likely to be species and size specific.

Overshot weirs provided substantially improved conditions for passage. Survival was much higher, especially for larvae and small-bodied natives during high discharge situations. Overshot passage tended to be associated with injuries, especially for large-bodied fish, but the short post-experimentation observation period made it difficult to determine whether these were fatal. Mortality, however, was greater during discharges into shallow tailwater. CFD modelling indicated that increased tailwater created a buffer which dissipated the energy of discharging water. Under low tailwater conditions, discharging water impacted the downstream apron but this was eliminated during high tailwater. Provision of a deep downstream plunge pool may therefore represent a suitable mechanism to improve conditions for downstream fish passage.

Experimentation with hydraulic modifiers did not provide adequate mitigation measures for juvenile golden perch and silver perch. Most responses were negative and mortality increased when hydraulic modifiers were added. CFD modelling revealed that many of the modifiers increase the efficiency of the structure. This increased efficiency led to higher discharges which changes pressure and shear profiles. The presence of a flow streamliner created a suction effect which created an area of negative pressure. Fish passing through this system would therefore undergo a rapid de-pressurisation, experience negative pressure and then re-pressurise. The impacts of these sudden pressure changes were not well studied but could explain why the modifiers did not provide positive benefits as anticipated.

CFD modelling augmented the biological data well. Improved understanding of the hydraulic parameters associated with each scenario led to a greater understanding of pressure, velocity and shear stress. Even with an improved understanding of hydraulic processes, causal factors were difficult to determine. This largely arose because all different experimental treatments were essentially associated with different hydraulic parameters. Whilst standardising the experimental method to operating regime provided practical examples of potential manipulations, it did not provide standardised hydraulic parameters. Future work should therefore focus on taking a reductionist approach to each hydraulic parameter and determining fish-related impacts on fish. Further CFD modelling could then be used to predict the usefulness of mitigation techniques based on expected fish responses.

6. RECOMENDATIONS

- Carefully consider fish-based impacts on any future construction of undershot weirs
- Where possible, construction of overshot weirs should be considered
- Installation of combination gates should be considered at sites requiring weir upgrades
- Existing weirs with shallow downstream aprons should be retrofitted with deep plunge pools or tailwater elevation devices to minimise impacts on fish
- Operation of undershot weirs could consider more frequent operation with small gate openings, especially during expected periods of larval drift
- Laboratory results should be field-validated at higher installations to determine the overall ecological impact of weir operation on fish communities.
- Weir construction engineers and fish biologists should form close collaborations to ensure that any future works programs consider fish welfare issues early in the design phase

7. REFERENCES

Abernethy, C. S., Amidan, B. & Cada, G. F. (2002). Simulated passage through a modified Kaplan Turbine Pressure Regime. Richland, Washington: Pacific Northwest National Laboratory.

Aitken, P. L., Dickerson, L. H. & Menzies, W. J. M. (1966). Fish passes and screens at water power works. *Proceedings of the Institute for Civil Engineering* **35**, 29-57.

Arlinghaus, R., Cooke, S. J., Lyman, J., Policanksy, D., Schwab, A., Suski, C. D., Sutton, S. G. & Thorstad, E. B. (2007). Understanding the complexity of catch and release in recreational fishing: an integrative synthesis of glab knowledge from historical, philosophical, social and biological perspectives. *Reviews in Fisheries Science* **15**.

Barry, T. & Kynard, B. (1986). Attraction of Adult American Shad to Fish Lifts at Holyoke Dam, Connecticut River. *North American Journal of Fisheries Management* **6**, 233-241.

Barthel, B. L., Cooke, S. J., Suski, C. D. & Philipp, D. P. (2003). Effects of landing net mesh type on injury and mortality in a freshwater recreational fishery. *Fisheries Research* **63**, 275-282.

Baumgartner, L. J. (2005). Effects of dams and weirs on fish migrations in the Murray-Darling Basin. 188pp. PhD Thesis. Canberra: University of Canberra.

Baumgartner, L. J. & Harris, J. H. (2007). Passage of non-salmonid fish through a Deelder lock on a lowland river. *River Research and Applications* **23**, 1058-1069.

Baumgartner, L. J., Reynoldson, N. & Gilligan, D. M. (2006). Mortality of larval Murray cod (Maccullochella peelii peelii) and golden perch (Macquaria ambigua) associated with passage through two types of low-head weirs. *Marine and Freshwater Research* **57**, 187-191.

Bayley, P. B. (1995). Understanding Large River: Floodplain Ecosystems. *BioScience* **45**, 153-158.

Bell, C. E. (1982). Immediate mortality of American shad in a hydroelectric tailrace at Holyoke Dam, Connecticut River. Masters Thesis. Amherst: University of Massachusetts.

Bell, M. C. & DeLacey, A. C. (1972). A compendium on the survival of fish passing through spillways and conduits 121pp. Portland, Oregon: US Army Corps of Engineers, North Pacific Division.

Berghuis, A. (2008). Performance of a single frequency split-beam hydroacoustic system: an innovative fish counting technology. Melbourne: Department of Sustainability and Environment.

Cada, G., Carlson, T., Ferguson, J., Richmond, M. & Sale, M. (1999). Exploring the Role of Shear Stress and Severe Turbulence in Downstream Fish Passage. pp. 57-57. Las Vegas, Nevada, USA: ASCE.

Čada, G., Loar, J., Garrison, L., Fisher, R. & Neitzel, D. (2006). Efforts to Reduce Mortality to Hydroelectric Turbine-Passed Fish: Locating and Quantifying Damaging Shear Stresses. *Environmental Management* **37**, 898-906.

Cada, G. F. (2001). The Development of Advanced Hydroelectric Turbines to Improve Fish Passage Survival. *Fisheries* **26**, 14-23.

Cada, G. F., Garrison, L. & Fisher, R. (2007). Determining the effect of shear stress on fish mortality during turbine passage. *Hydro Review* **4**, 52-58.

Chopin, F. S. & Arimoto, T. (1995). The condition of fish escaping from fishing gears--a review. *Fisheries Research* **21**, 315-327.

Clay, C. H. (1995). *Design of fishways and other fish facilities*. Boca Raton: CRC-Press.

Crabb, P. (1997). *Murray-Darling Basin Resources*. Canberra: Murray-Darling Basin Commission.

Davis, M. W. (2002). Key principles for understanding fish bycatch discard mortality. *Canadian Journal of Fisheries and Aquatic Sciences* **59**, 1834-1843.

Deng, Z., Guensch, G. R., McKinstry, C. A., Mueller, R. P., Dauble, D. D. & Richmond, M. (2005). Evaluation of fish-injury mechanisms during exposure to turbulent shear flow. *Canadian Journal of Fisheries and Aquatic Sciences* **62**, 1513-1522.

Deng, Z., Guensch, G. R., Richmond, M., Weiland, M. A. & Carlson, T. J. (2007). Prototype measurements of pressure fluctuations in The Dalles Dam stilling basin. *Journal of Hydraulic Research* **45**, 674-678.

Fange, R. (1966). Physiology of the swim bladder. *Physioloigical Reviews* **46**, 299-322.

Feathers, M. G. & Knable, A. E. (1983). Effects of depressurisation on largemouth bass. *North American Journal of Fisheries Management* **3,** 86-90.

Ferguson, J. W., Absolon, R. F., Carlson, T. J. & Sandford, B. P. (2006). Evidence of Delayed Mortality on Juvenile Pacific Salmon Passing through Turbines at Columbia River Dams. *Transactions of the American Fisheries Society* **135**, 139-150.

Gehrke, P. C., Astles, K. L. & Harris, J. H. (1999). Within-catchment effects of flow alteration on fish assemblages in the Hawkesbury-Nepean River system, Australia. *Regulated Rivers: Research & Management* **15**, 181-198.

Gehrke, P. C. & Harris, J. H. (2000). Large-scale patterns in species richness and composition of temperate riverine fish communities, south-eastern Australia. *Marine and Freshwater Research* **51**, 165-182.

Gehrke, P. C. & Harris, J. H. (2001). Regional-scale effects of flow regulation on lowland riverine fish communities in New South Wales, Australia. *Regulated Rivers: Research & Management* **17**, 369-391.

Gilligan, D. M. & Schiller, C. S. (2004). Downstream transport of eggs, larvae and juvenile fish in the Murray River: Impacts of river regulation on downstream dispersal. In *Downstream movement of fish in the Murray-Darling Basin* (Lintermans, M. & Phillips, B., eds.). Canberra: Murray-Darilng Basin Commission.

Gravel, M. A. & Cooke, S. J. (2008). Severity of barotrauma influences and the physiological status, postreleae behaviour and fate of tournament-caught smallmouth bass. . *North American Journal of Fisheries Management* **28**, 607-617.

Guensch, G. R., Mueller, G., McKinstry, C. A. & Dauble, D. D. (2002). Evaluation of fish injury mechanisms during exposure to a high velocity jet. p. 34. Richland, Washington: Pacific Northwest National Laboratory.

Halls, A. S., Hoggarth, D. D. & Debnath, K. (1999). Impact of hydraulic engineering on the dynamics and production potential fo floodplain fish popluations in Bangladesh. *Fisheries Management and Ecology* **6,** 261-285.

Hannah, R. W. & Matteson, K. M. (2007). Behaviour of nine species of pacific rockfish after hook and line capture, recompression and release. *Transactions of the American Fisheries Society* **136**.

Heisey, P. G., Mathur, P. & Euston, E. T. (1996). Passing fish safely: A closer look at turbine vs. spillway survival. *Hydro Review,* **35,** 42-50.

Humphries, P., King, A. J. & Koehn, J. D. (1999). Fish, flows and floodplains: links between freshwater fishes and their environment in the Murray-Darling River System, Australia. . *Environmental biology of fishes* **56**, 129-151.

Humphries, P. & Lake, P. S. (2000). Fish larvae and the management of regulated rivers. *Regulated Rivers: Research & Management* **16**, 421-432.

Humphries, P., Serafini, L. G. & King, A. J. (2002). River regulation and fish larvae: variation through space and time. *Freshwater Biology* **47**.

Jacobs, T. A. (1990). Regulation and Management of the River Murray. In *The Murray* (Mackay, J. & Eastburn, D., eds.). Canberra: Murray-Darling Basin Commission.

King, A. J. (2002). Recruitment ecology of fish in Floodplain Rivers of the Southern Murray-Darling Basin, Australia. PhD Thesis. Melbourne: Monash University.

King, A. J., Ward, D. A., O'Connor, P., Green, D., Tonkin, Z. & Mahoney, J. (2009). Adaptive management of an environmental watering event to enhance native fish spawning and recruitment. *Freshwater Biology* **55**, 17-31.

Kingsford, R. T. (2000). Ecological impacts of dams, water diversions and river management on floodplain wetlands in Australia. *Austral Ecology* **25**, 109-127.

Larinier, M. & Travade, F. (2002). Downstream Migration: Problems and Facilities. *Bull. Fr. Pece. Piscic.* **364**, 181-207.

Lu, X. X. & Siew, R. Y. (2006). Water discharge and sediment flux over the past decades in the Lower Mekong River: possible impacts of the Chinese Dams. *Hydrology and Earth System Sciences* **10**, 181-195.

Lucas, M. & Baras, E. (2001). *Migration of Freshwater Fishes*. Oxford: Wiley-Blackwell.

Mallen-Cooper, M. (1993). Habitat changes and declines of freshwater fish in Australia: What is the evidence and do we need more? In *Proceedings. Bureau of Resource Sciences (Australia)* (Hancock, D. A., ed.), pp. 118-123. Canberra: AGPS.

Mallen-Cooper, M. (1996). Fishways and freshwater fish migration in South-Eastern Australia. 429pp. PhD Thesis. Sydney: University of Technology.

Mallen-Cooper, M. & Brand, D. M. (2007). Non-salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage? *Fisheries Management and Ecology* **14**, 319-332.

Mallen-Cooper, M. & Copeland, C. (1997). Science and the management of freshwater fish: a case study of fishways and fish migration in the Murray-Darling Basin. In *Saving our natural heritage? : the role of science in managing Australia's ecosystems* (Copeland, C. & Lewis, D., eds.), pp. 262-271. Rushcutters Bay, NSW: Halstead Press.

Marttin, F. & De Graaf, G. J. (2002). The effect of a sluice gate and its mode of operation on mortality of drifting fish larvae in Bangladesh. *Fisheries Management and Ecology* **9**, 123-125.

Mathur, D., Heisey, P. G., Euston, E. T., Skalski, J. R. & Hays, S. (1996). Turbine passage survival estimation for chinook salmon smolts (*Oncorhynchus tshawytscha*) at a large dam on the Columbia River. *Canadian Journal of Fisheries and Aquatic Science* **53**, 542-549.

MDBC (2003). Native Fish Strategy for the Murray-Darling Basin 2003-2013. Canberra: Murray Darling Basin Commission.

Nichol, D. G. & Chilton, E. A. (2006). Recuperation and behaviour of Pacific cod after barotrauma. *ICES J. Mar. Sci.* **63**, 83-94.

NSW Department of Primary Industries (2006). Reducing the impact of weirs on Aquatic Habitat - NSW Detailed Weir Review. 126pp. Flemington, NSW: NSW Department of Primary Industries.

O'Connor, J. P., O'Mahony, D. J. & O'Mahony, J. M. (2004). Downstream migration of adult Murray-Darling fish species. In *Downstream Movement of Fish in the Murray-Darling Basin* (Lintermans, M. & Phillips, B., eds.). Canberra: Murray-Darling Basin Commission.

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

Pelicice, F. M. & Agostinho, A. A. (2008). Fish-Passage Facilities as Ecological Traps in Large Neotropical Rivers. *Conservation Biology* **22**, 180-188.

Poulet, N. (2007). Impact of weirs on fish communities in a Piedmont stream. *River Research and Applications* **23**, 1038-1047.

Reynolds, L. F. (1983). Migration patterns of five fish species in the Murray-Darling River system. *Australian Journal of Marine and Freshwater Research* **34**, 857-871.

Schreer, J. F., Gokey, J. & DeGhett, V. J. (2009). The Incidence and Consequences of Barotrauma in Fish in the St. Lawrence River. *North American Journal of Fisheries Management* **29**, 1707-1713.

Sokal, R. R. & Rohlf, F. J. (2001). *Biometry*. New York: WH Freeman and Company.

Stuart, I. G. & 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 & Management* **15**, 575-590.

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

Temple, S. A. (1987). Do predators always capture substandard individuals disproportionately from prey populations? *Ecology* **68**, 669-674.

Thorncraft, G. & Harris, J. H. (2000). Fish Passage and fishways in New South Wales - a status report. 36pp. Canberra: Co-operative Research Centre for Freshwater Ecology.

Walker, K. F. (1985). A review of the ecological effects of river regulation in Australia. *Hydrobiologia* **125**, 111-129.

Weitkamp, D. E., Sullivan, R. D., Swant, T. & DosSanton, J. (2003). Gas Bubble Disease in Resident Fish of the Lower Clark Fork River. *Transactions of the American Fisheries Society* **132**, 865-876.

Wertheimer, R. H. (2007). Evaluation of a Surface Flow Bypass System for Steelhead Kelt Passage at Bonneville Dam, Washington. *North American Journal of Fisheries Management* **27**, 21-29.

APPENDIX 1: DIMENSIONS AND HYDRAULIC PARAMETERS FOR CFD MODELLING OF DIFFERENT WEIRS CONFIGURATIONS.

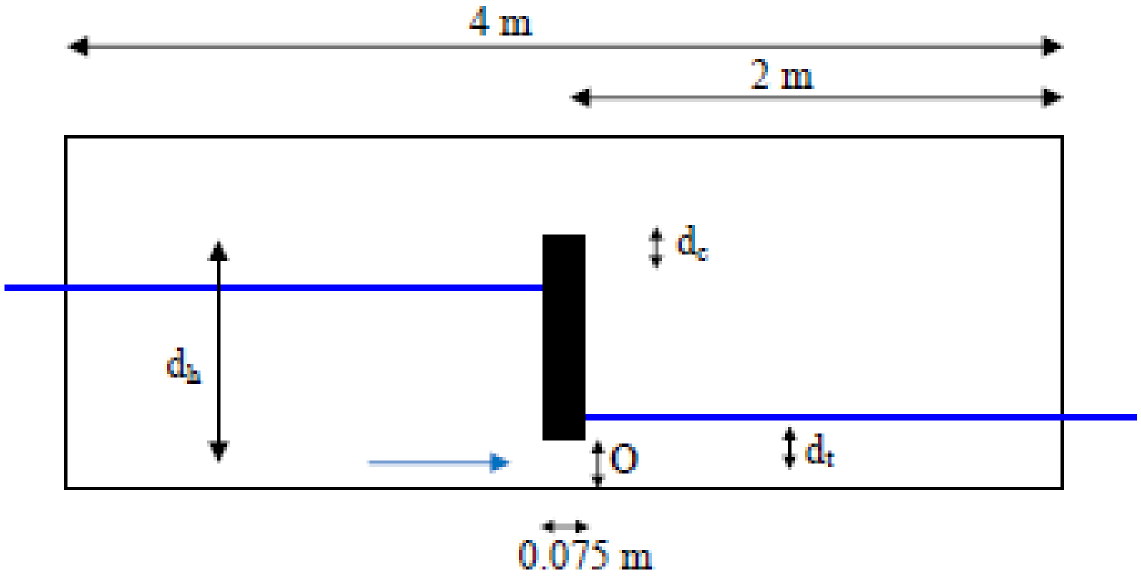


Figure A1 - Parameters for the undershot gate system.

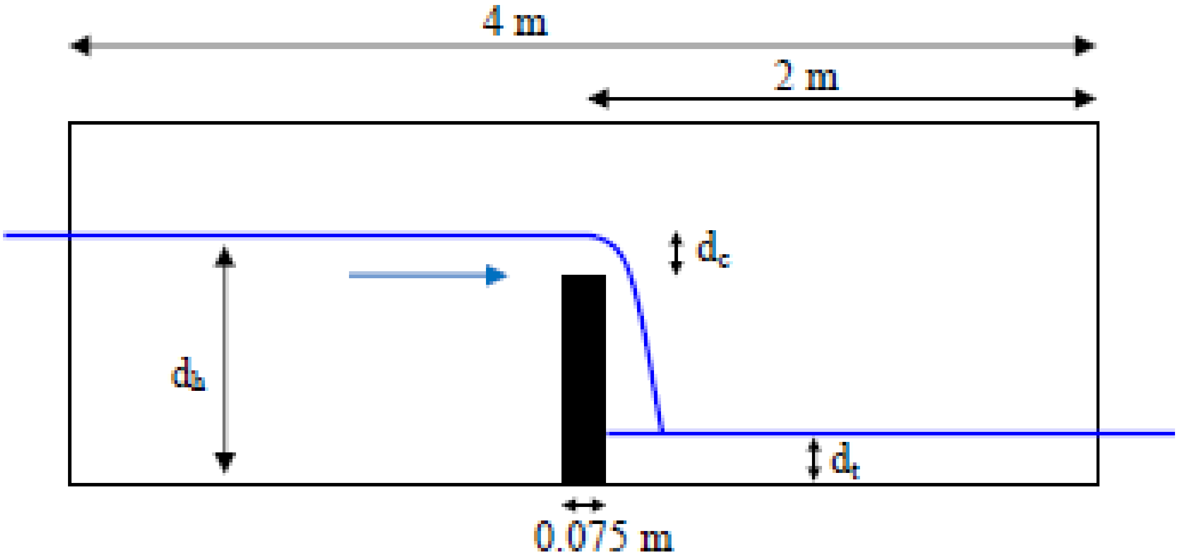


Figure A2- Parameters for the overshot gate system.

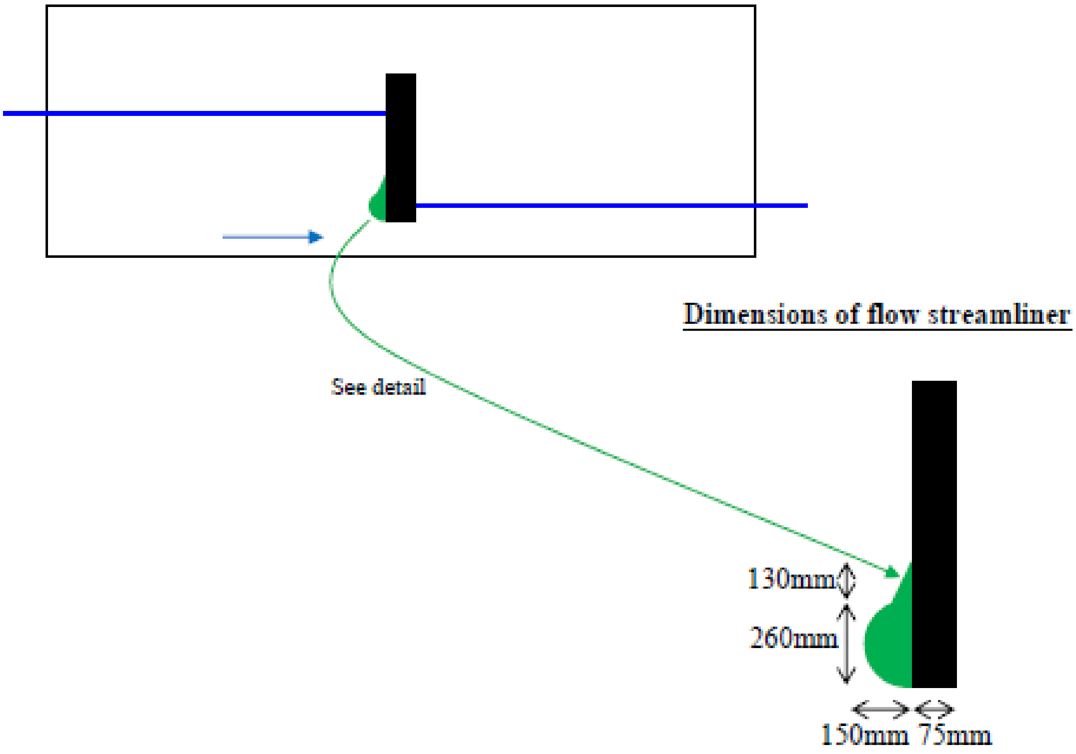


Figure A3 - Parameters for the undershot gate system with upstream flow streamliner.

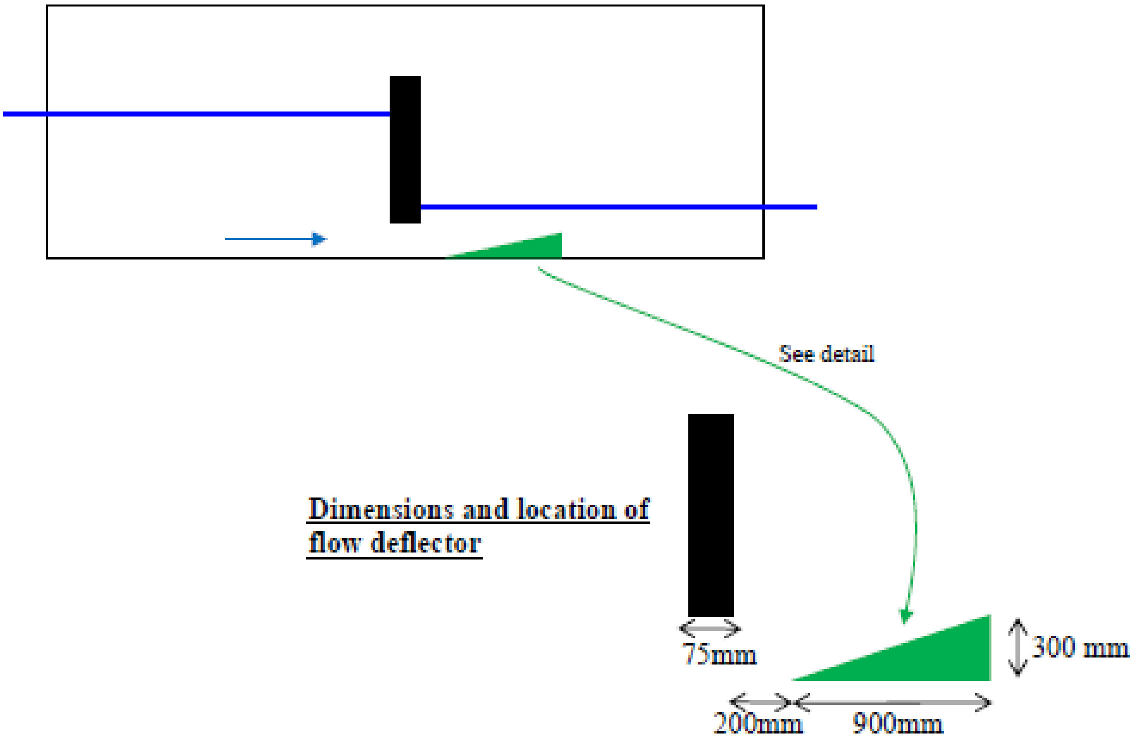


Figure A4 - Parameters for the undershot gate system with downstream flow deflector.

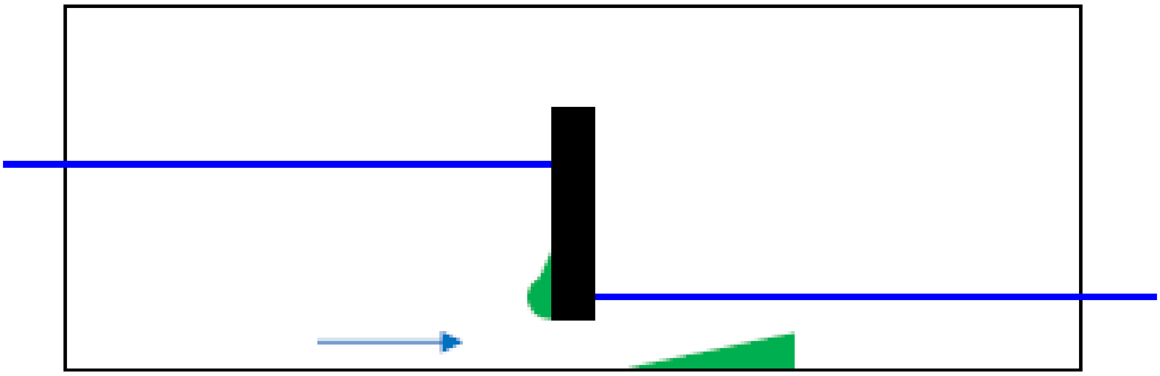
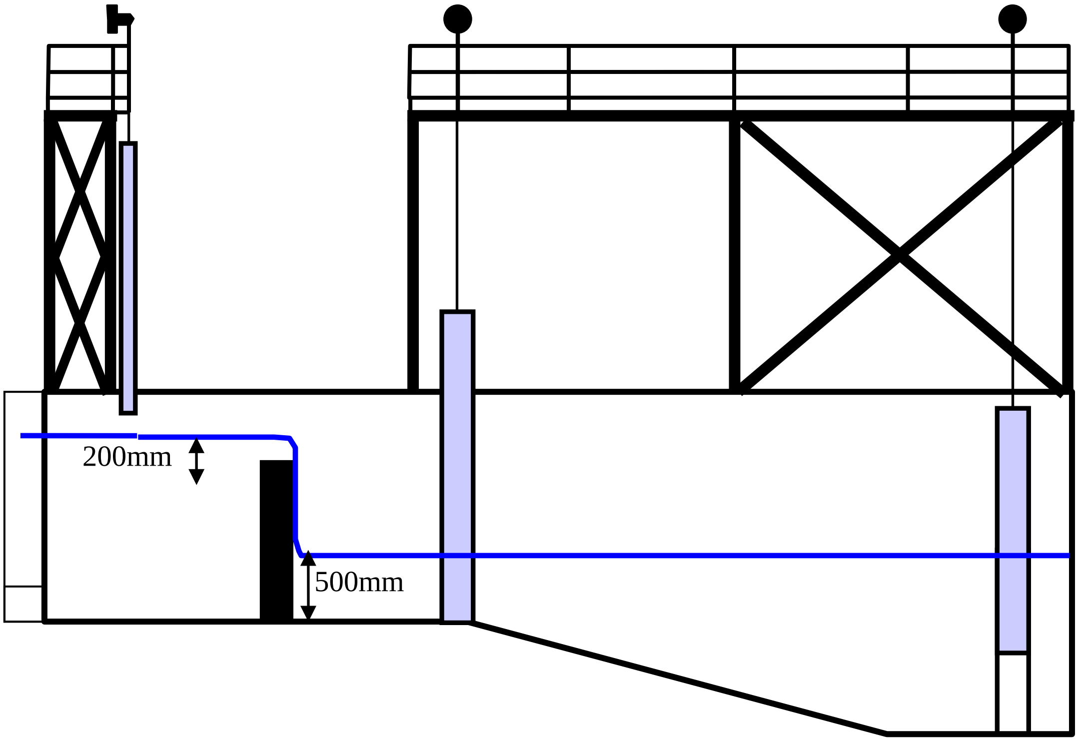


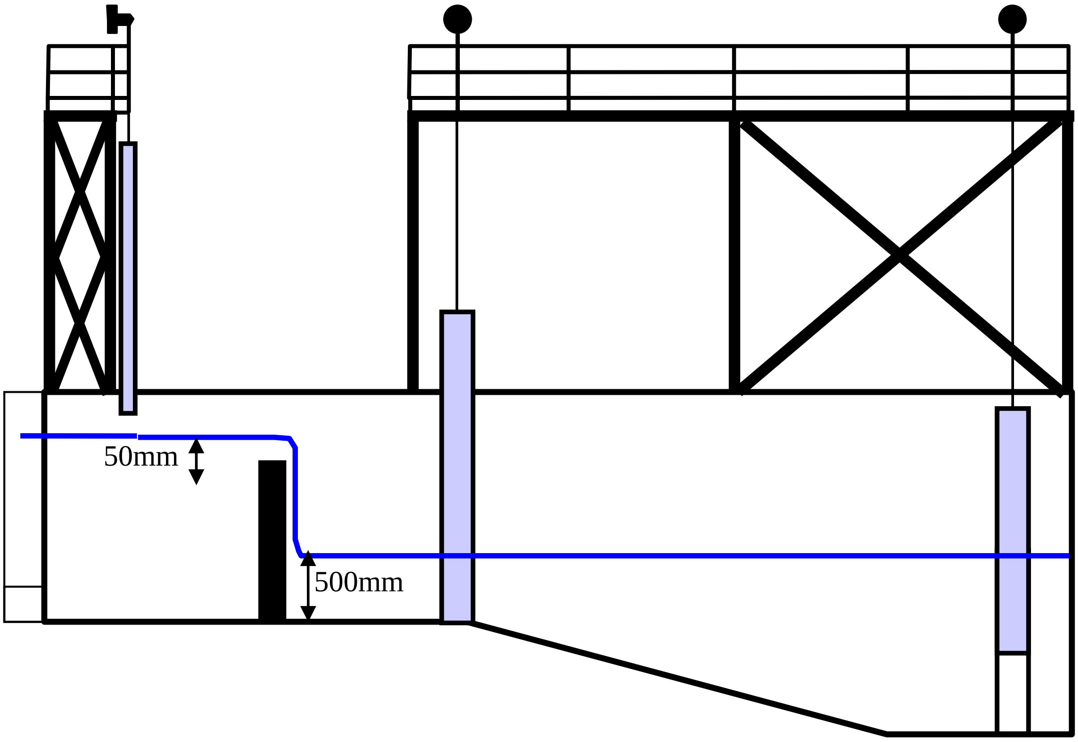
Figure A5 - Parameters for undershot gate with upstream flow deflector streamliner and downstream flow deflector.

Appendix 2: SUMMARY OF EXPERIMENTAL CONFIGUARTIONS

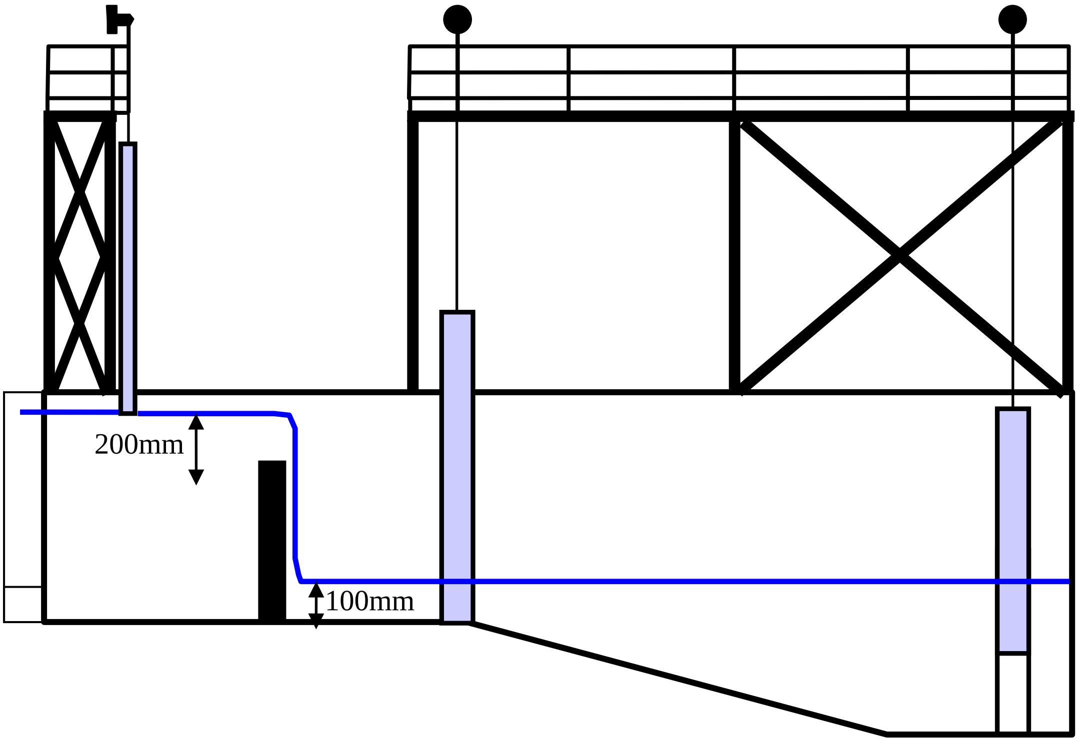
Experimental Configuration 1: Overshot (high crest, high tailwater)



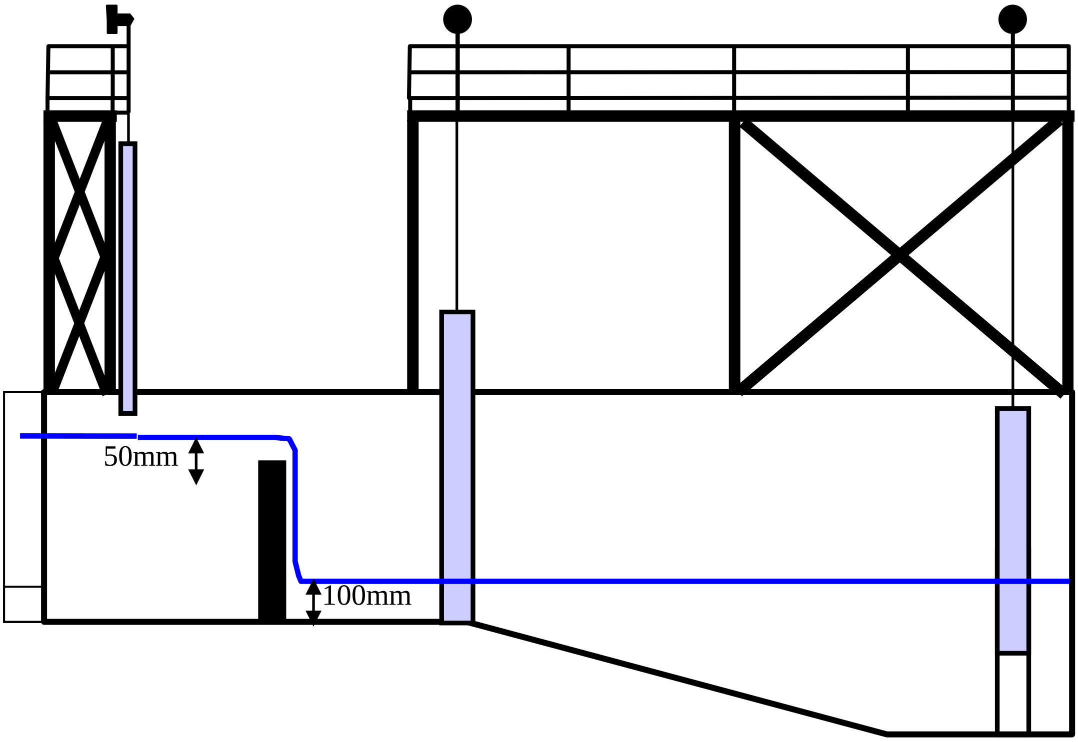
Experimental Configuration 2: Overshot (low crest, high tailwater)



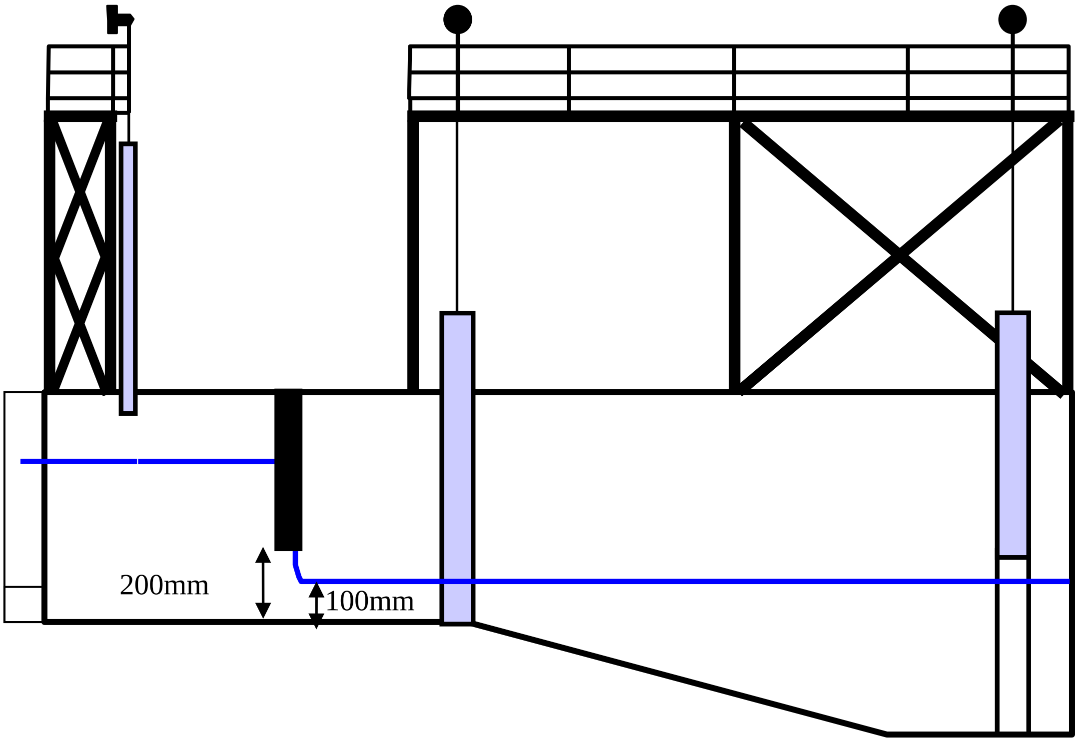
Experimental Configuration 3: Overshot (high crest, low tailwater)



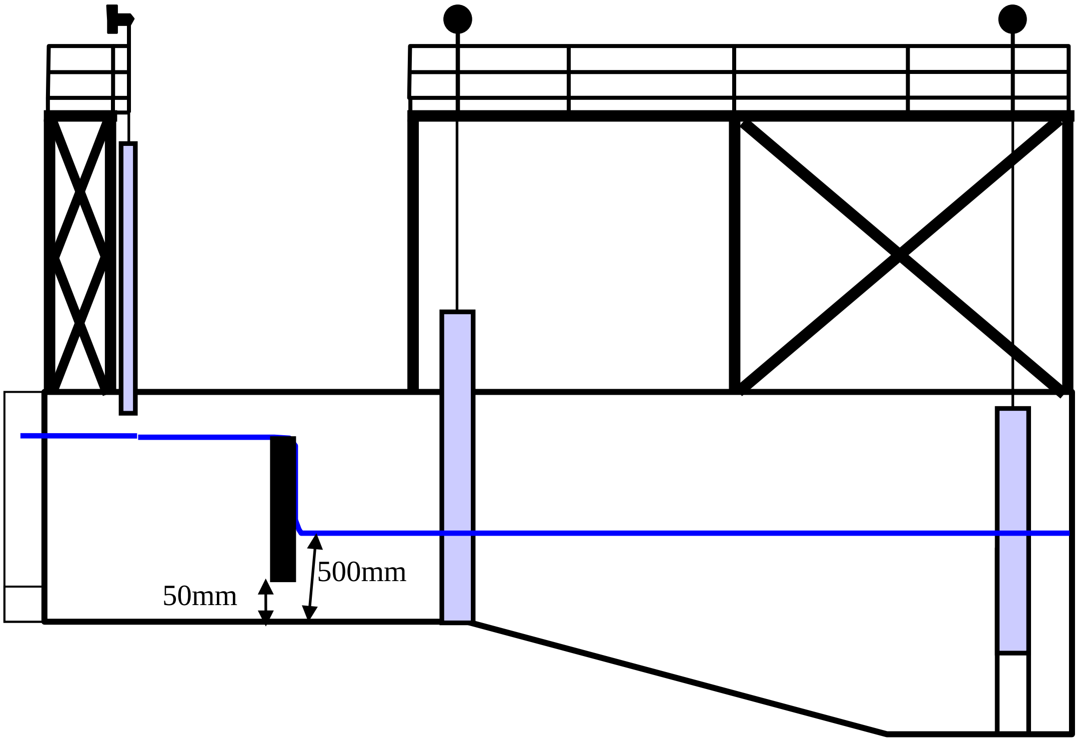
Experimental Configuration 4: Overshot (low crest, low tailwater)



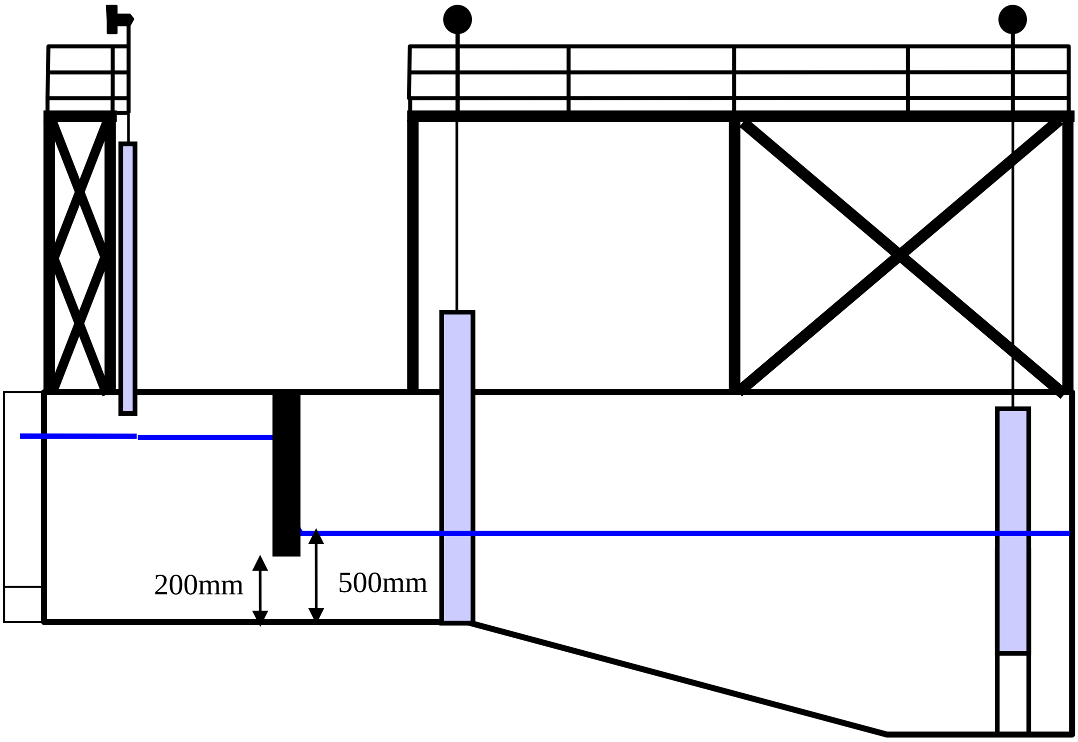
Experimental Configuration 5: Undershot (high opening, low tailwater)



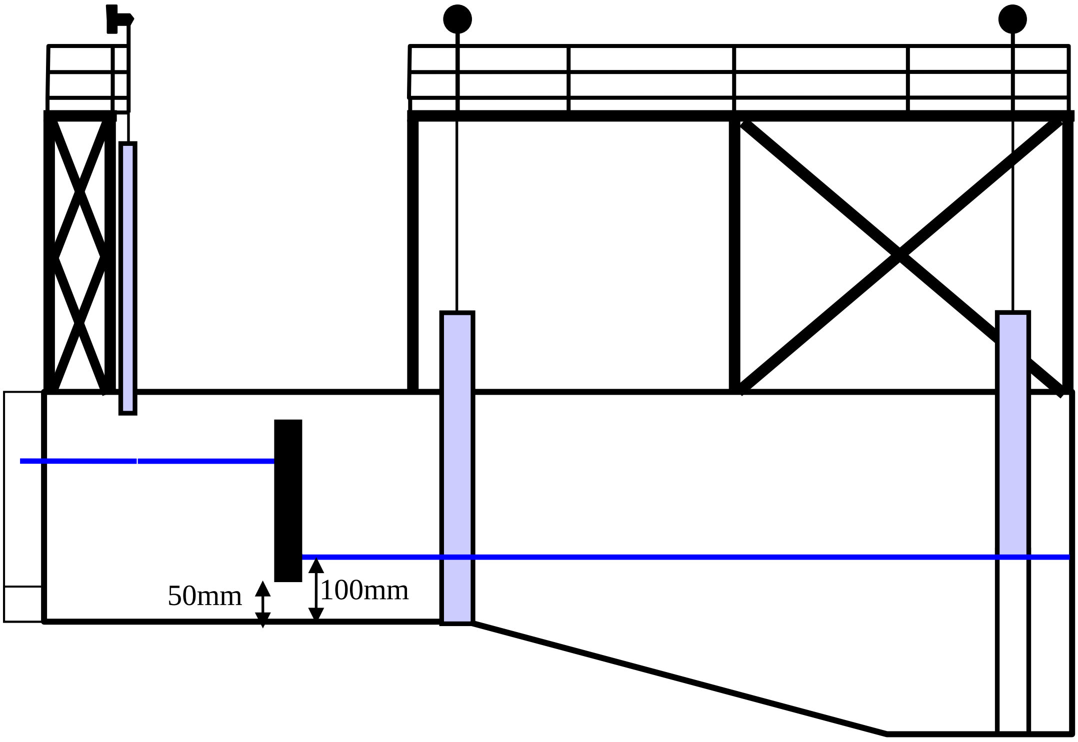
Experimental Configuration 6: Undershot (low opening, high tailwater)



Experimental Configuration 7: Undershot (high opening, high tailwater)



Experimental Configuration 8: Undershot (low opening, low tailwater)



APPENDIX 3: FUTURE RESEARCH SUGGESTIONS

Key Management Issue(s) (as identified in the Native Fish Strategy)

The following projects relate specifically to improving the collective knowledge and understanding of river regulation infrastructure and specific effects on fish. Initially, a number of factors related to infrastructure should be investigated to determine the impacts on fish, which was partly addressed in the current report. Now that preliminary investigations have identified potential sources of impacts, new research should be initiated to determine the scale of impacts on a Basin-wide scale and identify any species-specific effects that may require detailed management consideration. Once a more detailed understanding of the effects of river regulation infrastructure has been achieved, resources should then be directed to determine potential solutions that provide long-term protection for native fish.

In respect to the Native Fish Strategy, this research is important and directly related to the following objectives:

- To protect the natural functioning of wetlands and floodplain habitats by preventing fish entrainment into irrigation systems
- To modify flow regulation practices by improving the operation of irrigation infrastructure
- To create and implement management plans that protect fish by reducing the threat of entrainment or injury
- Manage fisheries in a sustainable manner by protecting source populations in main rivers and streams where irrigation water is drawn.

The specific development of research and management responses to these objectives will provide useful progress to successful implementation of the six driving actions of the Native Fish Strategy. Given the high profile of water delivery throughout the Murray-Darling Basin, community engagement is essential to ensure the objectives are successfully achieved.

Context, and how this addresses key management issue(s), strategies or policies

The Murray-Darling Basin supports at least 40% of Australia’s agricultural production, a population of over 2 million people and is one of Australia’s most important natural resources. The overall health of the Murray-Darling system has declined over the last 100 years largely due to factors such as over-fishing, water extraction, land clearing, alteration of natural flow regimes, riparian degradation and reduced connectivity. Whilst the degradation of the Murray River has had detrimental effects on virtually all resident biota, impacts on the abundance and diversity of native fish have been particularly profound. In particular, recent estimates suggest native fish numbers within the Murray-Darling Basin may now be 10% of pre-European levels.

Two major weir designs, undershot and overshot, are constructed on Australian waterways. Undershot weirs are usually operated via steel gates and water is released underneath the weir whilst overshot weirs are usually constructed from concrete or wood and water cascades over the weir crest. In Australia, many weirs that were constructed in the early 1900’s were of overshot design and are currently being upgraded to undershot designs to comply with safety requirements and to minimise maintenance. A series of recent small scale experiment on a low-level weir determined that undershot weirs contributed to high mortality of Golden perch *Macquaria ambigua* (up to 95%) and Murray cod *Maccullochella peelii* (up to 52%) larvae which drifted through the structure (Baumgartner *et al.*, 2006). Mortality due to overshot weirs was substantially lower (1.5%) (Baumgartner *et al.*, 2006). These results demonstrate potentially catastrophic effects of undershot weirs on native fish populations but further research is needed to determine if such mortalities are equal across all species and size classes of native fish.

The Commission's need to fund this work

Preventing and protecting fish from mortality at river regulation structures in a Basin-wide issue. The Native Fish Strategy provides a useful mechanism to benchmark the impacts of current practices by initiating targeted research throughout different regions of the Murray-Darling Basin. It also provides a framework to influence natural resource management on a whole-of-Basin scale by using the results of targeted research to develop practical outcomes that protect aquatic resources. No other organization has the sufficient resources or ability to influence management on a scale that could facilitate large-scale improvements to existing practices. Incorporating the effects of river regulation structures into the strategic objectives and key driving actions of the Native Fish Strategy will play a pivotal role in protecting native fish, particularly during early life history stages that are susceptible to entrainment.

Opportunities for linkage or collaboration

Projects identified on subsequent pages should be undertaken in a collaborative manner that includes both state-managed and private research institutions to undertake on-ground research. Depending on the nature of the work, some aspects could be undertaken by sole providers or collaboratively, especially where impacts act in multiple jurisdictions. Importantly, addressing irrigation infrastructure offers enormous opportunities for community engagement and involvement in research and on-ground works. Specifically, river operators should be engaged when determining potential solutions to mitigate the impacts of irrigation infrastructure on fish. This could be facilitated through the development of effective demonstration reaches that attempt to showcase ecological improvements to the wider-community, especially where large-scale uptake could enhance fish communities on a large-scale.

Funding bodies should also give consideration to co-investment. Water management agencies may be interested in co-investing in infrastructure that improves the environmental delivery of water. The development of ecologically-friendly infrastructure may also meet the strategic objectives of the national water initiative, especially where improvements in water delivery are a key outcome arising from the work. In these instances, the development of strategic co-investment strategies may provide a cost-effective method to achieve the multiple objectives, spanning a number of initiatives which are relevant on a multi-jurisdictional scale.

Project Suggestion 1: Understand impacts of shear and pressure change on native fish in the Murray-Darling Basin

Overview

One of the major findings of this study were that the actual mechanisms driving mortality could not be identified in isolation. The major factors were shear, velocity and pressure change but these were not adequately controlled as part of the existing study. Whilst we now have operational options to reduce impacts on fish, a lack of understanding of hydraulic impacts is currently precluding the design of effective engineering solutions. Understanding these mechanisms would help inform the design of future weir upgrades and also hydro facilities to minimize the impacts on fish.

Project Objectives

- To understand critical values of shear, pressure and velocity for a number of native fish species
- To determine where these critical values may be exceeded
- To scope engineering solutions that contain fish-friendly hydraulics for wider application in the Murray-Darling Basin

Key Tasks

- To perform a desktop review of methods to determine impacts of pressure, velocity and shear
- To construct specific lab equipment to test impacts on fish
- To run a series of lab trials to determine critical values for a range of species and life history stages
- To perform a global literature review of existing engineering solutions and recommend a number for application in the MDB

Anticipated Products

This project will provide a detailed understanding of critical values of hydraulic parameters that can be tolerated by fish. Lab facilities for further work will be acquired an be made available to collaborating organizations.

Anticipated Outcomes

The major outcome of this work will be an improved understanding of the mechanisms influencing fish mortality not just at dams and weirs, but at other sites where these critical hydraulic parameters are exceeded. It will enable the construction of effective engineering solutions to mitigate large-scale impacts on fish.

Opportunities for end-user involvement

River operators and engineers should be involved in the review phase of this project, especially when seeking to identify engineering solutions. Other industries such as mini-hydro or irrigation agencies may also find the information useful.

Mechanisms for transfer and adoption

The products and outcomes of this specific project could be transferred to end-users via:

- The production of a final report and summary brochure upon completion
- Presentations to interested community groups and also to a scientific audience via the annual Native Fish Strategy forum
- The dissemination of the project products via the Native Fish Strategy Coordinators and members of the Native Fish Strategy Implementation Working Group
- Engaging relevant media where possible (radio, TV and written press).

Estimated cost and duration

The project could be carried out by a single agency provided it can demonstrate sufficient experience in fish ecology and engineering expertise. The entire project should be delivered within 24-30 months for $200,000 - $400,000 (this would include the purchase of specialist equipment, operating expenses and staff).

Project Suggestion 2: Development of engineering solutions that can be retrofitted to existing weirs and mitigate downstream migration impacts

Overview

One of the major findings of this study was that the engineering solutions developed for wider application did not effectively mitigate the impacts of undershot weirs. Unexpected hydraulic outcomes largely contributed to this result, however, it became apparent that once the critical values of hydraulic parameters were known that effective solutions could be designed.

Project Objectives

- To use critical values of shear, pressure and velocity to design effective hydraulic modifiers to improve existing undershot weirs
- To identify key sites where these could be installed
- To ensure future installations are constructed in a fish-friendly manner

Key Tasks

- To perform a desktop review of existing hydraulic modifiers used elsewhere
- To workshop effective designs
- To create engineering drawings
- To suggest a list of sites where these solutions could be implemented

Anticipated Products

This project will provide a detailed engineering drawings and solutions suitable for adaption to existing weirs.

Anticipated Outcomes

The major outcome of this work will be an increased understanding of engineering solutions which can improve the ability of native fish to perform downstream migrations.

Opportunities for end-user involvement

River operators and engineers should be involved in the review phase of this project, especially when seeking to identify engineering solutions. Other industries such as mini-hydro or irrigation agencies may also find the information useful.

Mechanisms for transfer and adoption

The products and outcomes of this specific project could be transferred to end-users via:

- The production of a final report and summary brochure upon completion
- Presentations to interested community groups and also to a scientific audience via the annual Native Fish Strategy forum
- The dissemination of the project products via the Native Fish Strategy Coordinators and members of the Native Fish Strategy Implementation Working Group
- Engaging relevant media where possible (radio, TV and written press).
-

Estimated cost and duration

The project could be carried out by a single agency provided it can demonstrate sufficient experience in fish ecology and engineering expertise. The entire project should be delivered within 6-12 months for $150,000 (this would include the drafting of engineering drawings and production of a report).

Project Suggestion 2: Scoping screen technology to protect downstream migrants

Overview

In USA and Europe, many types of screens have been developed to improve the survival of downstream migrating fish. Many of these screens are suitable for large and small fish and are constructed on large-scales. There are currently no effective fish screens which have been implemented at dams and weirs in the MDB. Development of suitable screens should be seen as a priority for the future protection of native fish.

Project Objectives

- To perform a desktop review or physical inspection of effective screens
- To identify screens for potential installation in the MDB
- To identify key sites where these could be installed
- To scope the cost of these installations
- To prepare engineering solutions and provide recommendations for adoption in the MDB

Key Tasks

- To perform a physical and desktop review of existing hydraulic modifiers used elsewhere
- To determine operating parameters that would permit rollout in the MDB
- To create general engineering drawings of potential installations
- To suggest a list of sites where these solutions could be implemented

Anticipated Products

This project will provide a detailed understanding of screening solutions suitable for adaption to existing weirs.

Anticipated Outcomes

The major outcome of this work will be an increased understanding of engineering solutions which can improve the ability of native fish to perform downstream migrations.

Opportunities for end-user involvement

River operators and engineers should be involved in the review phase of this project, especially when seeking to identify engineering solutions. Other industries such as mini-hydro or irrigation agencies may also find the information useful.

Mechanisms for transfer and adoption

The products and outcomes of this specific project could be transferred to end-users via:

- The production of a final report and summary brochure upon completion
- Presentations to interested community groups and also to a scientific audience via the annual Native Fish Strategy forum
- The dissemination of the project products via the Native Fish Strategy Coordinators and members of the Native Fish Strategy Implementation Working Group
- Engaging relevant media where possible (radio, TV and written press).
-

Estimated cost and duration

The project could be carried out by a single agency provided it can demonstrate sufficient experience in fish ecology and engineering expertise. The entire project should be delivered within 6-12 months for $50,000 - $100,000 (this would include the drafting of engineering drawings and production of a report).

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.