

**EVALUATION OF FISHWAY DESIGNS FOR USE AT THE
EBB AND FLOW REGION OF RIVERS IN THE EASTERN
CAPE, SOUTH AFRICA**

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Abstract

Fishways are devices that are increasingly being used worldwide to assist aquatic biofauna to migrate through man-made barriers such as weirs and large-scale dams that are used for water storage, electricity generation etc. and have a negative impact on both the upstream and downstream movement of aquatic organisms. Fishways are usually low gradient channels with evenly placed chambers which allow such migrating aquatic species minimal stress on their passage over these barriers. Despite the existence of national and regional policies for their provision, their construction has often been inhibited through a lack of local assessment of the available designs, and use of ineffective international designs. As part of a larger national research programme, sponsored by the Water Research Commission, to develop a protocol for fishway design and implementation, this study sought to investigate the suitability of vertical slot and sloping baffle designs to assist the migrations of juvenile catadromic fish species in the ebb and flow region of rivers in the Eastern Cape, South Africa.

These fishways were initially tested under controlled conditions at the Experimental Fish Farm at the Department of Ichthyology and Fisheries Science, Rhodes University using various fish species. Using the performance data thus collected they were then installed and monitored in the field for the catadromic *Myxus capensis* (freshwater mullet) and *Monodactylus falciformis* (cape moony) migrations during March and November of 2005 at the Kowie River ebb and flow weir.

The laboratory tests showed that there was a significantly higher level of migration success in the vertical slot compared with the sloping baffle fishway under all conditions

($F=82.157$; $p<0.001$). There was, however, a slow decline in levels of success with increased discharge in the vertical slot fishway. This was in contrast to the sloping baffle design where success increased as discharge increased at a steep gradient ($F=74.894$; $p<0.005$). The level of success with the *M. capensis* was related to the size of the fish for both systems with success increasing from the small to the large fish ($F=17.755$; $p<0.001$). For the *M. falciformis* higher levels of success were found to occur in the vertical slot fishway compared to the sloping baffle fishway ($F=11.792$; $p<0.00086$), with no significant differences being found with an increase in discharge. Field data indicated similar trends with higher migration success using the vertical slot fishway. *M. capensis* were better able to negotiate both devices compared to the *M. falciformis* and overall levels of success were higher for both species in the field than under laboratory conditions where the migration urge may have declined.

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Chapter 1

Introduction

1. Literature Review

The aim of this study was to evaluate two fishway designs for use at the ebb and flow region of rivers in the Eastern Cape of South Africa. The investigations formed part of a larger fishway research programme funded and co-ordinated by the Water Research Commission of South Africa. This was in order to develop a protocol for determining the need for and appropriate design of fishways for use in South Africa. In order to contextualise the study and motivate the methods and experimental design, a brief literature review is provided below.

Steadily growing demand for water in South Africa and elsewhere has resulted in an increase in the construction of instream barriers for water storage. These potential fish migration barriers have led to renewed research into the provision of suitable mitigation measures that promote the free movement of fish and other migratory biota. The current paucity of information on migratory behaviour and capabilities of southern African aquatic biota has resulted in the need for research into the suitability of potential fishway designs before implementation can take place (Heath *et al* 2005). Through the controlled testing of identified fishway designs with representative fish species the development of effective devices will hopefully be achieved.

Fishways are devices that are now commonly employed worldwide to assist aquatic species to surmount man-made perturbations in rivers, such as gauging weirs, dams and causeways (Kowarsky and Ross 1981, Harris 1984, Rajaratnam *et al* 1986, Laine *et al* 1998, Kim 2000). They are normally low gradient channels with a number of pools that allow fish to move through or around the barrier without undue stress (Karisch and Power 1993, Clay 1995, Bunt 2001). The need to provide fishways on such man-made barriers has been recognised as a priority for environmental management and to protect aquatic biodiversity. Unfortunately fishway installation in South Africa has been slow in the absence of defined assessment methods necessary to support policy on their provision (DWAF 1991).

There are currently five types of fishway in common use today, including mechanical fish locks and lifts, pool and weir variants and simple bypass channels (Clay 1995, Laine *et al* 1998). It is only since the year 2000 that research efforts have been undertaken to address the requirements of indigenous species under southern African environmental conditions, where drought and human impact are commonplace (Bok *et al* 2004). A number of fishway designs have been shown to have promise (Heath *et al* 2005), but a completely effective design has yet to be developed. This has been in part due to a lack of funding, but also due to a considerable lack of information on instream barriers, design guidelines for suitable fishways and information on the swimming abilities of the migratory biota (Heath *et al* 2005).

The worldwide increase in interest and research effort on promoting free passage of aquatic organisms has led to a number of current fishway initiatives. These programmes, funded by the WRC, aimed to develop criteria for fishway designs for South African conditions and also investigate the swimming abilities of the migratory biota. They will culminate in the publishing of a book entitled “Guidelines for the planning and design of fishways in South Africa” that will allow the Department of Water Affairs and Forestry to make informed decisions on the implementation of future fishways.

1.1 Water as a resource

There are three primary driving forces that affect South Africa's freshwater environment and water availability. Firstly, the climatic conditions, which combine relatively low rainfall with high evaporation rates, often resulting in low run-off. Second is the rapid population growth and need for development through economic activities, leading to greater water demand and thirdly the increased pollution of available water resources (Walmsley 2002).

South Africa has a climate which is highly variable, both spatially and temporally. There are also extensive arid areas in the south central to southwest where a large portion of the country's rural communities are found; this is coupled with variable development needs, infrastructure and socio-economic situations as well as surface and groundwater systems (Goldblatt *et al* 1999). South Africa's rainfall is unreliable and unpredictable, with large annual fluctuations being the rule rather than the exception in most areas. There are also periodic severe and prolonged droughts, which often end in severe floods. Water resources are furthermore unevenly distributed in time, space and in source with much of the available water confined to large perennial rivers in the north (Mwendera *et al* 2003).

The national average annual rainfall is only 464 mm which is only slightly more than half that of the world average of 860 mm. In general it is therefore a dry country especially in the west (Figure 1.1). About 20% of the country has a total annual rainfall of less than 200 mm, 48% between 200 and 600 mm, while only about 30% has more than 600 mm. In total, 65% of the country has an annual rainfall of less than 500 mm. The majority of the Eastern Cape falls into this category with the coastal belt receiving a slightly higher level (Read 1985).

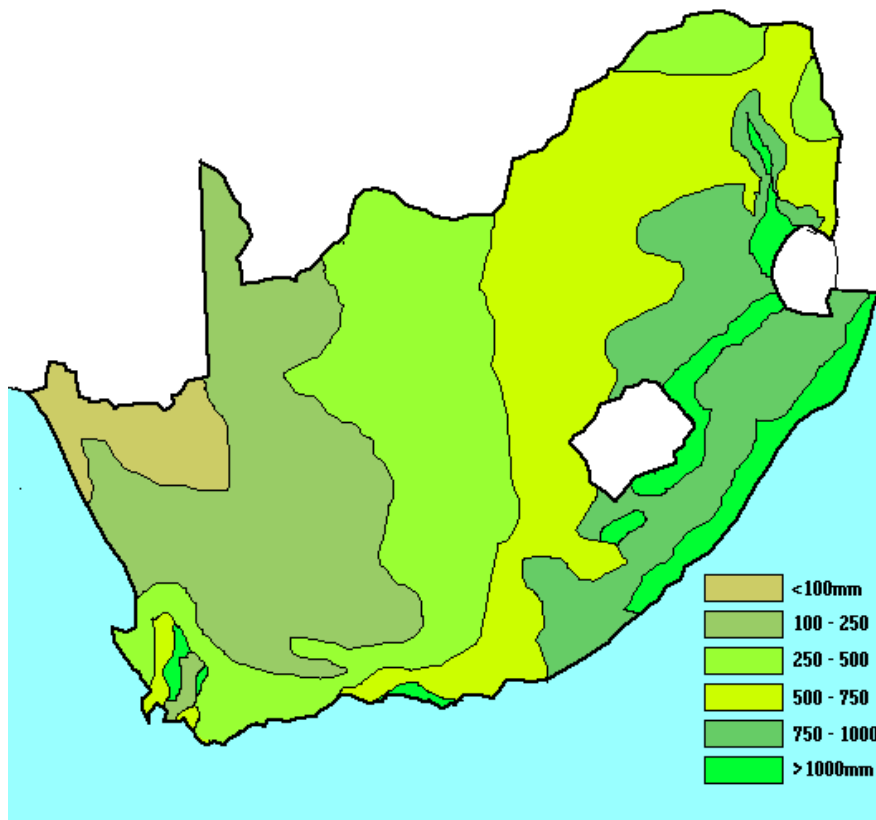


Figure 1.1: South African Annual Rainfall Estimates

Water is an important resource for social development and economic growth as well as from an environmental perspective. Sustainable development through sound management of water resources in South Africa is imperative, in order to counteract the combined effects of increasing environmental degradation, rural, urban and industrial development that are an integral part of a rapidly growing society. Furthermore, with this increasing degree of urbanisation, rising standards of living and increased agricultural activities country-wide, available water resources and the quality thereof are being negatively impacted. In a region where the allocation of water amongst its users in various sectors is highly inequitable and where the population continues to swell at around 3% per year it is becoming increasingly difficult to meet the needs and redress the inequalities of supply (Mwendera *et al* 2003). This use of a limited resource by modern society has further created a need for change in present and future water use (Holtzhausen 2002). These changes may ultimately lead to even greater pressure on already highly impacted levels of river discharge.

Freshwater is the resource most limiting to national development in South Africa and as a result there has been emphasis on the construction of numerous dams, other storage facilities, inter-basin transfers and supply schemes. Also there has been little or no concern for conservation and demand management, prevention of pollution and the need for water to maintain healthy ecosystems during the development of these schemes. It is unfortunate that many of these structures have been situated in drier portions of the country where evaporation rates are high which further exaggerates the problems of water shortage (Webster 2001). More recently, however, with the promulgation of the National Water Act (No. 36) of 1998 sufficient levels of compensation flow are required to be maintained to ensure an acceptable ecological status. The limitation, by this act, of non-consumptive activities, which may affect water quality, often results in less than ideal adaptive measures being taken to ensure the legislation is met.

1.2 River Regulation and its Impact

It is normally the unidirectional downstream flow of water in streams that places limitations on upstream movement of stream-dwelling organisms. An inevitable consequence is that downstream drift will occur, the effects being particularly severe during periods of higher than normal discharge. Low to moderate flows can also result in substantial fish stock losses due to drift under natural system conditions. Many stream animals have as a result developed a positive rheotactic response (Hultin et al. 1969; Elliott 1971; Lee & Fielder 1984; Williams & Williams 1993), an adaptation that causes them to orientate into the current and attempt to move upstream against it. This behaviour has been generally understood to be an adaptation in order to maintain populations in flowing waters. Although observed in invertebrates as well as fish the level of the response appears to be more advanced in fish (Lee & Fielder 1984). Large scale migrations of both adult and juvenile fish whilst driven by some biological mechanism are often influenced by the fish's rheotactic response, ensuring the fish orientate correctly.

Flood control schemes and impoundments while necessary for monitoring and regulating instream flow are also used in industrial and agricultural processes as well as for domestic supply purposes. These structures whilst useful for water storage and for reducing the risk of flood damage have major negative impacts on riverine ecosystems (Halls *et al* 1998) which include the alteration of the flow conditions, water chemistry and other physical conditions of the river system and also have a delayed longer term effect due to system fragmentation (Skelton 1990). Species that depend on longitudinal migrations within a river system become separated and isolated from breeding or feeding areas by these barriers (Russell and Rogers 1989). Whilst more severe impacts may be the reduction in biodiversity and carrying capacity of the system by habitat alterations (Skelton 1990).

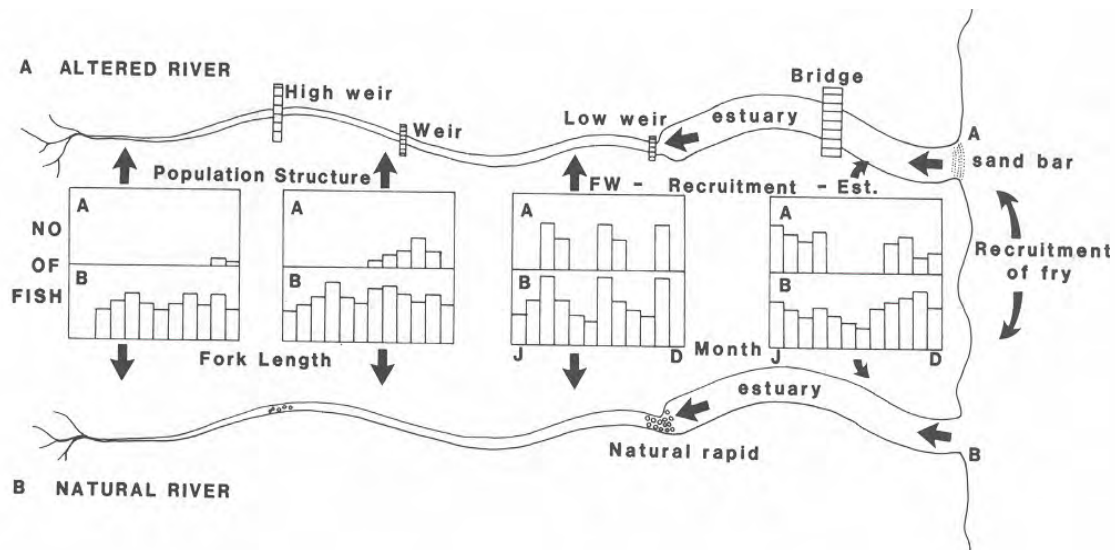


Figure 1.2: Diagrammatic Representation of Factors Affecting *Myxus capensis* Population Structure from Bruton *et al* 1987.

Many of the native species of fish found in South African freshwaters undergo some form of migration, either within a particular system or in a few cases from such a system into the ocean (Bruton *et al* 1987). It is through the building of dams and other instream barriers that the movement of fish and other aquatic biota are affected. These restrictions can then lead to reductions in abundance, recruitment and distribution of the affected

species (Figure 1.2). Impoundment of the Murray-Darling system in Australia has been shown to have had negative impacts on the fish fauna by suppressing breeding, (Harris 1984) and it is possible that similar affects have occurred locally. Impacts of instream barriers have also been noted on the spawning runs of anadromous fish species in the Northern Hemisphere. With an ever increasing number of small impoundments and unregistered “farm dams” being constructed along South African river systems, increased water abstraction directly from the river channels, fish movements are further limited.

The type of barrier and its position in the river system is an important aspect to consider when determining the impact it will have on migrating biota. Obstructions considered to be minor migration barriers in large systems or in the middle and upper reaches of rivers could in other circumstances become major barriers, especially to smaller sized species adapted to migrate into lower energy water flows and/or up relatively low gradients. Artificial tidal barriers could therefore be categorised as significant barriers as they could have a relatively larger impact on different migrating species and their ontogenetic stages e.g. larvae and small juveniles of catadromous species during their upstream migrations (Harris 1984, Stuart & Berghuis 2002).

The ability of fish to bypass physical barriers varies greatly. Small juveniles and larvae of many catadromous species trapped below tidal barriers face proportionately similar obstacles as large species trapped below high dams (Bainbridge 1958). Fish and other aquatic biota with the abilities to cling to or climb wetted surfaces would be less affected by physical barriers than those that lack this ability (Harris 1984). Furthermore the time at which migrations take place can impact on the ability of the fish to overcome a barrier. Migrations of both adults and juveniles occur at differing times with the majority occurring during low flow conditions (Mallen-Cooper 1997). Should the timing of a migration occur during a high flow period, it is possible that slower flowing waters along the stream margins would provide passage around some of the barriers that previously would have been impassable (Harris 1984).

1.3 Fishways, What and Why?

Fishways are often constructed in order to aid the movement of fish across instream barriers (Harris 1984; Kim 2001). They are generally perceived as hydraulic structures assisting upstream migrating fish in overcoming obstructions that block their way to spawning grounds although they can serve as routes for other purposes as well, such as feeding or over-wintering migrations. They are designed to permit fish passage past an instream obstacle by reducing the velocity and energy of flow through part of the channel (Laine *et al* 1998). The size of the pools, steepness and the type of opening between each section in a fishway all influence the velocity of the water flowing through the system and hence the ability of the fish to negotiate the fishway (Mallen-Cooper 1994).

High water velocity is the major limiting factor for fish migration and is related to the height and length of the structure (Harris 1984). Economic considerations can have a major influence on fishway design (Holtzhausen 2006) and it is often required that capital costs be kept down when the fishway is constructed (Harris 1984). By decreasing the length of a fishway, through increasing the gradient and in doing so the velocity, yet still maintaining successful passage one design may be preferred over another (Schwalme *et al* 1985; Stuart & Mallen-Cooper 1999).

Historically most European and American fishways were built in order to aid the upstream movement of large populations of valuable salmonids. Moves have recently been undertaken in other areas of the world, however, to allow the movement of species that are often poor swimmers and of less commercial value than salmonids as well (Laine *et al* 1998; Stuart & Mallen-Cooper 1999; Fievet 2000). It is, however, from these initial North American and European designs that fishways have been built in other parts of the world, and as a result many of them have been shown to be “ineffective in passing weaker native fish and typically weaker small fish” (Mallen-Cooper 1994, Stuart & Berghuis 2002). What has become particularly evident in subtropical regions is where the lack of research into biology and migratory life stages of aquatic species has resulted in the implementation of ineffective designs, (Stuart & Mallen-Cooper 1999) so that many

fish species have suffered reductions in their distributions, numbers and in some cases population stability. The design limitations of these earlier fishways have resulted in renewed research toward the development of design for non-salmonid fish species through collaborative efforts between fish biologists and hydraulic engineers (Harris 1984; Stuart & Berghuis 2002).

It was in 1990, at the “Fishways in South Africa” workshop, that the need to incorporate fishways in the building of new barriers across the country was identified (DWAF 1991). Existing man-made barriers such as gauging weirs and dams were given as major factors responsible for the reduction in numbers of migratory fish throughout South Africa (Skelton 1990). Their impacts, combined with the erratic nature of our river systems can affect the utilisation of fishways. Monitoring and performance data has also often been difficult to collect from the few fishways that have been constructed usually because of their remoteness and as such there is uncertainty regarding their efficacy. Recent monitoring of the approximately 57 recorded fishways in South Africa has revealed that only 73% of these are functional to any degree, most only being effective for the strongest swimmers of some of the species (Heath *et. al.* 2005).

1.4 Fishway Selection Criteria

Before a fishway is built at any barrier it is important to examine firstly whether or not it is necessary and secondly whether or not it is feasible. By answering a number of questions related to its provision the necessity for providing such fishways can be determined. Also a proposed fishway on a highly impacted system that has no threatened species would have a far lower priority than a fishway proposed for a system that is home to even only a few threatened species. Differing scores and criteria can be agreed upon by all water users and ecologists, for each system ensuring a wide level of acceptance (Bok *et al* 2004). See Figure 1.3 below.

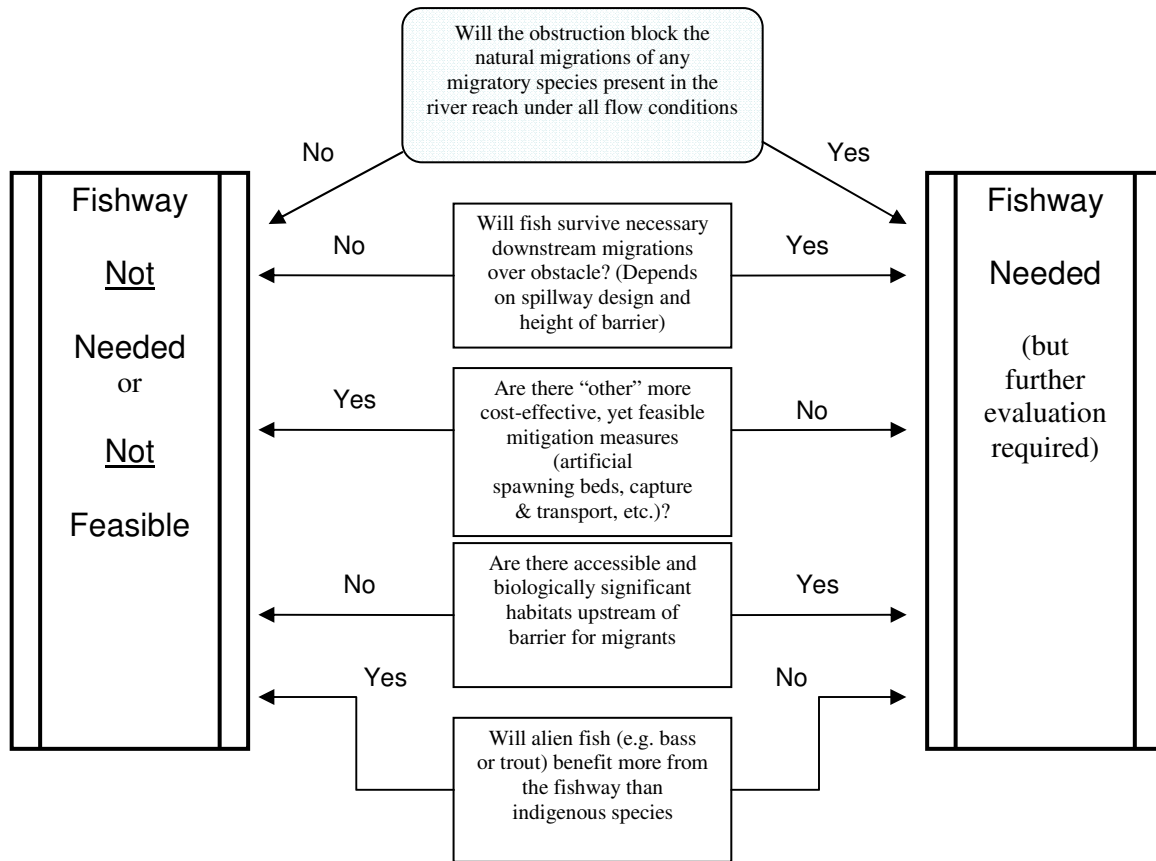


Figure 1.3: Protocol for assessing the need to provide a fishway at an instream barrier, adapted from Bok *et al* 2004

Once the criteria have been met and it is determined that a fishway is needed there are a further number of considerations to take into account before the correct design can be chosen. Included in the list of further considerations are biological constraints on design by the target species such as species composition, size range when migrating, swimming ability and behaviour (Harris 1984; Bok *et al* 2004). The hydrology of the river is also very important. The fishway should operate effectively over the normal range of river flows that might be expected during fish migrations (Rowland *et al* 2003). Where the flow is modified by a barrier both headwater and tailwater levels around migration times should be established. This is to ensure that the fishway is designed correctly, the entrance well sited and a design suitable for the type of flow is selected (Bunt 2001). Finally the topography of the fishway site should be taken into account. Where the

topography creates suitable conditions for one design of fishway it may preclude another, for example, large rock formations in the river bed or on the banks may allow for a less expensive structure to be built.

1.5 Fishway Types

There are a number of common fishway designs used to mitigate the effects of instream barriers. The primary designs include; pool and weir, vertical slot, rock ramp, bypass channels and Denil fishways (Clay 1995), however, there are other devices built specifically to allow fish passage that are not built to any one of these designs. The most common designs that have been used in South Africa are pool and weir and vertical slot types, with 32 of the former and 8 of the latter (Heath *et al* 2005). Although most of the South African fishways have been constructed using international designs, a small number have been modified in order to improve their suitability for local conditions.

1.5.1 Pool and Weir Fishways

Pool and weir fishways consist of a sloping channel which is divided into a series of pools separated by numerous weirs. Each of the weirs is set slightly lower than the preceding one and reaches across the full width of the channel. The weirs can be notched or sloped to alter the internal hydraulics as the water flows between pools, spilling over the weir crest (Kim 2001; Clay 1995). Pool and weir fishways are typical of high velocity fishways that cater largely for strong swimming species, such as the salmonids of the Northern hemisphere. The numbers of these structures across the country that are ineffective are an unfortunate example of the inappropriate application of foreign technology to local conditions (Heath *et al* 2005).

1.5.1.1 Sloping Baffle Fishways

The inclusion of a forward slope as well as a sideways slope across each weir in some pool and weir fishways is an adaptation specifically developed to allow juvenile mullet, macrocrustacea and eels to pass through. Although not ideally suited to climbing biota, the provision of a splash zone on these sloped fishways has been noted to improve the passage of macrocrustacea (Fievet 2000). In these sloping baffle fishways the most significant alteration to the fishway is the weir design, where a thicker weir is in place allowing the water to flow over the crest in an adherent nappe. Furthermore, due to the slope across the channel width a range of depths is available to the migrating fish allowing them to select their preferred depth and current speed when crossing the weir. This adaptation also allows for fish of different sizes to migrate in the same fishway. It was because of these characteristics that this was one of the designs chosen for testing in this study.

1.5.1.2 Vertical Slot Fishways

Vertical slot fishways are a variation of the pool and weir type designs. They consist of a similar sloping channel which is again divided into a number of pools. They differ from the pool and weir design in that each of the weirs does not extend the full width of the channel, but instead has a vertical slot that reaches from the top to the bottom of each weir (Harris 1984; Clay 1995). Water runs down the channel into each successive pool through the slot provided. As the flow is constricted in each slot it forms a jet of high velocity water which is then dissipated as it mixes into the pool below (Rajartnam *et al* 1986; Clay 1995). It is important that the velocity of the water through each of the slots is not higher than the burst swimming speed of the weakest target species as they need to be able to overcome this velocity to pass from one pool to the next. In some designs the walls may have either one or two slots or a small sill may be added at the base of the slot. A sill will prematurely dam the pool, thereby providing enough depth in each pool to accommodate fish even at low flows (Heath *et al* 2005). This type of fishway works well

where there are large fluctuations in river height and where fishway flow is unregulated, because they maintain constant velocity at varying flows (DWAF 1991).

Vertical slot fishways have been both monitored and tested extensively around the world for their suitability for passing non-salmonid fish (Berghuis *et al* 1997; Mallen-Cooper 1994a; Mallen-Cooper 1992; Schwalm *et al* 1985). Experiments with both wild caught and captive bred animals have displayed similar results and migratory ability (Mallen-Cooper 1992). They have been shown to be successful in passing both large and small indigenous fish, slot width dependant over a range of river flows and are fast becoming the most widely applied formal fishway design (Beitz 2001; Heath *et al* 2005).

Coastal river systems, however, provide some problems to fishway design, especially under low flow conditions that may be reduced further by water abstraction. There is a minimum flow required to drown out the slot, i.e. to fill each successive chamber such that the energy of the water flowing through the slot is dissipated on entering the next chamber. Under low river levels this may not be possible and the level of the tailwater pool may become affected (Kowarsky & Ross 1981; Russell 1991). This is important as it should be high enough to effectively drown the lowest pool, providing the same conditions as those pools higher up (Bok *et al* 2004). In tidal systems this can be of particular relevance where the lowest pool may become exposed at low tide, effectively preventing migration at these times (Russell 1991). Under conditions where a suitable pool is not available, the fish may be forced to wait further downstream until conditions improve.

Due to the design, velocity and turbulence levels within vertical slot fishways remain quite stable over a wide range of flows resulting in them being considered to be particularly suitable for South African conditions. One negative feature of the design, however, is that they do not provide any form of splash zone that is suitable for passing climbing fauna, common migrants in coastal rivers.

1.5.3 By-pass Channel Fishways

Whilst only a single example of a bypass channel has to date been built in South Africa this form of low gradient fishway, which mimics the natural rapids and riffles found in the particular river, it is a very effective mitigation method (Holtzhausen 2006; Schmutz *et al* 1998). They are built to suit specific sites taking into account the topography, nature of the barrier and target species making each channel different from the next. Bypass channels not only provide an effective means of overcoming barriers to migration but in many cases they also provide suitable habitat for a number of aquatic organisms allowing them to be integrated into river restoration programmes (Berghuis *et al.* 1997). Due to their suitability for such a wide range of migratory biota and the low maintenance required bypass channels have rapidly become the preferred option worldwide on low barriers (Jungwirth 1996), but due to their large space requirements, and hence high cost, they are seldom built (Bok *et al* 2004).

Consideration of the many fishway designs in operation worldwide and after periods of monitoring of some of these fishways in South Africa it has become apparent that two particular designs show the most promise for local conditions (Heath *et al* 2005). The pool and weir fishway with sloping baffles has been implemented in a number of cases on east coast rivers and at their recommended slope of 1:10 they have proven successful in passing both fish and macrocrustacea. The second design, the vertical slot fishway, has been extensively monitored under similar arid conditions to those that occur in South Africa. Their ability to operate under variable flow conditions, and at steeper gradients, has resulted in their being a high priority in terms of further research here.

1.6 Migratory Biota

Many of the fish found in river systems of the coastal fringe of southern Africa have diadromous, though primarily catadromous, life history styles (Bruton *et al* 1987, Harris *et al* 1998). These are often euryhaline species migrating in the lower coastal

reaches of rivers and there are many differences in the factors influencing their migration apart from body size at migration compared to the potadromic migrants further inland, which have to migrate in often higher energy systems. Added to this there are a number of differences that are apparent when examining the migratory biota of the coastal region alone. These differences allow for the division of the coastal region into two main zones, the South-East Coast and the West Coast (DWAF & IWQS 2002) (Table 1).

Table 1: The two coastal migratory regions in South Africa as determined by the size, swimming ability and migratory behaviour of the main groups of migratory biota present, from Bok *et al* 2004.

Migratory Eco-Region	Spatial Description	Main Migratory Species
1. South-East Coast	Mozambique to Palmiet River	A large variety of catadromous and amphidromous fish such as Mugilidae, Monodactylidae, etc. as well as crawling species of macrocrustacea and Anguillid eels.
2. West Coast	Palmiet River to Orange River	Two mullet species, <i>Mugil cephalus</i> and <i>Liza richardsonii</i> , no crawling species present.

There are at least 24 marine or estuarine spawning fish species that are known to migrate, primarily as juveniles, into freshwater zones of rivers along the south and east coasts of South Africa (Bruton *et al* 1987). The amounts of time spent in freshwater by each of the species varies greatly and there are only 5 species that are thought to have obligatory freshwater phases. These are the four freshwater eels; *Anguilla mossambica*, *A. bengalensis labiata*, *A. marmorata* and *A. bicolor bicolor* and possibly the freshwater mullet, *Myxus capensis* (Bok 1983). Other than the migratory fish species there are approximately 9 species of macrocrustacea that enter the freshwater reaches of rivers along the south east coast (Read 1985, Coetzee 1991). The importance of these relatively large invertebrates is often underestimated as they can have dramatic effects on sedimentation and the standing algal crop in many systems (Fievet 2000).

The two most suitable migratory species selected for this study were the freshwater mullet (*Myxus capensis*) and the cape moony (*Monodactylus falciformis*). The reasons for their selection were:

- i) Both species are commonly found in the estuaries in the Eastern Cape.
- ii) They were readily captured at collection sites
- iii) The two species have markedly different body shapes, making for interesting comparisons in functionality of the fishways.
- iv) Both species adapt well to captive conditions, making them suitable for laboratory studies.
- v) They migrate into the freshwater reaches of rivers in the Eastern Cape as early juveniles during the summer months, making them available at similar times.

The cape moony (*Monodactylus falciformis*), (Plate 1.1) is a widespread Indo-pacific species whose range extends far into the Western Cape (Smith & Heemstra 1991). It is regularly found in surf zones as mature adults and in estuaries and the lower freshwater reaches of rivers as juveniles. Monitoring of the movement of fish at a tidal weir on the Kowie River has revealed *M. falciformis* to be the second most numerous fish species at the barrier (Bok & Cambray unpub.). *M. falciformis* display a breeding peak, in near-shore surf zones, during the summer months of Nov-Jan which then corresponds well with the migratory peak during Jan-Mar, during which time the juveniles migrate into freshwater to feed (Lasiak 1984). Although the size of migrating *M. falciformis* varies widely it has been found that comparatively larger fish, with stronger swimming abilities have been found to enter the Kowie River fishway more freely (Bok & Cambray unpub.).

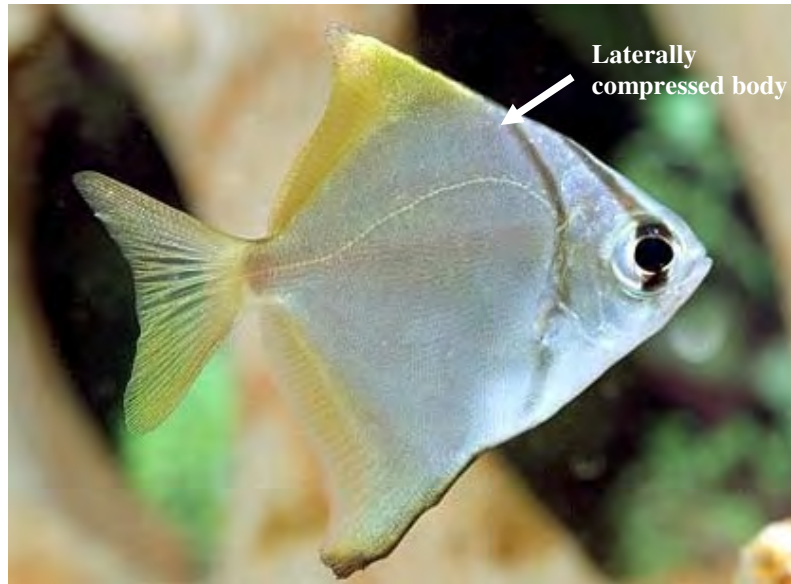


Plate 1.1: Cape Moony (*Monodactylus falciformis*)

The freshwater mullet (*Myxus capensis*) is endemic to the south and southeast coast of South Africa and is known to occur in the freshwater reaches of rivers and lagoons throughout its range (Bruton *et al* 1987). It has been suggested that the natural range of this species has been greatly reduced by human changes to riverine environments such as the building of weirs (Bok 1979). The young migrate into freshwater at a small size (15-40 mm FL) where virtually all growth occurs and emigration takes place at maturity before breeding at sea. The sex ratio is skewed in favour of females which is typical of catadromous fish (Northcote 1978). The species is well adapted to the strong selection pressures of its environment where males emigrate from rivers sooner after maturation than females despite the latter having a faster growth rate (Bruton *et al* 1987).

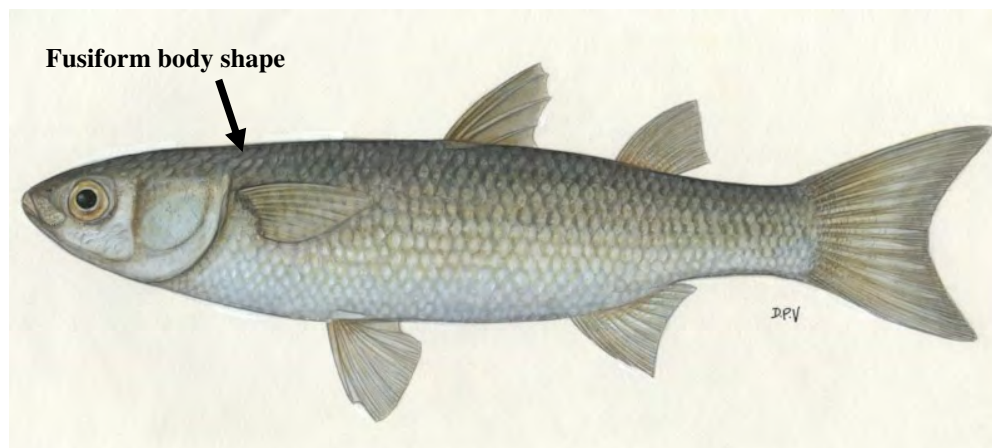


Plate 1.2: Freshwater Mullet (*Myxus capensis*), Smith and Hemstra 1991

M. capensis spawn throughout the year with a peak evident in spring (Bok 1984). It is suggested that this protracted spawning period would act as a buffer against recruitment failure resulting from short-term adverse conditions (Wallace 1975). Furthermore, continuous spawning would allow adult fish to emigrate from freshwater during rare and erratic periods of high flow that typify this relatively arid region. The resultant extension of the recruitment period would thus ensure that a portion of the juveniles will be able, at any suitable time, to recruit into an unpredictable freshwater habitat.

Mullet species like *Mugil cephalus* and *Myxus capensis* have been identified as having potential commercial value in the future. *M. capensis* in particular are believed to have an obligatory freshwater lifecycle phase. By reducing access to their available riverine habitat through structures such as ebb and flow weirs there is a great risk of damaging to their population structure. Since the propagation of most mullet species has still not been perfected and the continued culture of the species is reliant on the capture of wild fry (Durve 1975; Sebastian & Nair 1975; Eda *et al* 1990) it is important to maintain healthy populations of adult fish. By allowing their free movement into our river systems through the implementation of fishways, as well as with appropriate management protocols the commercial as well as environmental value of these fish can be preserved.

In order to meet the aim of this study therefore two catadromous fish species, *M. capensis* and *M. falciformis* were used to evaluate the suitability of vertical slot and sloping baffle fishways for use in the ebb and flow region of Eastern Cape rivers. This was undertaken through a series of controlled tests and field evaluation in the Kowie River, which was used as a representative river for the region.

Chapter 2

Materials and Methods

2. Materials and Methods

2.1 General Description

Trials were undertaken using two prototype fishways, namely a vertical slot fishway (Plate 2.1) and a sloping baffle fishway (Plate 2.2). Both of these designs had characteristics that made them potentially suitable for their use on tidal barriers. These included their ability to allow passage of small fish and crawling aquatic biota in the sloping baffle fishway. Both fishway designs were tested initially at the Rhodes University Experimental Fish Farm, using recycled and temperature controlled water. Later the fishways were taken into the field and a number of experiments were carried out at the ebb and flow weir of the Kowie River using the operating procedures developed under controlled conditions.



Plate 2.1: Vertical Slot Fishway used during experiments.



Plate 2.2: Sloping Baffle Fishway used during experiments.

The fishways could be adjusted from the upstream end, by raising or lowering the header tank attached to the fishway channel in order to alter the gradient and resultant water velocity. To change the gradient of the fishway channel the header tank was fitted with adjustable, slotted legs. To maintain the desired height a steel pin was inserted into the evenly spaced slots in the legs.

The model fishways were set up alongside the biological filter of the warm water system at the Rhodes University Experimental Fish Farm from where conditioned water could be pumped directly into the header tank. Water was supplied to the model fishways through the use of either a 1.1 kW Speck pump or a portable 3.5 kW Honda petrol pump. These pumps were capable of delivering 450 l/min and 930 l/min respectively. Discharge volumes of between 3 l/sec and 15 l/sec could be maintained for the duration of the experiments by varying the delivery rate into the system. The volume of water being pumped through the selected system at any one time was calculated using a 65 l

container, this would be held under the outlet pipes and timed until full. An average of three readings would then be used to determine the discharge rate. A diagrammatic representation of both fishways is shown in Figure 2.1 to illustrate the system configuration.

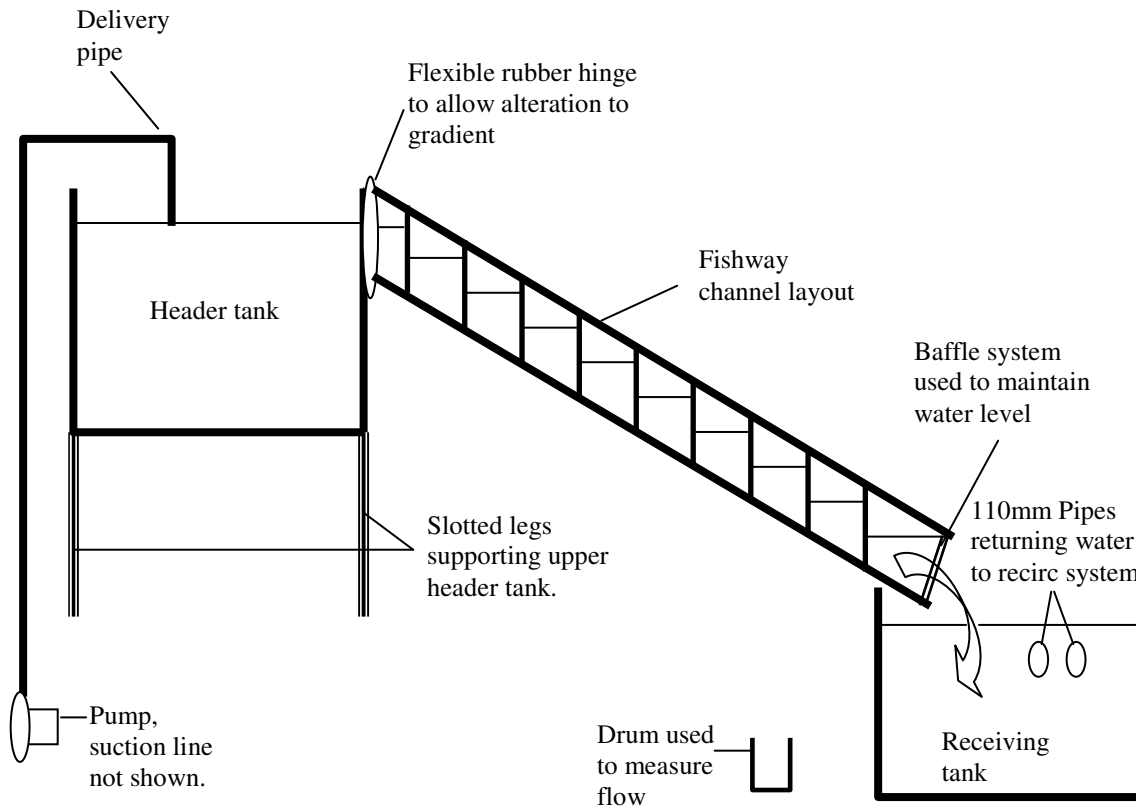


Figure 2.1: Fishway configuration during experimental trials.

2.2 Fishway Description

2.2.1 Vertical Slot Fishway

The mobile vertical slot fishway that was to be used in the experiments was based on the recommended layout as shown in Larnier *et al* (2002). It had no raised wall in the slot (Figure 2.2) and was designed and constructed at the Engineering Department of the University of Stellenbosch. It was made from marine plywood and painted with bitumen

waterproofing sealant and was 4.4 m long, in four sections and with 8 baffles spaced 50 cm apart. Two large, approximately 1000l tanks were positioned at each end, one as a header the other as a receiving and fish holding tank.

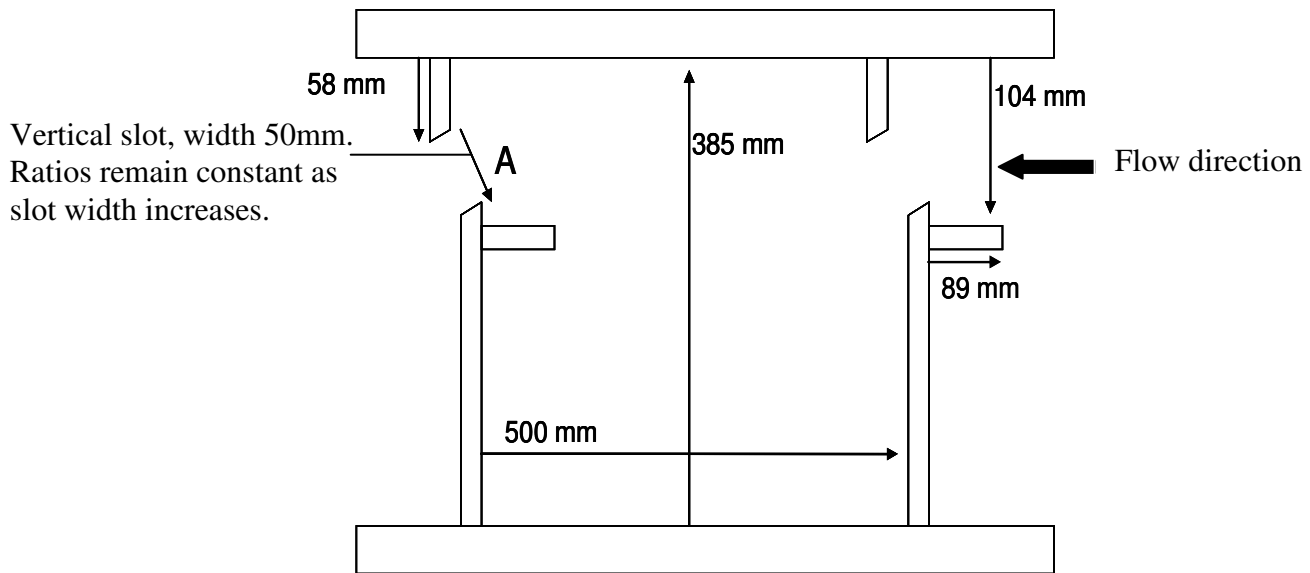


Figure 2.2: Plan view of a single pool in a Vertical Slot Fishway showing dimensions with respect to the slot width.
(adapted from Larnier *et al* 2002)

2.2.2 Sloping Baffle Fishway

The sloping baffle fishway (Figure 2.3) with channel length of 4.2m and width of 50 cm was built at the DIFS and the design was based on plans provided by Dr Anton Bok of Anton Bok & Associates cc. The system was built from plywood painted with a bitumen waterproofing sealant and held within a galvanised steel framework. Each of the seven shaped polystyrene baffles was inserted 50 cm apart creating pools that were 35 cm long, each separated by a 15 cm thick weir.

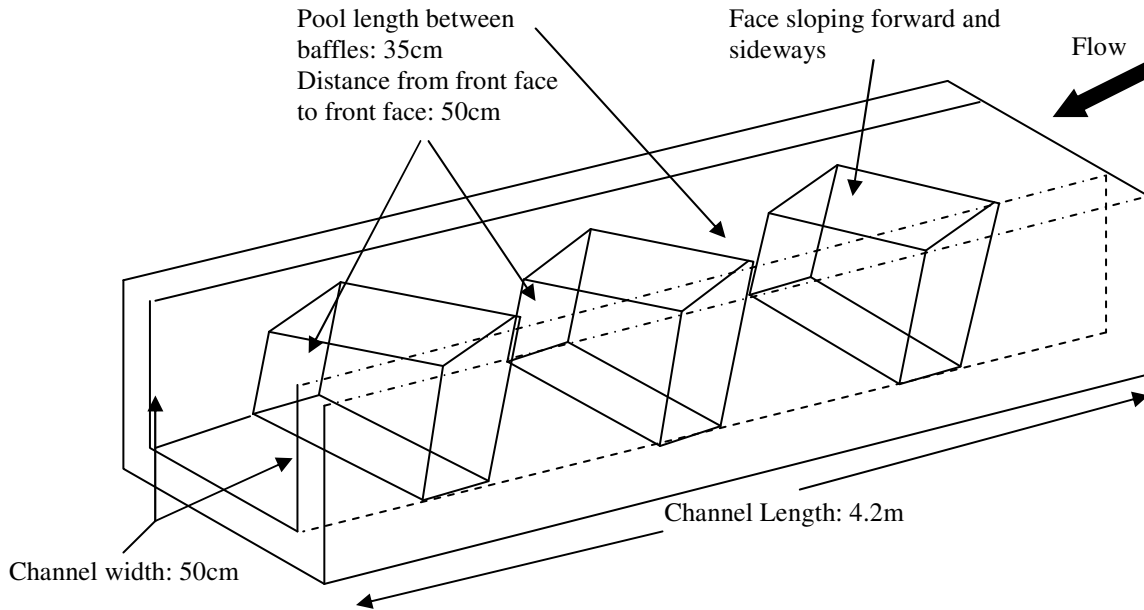


Figure 2.3: Diagram of two pools in a Sloping Baffle Fishway showing baffle dimensions and overall channel length.

The baffles were cut from a block of polystyrene and were double coated in bitumen sealant. The baffles were secured in the fishway by means of short lengths of wood, each attached to the channel walls preventing them from moving either forward or backward and floating up. The baffles were shaped with a forward slope as well as a sideways slope to create areas of differing depth and flow pattern. Furthermore the thickness of the baffles allowed for the water to travel over the surface in an even film.

2.3 Fish Collection

Early juvenile, freshwater mullet (*Myxus capensis*) and cape moony (*Monodactylus falciformis*) were collected in May, August and November of 2004 from the Keiskamma and Kowie Rivers in the Eastern Cape. Both river systems have permanently open estuaries with man-made barriers at and a short distance above the maximum tidal reach respectively.

The collection site on the Keiskamma River near Hamburg was at the base of DWAF gauging weir number R1H015. The weir is situated a short distance, approximately 400m, from the main road between East London and Port Alfred and is 110km from Grahamstown. The ebb and flow weir at this point, 18km from the mouth of the river (Read 1985), forms a migration barrier to the majority of the fish that reach the site despite the weir being equipped with a rudimentary fishway. Both *M. capensis* and *M. falciformis* were caught in the tailwater pool below the weir using a 3m long fine meshed (50 μm mesh) seine net that was drawn through the length of the pool. The fish were then transferred into the transport system and brought back to DIFS in Grahamstown.

The second fish collection site and field study site was at Waters Meeting Nature Reserve near Bathurst on the Kowie River. This site was again directly below a barrier weir situated immediately upstream of the tidal limit of the Kowie estuary, about 21 km from the mouth. The concrete structure is about 40 m long and 5 m wide with the downstream wall sloping at about 45 degrees to a shelf about 0.3 m above the surface of the tailwater pool. The fish were collected using the same small seine net as was used on the Keiskamma River. These fish were then transported to the DIFS in water from the Kowie River before being conditioned to the water in the warm water system at the DIFS through serial changes of 40l every 20 min.

In order to ensure sufficient numbers of fish were caught for use throughout the year return trips were made to both sites during May, August and November of 2004. The repeat trips also ensured that both species were caught in a variety of size classes.

2.3.1 Transport System

The fish caught below each of the weirs were transported in partially sealed polythene bags, each provided with a direct source of oxygen bubbled into the water through a

perforated, weighted PVC ring. The bags were placed inside 200l plastic drums for support, these being placed onto a trailer.

On arrival back in Grahamstown the water in each of the bags was slowly changed by the addition of water from the warm water recirculating system and removal of small volumes of water from the bags. This gradual water change of 40l every 20 min was to ensure that the temperature shock was not too great as to further increase stress and mortality. Despite the precautions taken during the capture and transport of the juvenile fish there was some degree of mortality experienced on each of the sample trips, this was estimated to be between 10 and 15%.

After the fish had been acclimatised to the water in the chosen holding system they were separated by species after which the *M. capensis* were further separated visually into two distinct size classes, simply a small and large size. The fish were allowed to settle in the system for up to two weeks before any experiments were carried out, during which time they were fed a high protein, trout starter diet that had been milled into a smaller more easily ingested size. The fish appeared to be in good physical condition and grew rapidly.

2.4 Experimental Procedure

As part of regular water quality monitoring ammonia, nitrite and nitrate were tested once a week while temperature and dissolved oxygen and pH readings were taken before each experiment. Random samples of thirty mullet (*Myxus capensis*), divided into two size classes: large (40-100mm) and small (20- 40mm) and moonies (*Monodactylus falciformis*) in a single test group, were used for each experiment in both the vertical slot fishway and the sloping baffle fishways. Gradients of 1:10 and 1:5 were tested, the 1:10 being considered a shallow gradient and 1:5 steep. Initially flow rates of 3, 5 and 7 l/sec were used, which were then later reduced to 4 and 8 l/sec as these flow rates created similar conditions to both the low and high volumes previously tested. Water levels were

allowed a period of ten minutes to stabilise after being established to ensure there were no fluctuations in water flow, and thus water velocity during the testing period.

A protocol for introducing fish into the fishways was devised based on previous work by Mallen-Cooper (1992, 1995), whereby the fish were placed directly into the first cell of the fishway ensuring a known number of fish entered the fishway. This protocol was adopted for the duration of the study. A slight adjustment was made in that the fish needed to be prevented from accessing the remainder of the fishway until the end of a short 30 min conditioning period. The chosen experimental flow rate was maintained for the duration of the conditioning period, which had been implemented in an attempt to reduce any effects of handling stress before the fish entered the fishway. After the holding period, the fish were allowed to enter the rest of the fishway to attempt to negotiate the channel. A trapping system designed to fit at the top of the fishway was used to remove fish that had successfully negotiated the fishway at five minute intervals.

In order to maximise the number of experiments that could be carried out it was necessary to determine what the optimal experimental time should be and whether all fish placed into the fishway could be expected to migrate. A random sample of fish was captured from the holding tank and placed behind a screen in the lowest pool of the fishway. After the conditioning period the screen was removed and timing of the fish's migration began. The trap at the top of the fishway was cleared of successfully migrating fish at five minute intervals until no further fish were found in the trap or after 1.5 hours had passed. The total number of successfully migrating fish was recorded, as was the time interval in which that number of fish was reached. The time interval after which no further migration was recorded would be used as the experimental time period for all future trials.

After the optimal experimental time had been established experiments at the experimental fish farm continued early in the mornings as it had been noted during the exploratory work that the intensity of migration began to decline towards midday and only resumed

in the late afternoon. By standardising the time of the experimental runs a potential confounding factor was eliminated.

2.4.1 Fatigue Experiments

Questions were raised during the laboratory trials regarding the effects of repeated exposure and resultant fatigue on fish entering and negotiating the fishways. The primary concern was of the effects of fatigue on the success of the fish should they be required to navigate the fishway more than once, or be exposed to lengthy fishways. Should fatigue be shown to have an effect on the migration success of the fish, what length of time could be considered a sufficient resting period, so as to eliminate these effects?

In order to test for fatigue effects on mullet (*Myxus capensis*) a series of trials was conducted in the vertical slot fishway that was followed by replicate trials in the sloping baffle fishway. The systems were set up at gradients of 1:8 and at flow rates of 6.5 l/sec, with two rest periods being used, one hour and two hours. A total of forty fish were randomly selected from a previously unused sample and any fish that escaped during testing were not replaced. A trapping system inserted at the fishway exit enabled the fish to be moved to a soft netting holding cage for the duration of the rest periods after each twenty minute exposure. The water flow in the systems was only stopped for the short time required to remove any fish that had not been successful in negotiating the fishway. The total number of fish successfully negotiating the fishway after each of five exposures was recorded.

2.4.2 Field Trials

Field testing of both model fishways took place on the Kowie River at the Waters Meeting Nature Reserve near Bathurst. The site was situated at S33° 32' 39"; E26° 46' 52" just upstream of the tidal limit where a weir was built in 1990 to provide water to the local municipality. This weir inhibited movement of juvenile catadromous fish into about 40km of freshwater habitat above the site until 1993 when a fishway was installed (DWAF 1995).

Two field trips were made to this site in order to test each fishway individually. The vertical slot fishway was tested between the 25th of February and the 4th of March 2005 and the sloping baffle fishway was tested between the 23rd and the 25th of March 2005. The field testing took place shortly after spring tide cycles and on both occasions the river was flowing strongly, breaching the majority of the weir width.

2.4.2.1 Vertical Slot Fishway

The vertical slot fishway was set up in three positions during the field tests (Plates 2.3-2.5). These positions varied in both the sighting of the entrance, placement of the header tank and position relative to the weir. It was not necessary to pump any water into the header tank of the fishway, as there was enough height to the top of the weir to siphon the water into the tank. A large diameter (110mm) reinforced pipe was used to create the siphon. When additional flow was required a second siphon pipe of various diameters could be added.

Fishway Positioning:

Position 1. The model fishway was placed on the lower apron of the weir, with the channel entrance facing slightly downstream, directly into the lower pool (Plate 2.3). The entrance was placed into an area of strongly uni-directional flow. The water flowing from the lower weir apron was not altered to direct any further water towards the fishway entrance. The fishway was tested at a 1:5 gradient in this position with a discharge of 8 l/sec.

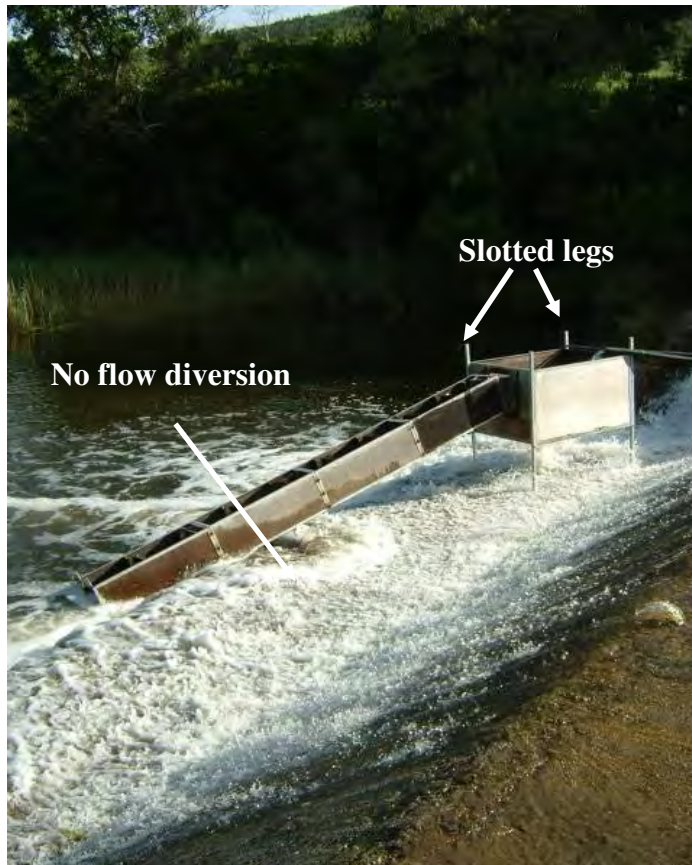


Plate 2.3: Vertical Slot Fishway position 1, on lower apron of weir entrance facing downstream.

Position 2. The vertical slot fishway entrance was again facing downstream, however, this time the model was placed directly over the existing concrete fishway (Plate 2.4). This placed the entrance into the lower pool away from the primary flow of the river and facing an area of overhanging riparian vegetation. This area is where the existing fishway entrance is located and large numbers of fish are known to accumulate here. The fishway was tested at a 1:4 gradient, the shallowest achievable in this position, with a discharge of 8 l/sec.



Plate 2.4: Vertical Slot Fishway position 2, placed over existing fishway.

Position 3. In order to test shallower gradients the model vertical slot fishway was placed in front of the weir in the lower pool (Plate 2.5). The channel was thus positioned parallel to the lower apron of the weir, the entrance facing slightly across the current. In this position the flow of the river was diverted using a number of sand bags in order to cause the majority of the overflow to pass the front of the fishway

channel. The fishway was tested at 1:6 and 1:8 gradients in this position at discharge volumes of 10 and 8 l/sec. The test gradients could not be precisely matched to those tested at the Experimental Fish Farm due to the uneven surface on which the legs were placed.



Plate 2.5: Vertical Slot Fishway position 3, below lower apron of weir with water diverted towards entrance with sand bags.

Two protocols were employed to test the vertical slot fishway in the field. Firstly, it was allowed to operate for 3 hours after which the water supply to the header tank was halted and a stop-net inserted at the entrance to the fishway. Any fish present in the sections of the fishway channel, as well as those that had successfully negotiated the fishway and were found in the trap at the top were identified and measured. This gave an indication of the level of use of the fishway in a set position. Secondly, fish were captured from areas where they were seen to accumulate and placed into the fishway. After an exposure time of 20 min the mesh trap would be removed from the fishway exit and the successful fish removed and measured. The procedure was repeated after a 40 min interval, at which time the water flow would be stopped. This gave an indication of the fish's ability to

negotiate the fishway when in a migratory phase. A total of 11 capture tests were conducted while the model was in position three.

2.4.4.2 Sloping Baffle Fishway

The sloping baffle fishway was set up in two positions during the field testing on the Kowie River. The positions varied in both the site of the entrance and position relative to the weir. It was not necessary to pump any water into the header tank of the fishway, as there was enough height to the top of the weir to siphon the water into the tank. A large diameter (110mm) reinforced pipe was used to create the siphon with additional flow being added through the use of a selection of other pipes in various diameters.

Fishway Positioning:

Position 1. In this position the model fishway entrance was placed facing downstream directly over the existing concrete fishway. This placed the entrance into the lower pool away from the primary flow of the river and facing an area of overhanging riparian vegetation. This area was where the existing fishway entrance is found and where large numbers of fish were known to accumulate. The fishway was tested at a 1:4 gradient, the shallowest achievable in this position with a discharge of 8.5 l/sec.

Position 2. In order to test shallower gradients the sloping baffle fishway was placed in front of the weir below the lower apron (Plate 2.6). The fishway channel was thus positioned parallel to the weir and the entrance faced across the current. In this position the flow of the river was diverted using a number of sand bags in order to cause the majority of the overflow to flow past the front of the fishway channel. A second siphon was used to increase the flow at the entrance to the fishway during low discharge experiments. The sloping baffle fishway was tested at gradients of 1:5 and 1:8 and flow rates of 8.5 and 12.5 l/sec in this position.



Plate 2.6: Sloping Baffle Fishway position 2, below lower apron with water diverted towards entrance.

Two protocols were employed to test the sloping baffle fishway in the field. Firstly, it was allowed to operate for a set length of time after which the supply pipes were removed from the holding tank and a stop-net inserted at the entrance to the fishway. Any fish present in the sections of the fishway channel, as well as those that had successfully negotiated the fishway and were found in the trap at the top were identified and measured. This gave an indication of the level of use of the fishway and the ability to find the entrance in a set position. Secondly, fish were captured in the tailwater pool from areas where they were seen to accumulate and placed into the fishway. After an exposure time of 30min the water flow would be stopped and successful migrants were counted and measured. This gave an indication of the fishes' ability to negotiate the fishway when in a migratory phase. A total of 12 capture tests were conducted while the model was in position two.

Chapter 3

Results

3. Results

3.1 Optimal Time Selection

The selection of an optimal experimental period was an important initial step as it ensured no time wastage during the experimental runs, and minimised fish stress and fatigue. When 40 *M. capensis* were placed in the fishway with a 1:8 gradient and a flow of 6.5 l/sec., most (approximately 80%) migrated up the fishway within 20 min in each of the five trials (Figure 3.1). After this time the number of successful migrants decreased sharply. It was thus decided that 20 min would be selected as the experimental time period.

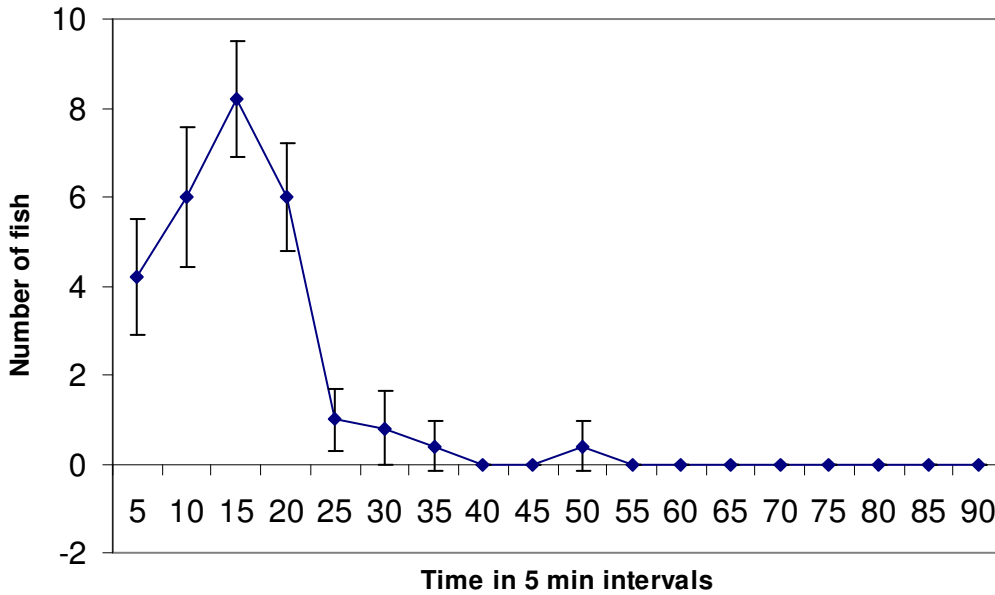


Figure 3.1: Number of *M. capensis* that successfully negotiated the vertical slot fishway. Mean of five trials with one standard deviation.

3.2 Vertical Slot Fishway

3.2.1 Shallow (1:10) Gradient Experiments

Mullet trials

The initial experiments, conducted with two size classes of *M. capensis* in the vertical slot fishway set at a shallow 1:10 gradient, yielded high migration rates ranging from 67% to 92% at flow rates of 3, 5 & 7 l/sec (Tables 3.1 and 3.2). *M. capensis* in the large size class (40- 120mm) were particularly successful in migrating up the vertical slot fishway and achieved success rates of greater than 75% at all three flow rates (Table 3.1). Significantly higher migration rates were achieved at the lower flow rates (3 and 5 l/sec), compared to the highest flow rate of 7 l/sec ($F= 11.378$; $p= 0.00026$).

Table 3.1: Migration success, with one standard deviation, of large (40- 120 mm) *M. capensis* at shallow (1:10) gradient and increasing flow rates in a vertical slot fishway.

Flow Rate (l/sec)	Mean number of fish per time interval	Mean number of successful fish	% Migration success
3	6.9 ± 1.4	27.6 ± 3.8	92 ± 1.6
5	6.85 ± 1.5	27.4 ± 2.5	91 ± 1.5
7	5.7 ± 1.3	23.2 ± 2.2	77 ± 1.3

The trend for the smaller size class of *M. capensis* (20- 40mm) was similar in that there was a higher rate of successful migration at the lower flow rates (Table 3.2).

The overall migration success of the smaller fish was, however, significantly lower (67- 83%) than that of the large fish ($F= 14.961$; $p= 0.0006$, Figure 3.2). The migration rate of the small and large fish, however, did not differ significantly at the lowest flow rate (3 l/sec). Some fin damage and scale loss was observed in the smaller fish at the highest (7 l/sec) flow rate.

Table 3.2: Migration success of small (20- 40 mm) *M. capensis* at shallow (1:10) gradient and increasing flow rates in a vertical slot fishway with one standard deviation.

Flow Rate (l/sec)	Mean number of fish per time interval	Mean number of successful fish	% Migration success
3	6.25 ± 1.79	25 ± 1.6	83 ± 5.2
5	5.7 ± 1.89	22.8 ± 0.84	76 ± 2.7
7	5.05 ± 2.2	20.2 ± 0.84	67 ± 2.7

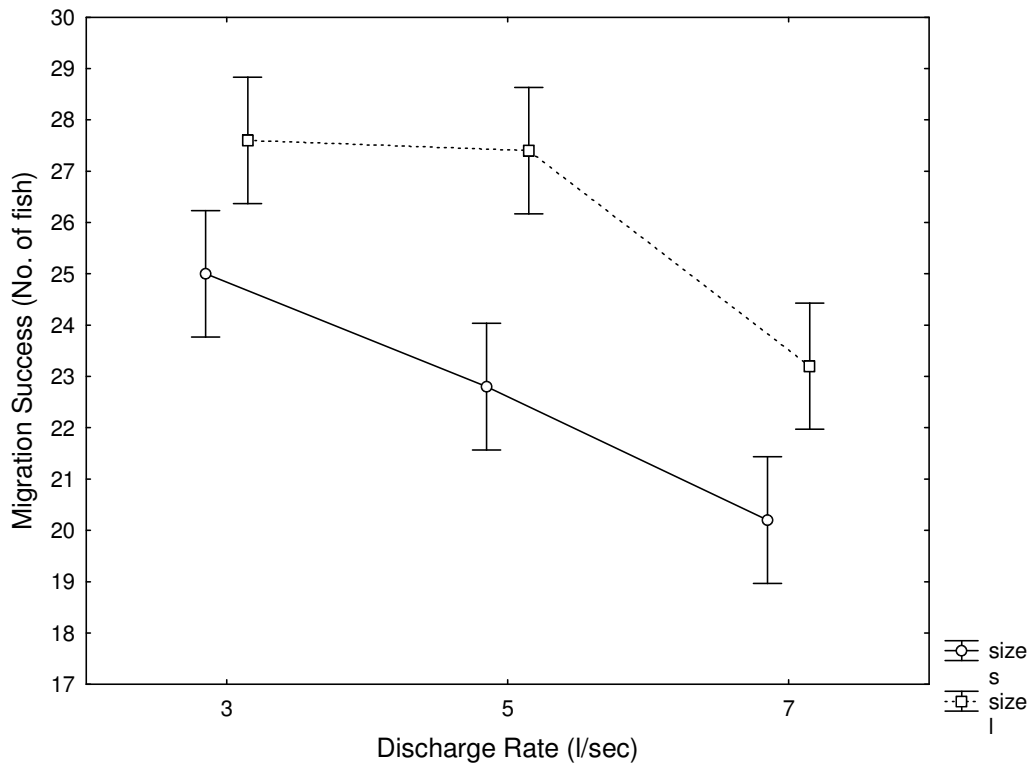


Figure 3.2: Effects of multiple discharge increases at a shallow (1:10) gradient on levels of success of small (20- 40mm) and large (40 -120 mm) *M. capensis* in a vertical slot fishway. Error bars represent 95% confidence intervals

In the second experiment conducted at 4 and 8 l/sec, the migration rate of the small fish at 4 l/sec was similar to that recorded at 3 and 5 l/sec in the initial trial series (Table 3.3). The results differed, however, for the larger size class with average success at 4 l/sec being only 75% compared to over 90% at both 3 and 5 l/sec in the initial trial series.

At 8 l/sec the success rate of the small fish was lower than that achieved at 7 l/sec, nonetheless, relatively high migration success rates of ca. 55% were reached. This was only 10% lower than success rates at 7 l/sec for the same sized fish. The large fish displayed a similar trend (Table 3.3) with migration success at 8 l/sec only 10% lower, and not significantly different ($F= 8.022$; $p= 0.1201$), to that recorded at 7 l/sec in the first trial series.

Table 3.3: Migration success of small (20- 40 mm) and large (40- 120 mm) *M. capensis* at 4 & 8 l/sec flow rates at shallow (1:10) gradient in a vertical slot fishway with one standard deviation.

Flow Rate (l/sec)	Fish size (Large/ Small)	Mean number of fish per time interval	Mean number of successful fish	% Migration success
4	Large	5.65 ± 1.0	22.6 ± 0.8	75 ± 2.9
4	Small	5.7 ± 1.7	22.8 ± 1.4	76 ± 4.9
8	Large	5.05 ± 1.9	20.2 ± 1.9	67 ± 6.4
8	Small	4.14 ± 2.8	16.6 ± 1.5	55 ± 5.0

For both small and large fish the migration success rate decreased from 4 to 8 l/sec., but the difference was not statistically significant for the large size class *M. capensis* (Figure 3.3). At 4 l/sec flow, the migration success rate of the small size class of *M. capensis* did not differ significantly from the large fish, but at 8l/sec, the success rate of the small fish (55%) was significantly lower than that achieved by the large *M. capensis* ($F= 11.378$; $p= 0.00026$).

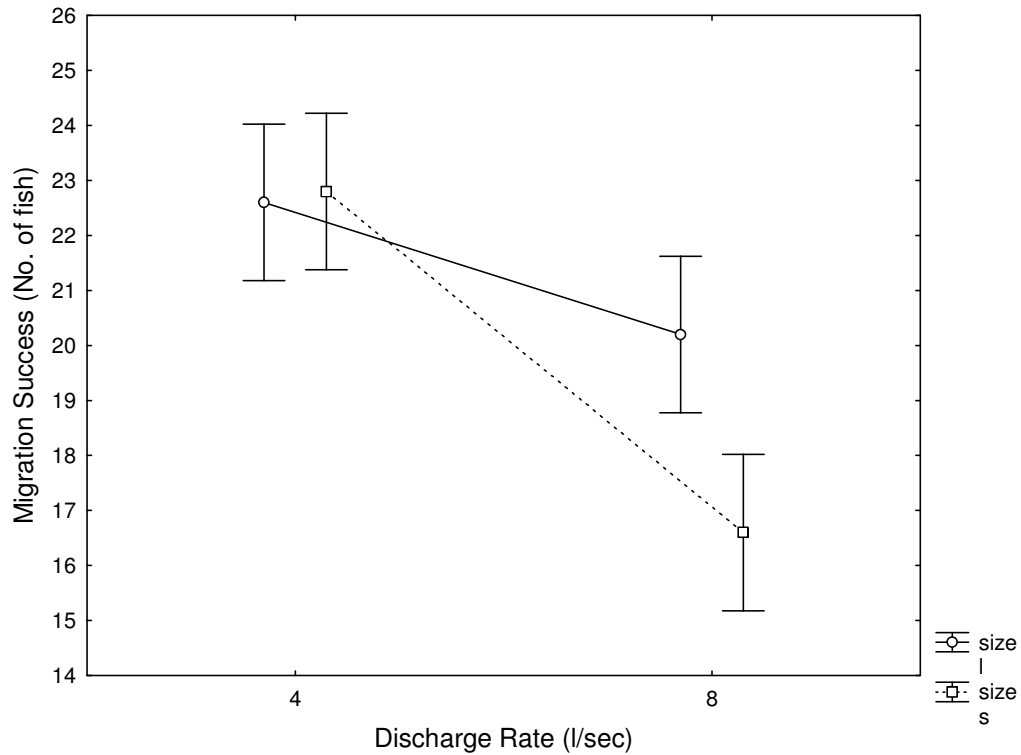


Figure 3.3: Migration success rate of small (20- 40mm) and large (40 -120 mm) *M. capensis* in a vertical slot fishway at water flow rates of 4 and 8 l/sec. at a shallow (1:10) gradient.

When examining the combined data for trials 1 and 2, a decline in success from lower to higher discharge volumes was evident (Figure 3.4). The decline began to occur at different flow rates for the two size classes of fish, with an immediate effect being noted in the small size class of fish, whereas the decline in the large fish only began when the flow rate was above 5 l/sec. There was a visible reduction in the success of the large fish between 3 and 4 l/sec; however, success at 5 l/sec was not significantly different to that at 3 l/sec. This was in contrast to the small fish which began to exhibit a significant decline at flow rates above 5 l/sec, likely to be as a result of new fish having been collected.

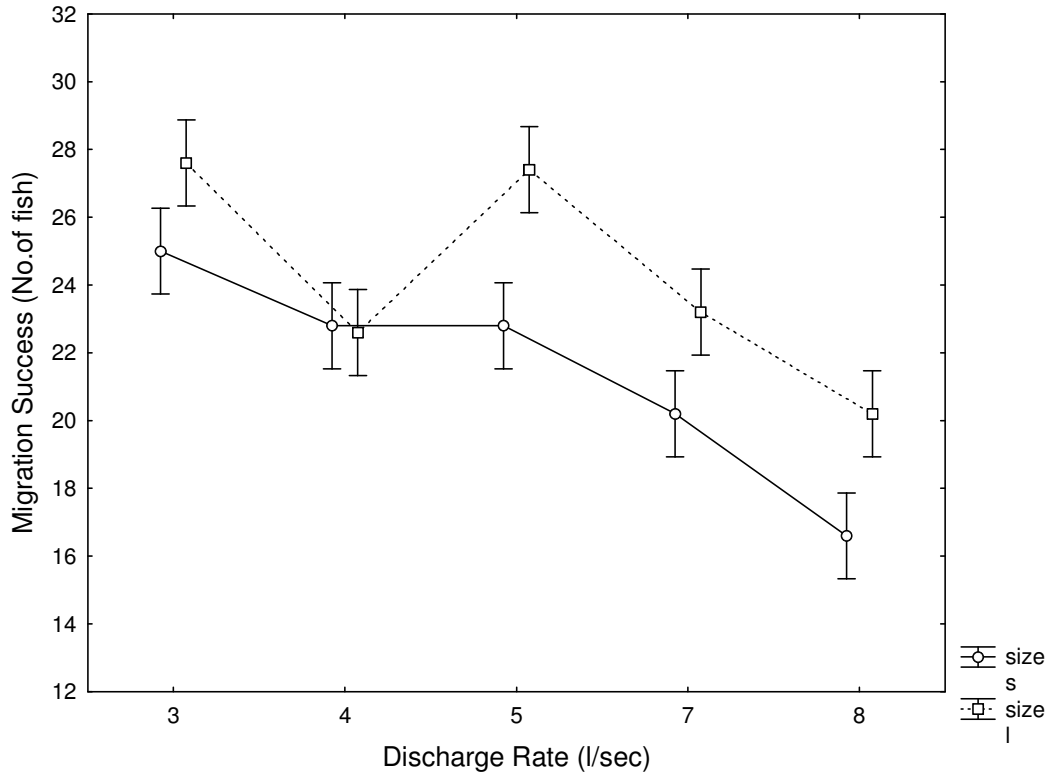


Figure 3.4: Combined effects of increasing discharge on successful migration at shallow (1:10) gradient of small (20- 40mm) and large (40 -120 mm) *M. capensis* in a vertical slot fishway

Moony trials

The latterly compressed moonies (*Monodactylus falciformis*) were able to negotiate the vertical slot fishway with mean success ranging between 60 and 71% at flow rates between 4 and 8 l/sec. (Table 3.4). No clear relationship (Figure 3.5) between flow rate and migration success emerged with the highest level of success (71%) being recorded at the intermediate flow rate of 5 l/sec. Migration success was significantly higher at 5 l/sec than at 8 l/sec ($F= 6.079$; $p= 0.025$), but not significantly different from success at 4 l/sec ($F= 2.227$; $p= 0.173$).

Table 3.4: Migration success of *M. falciformis* at shallow (1:10) gradient and increasing flow rates in a vertical slot fishway with one standard deviation.

Flow Rate (l/sec)	Mean number of fish per time interval	Mean number of successful fish	% Migration success
4	4.95 ± 3.9	19.8 ± 1.48	66 ± 4.9
5	4.025 ± 2.9	21.2 ± 1.48	71 ± 4.9
8	4.5 ± 2.8	18 ± 1.41	60 ± 4.7

Observations made during the trials revealed the laterally compressed *M. falciformis* would swim on their sides in very shallow water which enabled them to pass through fishway cells where the water was shallower than their body depth.

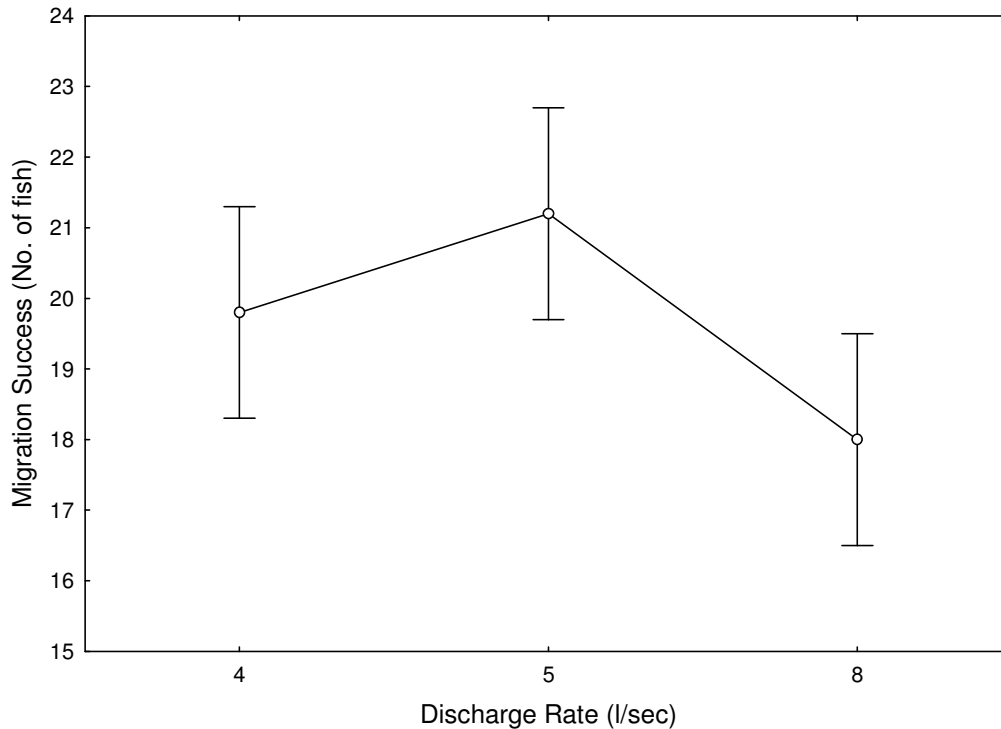


Figure 3.5: Mean migration success of *M. falciformis* at shallow (1:10) gradient for each of three flow rates in a vertical slot fishway

3.2.2 Steep (1:5) Gradient Experiments

The steep (1:5) gradient trials yielded similar trends to the shallow gradient experiment in that the migration success of the larger *M. capensis* was significantly higher ($F= 118.443$; $p < 0.05$) than that of the smaller fish (Table 3.5). Although the mean migration success rate decreased from 4 to 8 l/sec. for both size classes of fish, the differences were not significant ($F= 0.40984$; $p= 0.53111$) due to the wide variances in the data.

The migration success rate of the large fish was higher at both flow rates when compared to the 1:10 gradient, possibly as a result of an increased stimulation of their migratory response resulting from the higher water velocity. By contrast, the success of the small fish was lower at both flow rates compared to the shallow gradient.

Table 3.5: Migration success of small (20- 40 mm) and large (40- 120 mm) *M. capensis* at a steep (1: 5) gradient in a vertical slot fishway at 4 and 8 l/sec. flow rates with one standard deviation.

Flow Rate (l/sec)	Fish size (Large/ Small)	Mean number of fish per time interval	Mean number of successful fish	% Migration success
4	Large	6.65 ± 2.6	26.6 ± 1.5	89 ± 5.0
4	Small	4.65 ± 4.5	18.6 ± 2.0	62 ± 6.9
8	Large	5.65 ± 2.8	22.6 ± 2.0	75 ± 6.9
8	Small	3.4 ± 3.5	13.6 ± 1.1	45 ± 3.8

3.3 Sloping Baffle Fishway

3.3.1 Shallow (1:10) Gradient Experiments

Mullet Experiments

As with the vertical slot fishway, a slope of 1:10 was used for shallow gradient trials with the sloping baffle fishway. Two flow rates (4 and 8 l/sec) and two size classes of *M. capensis* (20- 40mm and 40- 120mm) were tested in this system. Based on their performance at a shallow gradient in the vertical slot fishway fewer experiments were conducted at the shallow 1:10 gradient in the sloping baffle system. The large fish were

exposed to the higher of the two flow rates given their greater swimming ability and the small fish were exposed to the lower flow rate.

The large (40 -120mm) and small (20- 40mm) *M. capensis* displayed similar levels of migration success (Table 3.6). The small *M. capensis* achieved a 74% level of success at 4 l/sec which was not significantly different to the 67% success achieved by the large *M. capensis* at 8 l/sec ($F= 3.361$; $p= 0.104$).

Table 3.6: Migration success of small (20- 40 mm) and large (40- 120 mm) *M. capensis* at two (4 & 8 l/sec) flow rates and shallow (1: 10) gradient in a sloping baffle fishway with one standard deviation.

Flow Rate (l/sec)	Fish size (Large/ Small)	Mean number of fish per time interval	Mean number of successful fish	% Migration success
4	Small	5.55 ± 4.11	22.2 ± 1.92	74 ± 6.41
8	Large	5 ± 4.54	20 ± 1.87	67 ± 6.23

Moony Experiments

Experiments were conducted with *M. falciformis* at three flow rates, a series of trials were carried out at 5 l/sec before the decision was taken to only conduct trials at 4 and 8 l/sec. Unlike the experiments with the *M. capensis*, the *M. falciformis* were not separated into different size classes due to their limited availability. The data collected during experiments with the *M. falciformis* showed a similar result for low flow rates to that obtained for the vertical slot fishway. Interestingly they displayed an increased ability to negotiate the sloping baffle fishway at low discharge (Table 3.7) with higher numbers of fish being recorded after 10 min than at the higher flow rates.

Table 3.7: Migration success of *M. falciformis* at three (4, 5 & 8 l/sec) flow rates and shallow (1:10) gradient in a sloping baffle fishway

Flow Rate (l/sec)	Mean number of fish after interval one	Mean number of fish per time interval	Mean number of successful fish	% Migration success
4	0 ± 0	4.6 ± 5.5	18.4 ± 2.0	61 ± 6.9
5	0 ± 0	3.8 ± 4.2	15.3 ± 3.2	51 ± 10.7
8	0 ± 0	3.8 ± 3.8	15.2 ± 1.3	51 ± 4.3

The results, however, showed no significant difference in recorded level of success for *M. falciformis* at all three flow rates ($F= 3.4214$; $p= 0.0738$). The success levels at 5 l/sec are more variable than those at 4 and 8 l/sec (Figure 3.6) with success in a single trial being higher than those in the remaining trials. The *M. falciformis* displayed similar behaviour when placed into the sloping baffle fishway as compared to the vertical slot fishway in that the fish again passed over the weirs by swimming on their sides under low flow conditions. A further interesting point was that in none of the experiments did any of the *M. falciformis* successfully negotiate the fishway during the first five minute time interval.

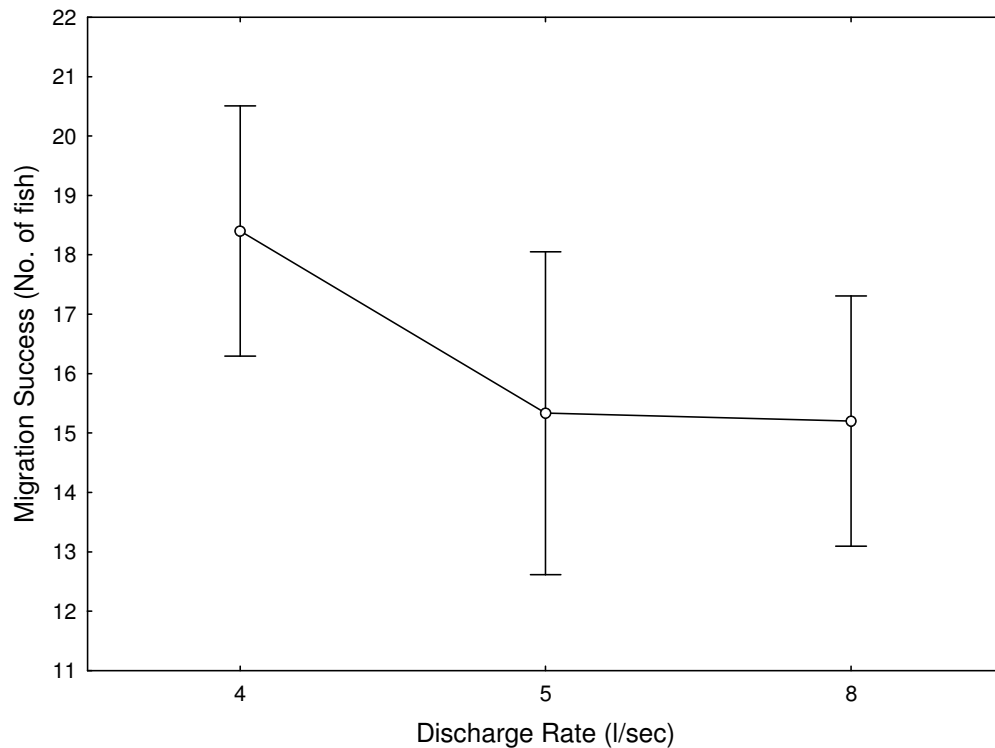


Figure 3.6: The effect of increasing discharge at a shallow (1:10) gradient on migration success of *M. falciformis* in a sloping baffle fishway

3.3.2 Steep (1:5) Gradient Experiments

Experiments at steep (1:5) gradients were only run with *M. capensis* due to the poor observed swimming ability of the *M. falciformis* at high current velocity. The fish were exposed to two flow rates (4 and 8 l/sec.) at this gradient in a series of five trials per size class.

This series of trials yielded the lowest levels of migration success for all the trials conducted with *M. capensis*. Both the large and the small fish showed a limited ability to navigate the sloping baffle fishway at the 1:5 gradient with migration success ranging from 20-51%. Migration success for the small fish was relatively low at both 4 and 8 l/sec flow rates in this gradient (Table 3.8). The larger *M. capensis* were able to navigate the sloping baffle fishway better than the small fish at both flow rates. In both size classes of *M. capensis* the level of success was observed to increase significantly ($F= 74.849$; $p < 0.005$) between 4 and 8 l/sec. The increased level of success is most likely due to the increase in depth of water over the baffle and the associated reduction in freefall height.

Table 3.8: Migration success of small (20- 40mm) and large (40- 120mm) *M. capensis* at a steep (1:5) gradient and 4 and 8 l/sec flow rates in a sloping baffle fishway with one standard deviation.

Flow Rate (l/sec)	Fish size (Large/ Small)	Mean number of fish per time interval	Mean number of successful fish	% Migration success
4	Large	2 ± 2.6	8 ± 1.2	27 ± 4.0
4	Small	3.8 ± 2.2	15.2 ± 1.3	20 ± 4.7
8	Large	1.5 ± 2.0	6 ± 1.4	51 ± 4.3
8	Small	3.1 ± 4.4	12.4 ± 1.1	41 ± 3.8

3.4 Combined Analysis

3.4.1 Mullet

An analysis of the combined data with systems, flow rates and gradients was performed. In order to suitably stabilise the variance it was necessary to transform the data. The modelling of this combined data set was therefore best undertaken by using an arc sin

square root of proportion to the number of fish +1 against the other factors. A Box Cox Transformation suggests that this is the most suitable transformation for this current model (Zar 1984). Further analysis of the main effects and other interactions was completed using the same model.

On fitting the main effects model it became apparent that a significantly higher level of migration success was achieved by all *M. capensis* placed into the vertical slot fishway ($F= 82.157$; $p< 0.001$). This is especially evident in steep gradient trials where migration success in the sloping baffle fishway does not exceed 51%. Further to this an increase in the gradient of either fishway was noted to reduce the overall migration success significantly ($F= 37.169$; $p< 0.001$). Differences in levels of migration success can also be related to the size of the fish, with larger fish achieving higher levels of migration success under all conditions ($F= 17.755$; $p< 0.001$), even having improved success as the energy in the system increased with the increase in gradient.

There were a number of second order interactions that had a significant effect on the level of success recorded; many of which can be related to the fishes' swimming abilities. Only one significant higher order interaction occurred in this model, that is the combined gradient, interval, size class third order interaction ($F= 10.759$; $p< 0.001$). This interaction can be biologically explained as a greater number of larger fish pass through the selected fishway at an earlier time interval than smaller fish at the selected gradient, probably again as a result of their stronger swimming ability (Figure 3.7).

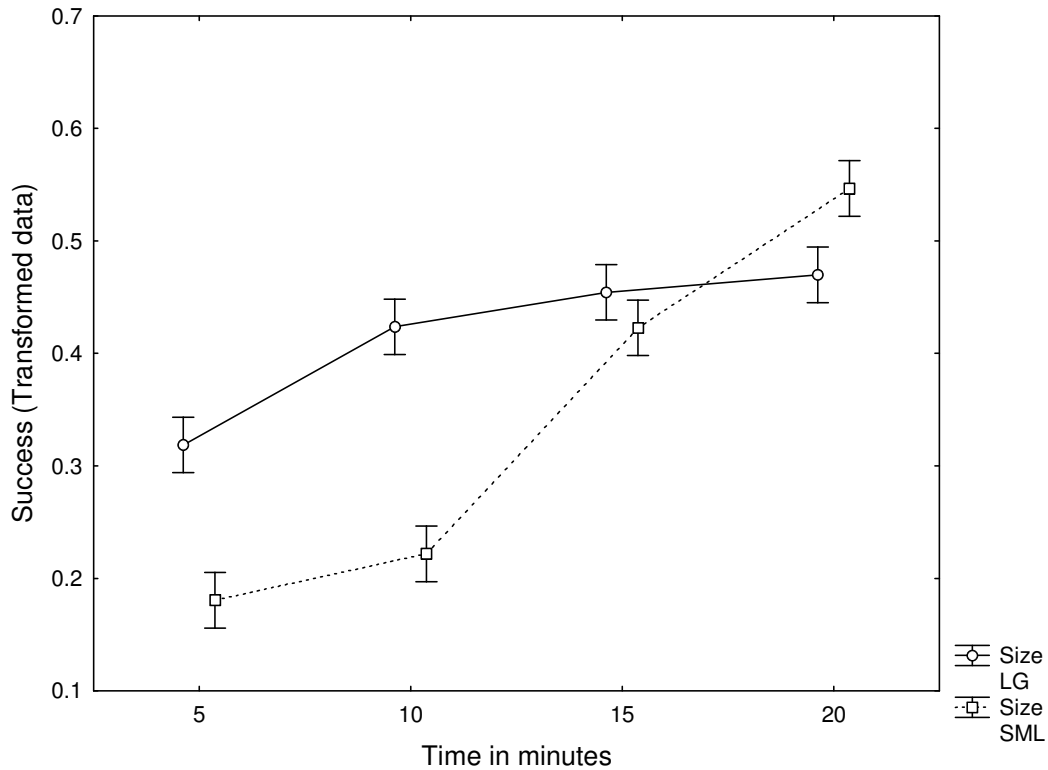


Figure 3.7: Graph showing increase in success of small (20- 40mm) and large (40- 120 mm) *M. capensis* over time

3.4.2 Moonies

The analysis of the combined data collected for the *M. falciformis* and the effects of each factor; discharge rate and system type were analysed using an arc sin square root transformation of proportion to the number of fish + 1, as for *M. capensis* above. For this model to be used a number of assumptions need to hold and these are tested through the application of a Box Cox Transformation. The Box Cox Transformation of this model has a 95% confidence interval around a mean of 1 in a Poisson distribution (Zar 1984).

As was found in the analysis of the *M. capensis* data there were a number of first order interactions when examining the main effects model. The fishway system used influenced the rates of migration success, with the vertical slot fishway resulting in a significantly higher passage rate under all conditions than the sloping baffle

fishway ($F= 11.792$; $p= 0.00086$). The lack of a significant effect of discharge ($F= 1.5292$; $p= 0.1929$) on the migration success of the *M. falciformis* may indicate the ability of these fish to escape highly turbulent flow due to their laterally compressed bodies. Very few higher order interactions occur in this model, the only significant interaction being an interaction between the system type and the time interval of migration success. In this interaction the time interval at which maximum migration was reached was adversely affected by the fishway type and higher migration success was achieved after a shorter time interval in the vertical slot fishway than in the sloping baffle fishway ($F= 26.920$; $p < 0.05$).

3.5 Fatigue Experiments

Fatigue experiments comprised two trials, of five repeat exposures of a single group of 40 *M. capensis* to each fishway type. Trials were of 20 min duration with one and two hour intervals between and were conducted at an intermediate (1:8) gradient and (6.5 l/sec) flow rate. The *M. capensis* used were from the large size class. The results (Table 3.9) indicate a substantial reduction in the level of success in both fishways between the initial exposure and the final exposure. The results also indicate a highly significant ($F= 37.971$; $p < 0.05$) level of interaction between the success related to the rest period that the fish were allowed, the longer rest period maintaining a higher level of migration success in both fishways.

Table 3.9: Levels of migration success of *M. capensis* during repeated trials in the sloping baffle and vertical slot fishway with either one or two hour rest periods

Fishway	Rest period (hrs)	Initial success (%)	Success after 5 exposures (%)
Vertical Slot	1	83.7 ± 1.7	3.8 ± 5.4
Sloping Baffle	1	86.2 ± 5.3	0 ± 0
Vertical Slot	2	82.5 ± 3.5	81.7 ± 1.6
Sloping Baffle	2	87.5 ± 3.5	53.2 ± 2.8

The fishway type employed therefore affected the level of success maintained ($F= 4.308$; $p= 0.045$). This fishway effect was noticed in the lower final success level recorded in the sloping baffle fishway after five exposures with two hour rest periods (Table 3.9).

Due to the limited amount of data available the use of an ANOVA was not ideally suited for the analysis. The data does not satisfy the assumptions for Levene's test of homogeneity in that the variances are not the same and the data is not normally distributed. For this reason the trends that were identified although highly probable cannot be statistically supported and thus remain hypotheses until further investigation has been carried out.

3.6 Field Experiments

3.6.1 Vertical Slot Fishway

3.6.1.1 Fishway Positioning

While in position one (Plate 2.3), with the header tank placed on the lower weir apron and at a gradient of 1:5, no fish were found to have entered or negotiated the fishway. It was then moved to position two (Plate 2.4), where it was placed directly over the existing concrete fishway. In position two the shallowest gradient achievable was 1:4 where a flow rate of 8 l/sec was established and maintained for a period of two days. Despite the steeper gradient a small number of fish were found to have negotiated the fishway after day one and again after the second day. It was then decided that the fishway should be moved into a position that allowed a shallower gradient to be tested.

Table 3.10: Record of fish that successfully migrated up the vertical slot fishway in the various positions at Waters Meeting on the Kowie River Estuary

Date	Fishway position	Duration of run (hours)	Gradient	Species	Number	Size
25 Feb	1	3	1:5	N/A	0	N/A
27 Feb	2	24	1:4	<i>M. capensis</i>	2	41- 46 mm
27 Feb	2	24	1:4	<i>M. falciformis</i>	6	31- 44 mm
28 Feb	2	3	1:4	<i>M. capensis</i>	6	34- 51 mm
28 Feb	2	3	1:4	<i>M. falciformis</i>	6	34- 44 mm
01 Mar	3	3	1:8	<i>M. capensis</i>	5	38- 63 mm
01 Mar	3	3	1:8	<i>M. falciformis</i>	16	31- 47 mm
02 Mar	3	12	1:8	<i>M. capensis</i>	59	47- 188 mm
02 Mar	3	12	1:8	<i>M. falciformis</i>	2	38- 44 mm
02 Mar	3	12	1:8	<i>Hypseleotris cyprinoides</i>	1	75 mm

After the fishway had been placed in position three (Plate 2.5) it was allowed to operate for a 3 hour period before capture experiments were conducted. In this position, at a gradient of 1:8 and at a discharge of 8 l/sec a number of both *M. falciformis* and *M. capensis* were found to have entered and successfully negotiated the fishway (Table 3.10). After being left to operate overnight at an increased discharge rate, further successful migrants, including a single specimen of *Hypseleotris cyprinoides* a red data listed species (Table 3.10) were found in the trapping system in the morning, indicating the successful configuration of the fishway.

3.6.1.2 Capture Experiments

A total of 11 capture experiments, in which seine-netted wild fish were placed directly into the fishway, were conducted while the vertical slot fishway was in position three. Only three trials (9, 10, 11) were conducted with exclusively small (20- 40 mm) *M. capensis* as the majority of the migrants captured were in the large (40- 120 mm) size range. The *M. capensis* were captured from areas of accumulation below the weir apron and placed into the lowest pool of the fishway. The fish demonstrated they were in a migratory phase and immediately moved upstream in the fishway.

The results from the capture experiments mirrored those obtained at the Experimental Fish Farm in that a high percentage of the large fish successfully negotiated the fishway at a majority of the flow rates tested (Table 3.11). The experiments where fish under 40 mm in length were tested yielded poor results and no fish less than 30 mm in length were able to swim through the fishway.

As the discharge rate through the fishway was increased, the level of migration success decreased (Table 3.11). Furthermore, the trials (4, 5 and 6) conducted at similar discharges at increasing gradient also resulted in reduced migration success rate. The reductions in success, however, were not as dramatic as those witnessed under controlled conditions. A single experiment was conducted at low flow (2.66 l/sec) resulted in only a 29.9% migration success rate. After the addition of a large pebble substrate, creating a continuous riffle, to the floor of the fishway the success rate was dramatically increased to 89.8%.

Table 3.11: Results summary of capture experiments in the Vertical Slot Fishway conducted at Waters Meeting on the Kowie River Estuary

Trial No.	Discharge in Fishway (L/S)	Fish size (Large/ Small)	No of fish used	% Success through fishway at a channel slope of 1:			
				5.0	6.6	8.1	10.6
1	9.31	Large	156	89.1			
2	2.66	Large	147	29.9			
3	2.66	Large	137	89.8*			
4	14.1	Large	87	51.7			
5	13.6	Large	196		74.0		
6	13.2	Large	122				82.8
7	8.2	Large	53		77.8		
8	10.1	Large	49		86.7		
9	8.2	Small	44			67.5	
10	10.1	Small	42			32.5	
11	8.2	Small	83			5.3**	

* Large pebble substrate added to form constant riffle

** Relatively small sized fish (15- 35 mm), largest fish successful

3.6.2 Sloping Baffle Fishway

3.6.2.1 Fishway Positioning

The sloping baffle fishway was tested in two positions in the field. In position one, when it was placed over the existing concrete fishway the steep gradient resulted in no fish being able to navigate the channel, despite the high concentrations of juvenile fish that were observed near the fishway entrance. The fishway was then moved in order to test shallower gradients (Plate 2.6). After allowing it to operate under natural conditions for two periods of three hours inexplicably no fish were found to have entered and successfully negotiated the fishway.

3.6.2.2 Capture Experiments

A total of 12 captured fish experiments were conducted while the sloping baffle fishway was in position two. Only a single experiment was conducted with a test group of primarily small fish, while all other experiments had mixed sizes and species. Due to the small numbers of *M. falciformis* captured before each experiment they were excluded from the analysis.

A relatively consistent level of migration success was obtained at all gradients tested (Table 3.12). In a single case where the smallest *M. capensis* (15- 35mm) were placed into the sloping baffle fishway, there was a relatively low success rate. There did not appear to be any adverse effects of increased discharge rate on the level of success achieved for a particular gradient. As the gradient is decreased though from 1:5 to 1:8.5 there appeared to be a slight increase in the overall migration success.

Table 3.12: Summary of capture experiments in the Sloping Baffle Fishway conducted at Waters Meeting on the Kowie River Estuary

Trial No.	Discharge in Fishway (L/S)	Fish size (Large/ Small)	No of fish used	% Success through fishway at a channel slope of 1:			
				5.0	6.6	8.5	10.6
1	7.6	Large	130	86.2			
2	11.9	Large	160		*37.5		
3	11.9	Large	106				85.8
4	13.3	Large	118	53.4			
5	2.48	Large	74	78.4			
6	12.5	Large	40	66			
7	12.5	Large	47	70.2			
8	8.5	Large	54	64.8			
9	8.5	Large	40			82.5	
10	8.5	Small	73			12.3	
11	12.5	Large	50			77.5	
12	12.5	Large	53			92.4	

* Data suspect due to sudden loss of water

Chapter 4

Discussion

4. Discussion

The suitability of vertical slot and sloping baffle fishways has been demonstrated for juvenile catadromous fish at the ebb and flow regions of Eastern Cape rivers. While many fish were able to navigate both fishway designs, it was evident that of the two designs a higher proportion of the most common migrants *Myxus capensis* and *Monodactylus falciformis* were able to negotiate the vertical slot fishway better than the sloping baffle fishway.

4.1 Optimal Time Selection

By determining that 20 min was the shortest suitable experimental time it was ensured that the fish were minimally stressed. This was supported by their returning rapidly to a perceived, normal behaviour. A wide variety of published fishway exposure times exist, ranging from as little as 20 min to upwards of 16 hrs, however, many of these also include systems monitored under natural operating conditions (Fisk 1959, Kowarsky and Ross 1981, Russell 1991, Mallen-Cooper 1992, Mallen-Cooper 1994). Many of the fish tended to migrate immediately so a relatively short time period (20 min) for testing was found to be adequate. Mallen-Cooper (1994) showed with golden and silver perch that 90% of fish placed into the fishway could negotiate it in less than 20 min at certain water velocities. After a number of experiments at an intermediate gradient (1:8.5) and at intermediate flow (7 l/sec) it was found that 20 min was sufficient to allow up to 80% of all *M. capensis* placed into the fishway to negotiate the channel, an acceptable level of migration for the design to be considered successful.

4.2 Controlled Testing

During the different phases of controlled fishway testing at the Experimental Fish Farm at the Department of Ichthyology and Fisheries Science it was shown that the use of mobile,

model fishways was a valuable method of determining the suitability of fishway designs for catadromous fish passage.

While laboratory trials have been shown as good indicators of fishway suitability they have often been based on forced swimming performance data of confined fish often in a less active migratory phase. They may therefore underestimate voluntary swimming ability and behaviour of fish under natural conditions, because of their behavioural inhibition to swim to complete physiological exhaustion in confinement, a statement supported by Bunt (1999) and Peake (2004).

Results collected during the various stages of experimentation indicated differing degrees of migratory ability in juvenile *Myxus capensis* and *Monodactylus falciformis*. Successful navigation of the two fishways varied between 45-92% for *M. capensis*, and 58-72% for *M. falciformis* in the vertical slot fishway. In the sloping baffle fishway, migratory success was somewhat lower, 25-74% for *M. capensis* and 42-64% for *M. falciformis*. Despite their being held under captive conditions for in excess of three months it was evident that juvenile *Myxus capensis* and *Monodactylus falciformis* maintained a migratory drive. The results do, however, suggest some reduction in migratory drive over time. This is evident in the reduction of migration success in the vertical slot fishway from 91% (\pm day 1) to 75% (\pm day 79) at similar flow rates for the large size *M. capensis*.

The size of *M. capensis* had an influence on both the time and success of fishway ascent. The larger size class of *M. capensis* navigated the fishways more rapidly and more effectively than the small size class. As the water flow through the fishways was increased the larger fish maintained a relatively higher level migration success rate compared to the smaller ones (Figure 3.2). This is important, as under natural conditions when flow into the fishway is uncontrolled and may reach discharges too great for the smallest of fish there may still be passage of some of the larger individuals. The single significant higher order interaction that occurred between gradient, interval and size class again supports previous findings that larger fish pass through the selected fishway more easily and faster, as a result of their improved swimming ability. This finding is

supported by Rulifson (1977) who found that larger mullet exhibited higher burst speeds than smaller ones; this would allow them to navigate a fishway in less time.

The success of *M. falciformis* using the fishway on the Kowie River seemed to be size related (Bok and Cambray unpubl.) with the larger fish being able to navigate the entire length of the fishway. Limited numbers of *M. falciformis* meant that only a single size group could be used (30- 55 mm). This may have been the main reason for the variable success rates recorded in trials with *M. falciformis* (Figure 3.6). Similar effects of size distribution on success have been found by Stuart and Mallen-Cooper (1999) in bony herring and olive perchlet, fish with similar body forms to *M. falciformis*.

The reduction in the level of ascent success with decreasing fish size under controlled conditions was consistent in all experiments. The effects of discharge, however, while showing a trend of decreasing ascent success with increasing flow rate were more variable. A reduction in the level of migration recorded with an increase in the discharge rate is typical of what has been found in other studies (Bainbridge 1958, Farlinger and Beamish 1977, Videler and Wardle 1991, Mallen-Cooper 1994, Slavik and Bartos 2002). The greatest reduction in success (31%) was recorded in the small *M. capensis* as discharge was increased from 3 l/sec to 8 l/sec in the vertical slot fishway. While the *M. falciformis* also displayed a tendency of reduced migration success with increasing discharge rate, these reductions were less marked than for *M. capensis*. In contrast to the steep gradient results from the vertical slot fishway, those for the sloping baffle fishway indicated an improvement in migration success for *M. falciformis* as the discharge rate was increased from 4 to 8 l/sec. While the overall levels of migration success were low (Table 3.8) in the sloping baffle fishway at the steep (1:5) gradient the results do suggest improved passage conditions as the flow rate was increased. The same occurs in the vertical slot fishway as the critical flow level is reached and the slot becomes drowned.

The comparison of the two fishways through a number of replicated experiments clearly revealed the superiority of the vertical slot fishway, under the conditions tested. While the sloping baffle fishway had comparable success in terms of percentage passage of fish at

shallow gradients and intermediate flow rates, a likely result of the modifications away from conventional pool and weir designs, it had poor success at high flows and steep gradients. The vertical slot fishway allowed superior migration success at all flow rates, gradients and in both experimental fish species over the sloping baffle fishway. These results are important, especially when considering the environment where such fishways are likely to be installed. A barrier at the ebb and flow of an estuary blocks the passage of large numbers of returning juvenile migrants and an inferior passage facility at this point would make more fishways upstream of less consequence.

The gradient of the proposed fishway played an important role in the levels of passage success achieved. While large reductions in success (74 to 20% at 4 l/sec in the small *M. capensis*) occurred with an increase in the gradient of the sloping baffle fishway, the effect of gradient was less extreme in the vertical slot fishway. Ebb and flow barriers are characteristically low height structures (Harris 1984), and as such optimal fishway gradients with maximum ecological benefits should usually be feasible with relatively low extra capital input, compared to their use on weirs and dams inland. This will therefore also mitigate in favour of the use of vertical slot fishways that allow faster ascent of the fish tested with less fatigue and exposure to predation than in the sloping baffle fishway design.

4.3 Fatigue Experiments

The effect of fatigue on migration success was tested through the repeated exposure of a single group of *M. capensis* to the same conditions in a vertical slot and sloping baffle fishway. High success was recorded in both fishways for the initial trials, however, fatigue was found to occur rapidly in the group of fish given a one hour resting period between trials, while no effect of fatigue was noted in those fish given two hours rest. Early experiments into the fatigue of other fish species have revealed sustained swimming speeds can be maintained for upwards of 200 min at submaximum velocities (Brett 1967; Hammer 1995) before fatigue occurs. As the velocity is increased so the time to fatigue decreases. It is therefore likely that the flow conditions at which trials were

conducted approached a maximum ascent velocity. The allocation of a pre-determined rest period was important for limiting stress and maximising physiological homeostasis.

The importance of fishway design to minimise fatigue on the test group was most apparent in the two hour rest group. The first trials in both fishways yielded high success rates when fish were replaced for the following trials, however, only those in the vertical slot fishway maintained a high degree of migration success. It was evident from earlier trials in the sloping baffle fishway that there was an initial delay in the passage of the test fish. This was assumed to be as a result of vertical velocities that occurred resulting in the fish having to explore each pool to a greater extent before passing to the next one thereby causing more fatigue.

The small size of the data set limited the analysis of the fatigue data. The results showed that the rest period the fish are given between trials is important in maintaining reasonable levels of passage success. In the majority of fatigue experiments conducted in an attempt to evaluate critical swimming speeds rest periods of more than 21hrs were the norm (Jain *et al* 1997). Further to this, Haro *et al* (2004) in a series of voluntary swimming trials only considered the first hour's data, conceding the possible effects of fatigue. A short, one hour, rest period between trials dramatically reduced the amount of time to observe fatigue, furthermore it has been observed that periods of stress can result in disorientation (Brick and Cech 2002). While it may take several hours for the fish to return to normal behaviour suitable conditions may result in this time being reduced to less than two hours, as recorded by Brick and Cech (2002). A short rest period could be compared to exposure to a long fishway, and as the fish become fatigued relatively quickly they would have very poor success, possibly even being washed out of the fishway.

The higher levels of success maintained in both the vertical slot and sloping baffle fishways after a longer, two hour, rest period suggested a fairly rapid recovery after exposure. This rapid recovery of fish strengthens the argument for resting pools in long fishways, these should be large enough to provide the fish with sufficient escape from

turbulence but also be designed in such a way as to ensure the migrants are able to find the entrance back into the fishway. Should there be a predatory risk at the fishway exit it may also be pertinent to provide refuge just below the exit thus ensuring the fish leave the fishway in a suitably fit state should there be a need to escape predators (Weyl and Lewis 2006).

4.4 Field Experiments

During field tests and observations of migrating *M. capensis* and *M. falciformis* under natural conditions it became evident that the correct positioning for a proposed fishway was critical to the successful ascent of the fishways. Upstream movement of these two species of fish is related to current speed and the presence or absence of riparian vegetation. *M. capensis* were found to remain in areas of open water, orientating into the current and even bypassing smaller barriers when in a migratory phase. *M. falciformis*, however, which also exhibited a high migratory drive and were able to navigate the fishways under high flow conditions, were most concentrated in the areas adjacent to riparian vegetation, and out of the main current.

The capture experiment results indicated that in the vertical slot fishway, as the discharge was increased (9.3- 14.1 l/sec) the level of migration success decreased (89.1- 51.7%). The evidence also suggested that as the gradient was increased (1:10.6 -1:5) the migration success decreased (82.8 -51.7%). The sloping baffle fishway results showed a similar trend with success of ascent decreasing from 86.2% to 53.4% as the discharge was increased from 7.6 l/sec to 13.3 l/sec and as the gradient was increased migration success again decreased. Under normal river conditions this area would be of low gradient and low velocity, conditions to which the species are accustomed and their success would remain accordingly high. Unfortunately though it appears that despite their strong urge to migrate the increasing velocity and turbulence with increasing discharge has a negative impact on migration success.

In order to test whether instream structures would assist fish passage at low, and super-critical flow levels an experiment using stones (30 – 90mm) was undertaken. The initial experiment with no substrate added to the fishway indicated a strong motivation by the migrating *M. capensis* to pass through the fishway, but unfortunately yielded low (30%) migration. This was due to the lack of pooling in the fishway cells which did not allow the fish to escape the high velocity flow. Through the addition of the stone a continuous riffle was formed and the migration success of the fish increased from 30% to 89%. This was an important qualitative result highlighting the effect of micro-eddies within the fishway channel to provide improved passage conditions (Hinch and Rand 2000).

From the data collected it could be inferred that the migratory drive of both *M. capensis* and *M. falciformis* under natural conditions was greater than that of fish held in captivity. This was indicated by the generally higher percentage success recorded in the field, at the steep gradients and high flow rates, than the success recorded under controlled conditions. It was found that the steepness of the gradient had only a marginal effect on the migration success, with an increase from 75% - 89% occurring at 1:5 in the field. The flow rates, however, (10.0, 11.9, 12.5, 13.3 l/sec) that in laboratory trials had been too turbulent, were still navigable in both fishways in field trials.

When considering fishway design the hydrodynamics of the system is important. In a system where the water flow varies at different times of the year it is important therefore to install a fishway capable of operating at all normal flows. In this regard the vertical slot fishway proved to be the most suitable design as it operated effectively at low flows and high flows. Furthermore the success of the system was not compromised at low flows due to the addition of an uneven substrate in the pools. The addition of attraction flow at the base of the fishway was noted to increase the numbers of mullet concentrating in the area. In this way it could be possible to draw the mullet towards the fishway entrance and still maintain easy access to more cryptic species.

The use of a vertical slot fishway in a position that maximises the entrainment of migrating fish at the ebb and flow region of rivers in the Eastern Cape would enhance

migration success of the two common catadromous species tested. It was also noted, however, that predatory fish species i.e. *Micropterus salmoides* did take advantage of the input of migrants up such fishways and as such may further impact their distribution (Weyl and Lewis 2006). The effects of such predation could be discouraged by provision of suitable protective cover for the migrating species.

Chapter 5

Conclusions and Recommendations

5.1 Controlled Experiments

From the experiments conducted under controlled laboratory conditions, a number of conclusions could be drawn regarding both the swimming abilities of the fish and the effectiveness of the fishway designs. The most important of these is that overall, higher levels of migration success, at all flow rates and gradients, were maintained in the vertical slot fishway than in the sloping baffle fishway. Other supporting conclusions include:

- *Myxus capensis* were found to maintain higher levels of migration success than *Monodactylus falciformis* at all flow rates and gradients. This was related to body shape.
- Successful navigation of both fishway designs decreased with an increase in the length of time that the fish were held in captivity, 91% (\pm day 1) to 75% (\pm day 79) in the vertical slot fishway. This indicated that the migratory drive of captive fish could be depressed.
- An increase in flow rate and or gradient significantly decreased the migration success of both species in both fishway designs.

5.2 Field Experiments

After a number of periods of field testing and numerous observations of migrating *M. capensis* and *M. falciformis* under natural conditions, it became evident that the high migratory drive of both fish resulted in an improved migratory ability compared to those under controlled laboratory conditions. There are a number of important that must be considered before fishways are installed at similar sites:

- The addition of substrate to the floor of the vertical slot fishway significantly improved migration success at low flow rates. The fish were able to utilise micro-eddies around the substrate to escape high velocity flow as they migrated through the pool.

- The positioning of the fishway entrance at the base of the weir is important. It should be positioned in such a way as to be accessible to all migrants without them having to alter normal migratory patterns.
- The addition of extra flow near the mouth of the fishway designed to improve concentrations of migratory fish is important for rheotactic migratory species. It was noted that other areas of attraction resulted in ineffective use of the permanent fishway.

5.3 Fatigue Experiments

Fatigue in the laboratory trials was important because it gave the most appropriate time period between trials and the most suitable angle of slope for fishway installation for use in the field. In conclusion it was found that the vertical slot fishway was again a superior design to the sloping baffle fishway where fatigue occurred more rapidly. In addition to the fatigue effect of the sloping baffle fishway other conclusions are as follows:

- A rest period of 120 min reduced fatigue.
- Given a rest period sufficient to allow the fish to return to normal behaviour the effects of fatigue are reduced.
- Stress induced by through handling, transportation and experimentation must be recognised and minimised to provide more reliable results.

5.4 Recommendations for Future Research and Fishway Design

Despite the selection of the vertical slot fishway as the most appropriate for use on regulated coastal rivers a number of recommendations are offered in order to further improve its performance.

- Further testing should be conducted with various substrate particles, sizes and angular or smooth particles. Exploratory testing demonstrated improvement in migration success with the addition of a stone substrate (Table 3.11).
- The placement of suitable resting pools and/or cover near the fishway exit should be investigated. Such places may be necessary in areas where predation at the fishway exit is a risk, ensuring that the fatigued, migrating fish do not become easy prey.
- Due to the low height of coastal barriers it is suggested that the gradient of the fishway be no greater than 1:7 under these circumstances. Similar gradients were found to produce consistently high levels of migration success at variable discharge rates (Table 3.11). Such a shallow gradient would maximise movement of the catadromic species tested into the freshwater reaches of a river system.
- Placement of the fishway entrance should be such that it attracts the maximum number of potential migrants. The varying positions tested in the field indicated the importance of position with no fish entering the fishway from areas where no accumulation had been noted (Table 3.10). “Dead end” areas should be eliminated thereby passively guiding the migrating fish into the fishway entrance.
- Investigation into the suitability of the vertical slot fishway for other estuarine and freshwater migrating species is necessary as it is important that all possible migrating species be accommodated.
- Fishway additions or modifications should allow passage of crawling and climbing species i.e. penaeid prawns and anguillid eels respectively.
- The addition of modified trapping systems at fishways may be suitable for the removal of alien fish species using the structures. They could be used to further add to the data base of alien fish movement in these river systems.

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