Guidelines for the Planning, Design and Operation of Fishways in South Africa

A Bok, P Kotze, R Heath & J Rossouw

TT 287/07

Water Research Commission

GUIDELINES FOR THE PLANNING, DESIGN AND OPERATION OF FISHWAYS IN SOUTH AFRICA

Report to the Water Research Commission

by

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With information previously obtained in WRC projects as listed in the Foreword.

A CD has been issued with this Report. This includes:

1. A photographic file of the fishways listed the Inventory of Fishways (Appendix A)
2. South African Migratory Biota Database (In Excel) Appendix B on the CD
3. A folder of the photographs contained in the report
4. Twin-Channel Vertical Slot Fishway Design and Tests (WRC Report KV 197/07)

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The CD also contains:

(i) An electronic copy of WRC report TT 287/07 (This report)

(ii) A folder of the photographs used in the report

(iii) An electronic copy of WRC report KV 197/07:
Twin-Channel Vertical Slot Fishway Design and Tests

FOREWORD

There has been a world-wide increase in interest and research effort over the last 15 to 20 years on promoting free passage of aquatic organisms in rivers, as part of the wider goal to restore and conserve aquatic ecosystems. There is an increased appreciation of the necessity of both adults and juveniles of a variety of species to undertake longitudinal movements in rivers as part of their life-history.

There are about 100 indigenous freshwater fish species in South Africa, including both the subtropical Zambezian and temperate ichthyofauna. The majority of these freshwater species undertake migrations for feeding, spawning, dispersion, colonization after droughts or for other environmental purposes. Many of these larger species are well known for undertaking spectacular spawning migrations after rains in summer. However, as our knowledge of fish habitat requirements increases, there is a growing body of evidence indicating that many fish species migrate various distances both upstream and downstream into more favourable habitats, as both adults and juveniles, at various times of the year, for a variety of reasons.

The presence of existing barriers to migration in rivers (weirs, dams, road bridges, causeways, etc.) is considered to be a major factor responsible for the reduction in numbers and range of many migratory fish and invertebrate species throughout South Africa. Most indigenous fish species in this country carry out annual migrations within river systems for a number of reasons such as to optimise feeding, to promote dispersal, avoid unfavourable conditions and to enhance reproductive success. Impassable fabricated barriers to migration are partly responsible for the threatened status of a number of Red Data species in southern Africa

In recognition of the South African needs, with regards to fishways, the Water Research Commission (WRC) has proudly funded a fishway research programme that has produced the following reports:

- Discharge measurements at natural controls in Western Cape Rivers (Barnard and Rooseboom, 2004), (WRC Report No. 1270/1/04).
- Guidelines for the planning, design and operation of fishways in South Africa (Bok, Rossouw and Rooseboom 2004), (WRC Report No. 1270/2/04).
- Development of criteria for the design of fishways for South African rivers and estuaries. (Heath, Bok, Fouche, Mastenbroek and Forbes, 2006), (WRC Report No. 1310/1/05).
- Twin-channel vertical- slot fishway design and tests in South Africa, (Rossouw, Kotze, Heath and Rose (WRC Report No. KV 197/07).
- Guidelines for the planning and design and operation of fishways in South Africa (WRC Report No TT287/07) (This report.)

This guideline document (TT 287/07) is the final product of the fishway research programme. The guideline has been developed to aid the regulators, scientists and construction engineers to use local best practice in a consistent manner. To determine if a fishway should be built and, if yes, how to determine the specific fishways design for South African conditions.

Furthermore, the guideline includes important issues such as construction, operation, maintenance and monitoring of fishways. The document also has valuable case studies of application of the guideline.

Dr Steve Mitchell
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1 INTRODUCTION

There has been a worldwide increase in interest and research effort over the last 15 to 20 years on promoting free passage of aquatic organisms in rivers, as part of the wider goal to restore and conserve aquatic ecosystems. There is an increased appreciation of the necessity of both adults and juveniles of a variety of species to undertake longitudinal movements in rivers as part of their life history. The earlier fishways were designed to cater for strong-swimming adult salmonids and were found to be ineffective for passing juveniles or smaller fish species.

The presence of existing barriers to migration in rivers (weirs, dams, road bridges, causeways, etc) is considered to be a major factor responsible for the reduction in numbers and range of many migratory fish and invertebrate species throughout South Africa. Most indigenous fish species in this country carry out annual migrations within river systems for a number of reasons such as to optimise feeding, to promote dispersal, avoid unfavourable conditions and to enhance reproductive success. Impassable fabricated barriers to migration are partly responsible for the threatened status of a number of Red Data species in southern Africa.

There are about 100 indigenous freshwater fish species in South Africa, including both the subtropical Zambezian and temperate ichthyofauna. The majority of these freshwater species undertake migrations for feeding, spawning, dispersion, and colonization after droughts or for other environmental purposes. Many of these larger species (e.g. *Labeobarbus, Barbus, Clarias*) are well known for undertaking spectacular spawning migrations after rains in summer. However, as our knowledge of fish habitat requirements increases, there is a growing body of evidence indicating that many fish species migrate various distances both upstream and downstream into more favourable habitats, as both adults and juveniles, at various times of the year, for a variety of reasons.

The harmful effect of barriers to migration is particularly severe in coastal rivers where a number of catadromous species need to migrate from their marine or estuarine spawning grounds into freshwater reaches of rivers for feeding purposes. As these fish migrate upstream as small juveniles, even low barriers of less than a meter can be impassable. Catadromous species include the threatened freshwater mullet *(Myxus capensis),* four species of freshwater eels and at least five species of freshwater prawns and crabs (Anton Bok, personal communication). In addition, there are over 20 species of marine or estuarine fishes that frequently enter freshwater in these coastal regions, even though this movement does not involve a major portion on the population. These migratory species, (particularly the eels, mullet and prawns) present a valuable resource (food, angling) and play a valuable role in the ecology of the coastal river systems.

The design limitations of these earlier fishways have resulted in a renewed research effort to develop designs for non-salmonid species by both hydraulic engineers and fish biologists in many countries around the world. This research has resulted in much-improved fishway designs that successfully pass a wide variety of fish and other aquatic migratory species.

Until recently, very limited research funding has been available in South Africa to investigate fishway facilities designed to cater for indigenous species under local environmental conditions. There is presently a paucity of readily available information on in-stream barriers in South African rivers. Even though impoundments (weirs and dams) require registration in terms of the National Water Act (Act 36 of 1998), the exact locality of them is not available due to the process of registration still taking place. Furthermore, the principles of the National Water Act (Act 36 of 1998) endorse Integrated Water Resource Management (IWRM) on a catchment scale.

These guidelines are for the planning, operation and design of fishways in South Africa. The Department of Water Affairs and Forestry (DWAF) has recognised that there is a need in South Africa for determining whether a fishway is required and, if it is required, what are the optimum and cost effective design criteria for South African rivers? It is further important to determine that once a fishway is constructed, whether it works and what maintenance is required to ensure continued functioning. Consequently several projects have been funded by the Water Research Commission and these reports should be read in conjunction with this guideline:

- Bok, A., Rossouw, J and Rooseboom, A (2004). Guidelines for the planning, design and operation of fishways in South Africa. WRC Report No. 1270/2/04.
- Barnard, M and Rooseboom, A (2004). Discharge measurements at natural controls in Western Cape Rivers. (WRC Report No. 1270/1/04).
- Heath, R., Bok, A., Fouche, P.S.O., Mastenbroek, W and Forbes, A (2005). Development of Criteria for the Design of Fishways for South African Rivers and Estuaries. WRC Report No. 1310/1/05.
- Research on facilitating free passage of migratory biota in South African waters with a view to producing guidelines for the planning and design on fishways in South Africa. (WRC Report No. 1409/1/07) - this project.

These guidelines have been developed through a collaborative and consultative process with leading South African fish experts, ecologists, hydraulics engineers and hydrologists who have given up their time to participate in a series of workshops and reviews.

1.1 How to use this guideline?

The following flow chart indicates how this guideline should be used and cross references the relevant chapters (Figure 1-1).

Chapter No.	Name and what chapter is about?	Cross reference
1	**Introduction:** Background to why fishways required, how to use these guidelines, relevant legislation and inventory of fishways in South Africa.	Appendix A
2	**Summary of procedures for provision of a fishway:** The standard procedures and protocols to be used to guide the various role-players when assessing the need for a fishway, how to build and operate the most appropriate fishway at a particular barrier are summarised. An outline of the whole process to ensure if a fishway is necessary, to the design, construction; monitoring and operational management of the completed structure is summarized.	
3	**Necessity for a fishway**: The process to determine whether a fishway is required at any particular in-stream barrier is mapped out according to existing legislation for an in-stream structure.	Appendix B

Chapter No.	Name and what chapter is about?	Cross reference
4	**Importance of providing a fishway**: An assessment protocol for ranking the priority for fishway provision is presented. Ecological and socio-economic criteria are used in assessing the importance of providing a fishway to enable a cost-benefit analysis of the fishway project to be undertaken and also to determine the relative priority of providing fish passage at a specific site.	Appendix B
5	**Biological considerations for fishway design**: This chapter is aimed at presenting guidelines to enable ecologist to provide engineers responsible for designing a fishway at a particular site, with all the relevant biological information required.	Appendix B
6	**Design process:** The process of using site characteristics (hydrology, hydraulics, suitable location, species of fish to be catered for, etc.) to determine type and optimum fishway design is presented in this chapter. Furthermore monitoring and maintenance of the fishway is also incorporated in the design process.	Chapter 5, Appendix B
7	**Hydraulic design of fishways:** The necessary theory to be able to analyse the hydraulics of a fishway is presented. This theory is used to illustrate the design calculations required to estimate the performance of pool and weir and vertical slot fishways.	Chapters 5 and 9
8	**Monitoring and Operational management:** Monitoring programmes for fishways are suggested to provide data on both the effectiveness of the fishway in terms of the internal hydraulics at various flows, as well as data on the migratory behaviour and swimming ability of the migrants. Construction protocols are presented to monitor the construction of the fishway at the approved site.	Chapters 6 and 7
9	**Examples of application of guidelines:** The procedure for selecting an appropriate fishway is illustrated using examples.	Chapters 3 to 8, Appendix B
10	**Summary, recommendations and concluding remarks**	Chapters 10
11	**References**	Chapters 1 to 10
Appendix A	**Inventory of fishways in South Africa**	CD
Appendix B	**South African Fish Migratory database and references**	CD

Figure 1-1 A flow chart indicating how this guideline should be used.

1.2 Existing legislation in South Africa

Environmental legislation has recently been promulgated in South Africa that adequately protects riverine ecosystems from man-induced impacts. If correctly and strictly applied, this new legislation should ensure that appropriate mitigation (e.g. fishway provision) is taken when in-stream barriers to fish migration are constructed. This legislation includes:

1.2.1 *The Environment Conservation Act, 1989 (No. 73 of 1989)*

In terms of Regulations (Section 21, Schedule 1, No.1 (j) published in Government Gazette No. 18261, 5 September 1997, in terms of the Environment Conservation Act, 1989 (ECA), appropriate environmental investigations (EIA's) are mandatory before approval for the "construction or upgrading of dams, levees or weirs affecting the flow of a river" will be given by the relevant authority. Thus, approval for the construction of any potential in-stream barrier can be made conditional to the provision of a successful fishway.

1.2.2 *The National Environmental Management Act (Act 107 of 1998)*

The National Environmental Management Act (Act 107 of 1998), in terms of Regulation 386, Activity 1 (m) gazetted in terms of Section 24, a basic assessment is required to be conducted before approval for any in-stream barrier construction is granted.

1.2.3 *National Water Act, 1998 (Act No. 36 of 1998)*

In the National Water Act (NWA), use of water is no longer limited to consumptive use, such as the abstraction of water, but includes non-consumptive activities that may have an impact on the resource quality. These "water uses", which require authorisation (usually in the form of a licence) are given in Section 21 of the NWA, and include:

- Section 21 (a): storing water;
- Section 21 (c): impeding or diverting the flow of water in a watercourse;
- Section 21 (i); altering the bed, banks, course or characteristics of a watercourse.

Thus, in terms of the NWA, the erection of any in-stream structure within a watercourse, which could theoretically impede fish passage, such as bridges, causeways, weirs, dams, etc., is listed as a water use, and would require a licence. If the proposed structure or "alteration" of the watercourse could impede aquatic biota migration, the granting of the permit should be conditional on providing free passage of aquatic biota past the potential man-made barrier.

In addition to the above authorisations, there are also control measures for a dam with a safety risk, which is defined as any dam which can contain more than 50 000 m^3 of water and which has a vertical wall height of more than 5 metres, or which has been declared as a dam with a safety risk. A dam safety licence is required from DWAF before any such dam with a safety risk may be constructed or altered.

The intention of the legislation in the NWA in relation to fish movement is apparent in the Government Gazette No. 20526, 8 October 1999, which states in Schedule 1 (The taking of water from a resource and the storage of water, Section 21 (a) and 1 (b)) under paragraphs 1.9 (3): "Where water is stored in a watercourse, the registered user must take reasonable measures to ensure that the movement of aquatic species is not prevented, including those species which normally migrate through the watercourse".

1.2.4 *National Environmental Management: Biodiversity Act, 2004*

The Biodiversity Act aims to create an enabling regulatory framework for integrated management of the country's biodiversity resources and is administered by DEAT. One of the four objectives of the act is to provide for co-operative governance in the management and conservation of biodiversity. Chapter 5 of the act deals with the control and eradication of alien and invasive species:

- To prevent, where possible, the introduction and spread of alien and invasive species, to ecosystems and habitats where they do not naturally occur;
- To manage and control alien specie and invasive species to prevent or minimise harm to the environment and the biodiversity in particular; and,
- To eradicate alien and invasive species from ecosystems and habitats where they may harm those systems or areas.

Therefore, in terms of the Environment Conservation Act, (1989) the National Water Act, (1998) and the National Environmental Management: Biodiversity Act, (2004) legislation exists to enforce the provision of fishways on any in-stream structure that threatens to impede the free passage of migratory aquatic biota present.

As discussed above, legislation prior to 1998 did not require environmental impacts to be undertaken when constructing in-stream barriers. As a result, mitigation measures such as the construction of fishways to ensure free passage of migratory aquatic biota were seldom undertaken. Almost 15 years ago it was estimated that South Africa had in excess of 5 000 registered weirs and dams with a wall height of over 5 m and a capacity in excess of 50 000 m^3, as well as approximately 1 150 gauging structures, diversion and storage weirs (Rowlston, 1990).

The above estimate does not include the enormous number of unregistered smaller weirs constructed by riparian landowners and local authorities for farming purposes or domestic consumption, thought to run into tens of thousands. Many of these existing in-stream structures are known to completely or partially block the natural migration of South Africa's riverine aquatic biota and are considered to be a major contributing factor to the threatened status of many of the indigenous fish species (e.g. Bok, 1983; Skelton, 1993; Skelton, 1998).

1.3 Inventory of fishway in South Africa

In spite of the well-documented negative impacts of in-stream barriers on aquatic migratory species in South Africa, there has been very little effort to date to establish an inventory of such barriers on a catchment basis, or to prioritise them in terms of their ecological impact and hence mitigation requirements.

Due to this lack of readily available information on in-stream barriers in South African rivers, an annotated inventory of all fishways in South Africa has been developed (Appendix A and Figure 1-2). There are a total of approximately 57 fishways in South Africa, of which about 42 are functional to some degree. Considering the functional fishways, the most common type is the Pool and Weir (32) and then the vertical slot (8). One rock ramp and one pre-barrage fishway have also been constructed. However, both the Pool and Weir and the Vertical-slot fishways constructed in South Africa have major differences compared to the typical designs from Europe or North America.

Preliminary findings indicate that South African species can negotiate fishways with velocities and turbulence levels greater than those recommended in similar work overseas. If these findings are correct then they will allow the construction of steeper and shorter Vertical-slot fishways, which will result in substantial savings on construction costs.

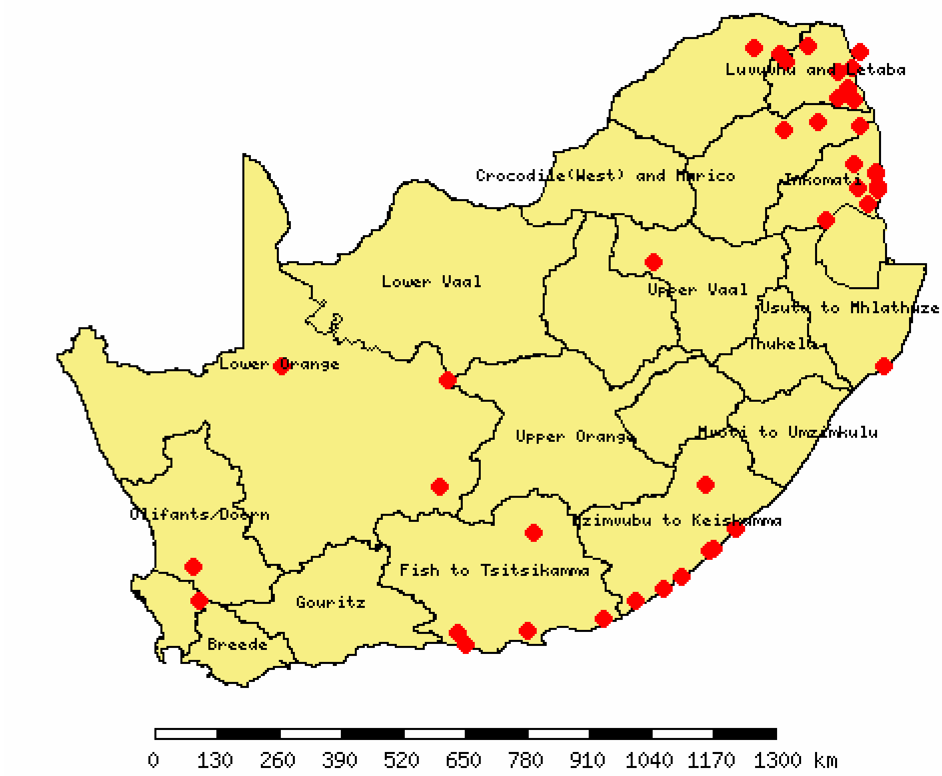

Figure 1-2 Location of fishways in South Africa per Water Management Area.

2 SUMMARY OF PROCEDURES FOR THE PROVISION OF A FISHWAY

2.1 Introduction

This chapter summarizes the standard procedures and protocols to be used to guide the various role-players when assessing the need for a fishway, and subsequently, to build and operate the most appropriate fishway at a particular barrier. An outline of the whole process from initial assessment (to ensure a fishway is necessary), to the design, construction; monitoring and operational management of the completed structure is summarized in Figures 2-1 and Table 2-1. A brief summary of the various procedures to be followed are discussed in subsequent sections of this chapter.

2.2 Necessity for providing a fishway

The first step when investigating whether a particular in-stream structure will block migrations of aquatic biota is to determine the presence of migratory aquatic species in the river reach under consideration, as well as the characteristics of the proposed structure and the site in terms of blocking of migrations. By answering a number of questions set out in a protocol (or steps) given in Figure 2-2, the necessity for providing a fishway at the structure can be determined.

As indicated in Figure 2-2, there are a number of special circumstances when the construction of a fishway is not required or cannot be justified. The criteria used in this assessment and the ecological basis for the decisions reached, are discussed further in Chapter 3.

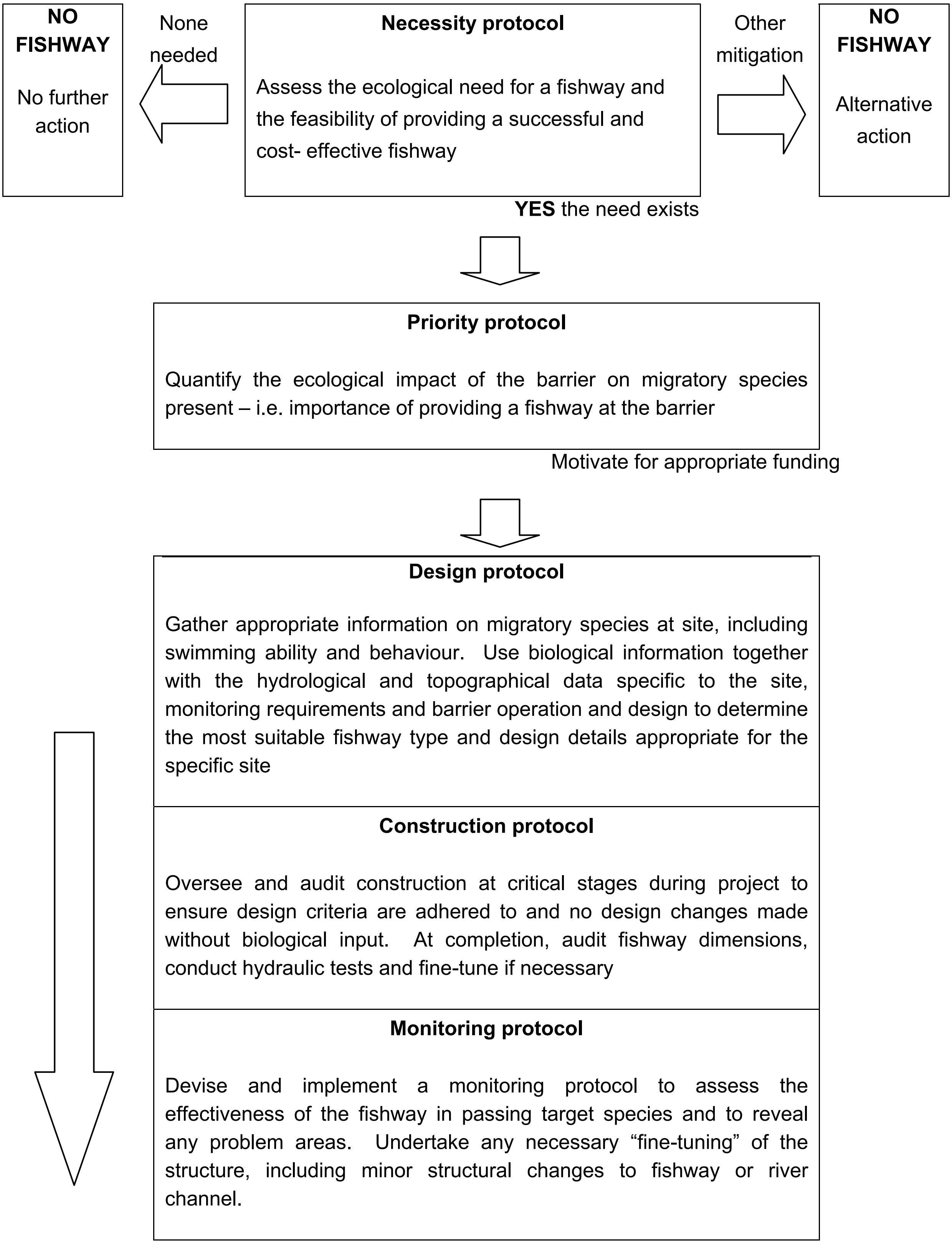

Figure 2-1 A summary of the procedure for the planning, design, provision and operation of a fishway at any particular in-stream structure.

Table 2-1 Summary of the proposed procedural steps to be taken, and by whom, when assessing the necessity for, design of and provision of a fishway at an instream barrier. (FC = Fishway Committee)

Step	Action/aspect to be addressed	By Whom
1. Environmental Impact Assessment Process	Preliminary design concept for in-stream structure, site selection and proposed operating strategy (i.e. details of proposed development)	Proponent/owner, engineers, government officials
	Assess the impact of the proposed structure on fish migration in the river reach in question (i.e. carry out EIA in terms of existing legislation) and produce environmental scoping report (ESR)	EIA Consultant, Biologists, hydrologists, government authorities
	Use protocol to assess the necessity for a fishway. Reach agreement on appropriate mitigation - e.g. alternative site; change barrier design, fishway provision, conduct studies to satisfy the EIA process.	All role players – EIA Consultant, biologists, engineers, government authorities, owner (proponent)
	Use Protocol to assess (rank) importance of providing fishway. Desktop survey of requirements of migrants in system, potential upstream habitat available, etc. Also identify knowledge gaps.	EIA Consultant, biologists, with inputs from hydraulic engineers and hydrologists
	Undertake pre-design surveys and base-line monitoring (if time and funding available) to fill knowledge gaps of particular system	EIA Consultant, biologists, hydrologists
	Use protocol to determine optimum fishway design for particular barrier. Study migratory characteristics, migratory season, swimming ability and behaviour (jump or crawl, etc.), hydrology of river, etc. Produce report on conceptual design of fishway(s)	EIA Consultant, biologists, hydraulic engineers, hydrologists
2. EIA Consultant and Fishway Committee	Undertake site visit (if necessary)and discuss and reach agreement on preliminary design details - e.g. size and location of fishway, slope of channel, headwater and tailwater pool levels, water volumes down fishway, proposed operational strategy, EWR releases, engineering issues, etc.	FC, Biologists, consulting and hydraulic engineers, RDM Office, owner of structure
	Production of preliminary design report, including drawings of fishway	FC, Consulting engineers/owner
	Audit and fine-tune preliminary design drawings (undertake second site visit to incorporate fish survey results and other biological, hydrological, hydraulic and engineering issues	Engineers, hydrologists, biologists
	Produce pre-construction fishway report with recommended design changes, as well operational management recommendations	FC, Biologists, hydrologists
	Incorporate recommended alterations and produce final design drawings for construction	FC, Engineers
3	Use protocol to audit construction - close monitoring of work, all modifications to original design to be approved by biologists	Engineers, biologists
4	Final audit and approval on completion of fishway (commissioning)	Owner (proponent), biologists and engineers
5	Use protocol to monitor effectiveness of fishway. Post-construction monitoring and evaluation - production of Evaluation Report and undertake minor structural modifications or additions, if necessary	Biologists and engineers
6	Fine-tune operational management of fishway and implement operational management strategy, including regular maintenance and repair	Owner (proponent), biologists, engineers

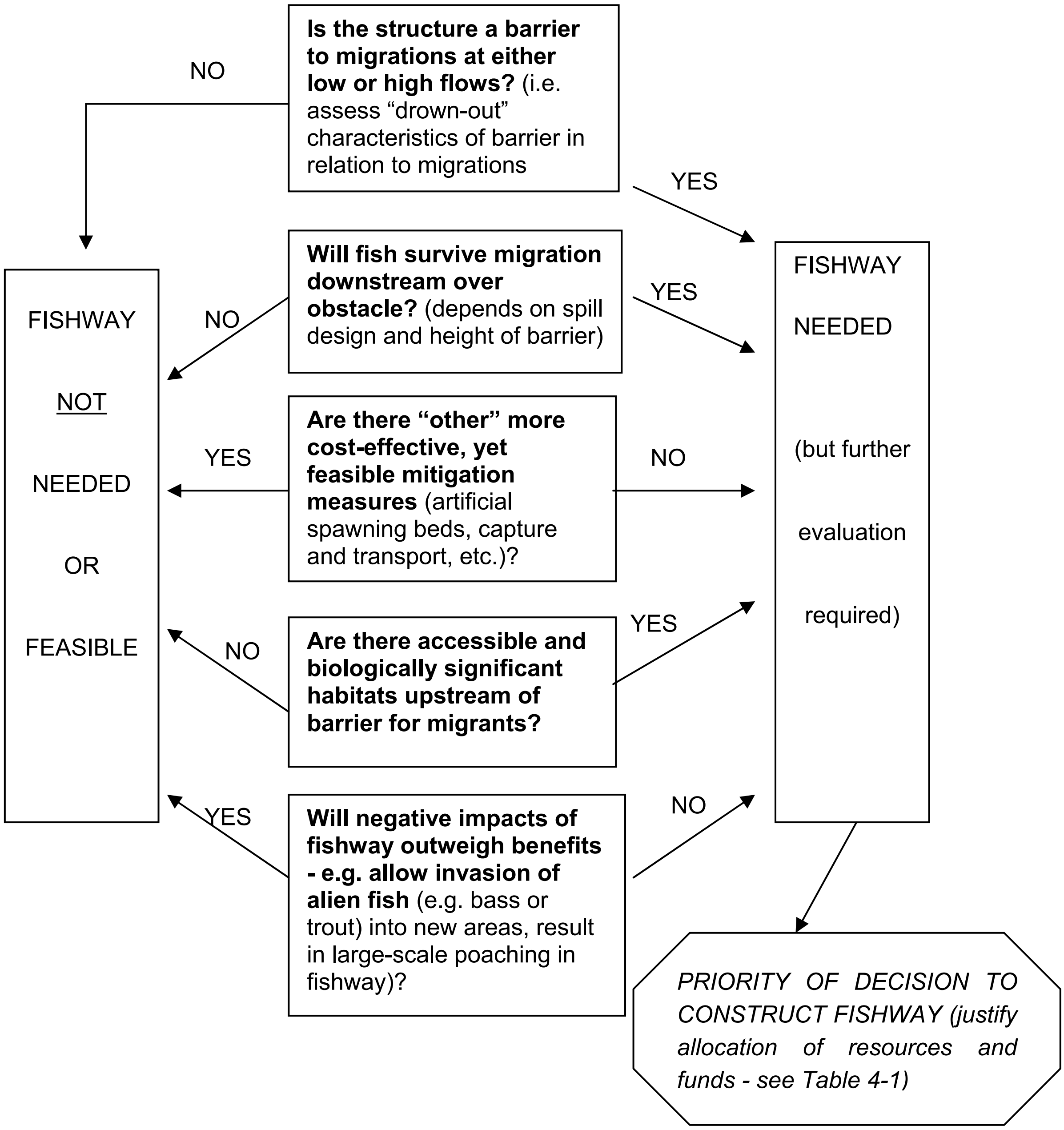

Figure 2-2 Protocol for assessing the need for providing a fishway at an in-stream barrier.

2.3 Importance for providing a fishway

Once the necessity for providing a fishway at a proposed in-stream structure has been established, the cost-benefit or relative importance of providing fish passage past the barrier should be assessed. This will allow managers to identify priority sites for fishway construction in a standard and structured way to help ensure that the limited funding available for fishway construction in South Africa is spent optimally and high priority sites receive the necessary attention.

A quantitative ranking scheme, using a number of ecological and socio-economic criteria, is given in Table 2-2. It must be stressed that this scoring scheme should be seen as a useful tool to standardize assessments and further evaluation should be guided by expert opinion and local knowledge. The criteria used and possible ratings attached to the scores obtained are discussed in further detail in Chapter 4.

Table 2-2 Proposed scoring scheme to determine the importance of providing a fishway.

Criteria	Max. Score	Site Score	Explanation
Socio-economic value of migratory species present	12		Value for food, angling, eco-tourism Low (4); moderate (8) and high (12)
Conservation status of migrants present (number of Red Data or threatened species)	12		Taken on a provincial level (4); national level (8); global level (12)
Ecological value of migrants (importance of role in eco-system functioning)	12		value in natural food web, e.g. high in reserves Low (4); moderate (8) and high (12)
Importance of upstream habitat to migrants	12		Low (4), moderate (8) and high (12)
Proportion of catchment/upstream habitat obstructed	9		<25% (3), 25- 50% (6), >50% (9).
Fish habitat integrity of river for migrants (i.e. PES/Management Class)	9		Poor, or Class E/F (3), moderate or Class C/D (6), good, Class A/B (9)
Percentage of stream flows that structure blocks fish passage due to drown-out characteristics of site	8		20 –40% (3); 40 – 60% (5), > 60% (8)
Feasibility of constructing a successful fishway (i. e. confidence of success)	8		Low (3), moderate (5), excellent (8)
Expense of fishway in relation to the ecological benefits	6		High (2), moderate (4), low (6)
Financial and other support from NGO's, government, special interest groups, etc.)	6		Low (2), moderate (4), high (6)
Presence of permanent/natural barriers downstream	6		None (6), rare (4), many (2)
TOTAL SCORE	**100**		

A score of >85 = Very High Priority; 75 to 85 = High priority; 50 to 75 moderate priority; < 50 = low priority

2.4 Biological considerations

The successful design of a fishway depends largely on providing the hydraulic and physical characteristics that cater for all the migratory species expected to use it. The biological information required, including the specific data required on the migratory behaviour and swimming ability of species expected to use the fishway, are listed in Table 2-3. A detailed discussion of how biological considerations influence fishway design is given in Chapter 5.

Table 2-3. Biological information required of migrants or target species in river reach.

Step	Requirement	Action / Explanations
1	Species and size range of migratory species present at site, or which are thought to migrate within the river reach	• Refer to Migratory Regions (discussed in Chapter 5) and the SAMigratoryBiota database (Appendix B) and all available sources to determine the migratory aquatic species expected at the site, • Undertake field surveys of fish populations in river reach concerned, if data are lacking or scarce, • Use available knowledge to determine size range of migratory species expected at site, • Dimensions of the fishway should accommodate both the smallest and largest fish targeted, i.e. the size range of migratory species that need to migrate past the barrier.
2	Swimming ability of migrants	• Swimming speed is related to fish length, as well as species of fish • Use available data on maximum swimming and jumping ability of various target species, • Fishway hydraulics should cater for smallest and weakest-swimming migrant targeted, while the dimensions of the fishway should accommodate largest migrant targeted.
3	Swimming behaviour and preferences of migratory species	• Use available data to determine whether target species prefer to jump or swim within nappe between pools, or prefer to crawl or climb on wetted perimeters (e.g. eels, prawns), etc. • If possible, observe migratory behaviour at barrier site, such as where migrants accumulate, preferred channels within river bed, etc.
4	Timing of and reasons for migrations	• Use available information to determine the time of the year that migrations usually occur – this is necessary to correlate migrations with the river hydrology, • Reasons for migration will determine ecological impact of delays at barrier (e.g. whether spawning or feeding migrations would be blocked) and thus whether the fishway should be effective during high river flows which may only last for short periods (see Chapter 5).

2.5 Hydraulic and Hydrological Considerations

The fishway should operate effectively over the “normal” range of river flows anticipated over the time period when the target species undertake their migrations. Thus the migratory period and reason for the migratory behaviour should also be considered in relation to the natural hydrology of the river or river reach. In rivers where the flow is regulated by releases from impoundments (including releases to satisfy the in-stream or ecological flow requirements or "Reserve"), these modified flow patterns and discharges need to be taken into account when designing the fishway.

The upstream (headwater) and downstream (tailwater) water levels at the barrier site over the range of flows during which migration normally takes place must be established to ensure that the appropriate fishway type is used and that the fishway is designed correctly. For example, pool and weir fishways normally operate effectively over a relatively narrow range of upstream water levels. Under these conditions, and if fish need to migrate at high flows (e.g. spawning migrations), a vertical slot type fishway may be more effective (see below).

For a more detailed discussion of site-specific hydrological and hydraulic considerations to be taken into account when planning fishway provision, refer to Chapter 6.

Table 2-4 Site-specific Hydrological and Hydraulic Considerations

Requirement	Action / Explanation
Range of flows over which the fishway should function successfully	Undertake hydrological analysis of the river at the site to establish: • Mean monthly flows, • Daily flows in critical months when migration of target species normally occurs.
Characteristic flow pattern at site	• Determine characteristics of flood hydrograph at site, particularly if spawning migrations occur during high flows, • Determine characteristic high and low flows (discharge duration curve) - number of days of the year that certain flows occur, • Determine flood levels to ensure the structure is protected from flood damage, • Quantify the change in flow pattern at the site caused by the structure and water use.
Headwater and tailwater levels	• Undertake hydraulic surveys to determine the head and tail-water levels over the range of river flows that the fishway should operate, • Ensure location and design of exit and entrance (for upstream migrating fish) of fishway will accommodate the headwater and tailwater pool level fluctuations at flows anticipated during the main migration periods.

2.6 Topographical Considerations

The physical or topographical characteristics of the river channel at the barrier site could influence the type of fishway that can be constructed, as well as details of the fishway design. If suitable rock formations are not present, or if the river channel is deeply incised, these features could greatly increase fishway construction costs or totally preclude fishway types requiring large amounts of space.

The information required and the influence of site-specific topographical features of fishway provision are discussed in some detail in Chapter 6 and summarised in Table 2-5.

Table 2-5 The influence of topographical features on fishway design and provision.

Topographical or Physical Feature	Influence on fishway provision
Presence of rock formations at river banks	• the foundations of a formal fishway often require suitable rock formations on the river bank, • the rock formations present could be incorporated into a "formal" fishway structure (e.g. bedrock used as floor of the channel), • suitable sloping rock formations on the river bank (or in greater river channel) could be used to form "natural-type fishways" such as rock-ramps or fish-ramps.
Presence of rock formations in the river channel below structure	• location of fishway entrance is largely determined by location of natural channels and pools in river-bed downstream of fishway, so as to enable easy access to the fishway, • suitable bedrock in the river bed could enable the construction of pre-barrages, i.e. a number of parallel low weirs, forming a series of pools below the barrier to help upstream migrants gain access to the fishway entrance, • pre-barrages built on bedrock or structural alterations of the river channel downstream could enhance the drown-out characteristics of the barrier. This could allow fish passage at high flows, ensuring only a relatively inexpensive "low-flow" fishway is required, or even possibly no fishway at all.
Sufficient space and suitable, gentle gradient on river banks	• "Close to nature" type fishways such as by-pass-channels (with gentle slopes of approximately > 1:15 or 1:20) are often the preferred option, but are only feasible if the topography is suitable and there is sufficient space.

2.7 The most appropriate fishway type

The main advantages and disadvantages of the three fishway types considered suitable for South African conditions, in relation to the various site-specific biological and physical factors listed earlier, are given in Table 2-6. A more detailed explanation of factors to be considered when selecting the most appropriate fishway type is given in Chapters 5 and 6.

Table 2-6 Advantages and disadvantages of the three most common fishway types

POOL AND WEIR	**ADVANTAGES** • Effective at passing a large variety of fish species at relatively low flows, • Can be modified (e.g. notched weirs, wide, sloping weirs) to operate effectively at very low flows, down to 4 l/s, • Can be modified to successfully accommodate climbing and crawling species, as well as very small (<20 mm long) fish. This is achieved by using wide, laterally-sloping weirs to provide wide, gently sloping wetted perimeters used for climbing.
	DISADVANTAGES • Does not operate effectively over a wide range of headwater pool levels, unless special inflow controls are provided, • Cannot accommodate large discharges, as turbulence levels within pools increase rapidly as flows in fishway increase, • Tend to accumulate sediment in pools (unless submerged orifices are provided).
VERTICAL SLOT	**ADVANTAGES** • Can operate very effectively over a wide range of headwater pool levels, • Passes small fish at slopes of up to 1:8, if turbulence levels and velocities are suitable, • Can easily accommodate large discharges as velocity and turbulence do not increase noticeably with increased flows (or water depths), • As slot extends to bottom of the weir, sediment does not accumulate in the pools.
	DISADVANTAGES • Does not appear to pass climbing and crawling species (elvers, prawns) unless a rough stone substrate is cast into the channel floor, as reported in Europe (FAO/DVWK 2002). Trials in SA using local crawling species are required to verify the above. • High maintenance requirements as slots are easily blocked with debris, unless effective debris reflectors can be used.
"NATURAL TYPE" by-pass canals and fish ramps	**ADVANTAGES** • Is often the "first choice" fishway type, which should mimic hydraulics in natural rapids and thus should provide passage for a very wide variety of species and size classes, • Do not require much maintenance and are largely self-cleaning, • Are aesthetically pleasing and provides additional "riffle-pool" habitat, thus suitable for natural areas and game reserves, • Can easily be combined with use of "pre-barrages" to facilitate migrations at high flows.

	DISADVANTAGES • Feasibility depends almost entirely on the suitability of the topography and foundation conditions (e.g. rock formations) at the site, • Requires a large amount of space on river banks due to the very gentle slope (>1:20) and thus long channel required), • May not operate at very low flows (< about 5 l/s) due to seepage, unless channel is lined, More difficult to accurately measure discharges over range of flows (when incorporated into gauging weirs).

2.8 Fishway dimensions and design

The most appropriate fishway type should have the internal hydraulics (water depths, flow velocities, turbulence) to cater for the smallest and weakest swimming species, but with the dimensions suitable for the largest migrants targeted. In addition, the fishway entrance and exit should be suitably located in relation to site-specific conditions. The reader is referred to Chapters 6 and 7 for a more detailed description of the parameters given in Table 2-7 as well as practical examples of how these parameters are applied in the fishway design process.

Table 2-7 Summary of recommended hydraulics parameters and fishway dimensions for pool type fishways (vertical slot and pool and weir types) in SA. These parameters can also be used as guidelines for "natural" type fishways (bypass channels, fish or rock ramps).

Fishway Parameter	General Recommendations
Width of pool	At least 2 times the length of largest fish catered for
Length of pool	At least 2.5 times the length of largest fish catered for
Depth of pool	• Small fish (20 to 200 mm in length): at least 300 mm (to reduce predation and limit turbulence), • Larger fish (> 200 mm): at least 500 mm, can be deeper to reduce turbulence, if necessary.
Maximum current velocities	• Very small fish (25 – 40 mm in length): <1.2 m/s, • Medium size fish (40 – 100 mm in length): <1.7 m/s, • Larger fish (100 – 400 mm in length): <2.0 m/s.
Turbulence (power dissipation per unit volume)	• Very small fish (25 – 40 mm in length): <150 watts/m^3, • Medium size fish (40 – 100 mm): <180 watts/m^3, • Larger fish (> 100 mm): <200 watts/m^3.
Drop between pools	• Very small fish (25 – 40 mm in length): <75 mm, • Medium size fish (40 – 100 mm in length): <150 mm,

Fishway Parameter	General Recommendations
	• Larger fish (100 – 400 mm in length): <200mm.
Channel slope	Depends on size range of fish. Narrow size range allows steep slopes, i.e. small pools with small drops or large pools with large drops. For the typical size range of fish in South Africa, slopes of 1/8 to 1/10 is normally required. Note: In specials circumstances such as on crump gauging weirs and at very low barriers (< ca. 1.5 m high), steeper gradients of up to 1:5 may be considered provided turbulence and maximum velocities are within the recommended maximums
Fishway entrance	Generally at the furthest point upstream that the fish can penetrate – usually in a suitable pool (low turbulence, sufficient depths) located at the base of the barrier.
Fishway exit	• Located in a quiet area, sheltered, low velocity, to prevent fish from being swept downstream and to afford protection from predators, • The invert level of the exit (i.e. water inflow) in rivers with long periods of low flow should be lower than that of weir/dam overflow to ensure that low flows are directed down the fishway, • May require control device to regulate flow down fishway.
Auxiliary and Attraction Water	• Auxiliary water – extra water provided into larger entrance (first downstream) pool of the fishway to attract fish into fishway, • Attraction water - water supplied external to the fishway and is used to attract fish to the general area of the fishway entrance.

2.9 Construction Protocol

Details of the construction protocol are indicated in Chapter 8, section 8.3 and the recommended construction protocol in Figure 8-1.

2.10 Monitoring and Operational Management

The newly commissioned fishway should be monitored to assess its effectiveness in passing the target species. This will enable any minor structural changes to be made and to fine-tune the operational management, if necessary. Funding for monitoring should therefore be included in the original budget for the provision of the fishway.

It is important that the monitoring program is well-planned and designed to answer a range of Key Questions on the performance of the fishway, in relation to the migratory ability and behaviour of the migrants. For a discussion of these Key Questions and additional background information and details of possible monitoring protocols, refer to Chapter 8. A summary of the most important aspects are given below.

Funnel traps can be set in various parts of the fishway and data recorded from the fish captured. The following actions should be taken:

- Capture fish at upper end of fishway (i.e. that have successfully negotiated the fishway) over a set period (12 or 24 hours) and determine numbers, species and size composition and additional biological data considered appropriate, such as sex ratios and sexual maturity and condition of migrants.
- Capture all fish entering fishway over comparative time periods and compare the data recorded with that in a) above. The percentage of fish entering the fishway that swim right through will indicate the effectiveness of the structure in passing fish.
- Measure appropriate abiotic parameters, such as water quality (e.g. temperature, conductivity, turbidity) in the fishway, headwater and tailwater pools and any atmospheric conditions (e.g. weather, barometric pressure) that may influence migratory behaviour.
- Determine fishway use over a range of discharges and correlate the measured fish passage through fishway with the changes in the hydraulic parameters.
- Carefully observe the fishway in operation for any problems such as debris blockages, accumulation of migrants at bottlenecks within the fishway due to high turbulence or velocities at critical points, presence of migrants below the barrier unable to find fishway entrance, etc.
- In cases where poaching of migrants within the fishway is seen to be a problem (or potential problem), appropriate actions to prevent this activity should be taken or recommended. This could involve education, law enforcement or constructing barriers to prevent unauthorised access to the fishway.
- Analyse data and make necessary changes to the fishway design and/or fine-tune operational management and maintenance programme of the fishway.
- In special instances where comprehensive monitoring is not possible, basic monitoring consisting of placing traps at the fishway exit (upstream end) during peak migratory periods to determine movement of species through the fishway, should be undertaken.

3 NECESSITY FOR A FISHWAY

3.1 Introduction

Existing legislation in South Africa (see Chapter 1, Section 1.2) is designed to ensure that the appropriate Environmental Impact Assessment (EIA) process is followed, before authorisation is granted for the construction of any potential in-stream barrier. This should include the potential for blocking the natural migrations of aquatic species in the river reach affected. The various procedural steps to be taken, and by whom, to determine whether a fishway should be build at any proposed in-stream structure, are given in Table 2-1 (Chapter 2). As can be seen, this process should form an integral part of the existing EIA procedures.

The provincial and national environmental agencies tasked with implementing the above legislation should therefore ensure that the necessity for a fishway has been adequately assessed in the EIA process before any approval for the construction of an in-stream structure is given. In addition, the Record of Decision for any approval should include specific conditions to ensure that an effective fishway is not only constructed, but that its effectiveness is proved by means of a fishway monitoring programme and that appropriate maintenance and operational management of the fishway in the long-term will be undertaken.

The first step, therefore, when investigating the barrier effect of any man-made in-stream structure, is to find out whether it is necessary, or feasible, or even desirable to ensure the free passage of migratory aquatic species past the potential barrier.

3.2 Situations where a fishway is not required or feasible

There are a limited number of rivers in South Africa, or specific reaches within these rivers, where the provision of a conventional fishway may not be required or even could have a negative impact on the indigenous aquatic biota present. In addition, there are instances where (for a variety of reasons) the limited ecological benefits derived from providing a fishway cannot justify the costs, in terms of funding or other resources required. These situations are discussed below.

3.2.1 *Natural absence of indigenous migratory aquatic species*

The site-specific information required to assess the presence or absence of migratory biota will (in most instances) have to be obtained from local experts or, where data are lacking, by conducting specific biological field surveys of the river reach in question. Available information on the distribution of aquatic species (fish, macro-invertebrate) is given in the SAMigratoryBiota database (Appendix B) and is also available in existing databases located at Museums and Academic Institutions (e.g. Albany Museum and South African Institute for Aquatic Biodiversity in Grahamstown).

The natural absence of migratory fish species present in the river reach in question that would use a conventional fishway could be due to one or more of the following reasons:

Only climbing species present

In rivers on the eastern and southern seaboard, indigenous anguillid eels may be the only migratory species naturally present in certain reaches. This is frequently the case upstream of a natural rapid or waterfall, which is a barrier to all fish except young eels. The unusual climbing behaviour of these catadromous species (i.e. adults migrating downstream to breed in the sea and juveniles migrating back into fresh water reaches of rivers) can be catered for by incorporating species-specific “eelways” in the design of the barrier spillway. In their simplest form, these consist of shallow, rough channels with a lateral slope to ensure a suitable sloping splash zone for eel migration is present at a variety of river flows (see Chapter 5).

Absence of suitable upstream habitat

There may be no (or minimal) suitable habitat present upstream of the proposed barrier and thus the ecological contribution of the river reach blocked off by the proposed in-stream structure is insignificant. This situation could arise when the in-stream barrier is located near the top of the catchment, or because the habitat upstream has been permanently destroyed by man’s activities (e.g. bulldozed, canalised).

Presence of existing impassable barriers

The presence of an impassable natural barrier (e.g. high waterfall) or man-made in-stream barrier (or barriers) in close proximity to the proposed structure could rule out any possibility of mitigation (i.e. facilitating upstream migrations) in the future.

However, the presence of migratory fish in the man-made impoundment that need to migrate upstream to breed or the possibility of fishway provision on existing barriers should be carefully assessed before a decision not to construct a fishway is taken. As information on the location of existing dams and weirs are not easily available and waterfalls are not always depicted on available maps, it is usually necessary to conduct field surveys to determine the presence of such barriers.

3.2.2 *Excessive height or poor design of the structure*

Mortalities of downstream migrants due to wall height

Fishways do not normally cater for downstream migrants, as these fish usually leave an impoundment via the spillway overflow water during high flows. As outlined below, when large adult fish fall over a high barrier wall to the river below, they can suffer high mortalities.

Examples include catadromous species such as freshwater mullet *Myxus capensis*, were the adults migrate downstream to breed in the sea and juveniles migrate back into fresh water reaches of rivers. Thus, a fishway allowing juvenile catadromous fish to migrate upstream over a barrier that is too high to allow the safe downstream migration of adults, could effectively prevent these fish from returning to their spawning grounds and have a serious negative impact on the population. In the case of potodromous species (i.e. where adults migrate upstream to spawn and the young fish migrate downstream), the mortality of these downstream migrants may not be substantial.

It has been shown that significant injury to all fish, regardless of size, occurs when the impact velocity on the water surface exceeds 15-16 m/s (Bell and Delacy, 1972, vide Larinier and Travade, 2002). This critical velocity is reached after a free fall of about 30-40 m for fish of 15-16 cm in length, but after only 13 m for fish longer than 60 cm. The terminal velocity of free-falling fish of less than 13 cm in length always remains below this critical velocity and these small fish are therefore not injured regardless of the height of the fall. Thus the motivation for providing a fishway on a high dam wall would have to be carefully evaluated in terms of the mortalities of the downstream migrants.

Spillway and stilling basin design

A large, deep pool (stilling basin) on the downstream side of the structure is required to avoid injury and mortalities to fish dropping over the wall. The presence of solid energy-absorbing structures below the barrier could cause very high mortalities. In addition, the water should fall freely into the pool below (no adherent nappe as would be the case with a gravity type spillway) to prevent injury to the fish due to abrasion on the spillway face.

Thus, it would be pointless to construct a fishway on a barrier that is not designed to allow the safe passage of downstream migrants.

High Costs due to length of fishway required

The funds required to construct an effective fishway (or fish lock, fish lifts) may be totally prohibitive due to excessive height of the structure, site topography, or location of barrier, operation of discharges (e.g. hydro-electricity generation), etc. If the environmental impact of not providing a fishway is significant, alternative proposals will need investigation, e.g. new barrier site, modified barrier design, netting the migrating fish at the foot of the obstruction and transporting to the river upstream of the barrier by means of tanker trucks, etc.

Biological and/or physical constraints of migrants

Even if funds are available, the excessive height of the barrier and/or other factors, such as limited swimming ability or unusual migratory behaviour of target species, hydrology of river, site topography, operation of discharges, etc., could make it highly unlikely that a successful fishway could be constructed. In such cases, the use of scarce funds on a structure, which has little chance of working, cannot be justified. Again, alternative project proposals will need investigation if the impact of not providing fish passage is considered significant.

3.2.3 *Alternative and more cost-effective mitigation is available and feasible*

Under certain conditions, the biological requirements of migrants can be suitably met (or compensated for) in ways other than by constructing a fishway. These “alternative” actions include:

Artificial spawn beds

If the spawning migrations of fish requiring gravel spawn beds located in suitable depths and river flow conditions (e.g. certain Labeobarbus species) are blocked, these spawning requirements could theoretically be created below the barrier. However, to ensure breeding success of the target species requires detailed information on the exact spawning requirements of adults and larval rearing and nursery conditions, such as water temperatures, substrate composition, hydraulic parameters (water depths and velocities), protection from predators, etc. In order to achieve these conditions, it will be necessary to have the capability to carefully manage water releases. Unfortunately, little is presently known regarding details of the breeding and larval rearing requirements of most of our indigenous species. Further research is therefore needed in order to make this option feasible in South Africa.

Capture and Transport

The capture of migrants below the barrier and then transporting and stocking the live fish upstream of an in-stream barrier may be feasible under certain circumstances. The high on-going costs of such an operation mean that a substantial long-term commitment in terms of funds and skilled labour is required. In addition, high mortalities of adult fish in spawning condition may occur when handled in this way. Thus capture, transport and stocking upstream is more feasible when juvenile fish are targeted and when used as an interim measure. Under normal circumstances capture and transport of migrants to habitats upstream of the barrier is therefore not considered a satisfactory long-term solution.

Captive breeding and restocking

Breeding of the impacted species in dedicated hatcheries and the restocking of young fish into the river reaches upstream of the barrier to compensate for the blocking of any breeding migrations, is undertaken extensively in North America and in parts of Europe. Normally commercially valuable fish such as trout or salmon are involved. Again, the high costs involved and lack of expertise in South Africa indicates that this option is probably not economically feasible or sustainable for indigenous fish species in this country. In addition, there are a number of dangers associated with any captive breeding and restocking programme, such as genetic contamination of wild stocks and introduction of disease via the hatchery-bred fish.

3.2.4 *Negative ecological impacts of providing a fishway outweigh the benefits*

At certain sites, the provision of a fishway may allow alien invasive species (e.g. bass, trout, carp) to penetrate upstream of a barrier structure that presently (or could in the future) prevents such invasions. The existing barrier could be a natural waterfall or an artificial weir wall. In this regard, the construction of in-stream barriers is an accepted conservation tool to protect vulnerable populations of indigenous aquatic species from alien invasive species stocked by man into the river downstream. Under these conditions, the provision of a fishway could have significant negative impacts on indigenous species present in the upstream reaches and should not be considered.

3.2.5 *Drown-out characteristics of barrier*

In many instances the site topography ensures that the water level downstream of a barrier rises more rapidly than the upstream water level with increases in river flow, thus effectively “drowning out” the structure at high flows. The drown-out characteristics of a barrier could be enhanced by modifying the river channel, such as by constructing pre-barrages or a series of low, passable weirs in the river channel downstream. Under these conditions, the structure may only form a barrier to upstream migration at low flows.

If it can be established that the target aquatic species usually migrate under high flow conditions when the barrier is drowned-out, and also that this situation occurs frequently, the provision of a fishway on the barrier in question may not be necessary. Further field studies at the site may be required to provide the information necessary to make an informed decision regarding the above.

3.3 Summary

The studies to determine whether a fishway is required at any particular in-stream barrier should be undertaken during the EIA process, which is required under existing legislation for any proposed in-stream structure. Data on the swimming ability and preferences, migratory behaviour as well as the migratory life-history of the aquatic species at the site, will need to be obtained from available published and unpublished sources. Input from a fish specialist familiar with the river in question will be required to provide the information necessary to make an informed decision. There is also a need to support studies which provide these essential data. This information, together with the field studies of the study area, will also be required to quantify (or rate) the ecological impact of any in-stream barrier to migration, as discussed in Chapter 4.

4 IMPORTANCE OF PROVIDING A FISHWAY

4.1 Introduction

Once the need for a fishway at an in-stream barrier (or proposed barrier) has been established, it is important to quantify the potential impact that would result if a fishway was not built. As discussed below, both ecological and socio-economic criteria are used in assessing the importance of providing a fishway to enable cost-benefit analyses of the fishway project to be undertaken and also to determine the relative priority of providing fish passage past the barrier in question.

This information on the relative importance of fishway provision at different sites will enable water resource planners and managers to make informed decisions to ensure that limited funds available for fishway construction are spent on those structures causing significant ecological damage. In addition, when retrofitting fishways on existing barriers in a particular river, it will enable the various sites to be prioritized and allow managers to determine which sites should be the first to receive a fishway. The availability of a suitable assessment protocol for ranking the priority for fishway provision is particularly important when river rehabilitation on a catchment scale is undertaken.

4.2 Criteria used for assessment

4.2.1 *Socio-economic value of the migratory species present*

The economic value of the migratory species in terms of commercial harvesting, as well as their value in terms of angling activities in the river system, is assessed. This evaluation should also consider the secondary or indirect economic spin-offs derived from angling, such as travel, accommodation, equipment purchases, etc. In addition, the importance of any subsistence fishing activities by the local communities within the river system should be assessed. River reaches that fall within nature reserves also have an eco-tourism value that could be negatively affected if important aquatic species are eliminated by a barrier to migration.

4.2.2 *Conservation status of migrants*

The number of migratory species that would be impacted by the barrier that have a threatened (vulnerable, rare of endangered) conservation status, as listed in the South African Red Data Book (1987) on fishes, is assessed. If any doubt exists in this regard, provincial conservation authorities, fish experts, relevant Museums, etc., should be contacted for the most recent conservation status classifications. Maximum scores are given to fish species threatened on a global level, with reduced scoring for fish threatened on a national and regional level, as indicated in Table 2-2.

4.2.3 *Ecological value of migrants*

The ecological importance of the migratory species in terms of their role in the food chain of the river systems or river reaches that could be impacted is assessed. Rivers flowing through protected areas and nature reserves (e.g. Kruger National Park), where a wide range of species (both terrestrial and aquatic) are dependent on healthy, viable fish and/or macrocrustacean populations as part of the food chain, would thus receive the highest score.

4.2.4 *Biological importance of upstream habitat to migrants*

The reasons for the upstream migrations of the biota are assessed in relation to the presence of suitable habitats upstream of the barrier. These upstream habitats could form vital components of the life history of the migrants present in the river reach in question, such as scarce spawning areas and rich larval or sub-adult feeding areas. Preventing access to these habitats could thus have significant negative impacts on the migratory species affected. The absence of these vital habitats in the river below the barrier (e.g. suitable spawning riffles often present only in the upper reaches or tributaries of a system) would also increase the ecological value of these habitats upstream of the barrier in question.

4.2.5 *Proportion of upstream habitat obstructed*

The proportion of the whole catchment of the particular stream lying upstream of the barrier, in terms of providing suitable habitat for the migratory species, is assessed. A barrier in the lower reaches of a river (i. e near estuary) will cut off relatively large areas of potential habitat upstream for catadromous (and potadromous) biota, compared to a barrier located in the upper reaches. Thus, sites located near the headwaters of a stream would normally have a lower score compared to sites located further downstream. However, the relative amount of the preferred habitat of each migratory species located upstream compared to downstream of the barrier, as well as the distances normally migrated, should be taken into account here.

4.2.6 *Condition of upstream habitat*

, Badly degraded reaches upstream of the barrier in question would be of little value to migrant populations, even if made accessible via a fishway. The Present Ecological State (PES) of the in-stream habitats in terms of suitability for the migrants (fish and macrocrustaceans) is thus assessed using the latest Resource Directed Measures (RDM) methodology (Kleynhans *et al.,* 2005). The resultant ecological categories (or management classes) are scored as indicated in Table 2-2.

The precautionary principle should be applied when the river upstream of the barrier is found to be badly degraded. Historical evidence of migrations within the river reach under consideration should be taken into account, as well as the feasibility of future rehabilitation of the upstream habitat for the migratory fish. Optimally, a habitat improvement program should be developed in conjunction with the provision of a fishway under these circumstances.

4.2.7 *Drown-out characteristics of the barrier*

The in-stream structure may become totally or partially inundated at high flows due to a relatively rapid increase in tailwater levels compared to water levels above the barrier. This reduction in head loss at the barrier during high flows may allow fish to swim over the structure, thus reducing its impact on migratory species. The natural frequency of occurrence of these high flows, which drown out the barrier, thus needs to be assessed and scored (see Table 2-2).

The drown-out characteristics of most in-stream structures are often difficult to assess without the relevant site-specific hydraulic and hydrological data and often a subjective, “best-guess evaluation” is necessary. If these data are not available, application of the “precautionary principle” is prudent and the structure should be assumed to be a barrier to migration at high flows as well as at low flows, unless evidence can be presented that proves otherwise.

4.2.8 *Feasibility of fishway construction*

Under certain conditions, the likelihood of the construction of an effective fishway at a particular site can be considered remote. For example, the barrier in question may be too high for a conventional fishway. In some cases the particular design or function of the barrier, the site topography, compulsory water releases (e.g. hydro-electricity generation), etc., may make the construction of a successful fishway very problematic and very expensive. Limited funds should preferably be spent at sites where the chances of constructing a successful fishway are high. Thus, an estimate of the likelihood or confidence of being able to construct an effective and successful fishway, is rated and scored as set out in Table 2-2.

4.2.9 *Cost-benefit analysis of fishway provision*

The costs of fishways are determined by aspects such the height of the barrier and size of migrants, as this influences the length, dimensions and design of the fishway. In addition, other important aspects influencing fishway costs include the geomorphology and topography of the site, maintenance and operational costs, etc. Thus an estimate of the costs of fishway construction should be undertaken and this expense related to the ecological benefits that should accrue if an effective fishway is constructed.

4.2.10 *Financial and other support*

The level of financial and other means of support from all Interested and Affected Parties (I&APs,) including the owner of the structure, relevant government departments, local angling clubs and non-government conservation organizations etc., should also be taken into account when assessing the priority for fishway construction. The involvement of interested members of the general public and special interest groups in assisting with fish surveys before construction, as well as future maintenance and monitoring of fishways is seen as an important and often neglected aspect of fishway provision in South Africa.

4.2.11 *Presence of existing barriers*

There is little value in providing a fishway on an in-stream barrier if there are already existing barriers (man-made or natural) in close proximity which are blocking migration within the river reach in question. However, the feasibility and likelihood of providing fish passage past any existing nearby man-made barriers (e.g. by provision of fishways or removal of the structures) in the future, should be taken into account. In addition, the distance from the nearest barriers (i.e. length of river still available to migrants) and the value of the habitats that will be made available if a fishway is constructed at the site under consideration should be assessed when scoring this criterion.

4.2.12 *Quantitative Assessment of Barrier Impact*

The assessment scheme or protocol to quantify the importance of providing a fishway at a particular barrier (Table 2-2) has been tested with some success in various parts of South Africa. However, this protocol should be seen as a working model that will probably be refined and modified with further use. These field trials highlighted the importance of having adequate information on the migratory biota and their life-history requirements, as well as detailed information on the value of aquatic habitats in the rivers within the study area. Unfortunately, in many regions of South Africa this information is lacking at present. This means that in many instances additional field assessments will be required to allow this assessment tool to be used with confidence.

It must be stressed that the proposed assessment protocol should be seen as a tool that can be used to assist in quantifying the importance of providing a fishway at any in-stream barrier in a standard and subjective manner. It is particularly valuable for ranking various barriers within a river catchment to assist in determining priority sites for fishway provision. However, the results obtained should be guided and modified by expert opinion, preferably by ecologists and engineers with local knowledge.

5 BIOLOGICAL CONSIDERATIONS FOR FISHWAY DESIGN

5.1 Introduction

This chapter is aimed at presenting guidelines to enable ecologist to provide engineers responsible for designing a fishway at a particular site, with all the relevant biological information required.

To be effective, fishways should be designed to provide hydraulic conditions within the fishway itself (i.e. maximum current velocities, turbulence values, etc.) suitable for the migratory species targeted. In terms of size, pool length needs to be at least two and a half times and the pool width twice the length of the largest fish to be catered for. The pools should also be large enough to ensure sufficient power dissipation and thus suitable turbulence levels.

In rivers where mass migrations occur, the fishway should be able to pass the numbers of fish expected to migrate without overcrowding. The size of the drop between pools (which determines the maximum current velocities and influences turbulence levels) is usually governed by the smallest and/or weakest-swimming migratory species in the river reach in question.

The swimming ability and behaviour of the migrants at each site will thus play a crucial role in determining the most appropriate fishway. The variety of fish species found in rivers in different regions of South Africa, as well as within different reaches of the same river, can vary considerably. This means that the swimming ability and migratory behaviour, as well as maximum size of the migratory aquatic species, can differ considerably from site to site.

Although swimming ability does vary considerably among different species, the swimming and jumping ability of a particular fish species is positively related to body length. Fishways designed to cater for small, weaker-swimming fish therefore need to have smaller drops between pools, as well a lower turbulence levels in the pools, compared to those for large fish.

It is thus essential to obtain details of the migratory species at each site before the fishway design process can begin.

In order to design a successful fishway, the following questions therefore need to be answered regarding the migratory species at the specific site in the river under consideration:

- Which migratory species must the fishway cater for?
- What size ranges must be catered for?
- What are the swimming/jumping/crawling abilities and migratory behaviour of the species to be passed?
- Under which flow conditions (i.e. high or low river discharges) do the natural migrations occur, i.e. for what range of river flows should the fishway be effective and will delays in migrations have significant negative impacts?

The following steps should generally be followed by an ecologist during a fishway assessment:

- **Species composition:** Determine the species composition (fish and other migratory aquatic biota) of the river reach or site of interest: This process could range from a desktop assessment using available distribution information to specialist field assessments (for data deficient areas).

The [1]SAMigratoryBiota database (database of available migratory information on South African Biota (Appendix B) can be used to determine a preliminary expected species list for a river system.

- **Is there a need for a fishway?:** Use the above information, together with data on migratory characteristics of the species to determine the necessity of a fishway at the specific site of interest (follow necessity protocol - Chapter 3). Refer to SAMigratoryBiota (Appendix B) and latest available information on conservation status, etc. required in this process. Determine site-specific conditions based on all available information and knowledge.

- **Priority of the fishway**: If various fishways or barriers are considered within the study area, the priority of fishway implementation between these sites can be determined using the priority protocol (see Chapter 4). This process will also quantify the ecological importance of providing a fishway at a particular site and justify the funds required in relation to the ecological and social benefits. Refer to SAMigratoryBiota (Appendix B) for information required in this process. Determine site-specific conditions based on all available information and knowledge.

- **Key species/groups to consider:** The key migratory species to consider, which will influence fishway design, should be identified during the necessity and priority protocol assessments and by referring to the SAMigratoryBiota Database. The choice of key species will be influenced by both socio-economic and biodiversity considerations, as discussed in earlier chapters.

- **Biological criteria:** Once the key migratory species have been identified for consideration in the fishway design, the following information should be gathered for each species (use SAMigratoryBiota excel-spreadsheet and any other information available):

  Size range of each species to be catered for. Of special importance is the size of the smaller fish (and/or weakest swimmers) and the larger fish to be considered, as this influences the hydraulic parameters required and the size of the pools, respectively. It is often ecologically acceptable to exclude both the very smallest and very largest fish, if this can significantly reduce construction costs (see Chapter 9).

  Swimming ability of each species within the designated size range to be catered for, using all available data sources, including the SAMigratoryBiota Database (Appendix B). Measured data on turbulence levels and current velocities negotiated during swimming trials using model fishways are only available for a few species. General recommendations are included in this report based on the best available data and expert opinion.

  Jumping ability of a species.

  Crawling and/or climbing ability of a species.

  Recommended hydraulic and design parameters and management guidelines.

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[1] Information on the migratory behaviour and abilities of South African fish and macrocrustacean species, as well as existing fishway types and designs known to pass various species, has been collated in a database (see Appendix B). This information were obtained from available literature, the on-going experimental fishway studies and fishway monitoring work, as well as information gleaned from fish experts throughout South African via a series of workshops. This information should ideally be consulted and applied by fish biologist during the planning and design process of fishways in South Africa. Season and flow conditions when the fish migrate

Use the above information to provide recommendations for the fishway design for consideration by the fishway design engineer:

Pool dimensions based on the maximum fish size to be considered – see above.

Maximum drop between pools / velocities / turbulence levels allowed in the fishway. This will be determined by the smallest or weakest migratory species to be considered.

Time period that the fishway must be functional (during which season and expected river flows must it function optimally).

Recommended fishway design(s) to consider (i.e. vertical slot, sloping baffle) based on known migratory behaviour and preferences of target species.

Details of a monitoring programme to determine efficiency of fishway.

Any other information that may be considered in the design and implementation of the fishway.

5.2 Types of Migration

Aquatic species undertake migrations for a variety of reasons, including movement to habitats suitable for spawning and larval rearing, to access suitable, rich nursery or feeding areas (good growth and high survival) and to seek refuge from unfavourable or harmful environmental conditions such as low water levels, extreme temperatures or an abundance of predators.

Migrations between various preferred aquatic habitats usually take place on a seasonal basis and are normally synchronised with the natural hydrology of the river to facilitate movement both up and downstream, and to utilize seasonally favourable habitats, as discussed further below. Smaller fish (e.g. juveniles and post-larvae) often undertake upstream migrations into suitable nursery or feeding habitats under suitable flows throughout the year, while adult fish undertake upstream spawning migrations during the summer months when the rivers are swollen after rains.

The various widely recognised types of migration that occur within aquatic habitats are given in Table 5-1.

5.3 Migratory Species to Consider in Fishway Assessments

The latest available fish and other migratory biota species distribution information should be applied to determine the specific migratory species to consider in a fishway assessment for a specific site. This process could range from a desktop assessment using available information to specialist field assessments (for data deficient areas). The SAMigratoryBiota database (Appendix B) summarises the most important aspects of the target species that need to be factored into the planning and design of a fishway. These include aspects such as the approximate size range of the migrants, their swimming, jumping and climbing ability, the reason for migrating (e.g. for spawning or feeding purposes) and the timing of the migrations in terms of season of the year and river flow during the peak migratory periods. This database can also be used to determine a preliminary expected species list for the river system under investigation

Table 5-1 Types of migratory aquatic biota in rivers in SA.

Terminology	Description / Definition
1. Potamodromous	Species whose entire life cycle is completed within freshwater and that undertake migrations within freshwater zones of rivers for a variety of reasons, such as for spawning, feeding, dispersion after spawning, colonisation after droughts, for over-wintering, etc.
2. Diadromous	A general term for species that migrate between fresh water and the sea or saline waters. Within this category, there are two forms of diadromy found in South African coastal rivers (see below).
2a. Catadromous	Diadromous species which spend most of their lives in fresh water and migrate to the sea (or estuaries) as adults to breed. The post-larvae and juveniles then migrate back to freshwater habitats. This term is used to include species a) which have an obligatory freshwater phase in their life cycle (obligatory catadromous) and b) which have a facultative habit of entering fresh water that is carried out by only a portion of the population (facultative catadromous)
2b. Amphidromous	Amphidromy includes diadromous species, which migrate both as adults and juveniles between fresh water and the sea (and visa versa) in an apparently haphazard way, but not for the purpose of breeding and that can spawn in fresh water or in saline water (the sea or estuaries).

5.4 Migratory Regions

As mentioned earlier, due to the large variety of fish species of varying sizes, migratory abilities and behaviour within various regions of South Africa, it is not considered feasible to recommend a single "one design fits all" fishway for the country. To assist planners to design the optimum fishway to suit particular local conditions, an attempt was made to demarcate various migratory regions within South Africa in terms of swimming behaviour and ability of the migratory biota found within these regions.

Available data on the migratory characteristics of the most important migratory species throughout South Africa were used in this attempt to demarcate migratory regions to facilitate decisions on fishway design. It was decided to consider coastal and inland regions separately, due to significant differences in species composition, as well as the size, migratory behaviour and reasons for migration of species in coastal rivers compared to inland rivers.

5.4.1 *Coastal Migratory Regions*

Catadromous species (both fish and macroinvertebrates) often form the bulk of the migratory species to be catered for in coastal fishways, particularly fishways built on barriers near the tidal influence of estuaries. These upstream migrations from estuaries are undertaken largely by post-larvae or juveniles for feeding and colonisation purposes, as discussed below.

There are at least 24 marine-spawning and estuarine-spawning fish species known to migrate (mainly as post-larvae and juveniles) into freshwater zones of rivers along the south and east coasts of South Africa (Bruton *et al.,* 1988). These diadromous species spend varying amounts of time in freshwater habitats in the lower river reaches, usually within 50 km of the top of the estuaries, which serve mainly as secondary nursery areas.

Only the four species of freshwater eels (*Anguilidae*) and possibly the freshwater mullet *Myxus capensis* (Bok, 1983), are thought to have an obligatory freshwater phase in their life cycle.

The other marine and estuarine species that migrate between fresh and estuarine reaches display varying degrees of dependence on freshwater habitats.

Of significance to the designs of fishways in these coastal rivers, is that these diadromous species are as small as 12 to 30 mm in length when migrating upstream and are thus relatively weak swimmers. This has a major influence on fishway design in these coastal rivers, as is discussed further below.

The more common diadromous fish species expected to use fishways on south and east coast rivers in South Africa are given in the SAMigratoryBiota database (Appendix B).

There are at least nine species of macrocrustacea (freshwater prawns and crabs) that are known to migrate between the sea or estuary and freshwater reaches of rivers along the east and south-east coasts of South Africa (Bickerton, 1989; Cyrus and Wepener, 1997; Coetzee, 1991). A list of these macrocrustacean species and a summary of their known migratory characteristics is given in the SAMigratoryBiota database (Appendix B).

In terms of swimming behaviour and ability of the migratory biota present, the South African coastal rivers could be broadly divided into two Migratory Regions, depending on the presence of climbing species (eels, prawns and crabs), as indicated in Table 5-2.

The South-East Coast Migratory Region could justifiably be divided into 2 sub-regions, with the Great Fish or Keiskamma River being the common boundary, in order to separate the sub-tropical from the more temperate species. However, in terms of our present knowledge of the swimming behaviour and ability of the main migratory biota, this additional subdivision will serve little purpose in terms of fishway design.

Table 5-2 The two coastal migratory regions in South Africa according to migratory behaviour and swimming ability of migratory biota present.

Migratory - region	Spatial Description	Main Migratory Species (known at present)
1. South-East and South Coast	Mozambique to Palmiet River	A larger variety of climbing species such a numerous macrocrustaceans and eels, as well as many catadromous and amphidromous fish such as mullet (Mugilidae), Monodactylidae, etc.,
2. West Coast	Palmiet River to Orange River	Two catadromous mullet species, *Mugil cephalus* and *Liza richardsoni*, no crawling species present that need to be accommodated

The absence of climbing biota on the West Coast has a major influence on fishway type and design. In terms of fish size and swimming ability, parameters used to determine minimum pool size, and the upper turbulence and velocity values within the fishway, the coastal rivers can be split into two groups. These are:

- **Group A:** Very small fish from 25 to 40 mm, restricted to within about 50 m from the tidal limit of estuaries, and
- **Group B**: Small to medium sized fish of 40 to 100 mm (and larger), located from about 50 to 120 km inland of the tidal limit of estuaries, comprising moderate to strong swimmers.

Table 5-3 Inland migratory regions and the main migratory groups and species.

Migratory region	Primary Rivers	Main Migratory groups	Key Migratory Species
Orange-Vaal region	Main stem and tributaries of the Vaal- and Orange River	Potamodromous species of the genera *Labeobarbus*, *Labeo* and *Barbus*.	*Labeobarbus aeneus, Labeobarbus kimberleyensis, Labeo capensis, Labeo umbratus, B. paludinosus* and *B. trimaculatus.*
Upper Limpopo region	Upper Limpopo River, Crocodile River West, Marico River, Lephalala River, Mokolo River, Mogalakwena River.	The catadromous eel, *Anguilla mossambica* and various potamodromous species, most importantly from the genera *Labeobarbus*, *Barbus* and *Labeo*.	*Anguilla mossambica,* various *Barbus* species*, Labeobarbus polylepis, Labeobarbus marequensis, Labeo rosae, Labeo ruddi, Labeo cylindricus, Labeo molybdinus* and *Mesobola brevianalis.*
Lower Limpopo, Incomati and Pongola region	Lower Limpopo River, Luvuvhu River, Letaba, Shingwedzi, Olifants, Komati River, Crocodile East, Sabie-Sand River, Pongola River, Usuthu River.	The catadromous eels of the Anguilla family, and the catadromous macro crustaceans of the genus *Macrobrachium*. Also various potamodromous species, most importantly from the genera *Hydrocynus*, *Labeobarbus*, *Barbus* and *Labeo*.	*Anguilla mossambica, A. marmorata, A. bengalensis labiata, A. bicolor bicolor, Hydrocynus vittatus Labeobarbus marequensis,* various *Barbus species, Labeobarbus marequensis, Labeobarbus polylepis Labeo rosae, L. ruddi, L. congoro, L. cylindricus, L. molybdinus, Chiloglanis anoterus, Chiloglanis swierstrae* and *Macrobrachium macro* crustaceans.
KZN inland region	Mkuze River, Tugela River, Umfolozi River, Umtamvuna River. Mzimvubu River.	The catadromous eels of the Anguilla family and potamodromous species of the genera *Labeobarbus* and *Labeo*.	*Anguilla mossambica, A. marmorata, A. bengalensis labiata, A. bicolor bicolor, Labeobarbus natalensis, Labeo rubromaculatus*
Cape inland region	Doorn River, Kromme River, Gamtoos River, Gouritz River, Kiekama River, Buffels River.	*Barbus, Labeo* and *Pseudobarbus* species	*Barbus amatolicus, Barbus andrewi, B. erubescens, B. serra, B. trevelyani, Labeo seeberi,* various *Pseudobarbus* species, *Sandelia bainsii*

As discussed below, the relative sizes of fish within these two groups from coastal rivers are factored into the fishway designs to ensure they have hydraulic parameters (maximum velocities and turbulence) suited to their differing swimming abilities.

5.4.2 *Inland Migratory Regions*

The bulk of the inland migratory species are from the potamodromous migratory groups with some catadromous species (mainly eels and freshwater prawns) also present in some areas. Adults of various species undertake spawning or reproductive migrations during high or receding flows, while sub-adults and juveniles often attempt to recolonise and disperse under these conditions. Various species furthermore migrate throughout the year with the aim of dispersal, feeding and avoidance of unfavourable conditions. The most important and widespread potamodromous migratory species in the inland rivers are from the families Cypriniidae (genera *Labeobarbus*, *Barbus, Labeo and Mesobola*) and Characidae (genera *Hydrocynus, Micralestes* and *Brycinus*). The catadromous freshwater eels (*Anguilidae)* and some *Macrobrachium* species (freshwater prawns) also inhabit the inland river systems of South Africa, and should be considered in fishway designs for inland rivers.

Table 5-3 provides an indication of inland rivers with similar migratory groups or species and can be used as a rough estimate of the species to be considered in general when a fishway is designed for a river within this migratory region. It must be emphasised that the species composition will however vary to some extent within a migratory region. The important migratory biota in headwater streams or tributaries may be different from those to be considered in the middle or lower reaches. A specialist investigation should therefore always be done to determine the specific species to consider for a certain site or reach of concern during the planning and design of a specific fishway.

5.5 Timing and Importance of Migrations

In terms of appropriate fishway design, the migratory periods of the target species should also be considered in relation to the natural hydrological cycle of the river. This aspect is of particular importance in South African rivers, as river flows usually vary considerably between the wet and dry seasons. The fishway should be designed to operate effectively over the time period and range of river flows likely to occur when the different biota in the river normally undertake their upstream migrations.

The reasons for the fish undertaking migration can also determine whether delays at a particular barrier will have serious negative impacts. For example, adult spawning migrations of fish are often timed to coincide with floods and high flows during the summer months, as only at these times are suitable habitats and optimum conditions for spawning, egg incubation and larval rearing available. In particular, these spawning migrations coincide with high river levels to allow fish to deposit fertilized eggs in an environment suitable for incubation. These preferred sites, such as upstream silt-free riffles or clean vegetation, are only inundated at high flows. These high-flow conditions usually persist for short periods only, i.e. for days rather than weeks. Thus, if these upstream spawning migrations are delayed for too long because a fishway is ineffective at high flows, spawning success could be compromised.

The upstream trophic migrations of juvenile fish, on the other hand (including catadromous fish of marine or estuarine origin) are for dispersal into favourable nursery areas. These migrations usually take place over extended periods in both summer and winter. Thus a delay of a several days or even weeks during floods or high river flow conditions should not have a serious negative impact. Fishways that target these species are therefore not required to operate effectively during short periods of high river flow. This could significantly reduce fishway costs, as providing a fishway to operate effectively at both high and low flows can be problematic and relatively expensive.

The requirement for a fishway to function over a wide range of river flows could therefore have a major influence on the choice of fishway type and design, as well as the size and cost of the structure (see Chapter 6 “Design Process”)

The most recent data on the timing of migrations in relation to the hydrological cycle for various species in rivers in various parts of southern Africa are given in the SAMigratoryBiota database (Appendix B). There are large gaps in our present knowledge, particularly regarding the timing and importance of the migrations of juvenile and sub-adult fish. It is anticipated that ongoing research on fish migrations and monitoring of existing fishways in various parts of the country, will throw more light on the timing of these fish movements.

5.6 Swimming Ability

The following aspects reflect the fishes’ swimming ability with regards to fishways.

5.6.1 *Speed and Endurance*

One of the most important factors influencing fishway design is the swimming ability of the migratory fish in terms of speed and endurance. Swimming speeds in fish are commonly classified into three categories (Beach 1984), namely:

- “sustained” – the speed which can be maintained for 200 minutes and longer,
- “prolonged” –the speed which can be maintained for between 15 seconds to 200 minutes, and which results in fatigue if continued, and
- “burst” – the speed which is the maximum a fish can maintain for up to 15 seconds.

5.6.2 *Physiological Factors*

The latter two swimming speeds are of relevance for fishway design. Burst speeds employ the white or anaerobic muscle. These muscles contract rapidly in the absence of oxygen and become exhausted when all the glycogen stores are converted into lactic acid and thus require a recovery period before further use. During prolonged speeds red (aerobic) muscles are employed. As this muscle contracts only when oxygen is readily available to the cells, low dissolved oxygen levels can have a significant negative effect on prolonged swimming ability. Water temperature can also have a profound impact on swimming performance and adverse temperatures (either too low or too high) can reduce performance by 50 per cent (Bell, 1986).

There is a direct correlation between absolute swimming speed and body length for a particular species. Thus larger fish can attain much higher swimming speeds than smaller fish. In addition, the swimming speed of a fish is closely related to its tail beat frequency. Research has shown that the distance moved during each body wave is about 0.7 of the fish length (Beach, 1984). However, it has also been shown that the twitch contraction time for the lateral swimming muscle is short for small fish and increases with fish length (Wardle, 1975 vide Beach, 1984). Thus, in relative terms, small fish can swim faster than larger fish, if swimming speed is measured in terms of body lengths per second (BL/s).

5.6.3 *Relevance to Fishway Design*

Prolonged speed is used when fish swim through long fishways. It is thus important that there are resting areas within the fishway with velocities below the prolonged speed of the migrating fish. As burst speed is considered equivalent to the maximum speed a fish can attain, it obviously influences the desired internal hydraulics within the fishway. For the fishway to be negotiable for the full size range of all the migratory species, the maximum velocity in critical areas of the fishway (such as over weir crests, through the weir notches or slots) should be less than the burst speed of the weakest swimmer. In addition, fish using burst speeds to negotiate fishways require quiet water with high dissolved oxygen levels in order to recover and replenish their glycogen stores.

The maximum velocity in a fishway is a function of the drop between the pools for both vertical slot fishways and pool and weir fishways. The allowable height of the drop is therefore a function of the swimming ability of the weakest swimmers that must utilize the fishway. The turbulence (Pv) in the pools is expressed as the power per unit volume in the pool in watt/$m^{3.}$ The parameters influencing the turbulence levels are therefore the product of drop between the pools and the flow rate, which describes the power of the flowing water (in watts), divided by the volume of water in the pool (in m^3).

The primary information regarding the swimming abilities of the key migratory species required by an engineer for the design of a fishway thus includes the following:

- Maximum allowable velocities within fishway (based on swimming speeds of fish).
- Maximum allowable drop between pools.
- Maximum allowable turbulence levels within fishway.

5.7 Swimming Speed

5.7.1 *International Studies on swimming speed*

The swimming performances of a variety of fish species found in the literature show that although large fish can swim much faster (up to 8 m/s for adult trout), small fish can swim much faster in terms of body length per second. Maximum swimming speeds are given in the region of 10 - 12 BL/s for large adult fish (Osborn and Powers, 1985; Bell, 1986) and from about 12 to 20 BL/s for fish less than 50 mm (Rulifson, 1977; Bell, 1986).

The data from international studies are largely based on maximum speeds obtained by fish in experimental swimming flumes and may be an under-estimate of potential short-term burst speeds. Data from Australia (Mallen-Cooper, 1992), as well as from this study, using fish swimming through model fishways, have recorded substantially higher maximum fish swimming speeds. As suggested by Mallen-Cooper (1992), this is probably because experimental studies of burst speeds in flumes are usually recorded for longer periods than the 1 to 2 seconds of burst speed needed for the fish to swim over the weirs or through vertical slots in a fishway.

Burst speeds recorded on Australian Bass (*Macquaria movemaculeata*) were found by Mallen-Cooper (1992) to vary from 20 to 25 BL/s for fish of 40 to 93 mm in size.

The increase in swimming ability with size of the fish has important implications for fishway design and thus ultimately the cost of fishway construction.

Thus, if a fishway is designed for only large fish species, their ability to negotiate higher water velocities (larger drops) would allow a steeper and thus shorter and cheaper fishway to be constructed. Similarly, steep fishways with small drops and small pools can be constructed if only small fish are considered.

For example, Mallen-Cooper (1992) showed that fishways near the coast in South East Australia need to cater for 40 mm catadromous bass. This size class was shown to have a NV95 of 1.0 m/s (i.e. 95% of fish could negotiate this velocity). Fishways 100 km upstream from the estuarine spawning grounds of the bass need to cater for larger 64 mm bass, which have an NV95 of 1.4 m/s. The increased swimming speed of the larger fish allows the inland fishway to be twice as steep, half the length and close to half the cost.

5.7.2 *South African studies on swimming speed*

Experimental data on the swimming ability of South African fish species are not readily available and existing results are highly variable. However, estimations of swimming ability obtained using fishway monitoring data, as well as from experimental swimming trials using model fishways, are given below. The burst speeds of the fish are taken as at least equal to the water velocity passing through the critical areas in the fishways that the fish were able to successfully negotiate. These values are therefore a baseline indication of velocities successfully negotiated and may not reflect the upper limits of each fish species. These data can, however, be used as a guide to estimate the swimming abilities of these and other similar species.

Trials with coastal species indicate that catadromous freshwater mullet (*Myxus capensis*) of 25 mm can swim at up to 50 BL/s and 50 mm mullet at over 30 BL/s, while Cape Moony (*Mondadactylus falcifirmis* of 50 mm in length can swim at over 30 BL/s through fishway baffles. Most of the inland fish species tested using a vertical slot design model fishway indicated average burst speeds ranging between 1.1 and 1.8 m/s. These trials also showed that presumably weak-swimming species such as juvenile *Oreochromis mossambicus* and *Pseudocrenilabrus philander* could attain burst speeds as high as 2.17 m/s (43BL/s) and 2.00 m/s (50BL/s) respectively, over short distances

However, as these estimated swimming speeds are high in comparison with international findings (see above), a precautionary approach is used to ensure fishways allow the smallest and hence weakest swimmers to pass through “without undue stress“. The estimated swimming speeds given above are thus treated as the maximum and lower values are recommended for fishway design.

5.8 Turbulence

Using the mean or maximum theoretical current velocity in a fishway in relation to swimming ability of the migrants as the only criteria for determining fishway design is not recommended. This is particularly true when there are a range of velocities present within the fishway and when turbulence levels are high (Larinier 2002b). Fish are very capable of detecting slight variations in water velocities and exploit the most favourable zones to negotiate high velocity areas. Small fish are particularly adept at using the lower velocities in the boundary layers near the walls and bottom of a fishway and also to rest in recirculating flows created by eddies.

An increase in the level of aeration and turbulence in the pools increases the difficulty for fish passage through a fishway. Where turbulence levels are high, swimming efficiency may drop significantly, and fish will have to expend considerably more energy to in order to attain comparable swimming speeds reached in quiet water (Larnier 2002b).

Thus, the maximum turbulence level within a fishway is often used as the main criteria to determine the suitability of the internal hydraulics for fishway passage.

Turbulence levels are quantified by the power dissipated per unit pool volume (Pv) and is directly related to the discharge, the head difference between pools (drop) and the volume of water in each pool - see Chapter 6 for the formula to calculate the Pv. Calculation of the turbulence levels within the pools of a fishway therefore also enables the minimum volume of water in the pools (i.e. pool size) to be determined. Thus the size of the target fish species, as well as the hydraulic conditions within the fishway (particular the volumetric dissipated power, or turbulence), should be used to determine the minimum dimensions of the fishway pools.

According to Lariner (2002), the maximum volumetric dissipated power for large salmon and sea trout is 200 watts/m^3, while levels of less than 150 watts/m^3 are advised for fishways designed for small fish and for relatively poor swimmers. As shown below, the South African fish species found migrating through existing fishways, as well as the species used in model fishway trials, appear to be capable of negotiating turbulence levels much higher that those recommended in the literature.

5.8.1 *South African Studies on turbulence levels and drop between pools*

The generally applicable maximum turbulence levels in pools recommended for South African fishway are given in Table 5-4 for coastal species and Table 5-5 for inland species.

The field trials with model fishways (both vertical slot and sloping baffle designs) on the Kowie River with catadromous fish species showed that both freshwater mullet and Cape moonies under 60mm in length were able to negotiate the fishways with turbulence levels in the pools of over 250 watts/m^3. However, high turbulence levels may become increasing stressful in long fishways when fatigue becomes important. Thus, as a precautionary measure, considerably lower levels are recommended when considering fishway design - see below.

Maximum turbulence levels and drop between pools successfully negotiated by the inland test species under experimental conditions ranged from 229 watt/m^3 and 89 mm (*Oreochromis mossambicus*) to 620 watt/m^3 and 163 mm, respectively (*Barbus radiatus*, *B. trimaculatus, Chiloglanis engiops, Labeo molybdinus, Mesobola brevianalis* and *Opsaridium peringueyi*). Refer to SAMigratoryBiota database (Appendix B) for more information on recommended turbulence levels, drop between pools and velocities for selected migratory species.

In spite of these trials showing fish can negotiate very high turbulence levels of well over 400 watts/m^3 in some instances, it is thought prudent to adopt a conservative approach when recommending optimum turbulence levels during the fishway design process, as discussed further below.

5.9 Recommended Maximum Current Velocities and Turbulence Levels

During the initial planning and design phase of a fishway, funding and/or engineering constraints may mean that in terms of the optimum design and dimensions, cutbacks and compromises may have to be made.

5.9.1 *Coastal Fishways*

When designing fishways at barriers near the tidal limit of estuaries, the size of the fish attempting to migrate upstream to inland nursery areas could vary from 10 mm to 200 mm.

Field studies have shown that fish of 10 to 25 mm in length are easily injured and are relatively weak swimmers, and require fishways with very low turbulence and low maximum current velocities. This translates into very long and expensive fishways. As a delay in the migration of these very small fish of one or two months to allow growth is ecologically acceptable, a fishway designed for fish over 25 to 30 mm in length would be the best practical option at most sites.

As juvenile catadromous fish migrate upstream away from the estuary, their size and swimming ability increase. They are thus able to negotiate fishways with higher maximum velocities and turbulence levels. Most fish over 50 km from the estuary would be longer than 40 mm in length.

For the purpose of setting guidelines for fishway design, the term "coastal rivers" includes those reaches of a river within about 120 km of the tidal limit. The recommended internal hydraulic parameters for fishways on these coastal rivers are given in Table 5-4.

The calculated average velocity in the above table can be considered high in relation to the swimming ability of the small fish, with the 25 mm fish expected to swim at 48 BL/s. However, these small fish have a natural ability to exploit the range of flows that exist at these critical areas in the fishway and can use lower velocity areas near the bottom (e.g. among rocks) and against the sides of the fishway, to negotiate these high velocity areas.

Table 5-4 Maximum values of hydraulic parameters recommended for fishways designed for coastal fishways.

Target species and size range	Maximum Turbulence (Watts/m^3)	Maximum drop between pools (mm)	Maximum water velocity (m/s)
Very small catadromous fish (25 – 40 mm) within 50 km of the estuary	150	75	1.2
Small fish, including catadromous species and other (> 40 mm) and weak swimmers, 50 to 120 km from the estuary	180	100	1.4

5.9.2 *Inland Fishways*

In terms of suitable internal hydraulics for a wide range of fish sizes using a fishway, if the current velocities over critical areas (through slots and over pool weirs) and turbulence levels are negotiable by the smaller fish, the fishway should be suitable for larger species. As mentioned above, a further proviso is that the pools should be large enough to cater for the biggest fish targeted.

In this regard, when designing a fishway to cater for adult spawning migrations, it may be ecologically acceptable to size the fishway pools to cater for the majority of the breeding population, while excluding the few very large individuals present.

The smaller pool size could reduce construction costs considerably, while not having a significantly negative impact on the breeding success of the population.

The recommended turbulence levels for inland fish species are between 150 and 220 watt/m^3, depending on the size of the smallest or swimming ability of the "weakest swimming" key migratory species (Table 5-5).

Recommended maximum drops between pools for inland fishways should range ideally between 100 and 200 mm, and maximum velocities should range between 1.4 and 2.0 m/s, depending on the abilities of the key migratory species (as mentioned above) (Table 5-5). These values should be considered as general guidelines for use in the design of inland fishways. The hydraulic parameters of each fishway should however be optimised using the available information on the migratory abilities and behaviour of the key species (Refer to SAMigratoryBiota database for further information regarding recommended turbulences, velocities and drop between pools for specific indigenous fish species - Appendix B).

Table 5-5 General guidelines of hydraulic parameters recommended for fishways designed for inland fishways.

Target species and size range	Maximum Turbulence (Watts/m^3)	Maximum drop between pools (mm)	Maximum water velocity (m/s)
Very small fish (<40 mm) and/or weak swimmers (1*)	150	100	1.4
Small to medium sized fish (40 - 100 mm) and/or moderate swimmers (3*)	180	150	1.7
Large sized fish (>100 mm) and/or strong swimmers (5*)	220	200	2.0

Where:

*Perceived swimming ability rating (SAMigratoryBiota database), 1=weak swimmer, 3=moderate swimmer, 5=strong swimmer.

5.10 Swimming Behaviour and Preferences

5.10.1 *Small fish (under 150mm in length)*

Observations in the field show that the juveniles of catadromous fish species (e.g. freshwater mullet, *Myxus capensis,* and Cape Moony, *Mondactylus falciformis*) prefer to wriggle over a natural in-stream barrier in shallow water, rather than jump. In addition, monitoring of pool and weir fishways with wide, downstream-sloping weirs and adherent nappe, has shown that many species of small fish can use "burst" swimming to swim through the nappe to the upstream pool. This behaviour has been observed in both inland and coastal fishways for a variety of fish species when under about 120 - 150 mm in length.

Observations of potamodromous species in the field have indicated that many species also jump when a barrier is encountered. Many *Cyprinid* species have been observed to be actively jumping over (or attempting to) barriers (e.g. *Barbus spp*). This has been true for both small and larger species. It has also been observed that the vast majority of species utilise their special adaptations for their primary means of attempting to negotiate difficult barriers within a system, i.e. mouth adaptations in *Chiloglanis spp*. that use their sucker-like mouths maintain their position within their natural environment (amongst rocks in fast-flowing waters). These fish have been observed to utilise their sucker-like mouths to maintain adherence to vertical rock surfaces when negotiating barriers with minimal water coverage as well as at times of fast flowing waters. Species with sub-terminal mouths (e.g. *Labeo spp*.) also utilise this adaptation to adhere to solid surfaces when negotiating difficult barriers. This is especially true when they are juveniles. These species are often observed clinging by means of their sub-terminal mouths to the substrate in high velocity currents below a barrier. A final swimming burst or jump is then often utilised to negotiate the remainder of the obstacle.

5.10.2 *Large fish (over 150 mm in length)*

The majority of the larger fish species in South Africa, such as the large Cyprinids (*Barbus, Labeos* and *Labeobarbus* species) are known to leap out of the water to pass over in-stream structures such as weirs. However, these species, as well as the bottom dwelling Clariids (e.g. Sharptooth Catfish, *Clarias gariepinus*) also negotiate wide, downstream sloping weirs by swimming in the adherent nappe, provided there is sufficient depth. In particular, species that are considered to have limited jumping abilities (e.g. *Austroglanis sclateri* and *Marcusenius macrolepidotus*) have been shown to utilise swimming abilities exclusively rather than relying on jumping abilities when negotiating a barrier. Laboratory experimentation has also confirmed these findings. The data gathered to date do, indeed, confirm that the majority of fish species (with a few exceptions) are opportunistic in choosing which method to utilise when negotiating barriers. Swimming, as opposed to jumping, seems to be the method attempted initially; then, failing this, jumping over the barrier is attempted. Potential reasons for this are that jumping requires more energy than swimming, and jumping also makes the fish more vulnerable to predation.

5.10.3 *Anguillid eels*

The leptocephalus larvae of the four marine-spawning South African *Anguillid* eel species metamorphose into glass eels of 40 - 60 mm in length once they enter the estuaries along the east and south coast (Bruton, Bok and Davies 1987). Both glass eels and the older pigmented elvers then migrate upstream from the estuarine environment into freshwater, with peak migrations taking place in mid-summer when the rivers are flowing strongly.

Eels cannot jump out of the water and vertical steps greater than 60% of the body length form impassable obstacles (Knight and White 1998). According to Porcher (2002), the maximum burst speed of elvers varies from 0.60 m/s to 0.9m/s. Thus vertical drops in water surfaces of only a few centimetres in height, such as found at a low, sharp-crested gauging weir, can totally block upstream eel migrations.

However, eels have a remarkable ability to overcome barriers to migration by leaving the water and climbing along the edge of the main river stream. Glass eels, elvers and juvenile eels under about 120 mm long can climb up rough, damp, almost vertical surfaces by using surface tension effects. The snake-like swimming movements allow an eel to lever its body against the surface irregularities or vegetation in order to climb efficiently. A fishway designed to accommodate the crawling behaviour of macrocrustaceans (see 5.10.4) should thus also be suitable for eels.

5.10.4 *Macrocrustaceans*

Machrobrachium prawns, as well as megalopa larvae of the freshwater crab (*Varuna litterata*) (Bok unpubl. data), migrate upstream (usually at night) in shallow areas at the edge of the current. When encountering an in-stream barrier (e.g. natural waterfall or man-made weir) they prefer to leave the water and crawl over or round an obstruction in the wetted area (splash zone) on the edge of the main flow.

Provided the climbing surface is rough and damp, the young prawns and crabs can climb almost vertical surfaces of over 2-3 m high in their upstream migrations. Fishways designed for barriers near the coast need to cater for this behaviour.

The only formal fishway design that to date has been shown to pass both elvers and macro-crustaceans is the “sloping weir” pool and weir fishway, such as on the Nhlabane Weir (Heath *et al.*, 2005 - see Plates 6-2 and 6-7), which has a sloping, wetted perimeter on the weirs at suitable flows. This fishway type is thus recommended at this stage for coastal rivers, unless a dedicated eelway/prawnway, such as a roughened, sloping channel or rock-ramp with shallow water flows and a “splash- zone”, can be constructed in addition to a more formal fishway. A typical natural type eelway/prawnway, as built on a low weir in the Nqabara River, is shown in Plate 6-6.

5.11 Choosing the most suitable fishway type

It must be emphasised that the best fishway type for a particular site is dependent on a range of biological, hydrological and engineering factors. It is important that the engineers and biologists are aware of the various constraints involved and reach agreement on the most practical, cost-effective and functional fishway to suit the specific conditions at each site.

Once the need for and the importance of providing a fishway at the site has been established, the steps to be followed for choosing the optimum fishway type to construct at any barrier, are given in Figure 5-1. As a general rule, the “natural type” bypass canal or fish ramp (Plate 6-12 to 6-17) should always be the first fishway to consider. Pre-barrages using natural rock formations, with or without notches, are also a preferred design for consideration. If it is not possible to construct a “natural type” fishway, then the merits of the other more formal designs should be assessed for each situation.

Details of the factors to be considered when choosing and designing a fishway are discussed in Chapter 6 and working examples of the process explored in Chapters 7 and 9.

5.12 Summary

The concept of a “one design fits all” fishway, which is guaranteed to be effective in different localities for a variety of species, is not considered realistic. As outlined in this chapter, both the design and size of each fishway will be largely determined by the swimming abilities and behaviour of the target migratory species present, as well as the hydrology in the river reach in question. The most important biological information required by engineers to facilitate fishway design include a list of which migratory species and what size ranges to consider, the swimming/jumping/crawling abilities and migratory behaviour of the target species, and the river flow conditions when their natural migrations occur. The steps outlined in the introduction of this chapter should ideally be followed by an ecologist during the environmental impact assessment process when appropriate studies to determine the necessity for and importance of providing a fishway at the site in question, should be undertaken.

Key migratory species generally differ to some extent between coastal and inland systems. Within these two systems there are differences in key migratory species for specific migratory regions. In terms of appropriate fishway design, the migratory periods of the target species should be considered in relation to the natural hydrological cycle of the river. This aspect is of particular importance in South African rivers, as river flows usually vary considerably between the wet and dry seasons.

The fishway should be designed to operate effectively over the time period and range of river flows likely to occur when the different biota in the river normally undertake their upstream migrations.

One of the most important factors influencing fishway design is the swimming ability of the migratory fish in terms of speed and endurance. Experimental data on the swimming ability of South African fish species are not readily available. However, estimations of swimming ability have been obtained using existing fishway monitoring data, as well as from experimental swimming trials using model fishways.

Maximum values of allowable turbulence levels, drops between pools and velocities have been recommended in this chapter for certain groups of fish, based on their size and/or swimming abilities. These values should be considered as general guidelines for use in the design of fishways. The hydraulic parameters of each fishway should, however, be optimised using the available information on the migratory abilities and behaviour of the key species found at the site.

It is furthermore emphasised that the best fishway type for a particular site is dependent on a range of biological, hydrological and engineering factors. It is important that the engineers and biologists are aware of the various constraints involved and reach agreement on the most practical, cost-effective and functional fishway to suit the specific conditions at each site. The importance of a multidisciplinary approach to fishway planning and design cannot be over-emphasised. The provision of a successful fishway therefore requires the close collaboration of fish biologists and hydrologists, as well as hydraulic and civil engineers.

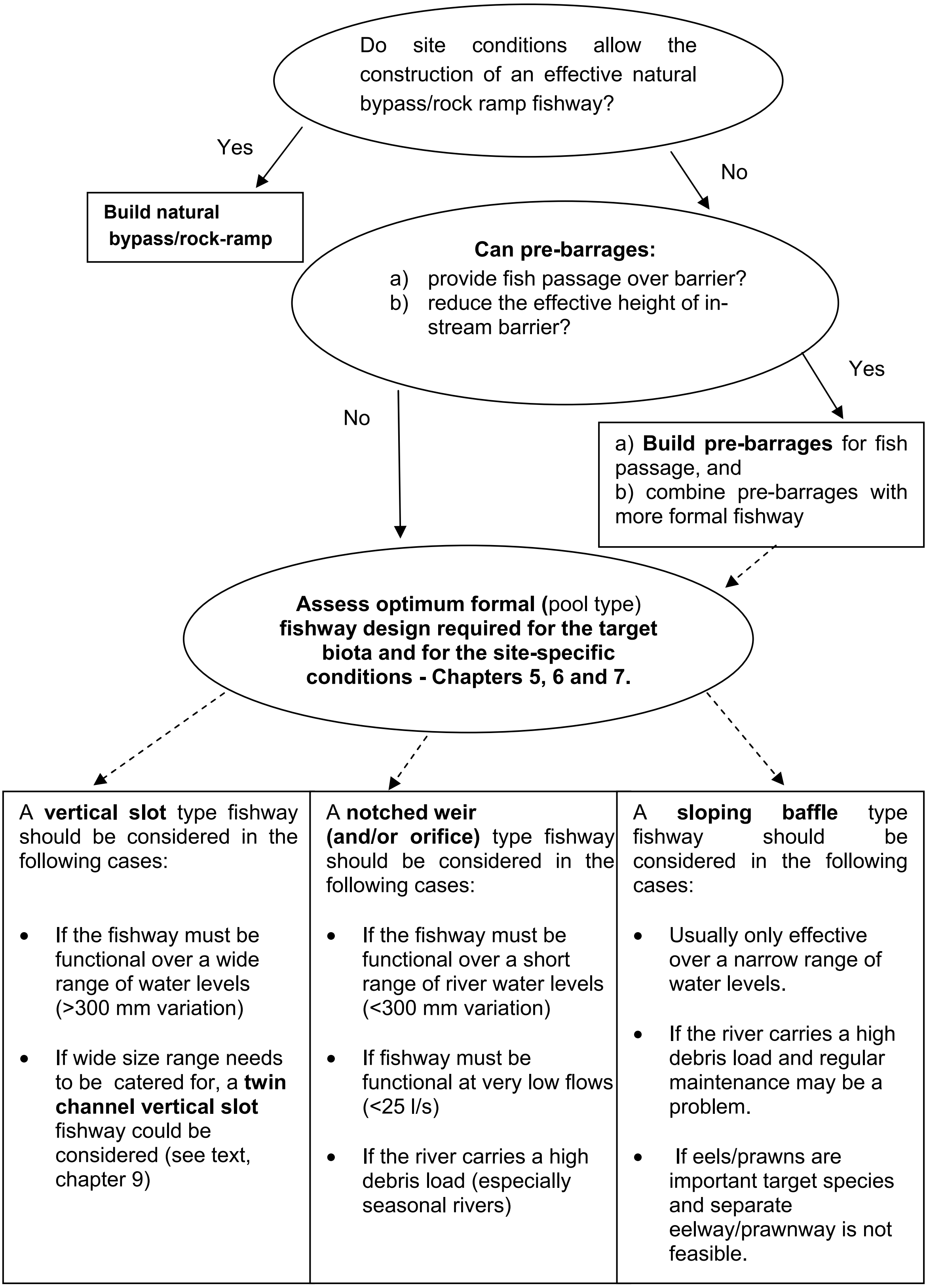

Figure 5-1 Flow diagramme outlining general procedures for choosing the optimum fishway type at all barriers

6 DESIGN PROCESS

6.1 Introduction

The design process can be summarized as follows:

- Assess the hydraulic and design parameters recommended for the proposed fishway by the ecological studies of the migratory species expected at the river reach under consideration (see Chapter 5), in terms of site-specific engineering and/or budget constraints.
- Establish under which flow conditions and periods during the year the natural migrations of the targeted biota are anticipated to take place at the site.
- Do a hydrological study to determine the flow conditions at the site.
- Do an analysis of the barrier hydraulics to translate the flow conditions to water levels up-and downstream of the barrier.
- Select a suitable location for the fishway. The positioning of the entrance for the fishway (i.e. downstream end) is one of the most important aspects of the design and will have a large influence on the success of the fishway.
- Select the type of fishways that can be considered at the site. The choice of fishway is dependant on the terrain, foundation conditions, variation in water levels at the site, preferences and migratory behaviour of target species, etc. Normally a fishway that allows for migration over a wide range of flow condition is preferred.
- Use the flow diagramme given in Figure 5-1 to assist in the process of selecting the optimum type of fishway design. If the site is not suitable for the preferred choice of a natural-like rock ramp or bypass channel, the relative merits of the vertical slot and pool and weir fishway types should be assessed.
- Modify, if necessary, the fishway dimensions recommended in the ecological study (see Chapter 5), such as the drop between the pools and the dimensions of the pools (length, width and depth). These dimensions will be determined by the swimming abilities of the weaker swimmers to be catered for and the length of the largest fish that need to be catered for. The ecological impact of excluding very weak swimmers and very large fish in order to reduce fishway costs should be assessed with input from ecologists.
- Do the hydraulic analysis of the selected fishway types to determine the velocities and turbulence associated with different water levels at the barrier. The hydraulics will be dominated by the selection of the drop between the pools, how these pools are created i.e. by weirs, slots, etc. and the size of the pools.
- From the hydrological analysis and the fishway hydraulics, determine the relative usability of the fishway during the migration season. This analysis is then used to select a suitable fishway design.
- Pay special attention to the design of the fish entrance to the fishway. The placing of this entrance is one of the most crucial aspects in the design. There should also be sufficient flow out of the fishway to attract fish to the entrance.

- The design of the water intake is also crucial. Pay special attention to aspects such as the safety with which the fish can exit on their way up the river. Debris is also a major problem and the use of debris deflectors to prevent blockage of the fishway should be considered.
- Allow for the monitoring of the fishway in the design. Removable fish traps at the exit and easy access to the fishway during migration, are minimum requirements to be able to establish whether the fishway is functioning properly.
- Allow for maintenance of the fishway. This includes removal of debris that may collect upstream and in the fishway.

Each of the above aspects will be elaborated upon in the following sections.

6.2 Selection of species for which the fishway should be designed

Before the design of the fishway is attempted, it is assumed that the necessity protocol has been completed (see Chapter 3) and the need for a fishway has been established. If applicable the priority protocol (see Chapter 4) has also been done and the relative importance of providing a fishway has been established.

From these two protocols the following have been established:

- The fish species which should be catered for in the design
- The season or flow condition during which migration of the various species can be expected.
- The swimming ability of the weakest swimmers which should be allowed for in the design. This should preferably be expressed in terms of drop between the pools (which determines the maximum velocity in the fishway) and the allowable turbulence level in the pools.
- The maximum size of the fish that should be catered for. This will determine the minimum size of the pools that will be acceptable.
- The need to provide for creeping or crawling species as these biota require specific hydraulic conditions (see Chapter 5).

The above information is normally gathered by ecologists doing the EIA for the proposed or existing barrier to fish migration

6.3 Hydrological studies

Engineering hydrology is concerned with the quantitative relationship between precipitation and runoff. The time-dependent variation in runoff is an important design parameter in the planning and design of fishways. Fish migrations are often seasonal and may be triggered by an increase in river flows, together with other factors such as changes in water temperatures, water chemistry and photoperiod (relative lengths of day and night). A number of species are known to migrate upstream to spawn under high flow conditions, whereas there is evidence that other species migrate upstream during low flows. It is thus important in the planning and design of fishways to obtain hydrological data over the period when the target species migrate.

The flow or runoff in South African rivers is highly variable. Most rivers have very little or no flow for long periods and these dry periods are often followed by floods. In general there is a scarcity of water in South Africa. This has led to many dams being constructed to provide water for industry, irrigation and household use. These dams have had a major influence on the runoff pattern in the rivers. Most of the major storage dams also create an impassable barrier to migrating fish. To be able to measure the flow in the rivers, DWAF has also constructed many measuring weirs. These weirs provide valuable information on the short and long term flow rates and flow volumes in the rivers.

To be able to plan and design a fishway at a barrier, it is important to know the flow pattern at the site. This flow pattern can be described in terms of a hydrograph where the flow rate as a function of time is graphically represented. Examples of such hydrographs are shown in Figures 6-1a and 6-1b.

Hydrographs such as these are available from DWAF for all their flow gauging stations. Where recorded data are not available, engineers and hydrologists can normally construct such hydrographs from rainfall records or known rainfall patterns. A handy summary of the data for the purposes of fishway design is in the form of the number of days per year that various flow rates are exceeded. Examples of such summaries are shown in Table 6-1 and Figure 6-2

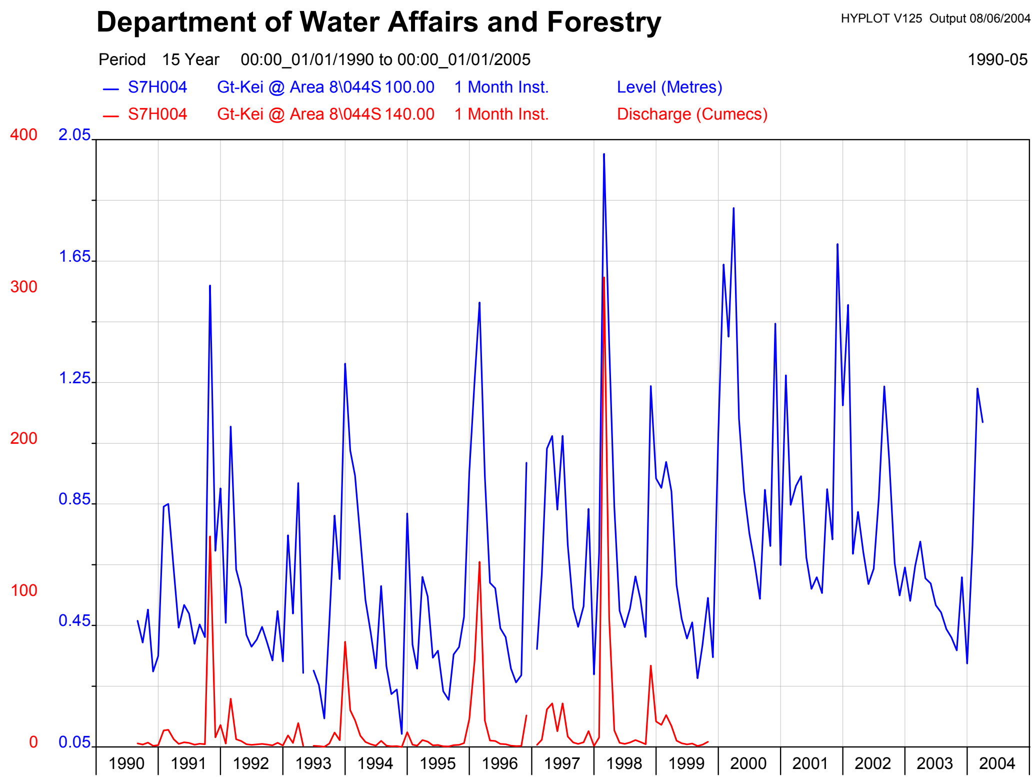

Figure 6-1 Hydrograph data in terms of water level (blue line) and discharge (red line) on the Great Kei River supplied by DWAF

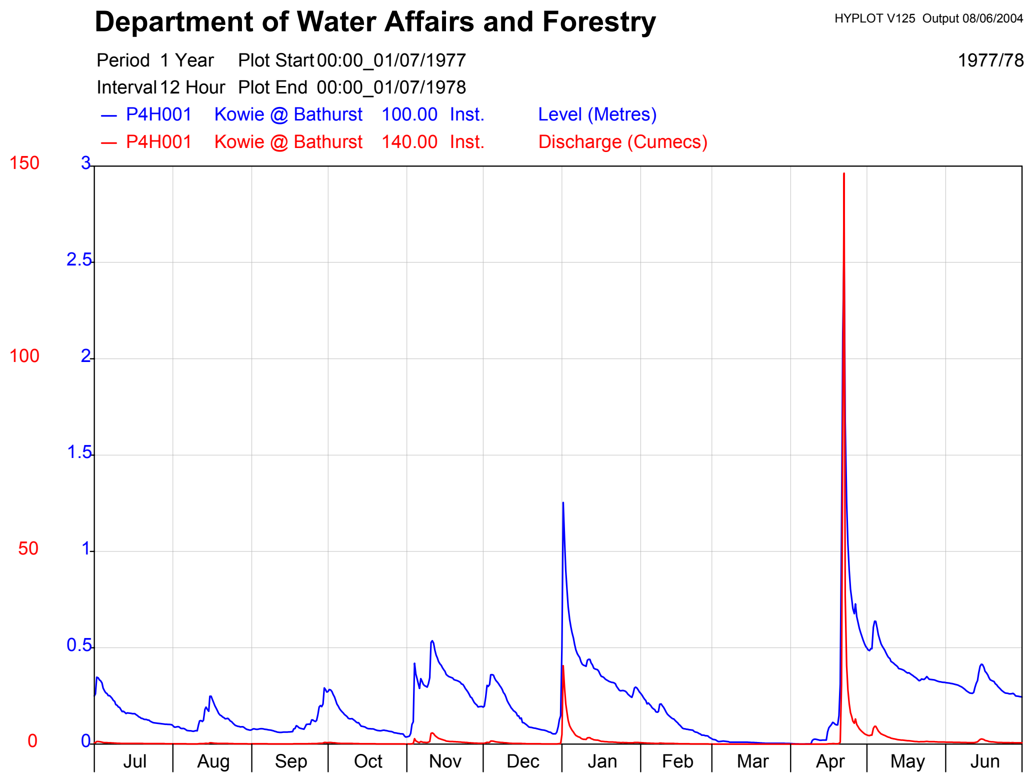

Figure 6-2 Hydrograph for data from a gauging weir on the Kowie River

A characteristic of most hydrographs is that each has a steep rising leg during which the increase in flow is quite rapid. The rate at which the flow decreases after the peak flow has been reached is much more gradual. It is often difficult to design a fishway to allow the passage of especially smaller fish during peak flow. It is mostly easier to design a fishway to operate efficiently during the more constant flows that occur after the peak of the flood. In this regard, there is some circumstantial evidence that most fish species appear to migrate during these more constant flows on the receding leg of the hydrograph.

River flows in many rivers where dams or abstraction weirs are constructed, are often controlled. Water is released according to agricultural and other demands and also to fulfill ecological demands. The flood peaks in many of these rivers are often reduced and the flow more constant than in uncontrolled rivers. The flow pattern resulting from the flow control should obviously be considered in the design of the fishway.

Table 6-1 Discharge Exceedance data for gauging weir on the Sabie River

Department of Water Affairs and Forestry   Hyflow   V135   Output   10/11/2006
Time-Weighted Stream Discharge Duration Analysis of Instantaneous Values. Interval
Sabie River @ Lower Sabie Rest Camp   Discharge (Cumecs)   Site X3H015
Percentage of Time that Parameter was Equaled or Exceeded.   Period of Record 10/12/1986 to 12/09/2006

%	Total	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	%
100	0.02	2.15	1.06	0.69	0.97	0.43	0.45	0.02	0.41	0.24	0.03	0.08	0.61	100
99	0.30	2.79	1.31	0.82	1.12	0.64	0.55	0.46	0.51	0.28	0.08	0.17	0.82	99
98	0.44	3.28	1.42	1.29	1.22	0.76	0.59	0.52	0.57	0.30	0.14	0.52	1.09	98
97	0.58	3.68	1.78	1.42	1.37	0.83	0.65	0.61	0.61	0.30	0.18	0.74	1.33	97
96	0.68	3.84	2.42	1.72	1.66	0.87	0.74	0.67	0.63	0.32	0.19	0.91	1.74	96
95	0.80	4.15	2.92	2.09	2.12	0.97	0.92	0.72	0.67	0.35	0.21	1.08	1.96	95
90	1.42	5.66	5.59	5.44	4.29	2.92	1.53	0.97	0.85	0.48	0.40	1.49	3.49	90
85	1.91	6.55	6.36	6.87	5.11	4.07	2.49	1.41	1.01	0.71	0.87	1.74	4.41	85
80	2.69	7.40	7.17	8.06	6.91	4.73	2.93	1.77	1.49	1.08	1.27	2.00	5.26	80
75	3.62	8.58	8.88	9.13	8.27	5.44	3.32	2.74	1.72	1.56	1.44	2.33	6.14	75
70	4.25	9.47	10.12	10.95	9.30	6.04	4.04	3.72	2.17	1.83	1.63	2.71	7.58	70
65	4.77	10.64	11.81	14.59	9.99	6.69	4.40	4.11	2.55	2.03	1.85	3.47	8.50	65
60	5.37	12.58	13.98	17.47	10.63	7.32	4.73	4.29	3.20	2.28	2.11	4.13	9.05	60
55	6.19	14.61	15.68	19.13	11.83	7.75	4.96	4.45	3.64	2.66	2.75	4.46	10.04	55
50	7.06	16.47	18.06	21.43	13.55	8.43	5.53	4.66	3.93	3.13	3.26	4.91	10.81	50
45	8.01	19.63	21.03	24.52	15.39	8.98	6.27	4.86	4.27	3.50	3.88	5.31	11.70	45
40	9.24	22.62	25.72	27.56	17.22	9.85	7.09	5.26	4.54	4.02	4.36	6.09	13.03	40
35	10.41	25.60	30.53	31.54	19.35	10.63	7.79	5.69	4.83	4.52	4.92	6.55	14.17	35
30	12.02	29.49	33.24	38.68	20.89	11.61	8.82	6.43	5.22	5.37	5.31	7.25	15.53	30
25	14.34	33.66	37.09	45.68	23.93	12.71	10.39	7.05	6.39	5.83	5.77	8.42	17.69	25
20	17.72	38.33	42.56	52.96	27.04	14.83	11.44	8.70	7.06	6.51	6.65	9.85	24.77	20
15	23.44	44.93	50.21	64.65	29.51	16.68	12.51	9.39	7.77	7.17	7.55	11.53	32.00	15
10	32.14	52.29	68.32	82.02	34.71	20.03	13.22	10.38	9.56	8.66	9.57	17.46	44.08	10
5	50.22	80.23	169.43	118.15	43.58	24.63	14.50	11.40	12.31	13.97	12.67	30.28	61.46	5
4	56.77	93.88	183.20	136.75	46.61	26.12	14.82	11.50	14.66	14.88	13.94	42.36	68.96	4
3	67.03	103.48	256.71	155.64	52.50	27.63	15.54	12.10	17.30	15.19	14.22	53.24	75.01	3
2	88.27	131.84	331.39	172.90	57.50	28.68	16.53	12.46	17.57	16.09	15.45	59.34	87.98	2
1	137.82	155.15	584.58	283.71	68.87	32.69	18.31	12.79	18.27	17.63	19.55	84.81	105.43	1
0	1353.23	544.29	1353.23	837.82	126.77	55.17	20.89	13.77	19.65	24.73	36.28	182.04	296.51	0

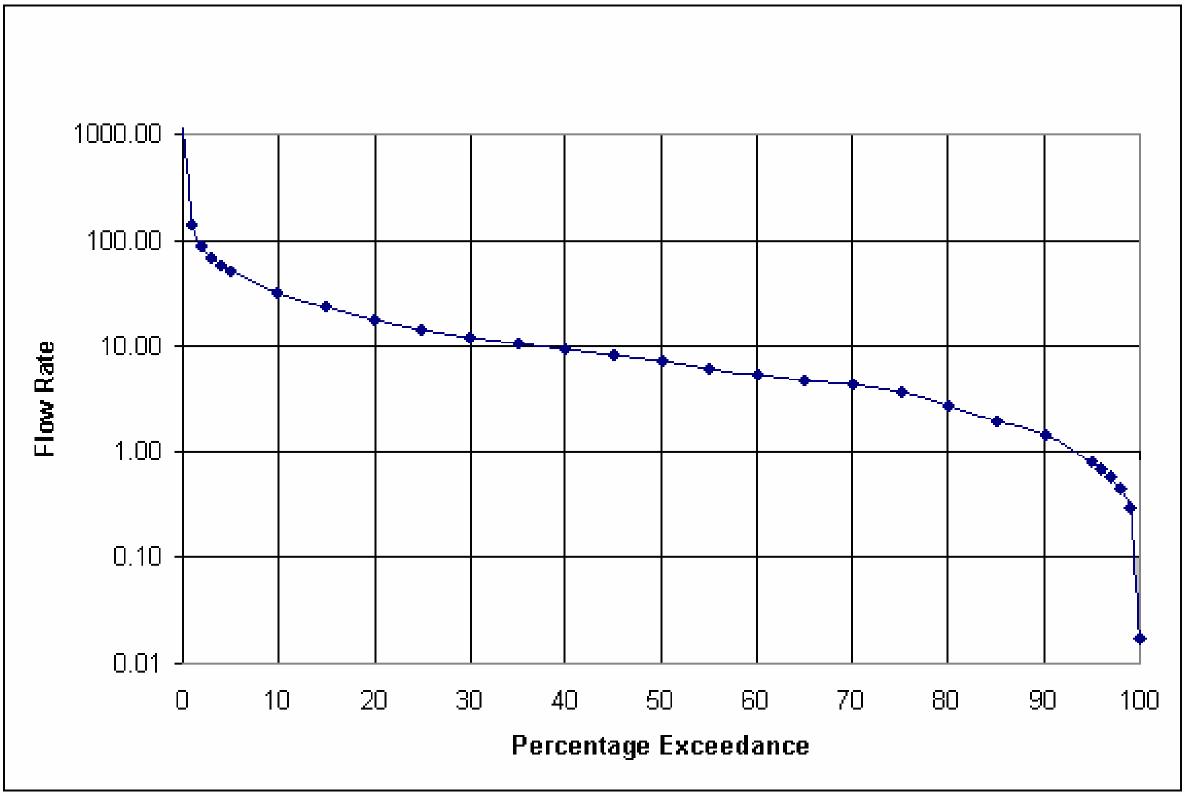

Figure 6-3 Discharge Exceedance curve for gauging station on the Sabie River

6.4 Barrier Hydraulics

6.4.1 *Water level fluctuations at the barrier*

The change in water level upstream of a barrier due to a change in flow in the river depends largely on the configuration of the barrier. A long horizontal weir across a wide section of the river can tolerate a relatively large change in flow without a major change in the water level upstream of the weir. Similarly a short weir will result in a higher change in water level for the same change in flow rate. The water level upstream of the barrier determines the flow rate through the fishway and changes in this water level with varying flow is therefore an important design parameter.

If the barrier under consideration is a flow-gauging weir, it should be realized that these weirs are normally designed to cause relatively large changes in the upstream water level to improve the accuracy of the flow measurement. This is normally achieved by varying the height of the crest of the weir along its length. In these so-called compound weirs the low flow is contained over the lowest crest and as the flow increases the higher crests starts overflowing. The placement of the fishway in this type of structure requires special attention.

The changes in water level downstream of the barrier with changing flows depend largely on the river cross sections and slope. In many cases the water level downstream of the barrier increases faster than the upstream level. Lower barriers may become submerged during major floods and under these conditions fish migration may be possible without the need for a fishway. It is therefore important to study the drown out characteristics of the weir to determine up to which flow the fishway should be designed to allow the passage of fish.

At most of the DWAF's flow gauging stations water levels are recorded both upstream and downstream of each structure. These levels are normally also calculated during the design of the gauging stations.

6.4.2 *Changes in river bed due to construction of weir and/or fishway.*

To allow easy access for the fish to the fishway, it is important to have the fishway entrance at a position where there is sufficient water depth in the river. This is especially important for fishways that are designed to operate during low flow conditions. Ideally the fishway entrance should be in a pool where the fish can wait for ideal conditions for negotiating the fishway. It should however be realized that the weir that forms the barrier and the fishway will influence the flow pattern in the river. If this causes siltation in the pool at the entrance to the fishway, the water at the intake may become too shallow for the fish to find the fishway. Similarly siltation may occur where the fish have to leave the fishway. This may cut off flow to the fishway or force the fish to exit the fishway in very shallow water where they will be prone to predation.

It is therefore important to estimate what influence a proposed barrier will have on the river configuration in the area of the barrier. The behaviour of the river bed after construction of a new barrier are often difficult to predict and monitoring of this behaviour is required to ensure that the fishway remains efficient after these changes. It will be necessary to adapt the fishway intake and outlet (or remove accumulated sediment from the river channel) if bed changes restrict access to the fishway.

6.5 Location of Fishway

6.5.1 *Fishway Entrance*

The position of the fishway entrance (i.e. downstream end) is of crucial importance for the success of a fishway. Fish usually swim upstream in or at the edge of the main flow, penetrating as far upstream as they can, and thus usually accumulate near the base of the barrier. Many existing fishways in South Africa and elsewhere have failed because the entrance was located too far downstream of the barrier (Bok, 1990). If fish cannot locate the entrance, then the time and expense put into the design will be wasted (no fish in = no fish out!).

The rule of thumb is that the fishway entrance should be located as near as possible to the furthest upstream point or line to which the migrating fish are able to penetrate and where they tend to congregate immediately downstream of the barrier in question. This is normally near the river bank at or as near as possible to the base of the weir wall that water depths and current velocities will allow.

In addition, fish (particularly small fish) migrating upstream avoids highly turbulent, high velocity water and prefers to swim on the side of the main stream, near the river banks. It is usually necessary to incorporate a 'folded-staircase type' of fishway design, set against the bank, to ensure that the fishway entrance is located at the base of the weir wall near the river bank. Where possible, the use of local knowledge and on-site observations should be used to confirm the optimum site for the fishway entrance.

Larinier (2002a) gives detailed advice about the placement of fish entrances at a variety of structures. Variation in the water levels downstream of the barrier must be taken into account when deciding on the location and levels of the downstream entrance. Several examples exist in South Africa where it is impossible for fish to reach the fishway entrance during low flows.

If fishways are designed to accommodate migrating fish during periods of low flow, it is also important that a deep pool should exist at or directly downstream of the fishway intake.

Fish that move up to the barrier during high flows and have to wait for lower flows before they can negotiate the fishway, will move to a pool further downstream if a suitable pool is not available from which they can enter the fishway.

Examples of good and bad practise regarding the placement of fishway entrances, both in South Africa and in Europe, are illustrated in Plates 6-2 and 6-5 to 6-7.

6.5.2 *Fishway Exit*

The fishway exit (i.e. upstream end or water inflow) of the fishway should be located some distance upstream of the weir crest in an area of low water velocity to ensure that tired fish exiting the fishway are not swept back downstream. Usually a location near the river bank and away from the spillway crest should be chosen. Examples of the location of fishway exits are given in Plates 6-2, and 6-5 to 6-7.

The inflow into the fishway is controlled at the fishway exit. It is recommended that the structure controlling the inflow into vertical slot and pool and weir fishways should be identical to the structures controlling the flow between the pools in the fishway, i.e. a vertical slot or weir. In small rivers with long periods of low flows the invert level of the exit (i.e. water inflow) should be lower than that of the barrier spillway to ensure that the fishway functions at low river flows.

To enable the fishway to operate effectively over a wide range of headwater pool levels, a possible solution is to extend the upstream (i.e. exit) section of the fishway within the range of headwater pool level fluctuations and to fit a number of exit ports to this section, which can be adjusted manually. However, it is seldom practical to have an adjustable control, except where regular access to the barrier is possible and where the headwater levels fluctuate very slowly. An example of such an arrangement is the series of exit ports over a range of Lake water levels designed for the Nhlabane Fishway, as shown in Plate 6-7.

6.5.3 *Auxiliary and attraction water*

Auxiliary water is additional water that is provided within the fishway to increase the water velocity and volume at the entrance to ensure that fish are attracted into the fishway. Provision of auxiliary water is important when the velocity and volume of water flowing down the fishway is relatively small compared to the water flowing over the rest of the barrier. This water is usually provided from a separate canal or pipe via a diffusing screen into the entrance (first downstream) pool of the fishway. An example of the provision of auxiliary water at a fishway is shown in Plate 6-8.

Attraction water is external to the fishway and is used to attract fish to the general area of the fishway entrance or to the side of the river where the fishway is located. For example, a portion of the weir crest adjacent to the fishway could be slightly lower so that the increased flow will attract fish to the river bank where the fishway is located. This attraction water is particularly important in large, wide rivers where fish could have difficulty finding the fishway entrance.

Plate 6-1 The Engelhardt Dam fish ladder on the 13 m high Letaba Dam, Kruger National Park, built in 1970. The entrance to the fishway is located too far down-stream of the barrier to be easily found by upstream migrating fish. The submerged fishway exit is located near the crest of the weir, allowing tired fish leaving the fishway to be swept downstream.

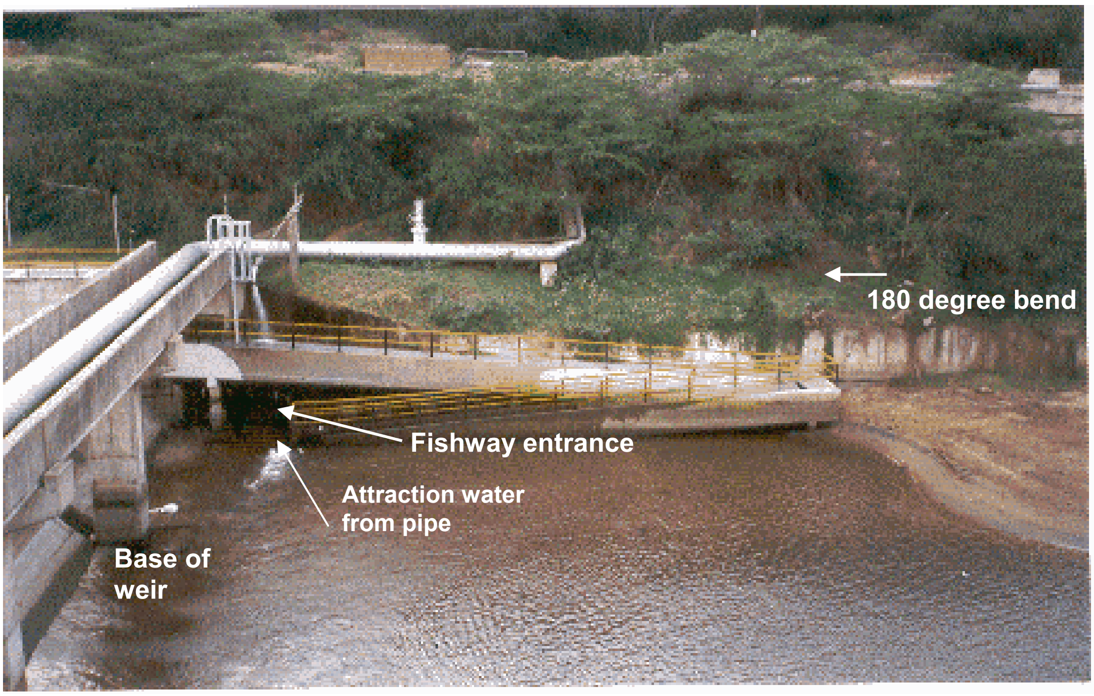

Plate 6-2 View of lower section of the Nhlabane Weir fishway on the left bank of the Nhlabane Estuary at low water level. Note folded staircase design with fishway entrance at the base of the weir at 90 degrees to river flow. Attraction water is seen being released via a pipe located adjacent to the fishway entrance.

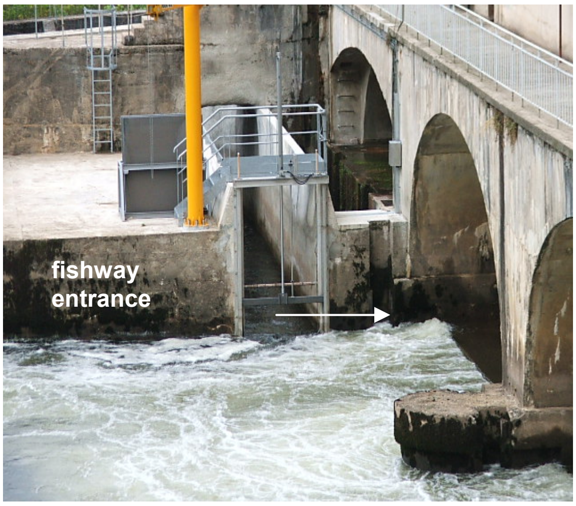

Plate 6-3 This fishway at Bergerac, France, has its entrance at the foot of the weir, and which also receives attraction water through an adjacent canal.

Plate 6-4 The fishway entrance at Mauzak, France, is situated adjacent and at 90 degrees to one of the outflows from the power station.

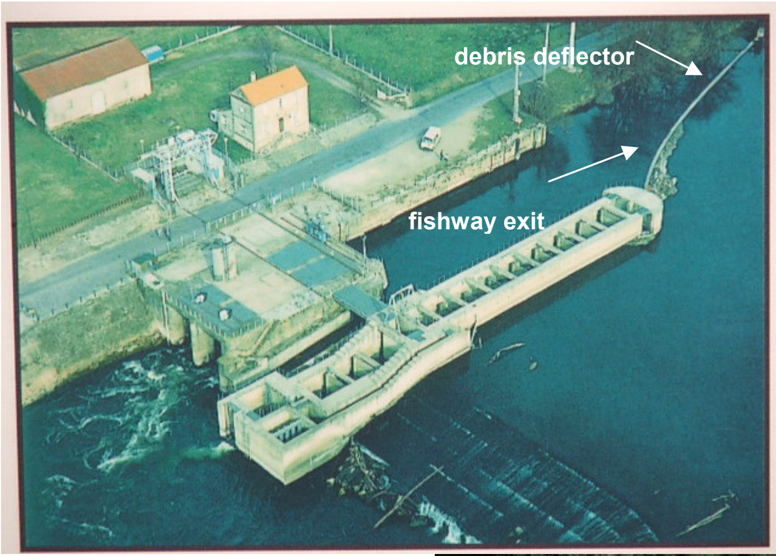

Plate 6-5 A photo of a poster of the fishway at Bergerac, France, illustrates the concept of placing the fishway entrance at base of the weir next to the main overflow, which serves as attraction water. The fishway exit is placed far upstream of the barrier to prevent fish leaving the fishway from being swept back downstream.

Plate 6-6 Fishway on the Nqabara River (Transkei). The entrance is at the base of the weir and the channel extends upstream, with the exit away from the spillway. Note the eelway/prawnway with entrance next to the fishway entrance, thus providing additional attraction water.

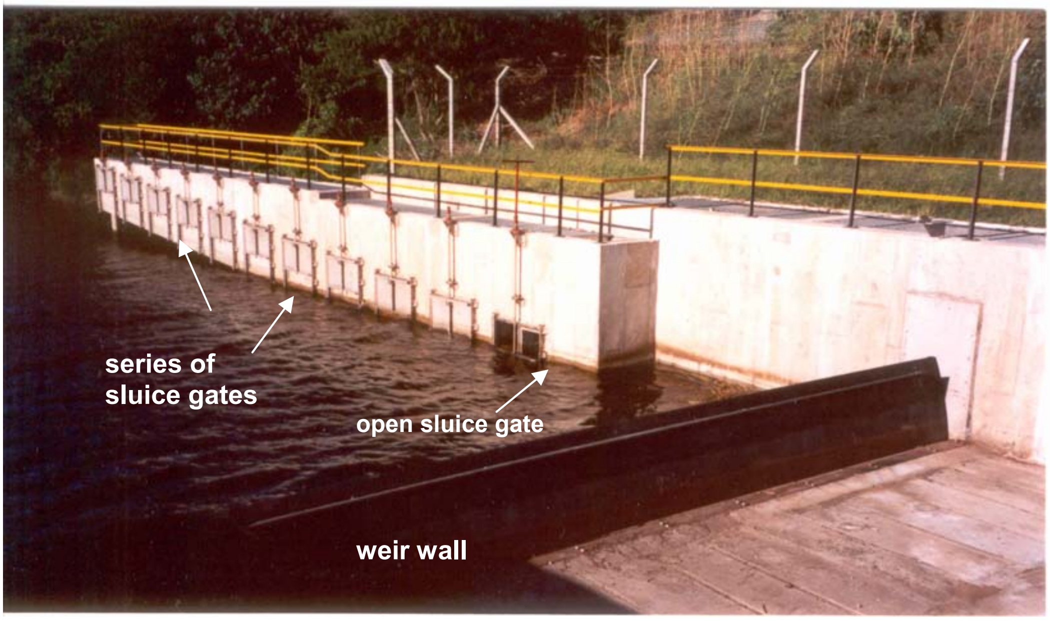

Plate 6-7 View of up-stream section of the Nhlabane Fishway showing the series of manually-operated sluices for letting water into the fishway and providing an exit for fish leaving the fishway.

Plate 6-8 Auxiliary water released into the last downstream fishway pool and blocked off with a screen from the main fishway channel at Soeix Gava Aspt, France.

The additional flow helps attracts fish to the fishway entrance.

Plate 6-9 Different kinds of debris deflectors used at fishway entrances in Europe

This attraction water flow should not create excessive velocities or turbulence at the fishway entrance, but should be designed to ensure that the fishway entrance becomes the upstream limit of migration. Water discharging from the fishway entrance should not be at more than about 90% to the flow direction of the attraction water or normal river flow in order avoid disorientation and to guide fish into the fishway (Mallen-Cooper and Harris, 1992). Examples of the provision for attraction water are shown in Plates 6-2 to 6-6.

6.5.4 *Sediment and Debris*

Sediments varying in size from fine silt to rocks and boulders may be deposited in a fishway (particularly on low weirs) where low velocities or stagnant water occurs in the fishway. Pool and weir fishways are particularly prone to sediment deposition. Care should therefore be taken in rivers with high sediment loads not to have pools that are too large or too deep and to ensure that regular maintenance and sediment removal is carried out.

In pool and weir fishways in rivers with high sediment loads, the incorporation of small scour pipes on the bottom of the fishway through the weirs is recommended. These can be blocked off, if necessary, during normal operations and opened to allow draining and washing out of accumulated debris during maintenance.

Many South African rivers carry a large debris load during floods. These include everything from plastic bags, floating plants such as hyacinths, branches and trees. This debris can easily block a fishway. It is often possible to alleviate the problem of blockage during high flows by:

- Careful design of the water intake to the fishway - e.g. having submerged intakes perpendicular to the normal flow direction of the river at the position of the intake.
- Providing a debris deflector (possibly consisting of steel bars or a cable located on the surface) at the exit (upstream end) to prevent leaves, reeds, logs, etc. from entering and clogging up the fishway. If bars are used, they should be spaced an appropriate distance apart so as not to prevent larger fish from exiting (or entering) the fishway. Any debris-deflector should also be self-cleaning to minimise the trapping of floating debris.

Plates 6-5 and (6-9 to 6-11) shows examples of debris accumulation upstream and in fishways and a number of intake designs aimed at preventing debris from accumulating upstream of and in fishways.

6.6 Selection of Fishway Type

6.6.1 *Bypass structure*

There is general consensus that the most effective fishway is some form of bypass structure where a nature like channel is constructed to bypass the barrier. Plates 6-12 to 6-17 illustrate a number of examples of these bypass structures.

The bypass channel can be in the form of a rough sloping channel or rock ramp such as in the Sabie River in the KNP (Plate 6-12), or some form of pool and weir structure where the weirs are preferably constructed out of natural material commonly built in Europe (Plates 6-13 to 6-17). As can be seen, the fish bypass channel can be combined with other structures, such as a canoe pass (Plate 6-17).

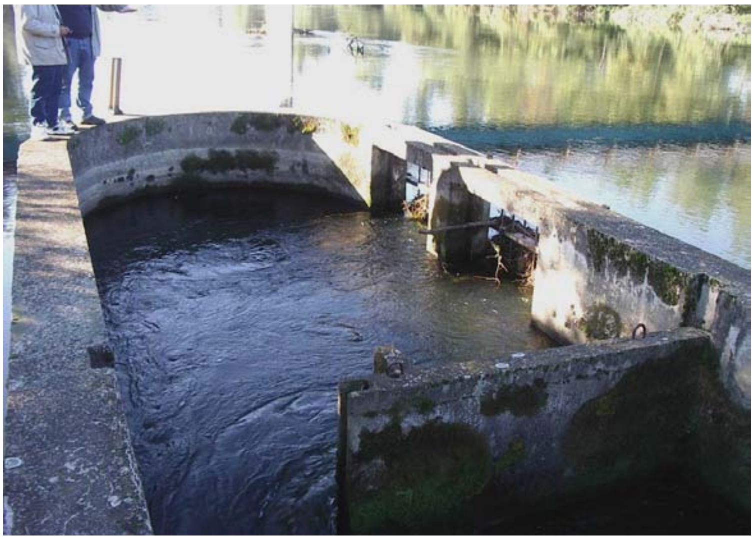

Plate 6-10

Exit of vertical slot fishway placed on side of most upstream pool at 90° to river flow at Lapin de Garenne, France. Note metal grid screens are partially clogged with debris.

Plate 6-11

Exit to pool and weir fishway at the Lebombo gauging weir on the Komati River. Note the design should allow most of floating debris to spill over into the river below the weir and not enter the fishway channel.

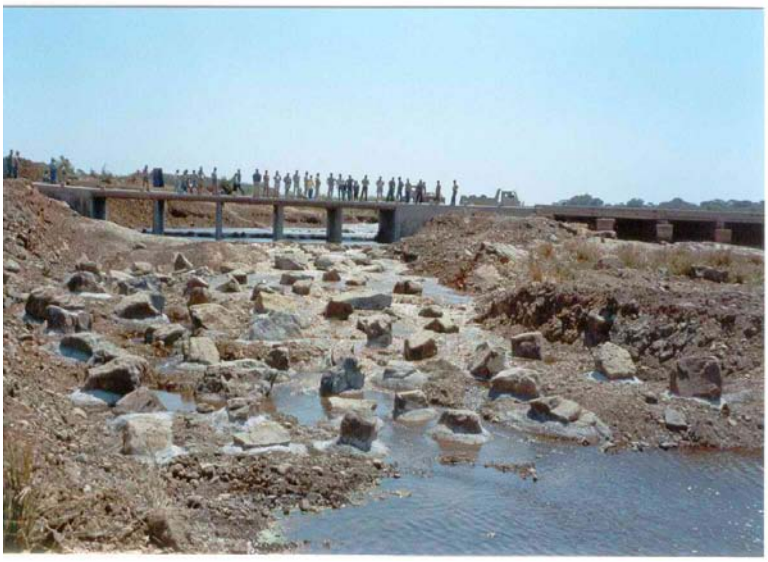

Plate 6-12 Bypass Rockramp fishway on the Lower Sabie River in KNP under low-flow conditions at commissioning in October 2001 showing placement of rocks.

Plate 6-13 Bypass channel on the Lenne River fishway, Germany

Plate 6-14 Bypass channel on the Siika Joki - White Fish River, Finland

Plate 6-15 A pool and weir bypass channel using large rocks in a natural channel at Harkort See weir, Germany.

Plate 6-16 Gently sloping bypass channel at Meillon, France

Plate 6-17 A fishway bypass channel (2) combined with a canoe pass (1) at Hattinghe in Germany. In practice fish use both channels, with larger, stronger-swimming fish using the canoe pass. Fish can move freely between rocks separating the two channels.

Plate 6-18 A series of pre-barrage walls below a weir at Gava de Oron, France.

Plate 6-19 Pre-barrage walls at Sus Miou, France.

Plate 6-20 Typical vertical slot fishway in France, at the Barrage de Chatellerault.

Plate 6-21 Large vertical slot fishway at Mauzak, France

Plate 6-22 Rocky stratum on the bottom of a vertical slot fishway pool at the Raffelberg II fishway in Germany.

Plate 6-23 Pre-barrage on Olifants River

In all cases attempts are made to simulate a natural river channel in which a wide variety of flow conditions occur across the channel, allowing a wide variety of species and sizes to negotiate the channel, often over a wide variation in water levels at the barrier.

To be able to construct such a bypass channel, sufficient space and suitable foundation conditions are required.

6.6.2 *Pre Barrages*

Pre-barrages where the drop at the barrier is divided in a number of smaller drops, is often a viable and effective solution. Plates 6-18, 6-19 and 6-23 illustrate typical examples of such pre barrage structures.

If the pre barrage is constructed out of natural material such as large rocks and the pre barrages are built relatively rough, a wide variety of flow conditions can be created allowing fish of different swimming abilities to find a way past the barrier.

A major advantage of pre barrages and bypass structures is that they normally do not become blocked by debris in that they tend to be self cleaning during high flows. The design of these types of structures however requires a degree of experimentation as exact hydraulic analysis of such structures is not possible. Such structures are normally adapted after construction to improve the flow conditions in areas where fish are expected to have difficulties in negotiating high drops or high velocities.

6.6.3 *Vertical slot fishways*

In vertical slot fishways, pools in the fishway channel are created by a series of slots that constrict the flow. Examples of such fishways are shown in Plates 6-20 to 6-22.

A major advantage of vertical slot fishways is that they can deal with large variation in upstream water levels without any variation in the velocities or turbulence in the fishway.

A disadvantage of these fishways is that they are easily blocked by debris, especially if the slots are very narrow. They also require a minimum flow before the pools fill up sufficiently to create sufficient depth at the slots for deep bodied fish to be able to swim through the slots. Tests with some species have however shown that if rock strata are placed on the bottom of the pool (see Plate 6-22) small fish successfully negotiate the fishway even at very low flows where very little water is present in the pools.

6.6.4 *Pool and weir fishways*

In pool and weir fishways, pools in the fishway are created by a series of weirs. Various weir shapes from simple horizontal weirs to sloping weirs or weirs with lower notches have been used in this type of fishway. Plates 6-24 to 6-29 show examples of a number of pool and slot fishways built in South Africa.

The major disadvantage of this type of fishway is that turbulence levels in the pools increases rapidly with increasing water levels. They are therefore only suitable in areas where the upstream water level does not vary by much more than 500 mm. Pool and weir fishways can however be designed to operate very efficiently at very low flows and to cater for creeping and crawling species. They also tend to be less prone to blockage by debris.

6.6.5 *Combination fishways*

It is often possible to combine fishways types. Pre barrages can be combined with all the other types of fishway where pre barrages are used to reduce the effective drop over the barrier resulting in a shorter fishway to cross the barrier. Similarly a fishway can be designed to work as a pool and weir fishway at low flows changing to a vertical slot fishway at higher flows, thereby limiting the increase in turbulence associated with the higher flows in a pool and weir fishway. Examples of such combined “Pool and Slot” fishways are shown in Plates 6-30 and 6-31.

6.6.6 *Multiple fishways*

It is sometimes difficult to provide for small and large fish and creeping and crawling species in one fishway. Providing two separate fishways can be more economical in some cases as it allows for steeper fishways to be constructed. Examples of the design of such a fishway are given in Section 9 of this report.

6.6.7 *Summary*

The advantages and disadvantages of fishway types are summarized in the Table 2-6.

Plate 6-24 – Pool and notched-weir fishway on the Lebombo gauging weir on the Komati River.

Plate 6-25 – Pool and slot fishway on Crocodile River.

Plate 6-26 : Haga-Haga River Pool and Sloping Weir fishway designed for small (<120 mm long) fish.

Plate 6-27 Close-up of sloping weir of the Nhlabane Pool and Weir fishway at low flows, looking up-stream. Note the wetted splash zone on sloping baffle at the edge of the main flow.

Plate 6-30 Close-up of "Pool and Slot" baffle at Riverside Weir Fishway in the KNP under low flow conditions.

Plate 6-29 Close-up view of weir notch in the Kanniedood fishway, KNP during low-flow conditions with no water flowing down the fishway.

Plate 6-28 View looking up-stream at the Kanniedood fishway on the Shingwedzi River in the KNP.

Plate 6-31 View of most down-stream slot of the "Pool and Slot" Ten Bosch fishway on the Crocodile River KNP, during low stream-flow conditions.

7 HYDRAULIC DESIGN OF FISHWAYS

7.1 Introduction

In Chapter 6 the advantages and disadvantages of fishway types considered suitable for South African conditions are summarized.

In this chapter the necessary theory to be able to analyse the hydraulics of a fishway will be presented. This theory will then be used to illustrate the design calculations required to estimate the performance of pool and weir and vertical slot fishways. These calculations combined with the hydrological data will be used in Chapter 9 to illustrate the procedures for selecting an appropriate fishway.

To be able to compare the relative merits of the fishways used in the example, all the fishways considered for this exercise will be 1.0 m wide.

The following structures are discussed:

7.1.1 *Pool and weir structures with*

- A full width horizontal weir
- A notched weir
- A sloping weir

7.1.2 *Vertical slot structure*

- Typical vertical slot with no sill
- Vertical slot with a sill in the slot - termed “pool and slot” fishway

The designs are aimed at providing a general-purpose inland fishway catering for a range of fish sizes from 40 mm to 400 mm. According to Table 5-5 these fish can cope with maximum velocities of 1.7 m/s (i.e. drop of 150 mm between pools) and turbulence levels of 180 watt/m^3. In Chapter 10 examples of designs aimed at more specific species in both a small and a large river will be given.

7.2 Definition of parameters

The basic layout of a pool and weir fishway is shown in Figure 7-1

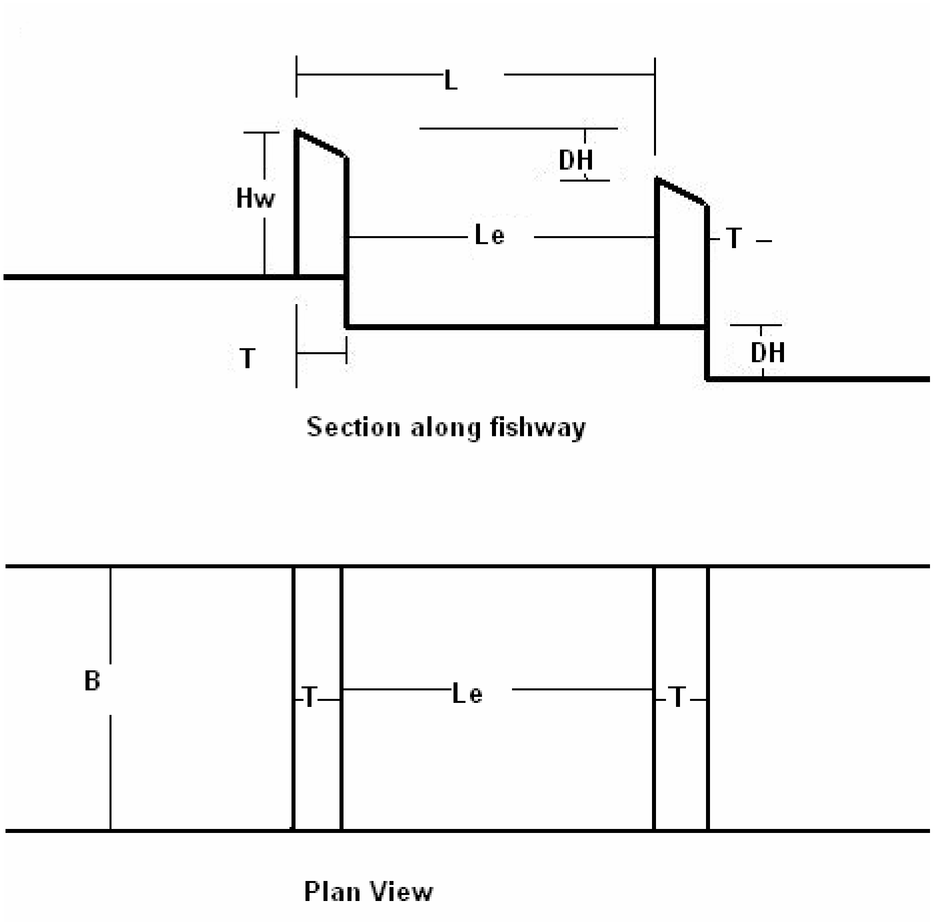

Figure 7-1: Pool and weir fishway: Definition of parameters

The following dimensions have to be selected by the designer:

- The drop between successive pools (DH), which is the same as the drop between successive weir crests
- The distance between successive weirs (L)
- The thickness of the weirs (T)
- The width of the pools (B)
- The height of the weir (Hw)
- The shape of the weirs, i.e. sharp crested weirs, broad crested weirs, weirs sloping in the flow direction, etc.

Other parameters which will be used are:

- The effective length of the pool (Le) where Le=L-T
- The water level in the pool relative to the crest of the weir. This is also called the head (H1)
- The water depth in the pool (D) where D=Hw+H1 for a pool with a horizontal bottom as shown in Figure 7-1. For a pool with a sloping bottom D refers to the average depth in the pool

- The volume in the pool (Vol) where Vol=D*Le*B
- The maximum velocity (Vmax) that occur in the fishway. This velocity normally occur where the water overflowing the weir strikes the water in the down-stream pool
- The flow rate or discharge (Q) in the fishway. This flow rate is normally expressed in liters per second (l/s) or in cubic meters per second (m^3/s), also referred to as cumecs

7.3 Selection of fishway dimensions

In Chapter 2, Table 2-7 some recommendations about fishway dimensions were summarized. Further background to these recommendations is given below.

7.3.1 *Drop between successive pools*

The basic principle in fishways is to divide the height to be overcome at the barrier into a number of drops forming a series of pools. The maximum velocities in critical areas of the fishway (slots or weirs between pools) should not exceed the burst speed of the weakest swimmer catered for.

The maximum velocities (Vmax) in a fishway normally occur at these drops and the maximum velocities are a function of the height of the drop (DH), i.e. the height difference between the water surface in successive pools.

This velocity (V_{max}) is given by:

$$V = (2\ g\ DH)^{0.5}$$

Where:

$g = 9.81 m/s^2$

The following table gives this velocity as a function of the height of the drop:

Table 7-1 Velocity as a function of the height of the drop

DH (m)	V_{max} (m/s)
0.05	1.0
0.10	1.4
0.15	1.7
0.20	2.0
0.30	2.4
0.40	2.8
0.50	3.1

7.3.2 *Length of pools*

This length refers to the distance between two successive weirs in the fishway. The effective length of the pool will be the above length minus the thickness of the weir. An effective length of at least 2.5 times the length of the largest fish catered for is recommended.

The length of the pool also determines the velocity that will reach the weir at the down-stream end of the pool. If this velocity is too high vertical velocities will be generated along the upstream face of the weir which should be avoided.

7.3.3 *Depth of pools.*

The minimum depth recommended at the start of flow in pool and weir fishways is 300 mm for fish of 20 to 200 mm in length and 500 mm for fish exceeding 200 mm in length. Deeper pools can be used to limit the turbulence in the pools. In vertical slot fishways no minimum depth can be specified, as this depth will be zero when there is no flow. This will be discussed when dealing with the design of vertical slot fishways.

7.3.4 *Width of the pools*

The minimum width of the pool should be at least 2 times the length of the largest fish to be catered for. A width of at least 0.6 to 0.8 times the effective length of the pool will ensure acceptable flow patterns in the pool.

7.3.5 *Volume in the pool*

The volume of the pools should be sufficient to dissipate the power of the water flowing through the fishway. The power generated is determined by the flow rate (Q) and the drop between the pools (DH). The volume in the pool is the product of the effective length, width and average flow depth in the pool (see examples later in this chapter). In many instances, it is the hydraulic conditions (particularly turbulence) and not the size of the fish that in practice determine the minimum dimensions of the pools.

7.3.6 *Weir Shape.*

Experience at existing South African fishways indicates that a weir sloping in the flow direction, with an adherent nappe to eliminate vertical drops from one pool to the next, is advantageous, especially for the smaller and weaker swimmers. A weir thickness (T) of twice the drop between the pools (DH), with a crest slope of 1:2 in the flow direction, as shown below, is recommended, i.e. T = 2 DH. Such an arrangement will ensure that no free drop of water occurs in the fishway and allow especially small fish to swim up the sloping weir.

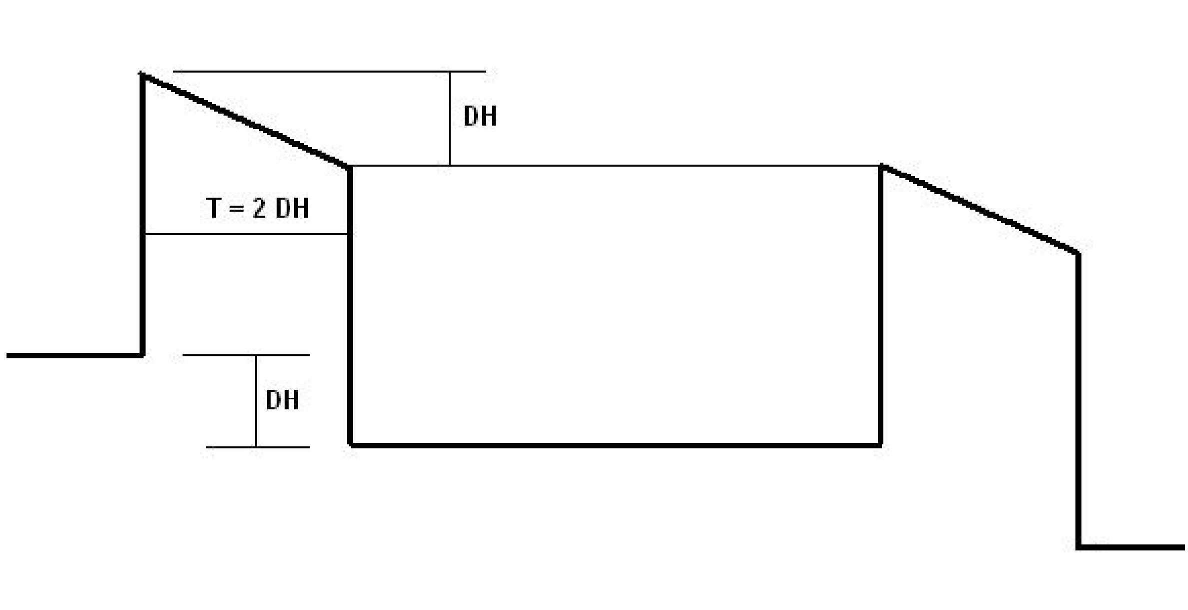

Figure 7-2: Recommended shape of weir

7.4 Design of a pool and weir fishway with a full width horizontal weir

7.4.1 *Dimensions*

The fishway is designed as a general purpose inland fishway catering for a range of fish species and sizes capable of negotiating maximum velocities of 1.7 m/s and turbulence levels of 180 watt/m^3. The largest fish to be catered for will have a length of 400 mm.

A drop between pools of 150 mm will result in maximum velocities of 1.7 m/s.

A weir thickness of at least twice the drop between the pools is chosen to allow for the crest slope in the direction of flow of 1:2. This will ensure that there is no free drop in water level at the end of the weir where the water enters the next pool. A weir thickness of 300 mm is used in this example

An effective length of the pools of at least 2.5 times the length of the largest fish catered for needs to be provided. The minimum effective length of the pools should therefore be 1000 mm. With a weir thickness of 300 mm, the distance between pools will be 1300 mm. The slope of the fishway will therefore be 150/1300 or 1/8.7. The width of the fishway is chosen as 1 m to allow comparison with alternative designs later in this chapter. This width is considered sufficient for smaller rivers and where large concentrations of migrating fish are not expected. In larger rivers a wider fishway will be required to ensure sufficient flow through the fishway to attract fish to the fishway entrance and to prevent overcrowding in the fishway.

A long section through the fishway is shown in Figure 7-3. The depth of the pools at the start of flow in this example is selected at 900 mm. The reason for choosing a relatively deep pool is to compensate for the expected high rate of increase in turbulence with increasing head over the wide weir.

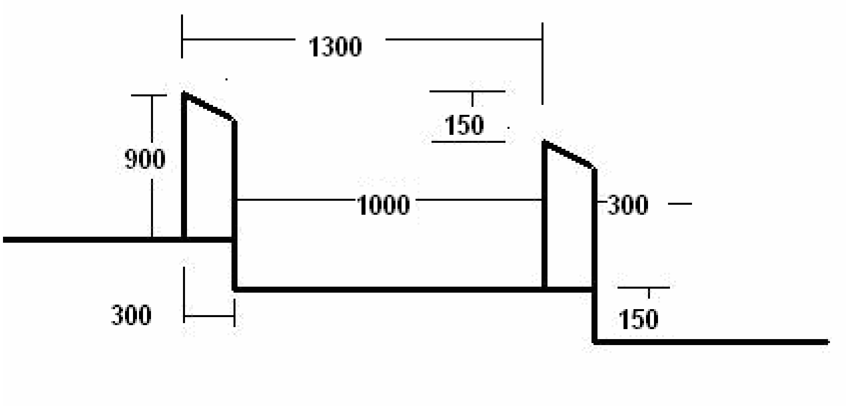

Figure 7-3: Long section through fishway

7.4.2 *Discharge*

The discharge through the fishway as a function of head will be as follows:

For H_1 between 0 and 150 mm:

$$Q_f = 2/3 \, Cd \, b \, (2 \, g)^{0.5} \, H_1^{1.5}$$

Where:

Q_f: discharge in m^3/s

Cd: discharge coefficient = 0.61 for weir shown in Figure 7-2

g: Acceleration due to gravity = 9.81 m/s^2

H_1: Head on weir in m

When H_1 exceeds 150 mm, the water level in the pool below the weir will be higher than the crest of the weir, and submerged flow will occur. This will reduce the discharge by a factor K where

$$K = (1 - ((H_1 - DH)/H_1)^{1.5})^{0.385}$$ As shown in sketch.

The discharge for submerged flow is given by $Q_s = K \, Q_f$

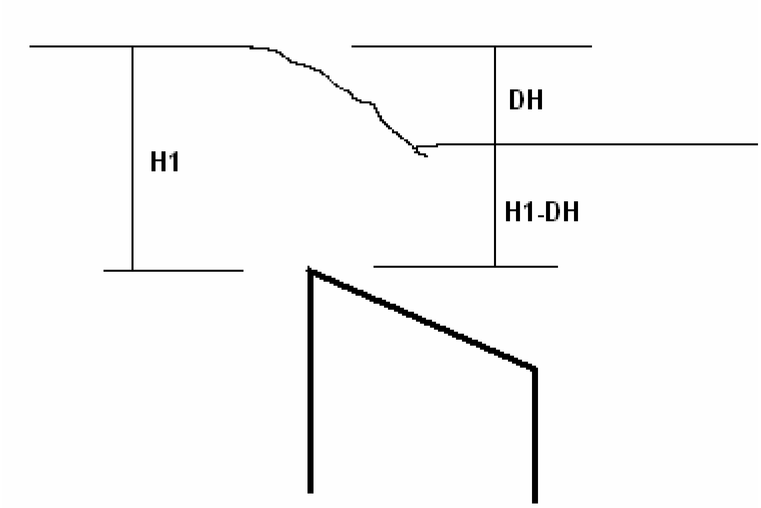

Figure 7-4: Submerged flow

7.4.3 *Turbulence*

The level of turbulence in the pools can be described in terms of the power dissipation per unit volume in the pool i.e.:

$P_v = \rho\ g\ Q\ DH/\ (L_e\ B\ D_e)$

Where:

P_v: Power dissipation per unit volume (watt/m^3)

ρ: density of water = 1000 kg/m^3

Q: discharge (m^3/s)

DH: drop between pools (m) = 0.150 m in example

L_e: Effective length of pool (m) =1.000 m in example

B: width of pool (m) =1 m in example

D_e: effective depth in pool (m) = $H_w + H_1 = 0.9 + H_1$ in example

7.4.4 *Evaluation of fishway*

The discharge and power per unit volume as a function of the head on the pool, is shown in Table 7-2.

The problem with this type of weir is illustrated in Table 7-2. At a head on the weir of 180 mm and a discharge of 134 l/s, the power per unit volume starts exceeding the allowable value of 180 watt/m^3. This fishway will therefore only be effective for a small variation in the depth of the pool upstream of the barrier.

7.5 Design of a pool and weir fishway with a notched weir.

7.5.1 *Dimensions*

The fishway is designed as an alternative to the fishway with the full width horizontal weir discussed in 7.4 above.

To be able to extend the range of upstream water levels for which the fishway will be effective, the horizontal weir discussed in Section 7.4 above, is provided with a notch of 300 mm wide by 300 mm deep as shown in Figure 7-5.

Table 7-2 Discharge and Turbulence: Full width pool and weir fishway

Pool and weir	
Channel width (B)	1.00 m
Pool depth (D)	0.90 m
Discharge Coefficient (Cd)	0.61
Drop between pools (DH)	0.15 m
Length between pools (L)	1.30 m
Thickness of weir (T)	0.30 m
Effective length of pools (Le)	1.00 m
Slope	1/8.7

H1 (m)	**Qf (l/s)**	**H2 (m)**	**K**	**Qs (l/s)**	**Vol (m^3)**	**Pv (watt/m^3)**
0.05	20.1	-0.100	1.000	20.1	0.950	31
0.10	57.0	-0.050	1.000	57.0	1.000	84
0.15	104.6	0.000	1.000	104.6	1.050	147
0.18	137.6	0.030	0.973	133.9	1.080	182
0.20	161.1	0.050	0.950	153.0	1.100	205
0.25	225.2	0.100	0.894	201.2	1.150	258
0.30	296.0	0.150	0.845	250.2	1.200	307

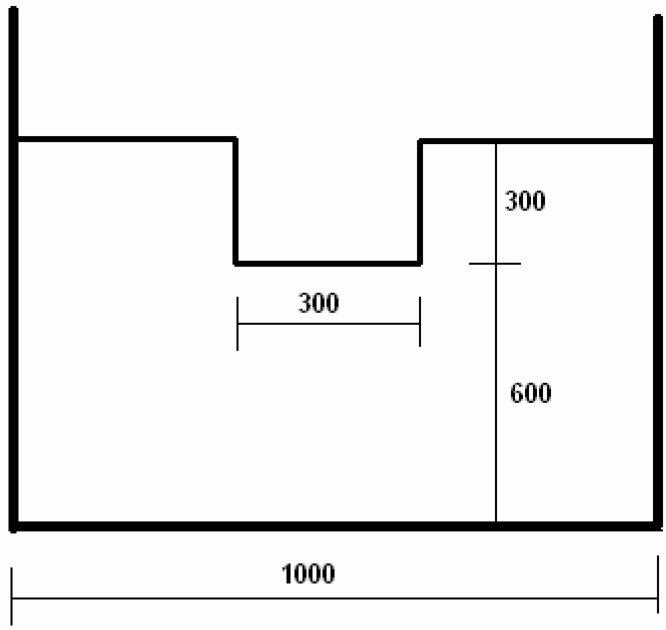

Figure 7-5: Weir with notch

With such a notch, the flow will be restricted to the 300 mm width of the notch, until a head of 300 mm develops over the notch. Once the head exceeds 300 mm, flow occurs over the full width of the fishway. To be able to arrive at a fishway that will cost approximately the same as the fishway in the previous example, the depth of the pool at start of flow is reduced to 600 mm.

7.5.2 *Discharge*

The formula for calculating the discharge is the same as given in Section 7.4.2 as follows:

- For H_1 less than 0.150 m free flow exists through the notch with B = 0.3 m
- For H_1 between 0.150 and 0.300 m, submerged flow exist through the notch and a correction to the flow must be made using the formula for submerged flow given in Section 7.4.2
- For H_1 between 0.3 and 0.450 m, submerged flow exists through the notch (B=0.3 m) and free flow occurs over the rest of the weir (B = 1.0-0.3=0.7 m)
- For H_1 above 0.450 m, submerged flow occurs in the notch and over the rest of the weir.

7.5.3 *Turbulence*

The calculation of the power per unit volume proceeds as in Section 7.4.3, except that the total discharge over the notch plus over the rest of the weir is used in the calculation.

The results are given in Table 7-3.

Table 7-3 Discharge and Turbulence: Pool and weir fishway with a notch in the weir

Notched weir	
Channel Width (B)	1.00 m
Pool Depth (D)	0.60 m
Discharge Coefficient Cd)	0.60
Drop between pools (DH)	0.15 m
Length between pools (L)	1.30 m
Thickness of weir (T)	0.30 m
Effective length of pool (Le)	1.00 m
Depth of notch (Dn)	0.3 m
Width of notch (Bn)	0.3 m
Slope	1/8.7

Notch					**Weir**				**Total**	
H1	**Qf**	**H2**	**K**	**Qs**	**Qf**	**H2**	**K**	**Qs**	**Q**	**Pv**
0.05	6	-0.10	1.00	6	0	-0.40	1.00	0	6	13
0.10	17	-0.05	1.00	17	0	-0.35	1.00	0	17	35
0.15	31	0.00	1.00	31	0	-0.30	1.00	0	31	61
0.20	48	0.05	0.95	45	0	-0.25	1.00	0	45	83
0.25	66	0.10	0.89	59	0	-0.20	1.00	0	59	103
0.30	87	0.15	0.85	74	0	-0.15	1.00	0	74	121
0.35	110	0.20	0.80	89	14	-0.10	1.00	14	102	159
0.37	120	0.22	0.79	94	23	-0.08	1.00	23	117	178
0.40	134	0.25	0.77	103	39	-0.05	1.00	39	143	210
0.45	160	0.30	0.74	119	72	0.00	1.00	72	191	267
0.48	178	0.33	0.72	128	96	0.03	1.00	96	225	305

The advantage of providing the notch in the weir is obvious from Table 7-3. At the stage where the notch is flowing full without water spilling over the rest of the weir (H1 = 0.3 m), the power per unit volume is 121 watt/m^3 at a flow of 74 l/s. The power per unit volume reaches the limit of 180 watt/m^3 at a head of 0.37 m at a flow of 117 l/s. As expected the turbulence increases rapidly after the full width of the weir starts spilling.

7.6 Design of a pool and weir fishway with a sloping weir

7.6.1 *Dimensions*

For comparison with the previous designs the width of the fishway is chosen at 1m, the drop between the pools at 150 mm and the weir thickness at 300 mm. The cross slope of the weir is chosen at 1:4. With a width of fishway of 1 m, this will allow for a head of 250 mm before the water flows over the full width of the weir. The pool depth is chosen as 650 mm at start of flow. The height of the weir at the opposite bank will therefore be 900 mm, agreeing with the dimension of the full width weir in the above example.

The selected dimensions are shown in Figure 7-6.

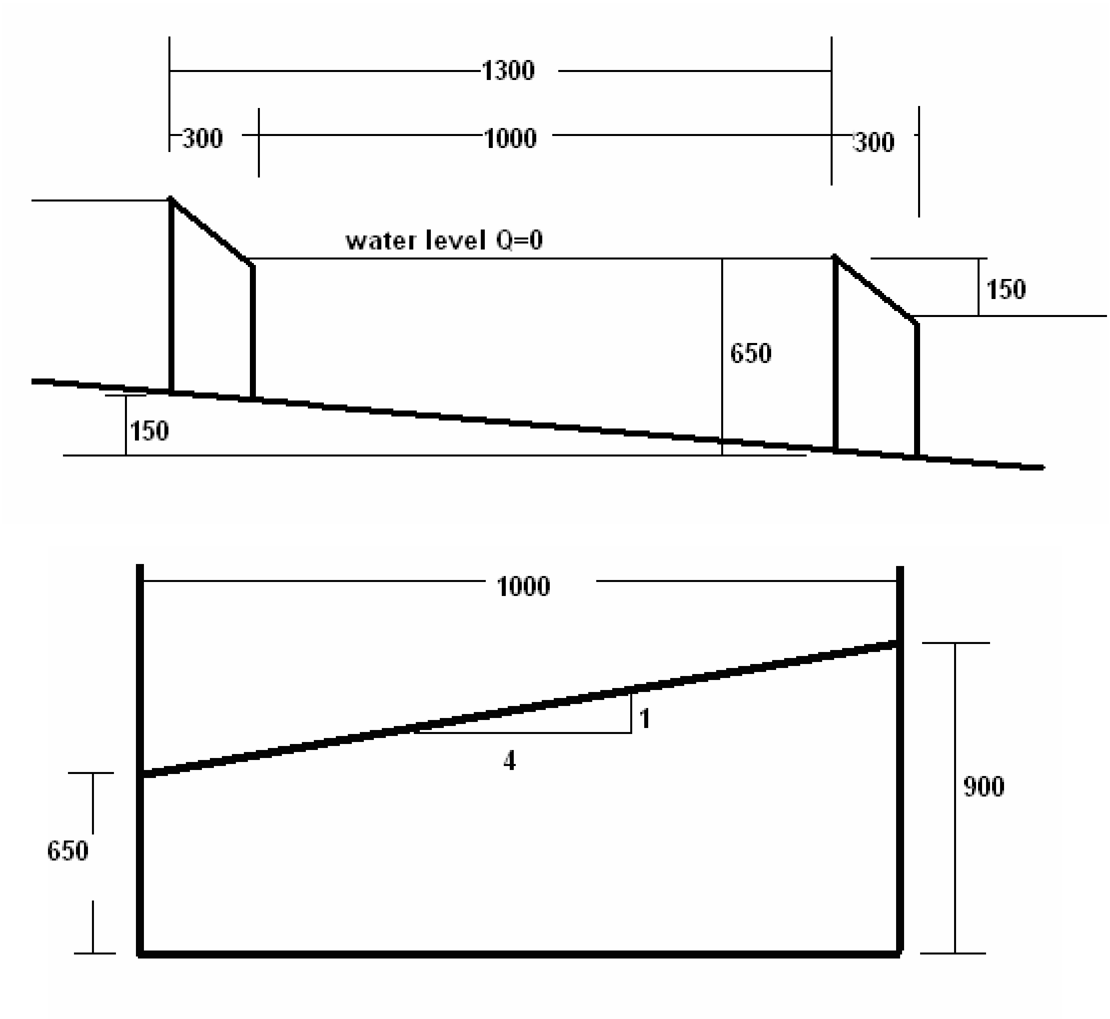

Figure 7-6: Layout of sloping weir fishway

7.6.2 *Discharge*

The approximated formula for free discharge reads:

$$Q = 8/30\ Cd\ (2g)^{0.5}\ \tan\theta/2\ H_1^{2.5}$$

Where:

$\theta/2$: the angle of the cross slope of the weir as shown in Figure 7-7

H_1: the head above the low point in the weir

Cd: discharge coefficient

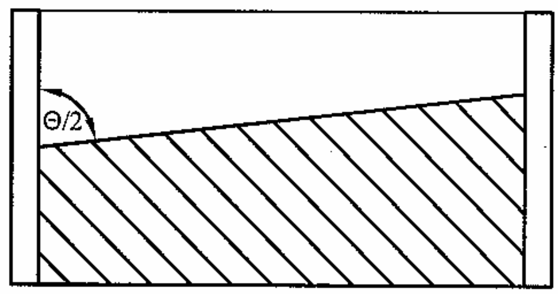

Figure 7-7: Sloping weir - Definition sketch

When the water level in the pool below the weir becomes higher than the crest of the weir (H1 above 150 mm in example), submerged conditions occur and the discharge will be reduced as described in section 7.3.2, i.e.:

$Q_s = K\ Q_f$

Where: $K = (1-((H_1\text{-}DH)/H_1)^{2.5})^{0.385}$ as shown in Figure 7-3

7.6.3 *Turbulence.*

The turbulence in the pools is calculated as before i.e.

$P_v = \rho\ g\ Q\ DH/\ (B\ L_e\ D_e)$.

7.6.4 *Evaluation of fishway*

To evaluate the performance of the fishway, the discharge and power per unit volume are calculated for various values of the head above the low point of the weir. The results are shown in the Table 7-4.

The sloping weir fishway has been developed to accommodate creeping and crawling species that needs a wetted splash zone to negotiate the weirs. The weirs in the example will become submerged over their full width when H1 reaches 0.25 m. At this stage the discharge will be 86l /s and the turbulence level at 154 watt/m^3. If the fishway is designed to reach a turbulence level of 180 watt/m^3 at a H1 value of 250 mm, the height of the weir can be slightly reduced. In this example this will be achieved if the minimum pool depth is reduced from 650 mm to 500 mm.

Table 7-4 Discharge and turbulence: Sloping weir pool and weir fishway.

Sloping weir				
Channel Width (B)	1.00 m		H1min	0.05
Pool Depth (D)	0.65 m		Step	0.05
Side slope of weir	¼			
Discharge Coefficient (Cd)	0.61			
Drop between pools (DH)	0.15 m			
Length between pools (L)	1.30 m			
Thickness of weir (T)	0.30 m			
Effective length of pool (Le)	1.00 m			
Slope	1/8.7			

H1 (m)	**Qf (l/s)**	**H2 (m)**	**K**	**Qs (l/s)**	**Volume (m^3)**	**Pv (watt/m^3)**
0.05	1.6	-0.100	1.000	1.6	0.625	4
0.10	9.1	-0.050	1.000	9.1	0.675	20
0.15	25.1	0.000	1.000	25.1	0.725	51
0.20	51.6	0.050	0.988	50.9	0.775	97
0.25	90.1	0.100	0.960	86.4	0.825	154
0.27	109.2	0.120	0.947	103.4	0.845	180

7.7 Vertical slot fishway

7.7.1 *Dimensions*

The design process for vertical slot fishways is illustrated below. For direct comparison with the pool and weir fishways discussed above, the same basic design parameters, i.e. a drop between the pools of 150 mm and a fishway width of 1000 mm is selected for this example.

The recommended layout by Lariner *et al.* (2002b), as shown below will be used in this illustration Figure 7-8:

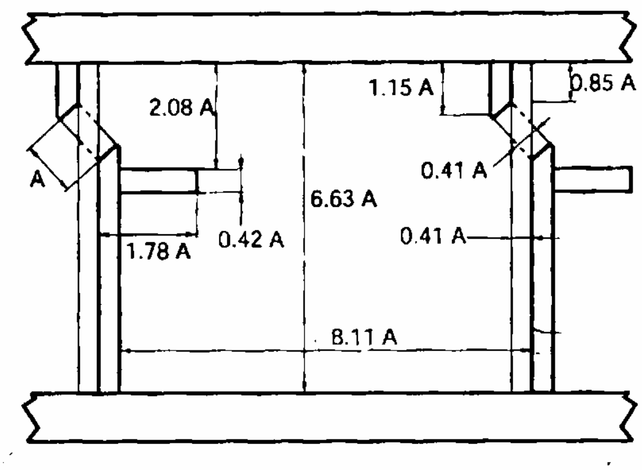

Figure 7-9: Recommended layout of vertical slot fishway (From Lariner *et al.,* 2002).

With the pool width (B) chosen as 1000 mm, the other important dimensions are:

- Width of slot: A = B/6.63 = 1000/6.63 = say 150 mm
- Effective pool length (Le) = 8.11A = 8.11*150 = say 1200 mm
- Allowing for a wall thickness of100 mm, the distance between pools will be 1300 mm, leading to a slope of 150/1300 = 1/8.67

7.7.2 *Depth of flow in the pools and discharge*

The recommended vertical slot fishway has a sloping bottom with no sill in the slots. At very low flows the depth in the pools will therefore be very low with critical flow in the slot, supercritical flow just down-stream of the slot and a hydraulic jump lower down in the pool. Under these flow conditions it is expected that it will be difficult for fish to negotiate the fishway. As the flow increases the hydraulic jump will move upstream, eventually drowning the critical flow in the slot. This is illustrated in Figure 7-9.

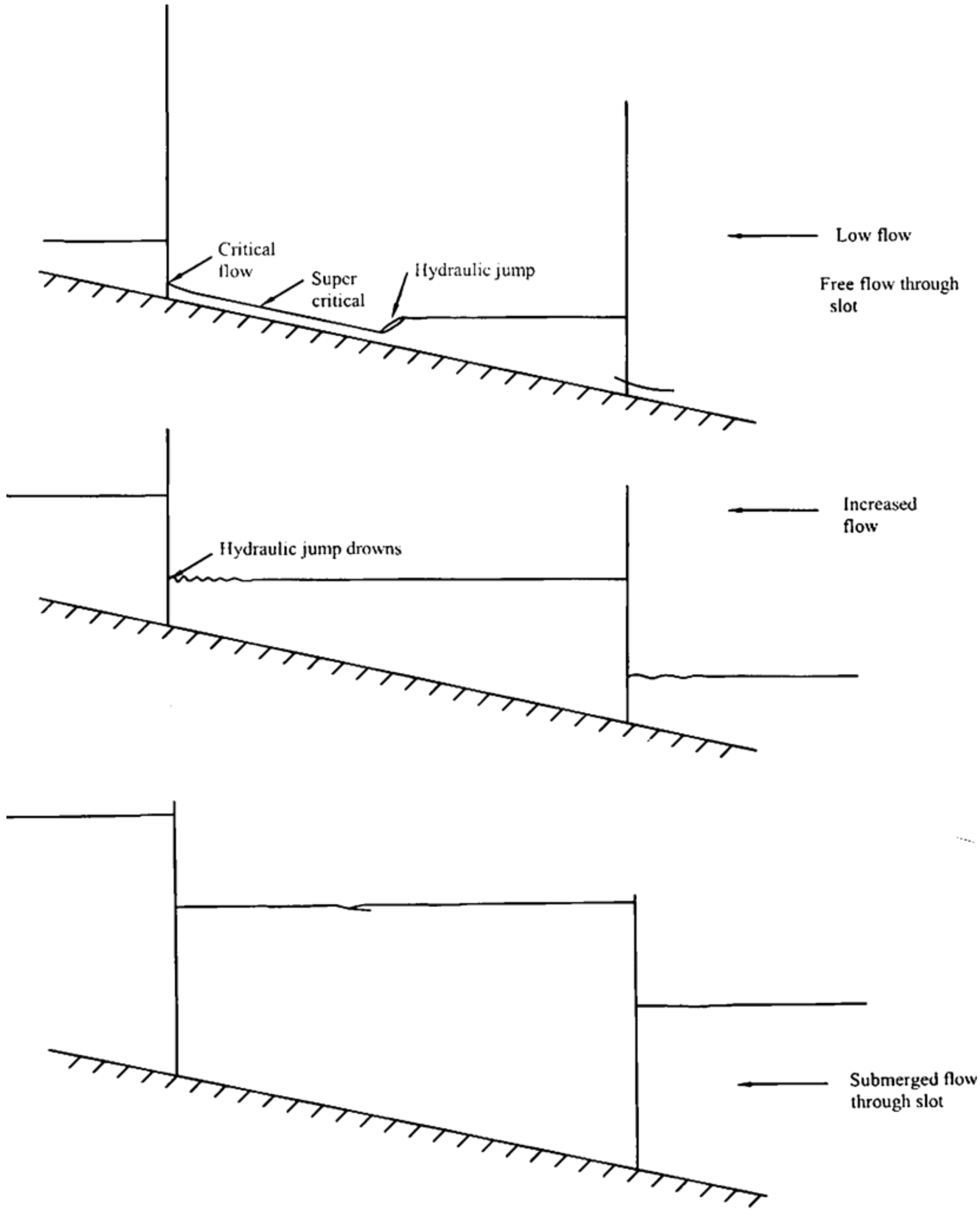

Figure 7-10: Flow conditions in vertical slot fishways

A minimum flow is therefore required for the water level in the pool below the fishway to increase sufficiently to drown the flow in the slot. Once this happens the discharge through the fishway is determined by the head of the water in the pool upstream of the intake, relative to the crest of the control at the intake and the drop between this level and the level in the first pool in the fishway. This is illustrated in Figure 7-10.

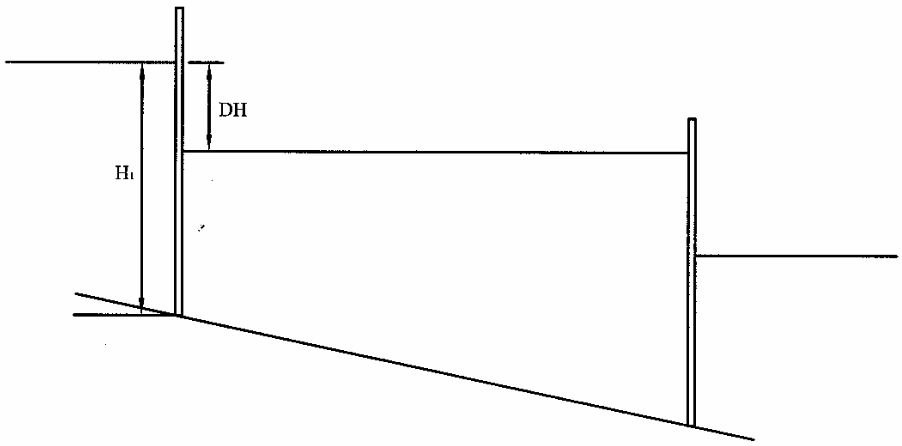

Figure 7-11: Vertical slot fishway: Definition of parameters determining discharge through fishway

At low flows when the water level in the pool below the intake slot is below the level of the floor in the slot (unsubmerged condition), the flow is controlled by critical flow in the slot. The discharge is given by:

$Q_f = 2/3\ C_d\ b\ (2g/3)^{0.5} H_1^{1.5}$

Where:

Q_f: Discharge (m^3/s)

b: width of slot (m) = A in Figure 7-8

g: acceleration due to gravity (9.81 m/s^2)

H1: head at slot (m)

Cd: discharge coefficient- 0.9 in example (depends on shape of slot)

At higher flows when the water level in the pool down-stream of the weir is higher than the critical depth in the slot, the discharge Qs is given by:

$Q_s = Cd\ b\ H_1\ (2\ g\ DH)^{0.5}$

Where:

Q_s: Discharge (m^3/s)

b: width of slot (m) = A in Figure 7-8)

g: acceleration due to gravity (9.81 m/s^2)

DH: drop between two pools (m)

C_d: discharge coefficient

The discharge coefficient depends on the shape and form of the slot. For a rounded slot Cd =0.85 and for a sharply bevelled slot Cd =0.61

7.7.3 *Turbulence*

It is now also possible to calculate the dissipated power per unit volume as:

$Pv = \rho\ g\ Q\ DH/Vol$ as before.

7.7.4 *Evaluation of fishway*

The results of these calculations are summarized in Table 7-5.

At low flows when the pools are not filled with water, supercritical flow occurs below the slot and high turbulence levels are experienced. Once the head on the pools exceed the drop between the pools (0.15 m), the flow stabilises and near constant turbulence levels are experienced. In the example the pools fill with water at a flow of about 13 l/s and thereafter the turbulence level stabilises around 200 to 230 watt/m^3, irrespective of the upstream water level or flow volumes. The turbulence levels are higher than the allowable 180 watt/m^3. To overcome this drop between the pools can be lowered or a sill can be constructed in the slot to increase the volume in the pools, thereby reducing the turbulence. Decreasing the drop between the pools from 150 mm to 135 mm, will ensure that turbulence levels remain below 180 watt/m^3 for all flows exceeding 10 l/s.

The ability of vertical slot fishways to operate under a high variation in water levels while maintaining favourable velocities and turbulence levels is a significant advantage at barriers where large variations in levels are expected. The ability to handle large discharges in large rivers where the attraction flows from the fishway have to compete with large river discharges is a further advantage. Generally, the higher the percentage of the river flow passing through the fishway, the greater the attraction into entrance.

Table 7-5: Discharge and Turbulence: Vertical slot fishway

Vertical slot without sill	
Slot width (b)	0.15 m
Channel width (B)	1.00 m
Discharge Coefficient (Cd)	0.61
Drop between pools (DH)	0.15 m
Length between pools (L)	1.30 m
Thickness between pools (T)	0.10 m
Effective length of pool (Le)	1.20 m
Slope	1/8.7

H1	Yc	H2	H2/H1	Q	Vs	Vol	Pv
0.050	0.033	0.000	0.000	0.0026	0.572	0.011	349
0.100	0.067	0.000	0.000	0.0073	0.809	0.043	247
0.150	0.100	0.000	0.000	0.0134	0.990	0.090	219
0.200	0.133	0.050	0.250	0.0206	1.144	0.150	202
0.250	0.167	0.100	0.400	0.0288	1.279	0.210	202
0.300	0.200	0.150	0.500	0.0378	1.401	0.270	206
0.350	0.233	0.200	0.571	0.0477	1.513	0.330	213
0.400	0.267	0.250	0.625	0.0582	1.617	0.390	220
H1	**Yc**	**H2**	**H2/H1**	**Q**	**Vs**	**Vol**	**Pv**
0.450	0.300	0.300	0.667	0.0706	1.716	0.450	231
0.500	0.333	0.350	0.700	0.0785	1.716	0.510	226
0.550	0.367	0.400	0.727	0.0863	1.716	0.570	223
0.600	0.400	0.450	0.750	0.0942	1.716	0.630	220
0.650	0.433	0.500	0.769	0.1020	1.716	0.690	218
0.700	0.467	0.550	0.786	0.1099	1.716	0.750	216
0.750	0.500	0.600	0.800	0.1177	1.716	0.810	214
0.800	0.533	0.650	0.813	0.1256	1.716	0.870	212
0.850	0.567	0.700	0.824	0.1334	1.716	0.930	211
0.900	0.600	0.750	0.833	0.1413	1.716	0.990	210
0.950	0.633	0.800	0.842	0.1491	1.716	1.050	209
1.000	0.667	0.850	0.850	0.1570	1.716	1.110	208

The problem with critical flow in the slots at low flows can be overcome to some extent by placing roughness in the form of rocks and boulders on the bottom of the fishway. Experiments in small scale models have shown that the placement of bottom strata dramatically increases the ability of small fish to negotiate this type of fishway at low flows. The provision of rock strata on the bottom also improves the velocity distribution in the fishway (see Figure 7-11). The low velocities near the bottom combined with a continuous slope (i.e. no steps in the bottom) allows weak swimmers and some creeping and crawling species to migrate upstream along the bottom.

Research elsewhere (FAO/DVWK 2002) stresses the importance of having a continuous slope of rock strata along the bottom of the fishway, which is contiguous with the river-bed down-stream of the fishway.

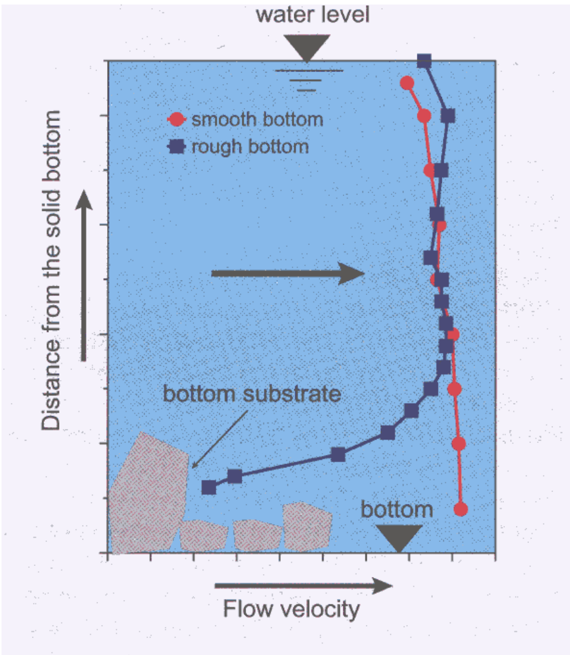

Figure 7-12 Velocity distribution in a vertical slot fishway (FAO/DVWK 2002).

7.8 Pool and Slot Fishway

One way to eliminate the problems with low flows in a vertical slot fishway is to provide a sill in the slot to form a pool upstream of the sill. At low flows the sill controls the flow and the fishway acts as a pool and weir fishway. At higher flows the water levels in the pool below the weir drowns the flow over the weir and the fishway starts acting more like a vertical slot fishway. At high flows the slot controls the flow and in effect becomes a vertical slot fishway.

To illustrate the effect of the sill, a 150 mm high sill is placed in the slot of the vertical slot fishway discussed in section 7.6 above, while maintaining a drop between the pools of 150 mm. In the analysis the fishway is treated as a pool and weir fishway until water level at the upstream end of the pools exceed the critical depth on the sill. Thereafter the fishway is analysed as a vertical slot fishway. The results of the analysis are shown in Table 7-6.

In the analysis the turbulence levels remained below acceptable values of 180 watt/m^3 for all flow rates.

From Table 7-6 it can be seen that providing the sill in the Pool and slot fishway, eliminates the problem with minimum flow requirements. The pool created by the sill ensures that turbulence levels remain low, especially at low flows. At high flows the turbulence levels remain below the acceptable limit of 180 watt/m^3.

The pool and slot fishway therefore seems to be ideal for combining the best characteristics of pool and weir and vertical slot fishways. The only criticism against the pool and slot fishway is that it does not allow a continuous slope along the bottom as in the case with the vertical slot fishway.

Table 7-6 Discharge and Turbulence: Pool and slot fishway

Slot with Broad crest sill	
Slot with (b)	0.15 m
Channel Width (B)	1.00 m
Sill Height	0.15 m
Discharge Coefficient sill (Cd_1)	0.90
Discharge Coefficient slot (Cd_2)	0.61
Drop between pools (DH)	0.15 m
Length between pools (L)	1.30 m
Thickness of wall (T)	0.10 m
Effective length of pool (Le)	1.20 m
Sill Slope	1/8.7

H1min	0.050
H1max	1.000
Step	0.050

H1	Yc	H2	H2/H1	Q	Qs	Vslot	Vol	Pv
0.050	0.033	-0.100	-2.000	0.0026	0.0026	0.572	0.150	25
0.100	0.067	-0.050	-0.500	0.0073	0.0073	0.809	0.210	51
0.150	0.100	0.000	0.000	0.0134	0.0134	0.990	0.270	73
0.200	0.133	0.050	0.250	0.0206	0.0206	1.144	0.330	92
0.250	0.167	0.100	0.400	0.0288	0.0288	1.279	0.390	109
0.300	0.200	0.150	0.500	0.0378	0.0378	1.401	0.450	124
0.400	0.267	0.250	0.625	0.0582	0.0582	1.617	0.570	150
0.500	0.333	0.350	0.700	0.0785	0.0785	1.716	0.690	167
0.600	0.400	0.450	0.750	0.0942	0.0942	1.716	0.810	171
0.700	0.467	0.550	0.786	0.1099	0.1099	1.716	0.930	174
0.800	0.533	0.650	0.813	0.1256	0.1256	1.716	1.050	176
0.900	0.600	0.750	0.833	0.1413	0.1413	1.716	1.170	178
1.000	0.667	0.850	0.850	0.1570	0.1570	1.716	1.290	179

Some small species and weak swimmers prefer to move along the bottom when continuous rock strata is placed on the bottom, making use of the lower velocities near the bottom created by the bottom roughness. If the sill can also be constructed at a slope, i.e. without any vertical face, and if the rock strata imbedded in concrete can cover the sill, this may help to improve the chances of the weak swimmers to negotiate the fishway. Placing rock strata on the bottom is also reported (FAO/DVWK, 2002) to allow the creeping and crawling species to move through the fishway along the bottom via the bottom strata.

7.9 Comparison of the fishways

The results of the analyses of the three pool and weir fishways and the two vertical slot fishways are shown in Table 7-7. The operating head and flow rates for which the turbulence remains within the accepted limits are given in the table.

Table 7-7: **Comparison of fishways**

All fishways is 1000 mm wide, Max velocities <1.7 m/s, turbulence <180 watt/m^3.

Drop between pools 150 mm and slope 1/8.7 unless indicated differently

Fishway type	Operating head range (m)	Operating flow range (l/s)
Full width weir	0 - 0.180	0 – 134
Notched weir	0 - 0.370	0 - 117
Sloping weir	0 - 0.27	0 - 103
Vertical slot*	0.14 >2	13 - >300
Slot with sill	0 - >2	0 - >300

* Drop reduced to 135 mm, slope 1/9.6

The advantages of pool and weir fishways are that they can operate at relatively low flows but the major disadvantage is that they cannot tolerate large variations in water level at the barrier. The vertical slot fishways operate over a much wider range of water levels and the provision of a sill in the slot improves the hydraulic behaviour of the fishway. A vertical sill in the slot can be a hindrance to weaker swimmers and species that crawl along the bottom. The sill should preferably have a relatively mild downsteam slope and should be roughened to allow easy movement of fish along the bottom.

The maximum velocity in all the fishways discussed above will be approximately 1.7 m/s.This velocity only allows for fish larger than 40 mm and smaller than 400 mm in inland waters. If weaker swimmers and smaller fish must be accommodated, smaller drops and therefore flatter slopes will be required. Allowance for weak swimmers and large fish in a single fishway invariably results in flat slopes which can result in long and expensive fishways. If for instance the fishway must allow for fish below 40 mm, the drop between pools must be reduced to 100 mm (see Table 5-5). If the fishway must also cater for fish up to 600 mm in length, the pools must be at least 1500 mm long, the weirs 200 mm wide, leading to a slope of 100/(1500+200) or 1/17.

Such flat slopes are often not financially feasible and the possibility of constructing separate fishways for the small and large fish should be considered. In Chapter 10 some examples will be given of fishways where special attention will be given to accommodating weaker swimmers.

Analysis of vertical slot fishways aimed at the three categories of inland fish shown in Table 5-5 are shown in Table 7-8. In this analysis a sill of a height equal to the drop between the pools have been used. Limiting turbulence levels, velocities and pool lengths have been adhered to and a minimum slot width of 75 mm has been assumed. The results are as follows in Table 7-8.

The most common inland fishway will probably be a vertical slot fishway catering for fish between 40 and 400 mm. Such a fishway will have to have a maximum slope of 1/9 to keep the velocities and turbulence within acceptable limits. The flat slopes required to cater for very small to very large fish in one fishway is again illustrated by the last row of Table 7-8. The decision about the swimming ability of the weakest swimmer as well as the maximum size that should be allowed for in the fishway will therefore have a strong bearing on the cost of the fishway.

Table 7-8: Maximum slopes for vertical slot fishway for inland fisheries for various categories of fish

Fish size (mm)	**Allowable drop (mm)**	**Allowable Turbulence watt/ m^3**	**Slot width (mm)**	**Fishway width (mm)**	**Pool length (mm)**	**Drop (mm)**	**Turbul. watt/m^3**	**Slope 1/$_3$**	**Comment**
<40	100	150	75	500	600	80	150	9	Drop determined by turbulence
40-100	150	180	150	1000	1200	150	180	9	Both drop and turbulence reach maximum
>100	200	220	150	1000	1200	170	220	8	Drop determined by turbulence
40 - 400	150	180	150	1000	1200	150	180	9	Both drop and turbulence reach maximum
<40 - 600	100	150	180	1200	1500	100	80	16	Slope determine by small drop and long pools.

7.10 Construction Protocol

The following construction protocol should be followed after the design has been approved in order to monitor the actual construction of the fishway at the approved site. From experience it is imperative that the site engineer and the biologists work together during the construction phase so that possible construction errors are prevented. A flow diagramme outlining the various steps to be undertaken to ensure successful construction and commissioning of a fishway, is given in Figure 7-12.

7.10.1 *Project Management*

When a fishway is constructed as part of a larger project (e.g. incorporated into a proposed weir), the standard civil engineering project management procedures should be sufficient to ensure that the previously approved designs and dimensions are strictly adhered to. In addition, it must be clearly stipulated in the construction contract that any changes to the final designs during construction due to “on site” problems encountered, should not be made without prior approval from both the fish biologist and/or hydraulic engineer involved in the fishway project.

7.10.2 *Work Performance*

Accuracy

Specific constraints regarding the level of accuracy required for essential dimensions of pools and slots, invert levels of all walls, weirs and water feed channels, etc. should be set out in the specifications. Levels should be accurate to the nearest centimetre.

Auditing of Construction

Regular site visits should be undertaken by the individual (or individuals) familiar with the design criteria of the fishway (fish biologist and/or hydraulic engineer). Site visits should at least be undertaken at the following critical stages:

- Completion of excavation work;
- Completion of shuttering, before pouring of any concrete;
- Completion of any critical elements of the work;
- Final completion, but before site is handed back.

Aspects of concern include the presence of sharp edges that could injure migrants, the presence of a suitable channel and holding pool in the river bed below fishway (i.e. make sure that this area has not been altered or filled in with rubble) and that all dimensions specified in the design drawings have been adhered to.

Final Acceptance

Undertake an accurate hydraulic audit of the fishway, including the accurate measuring of fishway dimensions and levels of upstream sill and the crest of each pool spillway and notch (if present), dam or weir spillway crest level, etc. and record on “As Built” drawing.

The fishway structure should be flooded and the hydraulic functioning assessed before the work is finally approved. At this time, discharges and current velocities, etc. at various water levels should be calculated (or measured). If necessary, minor alterations to the dimensions of critical areas (slot widths, weir crest levels) should be made to improve the hydraulic performance within the fishway.

1. Project Planning:

- Ensure standard project management procedures are in place for fishway construction
- Ensure strict adherence to specifications of fishway design, with small margins of error
- Any changes in design or dimensions to be authorised by the responsible fish biologist and/or hydraulic engineer prior to implementation

↓

2. Auditing during construction:

- Regular site inspections undertaken by fish biologist and/or hydraulic engineer at critical stages in construction
- Ensure any proposed design changes are approved by biologist/hydraulic engineer beforehand
- Ensure any alterations made to river bed down-stream of structure are taken into account in location of fishway entrance

↓

3. Final Audit:

- Ensure all dimensions of fishway are as per final design
- Do accurate survey of fishway (level of upstream sill and link with water level recorder datum level (if present), level of entrance platform, level of crest of each pool spillway and notch (if present) and measure actual width of each notch or slot, full supply level of dam (spillway crest level), etc. and record on “As-built” drawing)
- Allow discharges down fishway and inspect critical areas for potential problems (e.g. high velocity and/or turbulence)
- Make minor alterations, as required, to improve functioning of fishway
- Give final approval and commission fishway

Figure 7-12 Construction Protocol for the provision of a fishway.

8 MONITORING AND OPERATIONAL MANAGEMENT

8.1 Introduction

There is a paucity of quantitative data on the performance of existing fishways in South Africa, particularly information identifying the designs that are more successful in allowing the passage of the full range of target species. In addition, more information is required regarding the swimming ability and the migratory behaviour of indigenous southern African fish species. Carefully designed fishway monitoring programmes on existing fishways in South Africa could supply this information and thus help to ensure the development of improved fishway designs and operation in southern Africa.

Fishway monitoring should therefore be designed to provide data on both the effectiveness of the fishway in terms of the internal hydraulics at various flows, as well as data on the migratory behaviour and swimming ability of the migrants. (Note: In this context the word “fish” is used for all migratory aquatic biota, including crustaceans (prawns and crabs) as well as eels).

8.2 Fishway Monitoring Protocol

The majority of fishway assessments in South Africa in the past have simply involved catching and recording the fish moving through the fishway during peak migration periods by placing a trap at the upstream end or exit. This information does give an indication of what species can successfully negotiate the fishway, but these data have limited value in really assessing the effectiveness of the fishway being studied.

To accurately assess fishway performance, information is required on the number and size composition of fish species attempting to migrate past the barrier, but could not find the fishway entrance, as well as the fish which entered the fishway but were unable to reach the top. In addition, in order to better understand the environmental cues which stimulate fish migrations, a host of environmental parameters (abiotic and biotic) need to be measured during the monitoring period, which should be over months rather than weeks. It is apparent that carefully planned monitoring programs and more sophisticated monitoring methods are required to assess the effectiveness of fishways in South Africa, in order to improve their design and to optimise their management.

Details of the monitoring procedures to be used and the techniques and equipment used to collect the data will naturally vary from site to site, but a generic fishway monitoring programme should attempt to answer the questions posed below.

8.2.1 *Key Questions*

8.2.1.1 Biological/Ecological Parameters

- What species, size and numbers of fish successfully pass through the fishway?
- What species, size and numbers of fish attempt to use the fishway (i.e. are actively migrating and enter the down-stream end of the fishway)?
- What species, size and numbers of fish actively migrating are blocked by the barrier in question and what proportion actually enter the fishway?

- Why are the fish migrating? Reasons could include sexual reproduction, colonization/dispersion, feeding, over-wintering, etc.

8.2.1.2 Physical Parameters

- Do the water discharge rates down the fishway impact on successful use of the fishway by the different species, or size of fish?
- How does the internal hydraulics in the fishway (current speed, turbulence and depths in critical areas) change at the various discharges?
- How does the discharge down the fishway vary with changes in stream flow in the main river channel?
- At what levels of stream-flow or stages of the flood hydrograph do peak migrations in the river take place?
- Do peak migrations in the river correspond to peak movement through the fishway - i.e. is the fishway effective at river flows when peak fish migrations occur?
- When (time of day/night, season) do migrations of the various species occur?
- How does water quality (temperature, conductivity, pH, turbidity) impact on fish migration?
- What other environmental cues (barometric pressure, air temperature, wind, phase of the moon, tidal cycle, etc.) appear to influence fish migration?
- Are there physical constraints down-stream that could impact on fish migration at the fishway site, such as natural or man-made barriers, closed estuary mouth, etc?

8.2.2 *Data Collection*

As mentioned above, the techniques and equipment used to collect the data required to answer the questions posed above, will vary depending on conditions at the site. In some instances, collection of quantitative data will be virtually impossible, such as numbers of fish migrating during flood conditions, and visual estimations will have to suffice. The data collection equipment and procedures suggested below should therefore be used as a guide and adapted as the need arises.

All data collected during each monitoring session should be accurately recorded on field data sheets.

8.2.2.1 Fish Capture

Details of fish capture methods as well as equipment will vary depending on the physical constraints at the site and type of fishway. Care should be taken to ensure that traps placed in the fishway do not interfere significantly with the internal hydraulics of the fishway. The following gear should be used where appropriate:

- **Funnel trap nets**. These should be designed to fit snugly into the fishway pools. Funnel placement should be aimed at capturing fish moving both upstream and down-stream. These traps should be sufficiently large and include areas of slow-flowing water so that the fish can be held without injury or stress for long periods and can be easily removed alive for identification and measuring.

Ideally, a funnel trap for the fishway exit (upstream end) as well as for the down-stream end (most down-stream pool) should be constructed to allow paired sampling to take place. In natural-type fishways, wing-nets on the side of the traps may be necessary to guide the migrating fish into the funnel trap.

- **Stop nets**. A sufficient number of stop nets (at least 4) consisting of fine-meshed netting attached to a solid (normally rectangular) frame that fits tightly in the fishway channel will allow sections of the fishway to be partitioned off. Placement of the nets will enable the fish present in each section (e.g. top, middle and bottom) to be captured and analysed separately in order to detect the presence of bottlenecks in the fishway.
- **Dip nets.** Their size should match the internal dimensions of the fishway channel or pools to ensure effective operation.
- **Other fishing gear**. The standard range of fish capture methods and equipment should be used for sampling both in the fishway and in the river down-stream of the barrier, depending on the conditions. This gear could include electro-fishing apparatus (fish-shocker); seine nets, throw nets, fyke-nets and fish-traps. Destructive sampling gear such as gill nets should be used with caution.

8.2.2.2 Sampling Down-stream (and Upstream) of the Fishway

It is important to establish what species and size range are present down-stream of the barrier weir that could potentially use the fishway. In addition, the species and size range that actively migrate and are blocked by the barrier weir should be determined, as this may differ from that found in the fishway. In some cases, the species and population structure of migratory species upstream of the fishway should be established.

Down-stream

The full range of habitats presents below (for about 100 m) the fishway and barrier weir should be sampled for fish. To achieve this, a variety of catch methods should be used to ensure that all species, as well as all size classes, are sampled. Methods employed could include throw nets, dip nets, gill nets, seine nets, and traps. Sampling frequency will depend on river conditions (e.g. flow levels), and whether fish are actively migrating through the fishway. When fish are actively migrating and the fishway itself is being intensively monitored, a sampling frequency of up to once a day with a seine net (throw-net/electro-fish shocker) at the fishway entrance, in order to catch fish attempting to enter the fishway, is suggested.

8.2.2.3 Sampling in the fishway

Upstream migrants who have successfully negotiated the fishway should be captured by means of funnel traps placed at the upstream end, i.e. near the exit of the fishway. In long fishways, a trap could be placed within the fishway (e.g. at the halfway stage or first bend or resting pool in fishway). A trap should also be placed at the bottom of the fishway to catch all migrants that enter the fishway. Comparative catch data from these localities should indicate whether some species or size classes enter the lower part of the fishway, but have difficulties negotiating the entire structure.

Bottlenecks in fishway

Various sections of the fishway should be blocked off with stop nets and sampled with dip nets or an electric fish shocker at high, medium and low flows. Accumulation of fish at any point will indicate whether there are any bottlenecks within the fishway when operating at various flows.

Down-stream migrants

A two-way trap could be installed half-way up (or bottom of) the fishway to capture fish moving both up and down the fishway. Large-scale use of the fishway for down-stream migration is usually not anticipated, as studies elsewhere have shown that down-stream migration usually takes place over the weir crest when it overtops during high water levels.

8.2.2.4 Data Collected from Fish

Details of each fish should be recorded, including:

a) Date, time period and locality captured,

b) species, and

c) length and sexual condition/gonadal maturity (if adult).

Fish captured in the river below the barrier should be returned unharmed to the site of capture, if possible. Fish captured in the fishway migrating upstream should be placed unharmed upstream of the fishway, while down-stream migrating fish should be placed in the river below the barrier.

8.2.2.5 Fish tagging or marking

This is normally only feasible if an intensive, long-term study is intended. Fish captured swimming upstream in the fishway or at the exit of the fishway should be tagged or fin-clipped and returned unharmed upstream of the weir. Fish captured swimming down-stream in the fishway or captured in the river down-stream of the fishway should be tagged and released below the weir. Any recaptures will enable subsequent down-stream or upstream migration of these fish to be detected.

8.2.2.6 Abiotic Data

The following water quality data from the fishway (and in some instances, in the river or tailwater pool down-stream of the fishway, as well in the headwater pool) should be recorded during each monitoring session, e.g. once or twice (dusk and dawn) daily and more often if the water conditions change rapidly (e.g. during floods):

- Temperature - maximum and minimum
- conductivity (or TDS)
- turbidity

If considered necessary (i.e. likely to change during the monitoring session), parameters such as pH and dissolved oxygen could also be measured at suitable intervals.

Further data recorded during each monitoring session (i.e. between setting and clearing of the traps) should include:

- headwater and tailwater levels at the barrier,
- water flow volumes (or water depths) spilling over the weir crest, and/or via attraction water outlet, if applicable),
- water volumes down fishway (including any auxiliary water),
- weather conditions (rain, cloud cover, air-temperature, wind speed and direction, barometric pressure).

8.2.2.7 Incidental observations

Observations of additional factors that may possibly influence fish migration or that may be of value in understanding fish migration should be recorded for each monitoring session, such as:

- presence of predators such as birds, otters, etc.;
- unusual migratory behaviour, (e.g. crawling or leaping activity) or accumulations of fish at the entrance, exit or in sections of the fishway;
- changes in water flow down fishway during session due to regulation of inlet sluices, manipulation of attraction or auxiliary water, rise or drop in river flow, changes in water quality, etc.

8.2.3 *Monitoring Period and Frequency*

Ideally, monitoring during the first few years after construction of the fishway should take place over the entire period of the year during which fish movement is likely to take place and when the fishway is operational, i.e. when there is water flowing down the fishway. However, in practice the intensity and duration of any monitoring programme is usually governed by factors such as available funding and manpower. After commissioning of the fishway, an initial monitoring period of at least one month during the peak migratory period will be required to assess its effectiveness and to fine-tune its operation.

8.2.3.1 Long-term, Low-intensity Monitoring

Ideally, low-intensity fishway monitoring should take place continuously during the entire period during which the fishway is operational. The level of intensity will naturally depend on available staff and funding, as well as numbers of fish moving through the fishway at the time.

<u>Sampling Frequency</u>

Clearing and resetting of traps within the fishway should take place at least once (preferably twice, at dawn and dusk) every 24 hours.

<u>Data Recorded</u>

The standard data as listed in the fishway monitoring field data sheets should be filled in. The minimum information recorded from the fish captured would be the number and the size range of each species, with preferably the size of a representative sub-sample of each species measured individually. The water quality data could be obtained (or extrapolated) from existing water quality monitoring programmes that are in place at or near the fishway site.

8.2.3.2 Intensive, Short-term Monitoring

Intensive monitoring should ideally take place during periods of peak migration, usually thought to occur after rainfall events in spring and summer and/or during and immediately after floods and freshets. At this time as much information as possible on fish movements and related abiotic factors, should be collected.

Sampling Frequency

Clearing of traps within the fishway should take place every 4 to 8 hours, depending on the numbers of fish migrating through the fishway. Sampling at dawn and dusk will allow diurnal migratory peaks to be determined. Variable water quality data such as water temperature, conductivity and turbidity should be obtained 2 to 3 times a day (dawn, midday and dusk), if found to change significantly. Other abiotic parameters should be measured once a day unless conditions are obviously fluctuating (e.g. during floods).

Data Recorded

This should include detailed water quality data and other abiotic data (see above) and measurements from all (or most) of fish caught, as set out in the fish monitoring field data form. Fish could be tagged and released as described above, if a long-term programme is envisaged.

Paired Sampling

During the period of active migration it is important to assess the effectiveness of the fishway by means of paired sampling. The objective is to compare the fish that located and entered the fishway (bottom sample) to an independent sample of fish that located, entered and successfully passed through the full length of the fishway (top sample). To achieve this, a funnel trap should be placed at the top of the fishway for 24 hours, followed by a funnel trap placed at the bottom of the fishway for 24 hours. This should be done on consecutive days to provide paired samples for comparison.

Stop Nets

During this period of intense migration, the use of the stop nets to divide the fishway into top, middle and bottom sections as described above should be undertaken in order to find if any bottle-necks are present.

Hydraulic Data

Information on fishway operation, such as depths of water over baffles and flow volumes and velocities within the fishway should be measured, if possible. Once the relationship between water depths over the baffles, discharge down the fishway and current velocities have been established, only water depths need to be measured for each sampling session.

8.2.4 ***Supporting Studies***

Where feasible, hydraulic studies of the fishway should be undertaken to supplement the fish migration monitoring data. This will allow information on the hydraulic conditions within the fishway (current velocities at critical areas, turbulence, etc.) at various discharges in the fishway to be correlated with the swimming performance of the fish found using the fishway at these times. These hydraulic data can be obtained theoretically, via model studies under controlled conditions in the lab or measurements taken in the fishway in the field during the monitoring programme.

8.3 Management

The information gathered during the monitoring should allow a successful operational management and maintenance plan to be put into place. This should include aspects such as the release of optimal discharges down the fishway, providing additional protection to the migrants from predation, if necessary, placement of debris deflectors or the manual removal of debris and/or sediment from the fishway, increasing attraction or auxiliary water flows, etc.

8.4 Conclusions

It is anticipated that carefully designed monitoring programmes on the various existing fishways in South Africa will make a valuable contribution to the current fishway provision programme in South Africa. Not only will the information allow the effectiveness of the individual fishways monitored to be improved, but these data should facilitate the development of more effective fishway designs suitable for the hydrological conditions and migratory species found in this country.

9 EXAMPLES OF APPLICATION OF GUIDELINES

9.1 Introduction

In Chapter 6 the design process were described and in Chapter 7 the hydraulics of fishways were discussed. To illustrate the application of these procedures two examples will be given in which the complete process will be applied to proposed weirs in the Sabie and Kowie Rivers

9.2 Preliminary biological considerations for a fishway design aimed at the Sabie River, Mpumalanga.

9.2.1 *Introduction*

The biological criteria of a river reach should be the primary determining factors in a fishway assessment. A case-study is presented below to outline the questions asked, processes involved and the biological information that is required from an ecologist for the purpose of fishway assessments.

9.2.2 *Methodology*

On request from engineer or client to provide biological information for the purpose of fishway design, the following procedures should ideally be followed (see Chapter 5 for more detail):

- Determine the species composition of the area of interest.
- Determine the need for a fishway at the barrier under investigation through the application of the necessity protocol. The priority protocol can also be used to determine the relative priority of providing different barriers with fishways.
- Determine the key species/groups to consider.
- Gather the biological criteria of importance for the key species.
- Provide the engineer/client with summarised biological criteria that should be considered in the fishway assessment.

9.3 Results and discussion

Study area/site: The river reach to be considered include the main stem of the Sabie River (Mpumalanga) within the Kruger National Park boundaries.

Expected species diversity: Thirty five fish species can be expected within the study area (Table 10-1). One migratory aquatic macro-invertebrates of the genus *Macrobrachium* (fresh-water prawns) occurred in the system under natural conditions (Table 9-1). The presence of the Corumanu Dam in Mozambique has been responsible for the disappearance of this prawn from the Sabie River. It should therefore be considered in fishway design for the Sabie River as it may populate this river again should downstream barriers be addressed and mitigated.

Necessity and priority protocols: Not completed for the purpose of this case-study

(see chapters 3 and 4 for detail on the application of the necessity and priority protocols).

Key species/groups and their biological criteria to consider:

It is known that all fish of all size ranges migrate for various reasons, but it may not be economically viable or ecologically necessary to cater for all size ranges of all of the fish that occur within the river system. If the fishway is located within a protected area (e.g. South African National Park such as the Kruger National Park), the primary objective of the fishway will be to contribute to biodiversity conservation. This means that the barrier to be constructed should have the minimum possible impact on natural ecological processes of the aquatic ecosystem. The fishway should therefore consider as many species as possible that undertake migrations at some/all stages of their life cycle. Migration is important for the survival of at least 21 of the expected fish species/groups in the system (migratory importance rating of 4 or 5 in SAMigratoryBiota database - Appendix B) and one macro-invertebrate group (*Macrobrachium* spp.). It is therefore critical that the requirements and abilities of these species are met by the fishway design (Table 9-1). Migration is considered moderately important for the survival of a further 11 species/groups (migratory importance rating of 3 in SAMigratoryBiota database - Appendix B). Migration is of little importance to the survival of another 6 expected species.

Table 9-1: **Target migratory fish species and relevant information to be considered in fishway design for the Sabie River.**

Species	Impor-tance of migra-tion for species survival	Recommended maximum A-turbulence, B-drop (mm) between pools and C- velocities (m/s) (based on classes s)	Approximate size range to consider in fishway design (Age/size when migrating)	Time of year when migrating	River flow when migrating
***Hydrocynus vittatus* (adults)**	5	A=220 watt/m^3 ; B=200 mm ; C=2.0 m/s	Consider 400 mm maximum length (250 – 600 mm)	[S1]December to January for breeding. All year for rest	[B1]rainy, high. All flows for rest
***Hydrocynus vittatus* (juveniles)**	5	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	50 – 250 mm	whole year	all flows
Labeobarbus marequensis	5	A=220 watt/m^3 ; B=200 mm ; C=2.0 m/s	Consider 100 to 300 mm [[K1]45 mm sub-adults. [P1] maturity males 70+ ; fem 280+mm up to 450 mm)]	[S1]spring/early summer [[K1]to late summer] [B1]October to April (Sept/Oct and Feb-[Vlok pers comm]) [M2] Nov/Des peak. [M2] May to July in Letaba River.	[S1]rising/swollen rivers
***Anguilla marmorata* (adults)**	5	A= 150 watt/m^3; B= 100 mm; C= 1.4 m/s	adults (down): 550 mm [J1]Upon maturity	[S1]Adults: Rainy season (likely spring)	[S1]adults: strong/high flows
***Anguilla marmorata* (elvers)**	5	A=100 watt/m^3 ; B=75 mm; C=1.2 m/s (NOTE: separate "substrate" eelways or sloping weir fishways recommended)	30-150 mm (TL)	[S1, B7]Elvers: rainy season to late summer	[B7]high flows, receding limb.
***Anguilla mossambica* (adults)**	5	A= 150 watt/m^3; B= 100 mm; C= 1.4 m/s	adults (down): 55 cm [J1]Upon maturity	[S1]Adults: Rainy season (likely spring)	[S1]adults: strong/high flows
***Anguilla mossambica* (elvers)**	5	A=100 watt/m^3 ; B=75 mm; C=1.2 m/s (NOTE: separate "substrate" eelways or sloping weir fishways recommended)	30-150 mm (TL)	[S1&B7]Elvers: rainy season to late summer	[B7]high flows, receding limb.
Where K[1], P[1],S[1] etc. refers to the reference used in the South African Migratory Biota Database (Appendix B)					

Species	Impor-tance of migra-tion for species survival	Recommended maximum A-turbulence, B-drop (mm) between pools and C- velocities (m/s) (based on classes s)	Approximate size range to consider in fishway design (Age/size when migrating)	Time of year when migrating	River flow when migrating
Macobrachium spp	5	A=100 watt/m^3 ; B=75 mm; C=1.2 m/s (NOTE: separate "substrate" prawnways or sloping weir fishways recommended)	adults downstream, both post-larvae and adults upstream)	summer?	medium/low flows?
Brycinus imberi	4	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	30 -150 mm	[S1]summer to late summer after rain. [M2] February to March.	[B1]In spate. (juveniles receding floods)
***Labeo congoro* (adults)**	4	A=220 watt/m^3 ; B=200 mm ; C=2.0 m/s	100-350 mm	[S1]Summer floods, late summer	flooding/swollen, receding floods
***Labeo cylindricus* (juvenile)**	4	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	50-75 mm	[J1]Early to [K1&L1]late summer, with rains. [M2]September to December. March dispersal.	[S1]Floods (summer)
***Labeo cylindricus* (adults)**	4	A=220 watt/m^3 ; B=200 mm ; C=2.0 m/s	75-250 mm	[S1]summer	[S1]Floods (summer)
***Labeo molybdinus* (adults)**	4	A=220 watt/m^3 ; B=200 mm ; C=2.0 m/s	90 – 350 mm	[B1]January to March, [D3]even April [[K1]late summer heavy rains]. [M2] September to December, November peak. [M2] February to May	[K1&S2]swollen rivers
***Labeo molybdinus* (juveniles)**	4	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	[K3]20 – 90 mm	all year	all flows
Labeo rosae	4	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	Consider 90 – 300 mm [[C1]all sizes (40-90 mm), [P1]Mature at 90 mm in males, 125 mm females to 400 mm]	[S1]Start of rainy season (spring/ summer). October - Mei. ([M2] February-March)	rising/swollen rivers. Receding waters for juveniles)

Species	Impor-tance of migra-tion for species survival	Recommended maximum A-turbulence, B-drop (mm) between pools and C- velocities (m/s) (based on classes s)	Approximate size range to consider in fishway design (Age/size when migrating)	Time of year when migrating	River flow when migrating
***Labeo ruddi* (adults and sub-adults)**	4	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	50 – 300 mm [[K1]50 mm-300 mm. Juveniles- 40-50]	[S1]Summer floods [[K1]including late summer]. [M2]November - January.	[B1]flooding and [[K1]heavy rains]
Barbus annectens	4	A=180 watt/m^3 ; B=100 mm ; C=1.4 m/s	40 – 75 mm	Rains (spring/ summer)	[A1]Moderate flows
***Barbus paludinosus* (adults)**	4	A=180 watt/m^3 ; B=100 mm ; C=1.4 m/s	40-150 mm ([B4]Young and adults)	[S1]Rainy season (spring/summer [[K1]including late summer]). [M2] September to November peak	.[M2] low river levels. Floods (summer)?
***Barbus toppini* (adults)**	4	A=180 watt/m^3 ; B=100 mm ; C=1.4 m/s	30-40 mm	[S1]Rainy season (spring/summer [[K1]including late summer])	[S1]Flood/high flows
***Barbus trimaculatus* (adults)**	4	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	50 -150 mm	[S1]Spate after rain / summer [[K1]including late summer] / spring. [M2]Before rain in September. [M2] September-October peak. M2 August to November and February - March.	[S1]Flood/high flows. [M2] before rains
***Barbus unitaeniatus* (adults)**	4	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	50 -150 mm	[K2]Rainy season /summer. [M2] September to December.	[S1]Flood/high flows
***Barbus viviparus* (adults)**	4	A=180 watt/m^3 ; B=100 mm ; C=1.4 m/s	30-70 mm	[S1]Rainy season /summer [[K1]including late summer])	[S1]Flood/high flows
Chiloglanis swierstrai/engiop s	4	A=180 watt/m^3 ; B=150 mm ; C= 1.7 m/s	35 – 70 mm	Spring and summer for reproduction. [M2] November for breeding.	High for reproduction. Receding floods.
Mesobola brevianalis	4	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	35 – 75 mm	early to late summer	swollen rivers edges inundated

Species	Impor-tance of migra-tion for species survival	Recommended maximum A-turbulence, B-drop (mm) between pools and C- velocities (m/s) (based on classes s)	Approximate size range to consider in fishway design (Age/size when migrating)	Time of year when migrating	River flow when migrating
***Micralestes acutidens* (adults)**	4	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	30-80 mm	[S1]Rainy season (spring/summer [[K1]including late summer]) [M2] September - March, peak October/November and March.	after rains
Opsaridium (zambezense) peringueyi	4	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	Reproductive migrations 50 mm – 90 mm. (Dispersal 30 mm – 90 mm)	Spring and summer	Not in flood, freshets & lower flows
Chiloglanis anoterus	4	A=180 watt/m^3 ; B=150 mm ; C= 1.7 m/s	30 mm-65 mm	Rains (spring/ summer)	[P1]Floods (summer). Receding flows.
***Tilapia rendalli* (sub-adults & adults)**	3	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	60 – 300 mm [[P1]Sexually mature 4-5 months]	[S1]Rainy season (spring/summer [[K1]including late summer]). [M2] September to March, peak downstream in March.	[B1]Floods. Swollen rivers
Barbus afrohamiltoni	3	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	40-175 mm	Rains (spring/ summer)	Receding flood waters
Barbus eutenia	3	A=180 watt/m^3 ; B=100 mm ; C=1.4 m/s	40 – 140 mm	[S1]Summer	[S1]rainy season
Barbus radiatus	3	A=180 watt/m^3 ; B=100 mm ; C=1.4 m/s	35-120 mm	Rains (spring/ summer)	[A1]Some flow dependence
***Marcosenius macrolepidotus* (adults)**	3	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	50 mm-300 mm	[B1&P1]Rainy season, [M2] December to April (peak February to April). [M2] March to May peak.	[S1]Flood/high flows
Oreochromis mossambicus (sub-adults)	3	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	60-90 mm	[[K1]including late summer]. [M2] Spring.	[K1]swollen rivers
Petrocephalus wesselsi (catastoma)	3	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	50-130 mm	[B3]A summer rainy season spawner. [M2] December to February.	[B3,B1&P1]Rainy season

Species	Impor-tance of migra-tion for species survival	Recommended maximum A-turbulence, B-drop (mm) between pools and C- velocities (m/s) (based on classes s)	Approximate size range to consider in fishway design (Age/size when migrating)	Time of year when migrating	River flow when migrating
Synodontis zambezensis	3	A=180 watt/m^3 ; B=100 mm ; C=1.4 m/s	50 mm-200 mm	Rains (spring/ summer). [M2] November to March.	In dirty flood waters
***Tilapia rendalli* (fingerlings)**	3	A=180 watt/m^3 ; B=100 mm ; C=1.4 m/s	20-60 mm	[S1]Rainy season (spring/summer [[K1]including late summer])	[K1]swollen rivers
Chiloglanis paratus (adults)	3	A=180 watt/m^3 ; B=150 mm ; C= 1.7 m/s	30 mm -65 mm TL	[S1]summer / rains. [M2] November for breeding.	[P1]Floods (summer)
Glossogobius giuris	3	A=150 watt/m^3 ; B=75 mm(coastal) 100 mm(inland) ; C=1.2 m/s (coastal) 1.4 m/s (inland)	30-150 mm	all year (summer)	lower flows
***Clarias gariepinus* (adults)**	2	A=180 watt/m^3 ; B=150 mm ; C= 1.7 m/s	Consider 150 to 400 mm TL in fishway design. ([P1]150 mm in males and about 190 mm in females to 1400 mm)	[J2]Early summer months	[S1]summer floods [V2]Considerable rainfall
***Clarias gariepinus* (fingerlings)**	2	A=180 watt/m^3 ; B=150 mm ; C= 1.7 m/s	30-150 mm	[B2]Mid-spring to mid-autumn. [M2] Breeding from September - December. December to May dispersal.	[S1]temporary floods
***Oreochromis mossambicus* (adults)**	2	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	90 – 300 mm	summer (temp dependant). [M2] February to May (Dispersal).	[S1]rainy season
Schilbe intermedius	2	A=180 watt/m^3 ; B=100 mm ; C=1.4 m/s	80 mm-300 mm	Rains (spring/ summer). [M2]February to May.	Flood & receding flood
Glossogobius callidus	2	A=150 watt/m^3 ; B=75 mm(coastal) 100 mm(inland) ; C=1.2 m/s (coastal) 1.4 m/s (inland)	25-60 mm	all year	medium

Species	Importance of migration for species survival	Recommended maximum A-turbulence, B-drop (mm) between pools and C- velocities (m/s) (based on classes s)	Approximate size range to consider in fishway design (Age/size when migrating)	Time of year when migrating	River flow when migrating
***Oreochromis mossambicus* (fingerlings)**	1	A=150 watt/m^3 ; B=100 mm ; C=1.4 m/s	30-60 mm	Throughout the year - more during higher flows. [M2]Spring.	All flows
Pseudocrenilabrus philander	1	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	20-130 mm	[S2]Breeds from early spring to late summer. [V2]Upstream autumn?	?
Serranochromis meridianus	1	A=180 watt/m^3 ; B=150 mm ; C=1.7 m/s	35-300 mm	none	NA

9.3.1 *Summarised biological criteria:*

The most important biological criteria to be considered in the fishway design for the Sabie River is summarised in Table 9-2.

9.4 Fishway Design Sabie River

9.4.1 *Design Criteria*

The ecological report above recommends a maximum velocity of 1.7 m/s and a maximum turbulence level of 180 watt/m^3 for the fishway. The specified maximum velocity is associated with a maximum drop between pools of:

$$DH = 1.7^2/2\,g = 0.15 \text{ m}.$$

The ecological study requires a maximum size of fish to be allowed for in the fishway of 400 mm. The effective length of the pools will therefore have to be at least 1.0 m i.e. 2.5 times the length of the largest fish to be catered for.

9.4.2 *Fishway dimensions*

If the drop between the pools is 150 mm, the weirs in a pool and weir fishway will have to be 300 mm thick to allow for a 1:2 slope in the flow direction. In a vertical slot fishway the walls between the pools can probably be thinner depending on the material used for construction (assume 100 mm thick walls). The distance between pools in the pool and weir will therefore be 1.3 m, i.e. 1.0+0.3 m. The maximum slope in the pool and weir fishway will therefore be 0.15/1.3 or 1/8.7 and in the vertical slot fishway about 0.15/1.1 or 1/7.3

Table 9-2: **Summary of important information to consider in fishway design for Sabie River.**

Required Information	Best available knowledge
Target migratory species /groups	See Table 9-1. The species rated between 4 and 5 have a high need to migrate in order to survive
Reason for migration	Some species undergo mass migrations for reproduction (spawning) while most species will migrate at some stage for dispersal, feeding and avoidance of unfavorable conditions.
Size range (length) to be catered for	The size ranges of fish that may require passage through the fishway range between 20 mm and 400 mm. The maximum length of fish to be considered in the fishway design is **400 mm**. A pool length of **1000 mm** (2.5 times 400 mm) should be adequate to pass most of the migratory individuals. Slot width of 150 mm recommended.
Migratory behaviour	Most of the fish species will negotiate fishway by swimming against the current (*Barbus* spp., *Labeobarbus* sp., *Labeo* spp., *Cichlid* spp., etc). Some species (*Chiloglanis*, *Labeos*) may use their mouth parts to cling to bottom or sides. Some may attempt to jump as a last resort (*Barbus*, *Labeobarbus*, *Cichlid* spp). The freshwater prawn may crawl between substrates placed on bottom of fishway.
Timing of migrations	Some species may migrate all year round for dispersal, feeding and avoidance of unfavourable conditions. The primary reproductive migrations will take place in receding floods during high flow season (September to February). The fishway should therefore be able to pass especially adults during and after the high flow period (receding floods) and smaller species/juveniles/sub- adults during rest of the year.
Drops between pools	Most of the key migratory species should be able to negotiate a drop of **150 mm**. Although a drop of 100 mm is recommended for some species, they should be able to use the slower areas along the bottom (with rock/cobble substrate) to negotiate the fishway. A fishway with a drop of 100 mm will be within the limits of all species, should the conservative (more expensive) approach be considered.
Swimming speed	Laboratory and field trials have shown that the majority of the key migratory fish species can successfully negotiate a water velocity through the slot opening of between 0.9 and 1.8 m/s. A water velocity through the slots of 1.7 m/s is recommended. This velocity should allow the vast majority of important migratory fish species and size ranges present to successfully negotiate a vertical slot type of fishway channel with bottom substrates (cobbles). A fishway with a maximum velocity of 1.4 m/s will be within the limits of all species.
Turbulence levels negotiated by weakest swimmer targeted	The turbulence ranges within each bucket that fish have successful negotiated is between 90 and 620 watts/m^3. It is, however, recommended that the turbulence levels not exceed **180 watts/m^3**.

Required Information	Best available knowledge
Jumping abilities	Jumping ability ranges from poor to very good jumpers (1.4 m high).
Climbing/crawling abilities	Climbing ability ranges from poor to excellent. The freshwater prawn and the eels have excellent climbing abilities. Bottom substrates (cobbles) in the fishway will enhance their ability to negotiate the fishway successfully.
Recommended fishway design	A **vertical slot** design is recommended. Combinations of different designs or channel sizes within a vertical slot (Twin Channel Vertical Slot) may be considered to cater for the wide range of species and sizes. A pool and weir type should be the second option. A separate “substrate“ prawnway or sloping weir fishway should be considered if prawns manage to recolonise this river system.
General recommendations	Both hydraulic and biological tests have shown that the success rate of fish attempting upstream passage through a fishway channel is greatly improved by placing a **substrate of rock/pebbles onto the bottom** of the channel. This allows for weaker swimming, crawling or smaller species to find suitable hydraulic conditions to facilitate their passage. This would also allow for other aquatic biota that need to migrate (e.g. prawns, etc.) to find hydraulic characteristics within the channel that suit them. It is important that the design should incorporate facilitate to allow for **monitoring** options (see monitoring guidelines, Chapter 8).

A suitable pool width for the fishway will be 2 times the length of the largest fish, i.e. say 0.8 m. A depth of the pool and weir fishways of at least 500 mm will be required.

For the purpose of hydraulic analysis the following fishway dimensions have been chosen to comply with the minimum requirements above:

- Vertical slot fishways:
  - Drop between pools 150 mm
  - Slot width 150 mm, considered a minimum width for general purpose fishways to be able to deal with debris
  - Width of fishway 1 m (i.e. 6.63 x slot width, see Figure 7-8)
  - Length of pools 1.2 m (i.e. 8.11 x slot width)
  - Distance between pools 1.3 m
  - Slot without a sill and a slot with a sill of 150 mm high
  - Rock strata, at least 150 mm thick, placed on bottom of the fishway reaching up to level of the crest of the sills.

- Pool and weir fishways
  - Drop between pools 150 mm
  - Width of fishway 1 m. This agrees with width chosen for the vertical slot fishways and is probably also a minimum width for general purpose fishways
  - Distance between pools 1.5 m and weir thickness 0.3 m, leading to an effective pool length of 1.2 m
  - Initial depth at start of flow is 600 mm
  - Horizontal weir over full width and weir with a 300 mm x 300 mm notch.

The length and width of the pools are slightly larger than the minimum requirements, allowing for fish up to 480 mm to be accommodated. The reason for choosing slightly larger than minimum dimensions is to prevent overcrowding in the pools during mass migrations. The larger pool dimensions also corresponds to a slot width of 150 mm for the vertical slot, considered a minimum size if only one slot is used. The longer pools will lead to slightly flatter slopes i.e. 1/10 for the pool and weir fishways and 1/8.7 for the vertical slot fishway. The larger pools will also slightly reduce the turbulence levels in the pools.

9.4.3 *Hydraulic analysis*

The hydraulic analysis along the lines of the analysis for the fishways in Chapter 7 was done and the results are summarized in Table 9-3. A sloping weir fishway was not considered since no creeping or crawling species are catered for.

In the pool and weir fishway the limiting factor in each case is the turbulence level which reaches its maximum allowable value at heads on the pool of 160 mm and 400 mm respectively.

In the vertical slot fishway without a sill in the slot the turbulence levels exceeded the allowable values at a drop between the pools of 150 mm. The turbulence levels become acceptable if the drop is reduced to 135 mm, decreasing the slope from 1/9 to 1/10. In the vertical slot fishway with a 150 mm sill in the slot, the limiting velocity and turbulence level is not exceeded at any flow.

Table 9-3: Hydraulic analysis: Pool and full width weir

Pool and weir						
Channel width (B)		1.00 m				
Pool Depth (D)		0.60 m				
Discharge Coefficient (Cd)		0.61				
Drop between pools (DH)		0.15 m				
Length between pools (L)		1.50 m				
Thickness of weir (T)		0.30 m				
Effective length of pool (Le)		1.20 m				
Slope		1/10.0				
H1 (m)	**Qf(l/s)**	**H2 (m)**	**K**	**Qs (l/s)**	**Vol (m^3)**	**Pv (watt/m^3)**
0.05	20.1	-0.100	1.000	20.1	0.780	38
0.10	57.0	-0.050	1.000	57.0	0.840	100
0.15	104.6	0.000	1.000	104.6	0.900	171
0.16	115.3	0.010	0.994	114.6	0.912	185
0.20	161.1	0.050	0.950	153.0	0.960	235
0.23	201.3	0.082	0.913	183.8	0.998	271
0.25	225.2	0.100	0.894	201.2	1.020	290
0.30	296.0	0.150	0.845	250.2	1.080	341
0.35	373.0	0.200	0.804	300.0	1.140	387
0.40	455.7	0.250	0.769	350.5	1.200	430
0.45	543.8	0.300	0.739	401.8	1.260	469

Table 9-4: Hydraulic analysis: Pool with notched weir

Notched weir	
Channel Width (B)	1.00 m
Pool Depth (D)	0.60 m
Discharge Coefficient (Cd)	0.60
Drop between pools (DH)	0.15 m
Length between pools (L)	1.50 m
Thickness of weir (T)	0.30 m
Effective length of pool (Le)	1.20 m
Depth of notch (Dn)	0.30 m
Width of notch (Bn)	0.30 m
Slope	1/10.0

Notch					Weir				Total	
H1 (m)	**Qf(l/s)**	**H2(m)**	**K(l/s)**	**Qs (l/s)**	**Qf**	**H2(m)**	**K**	**Qs(l/s)**	**Q**	**Pv Watt/ m^3**
0.05	6	-0.10	1.00	6	0	-0.40	1.00	0	6	11
0.10	17	-0.05	1.00	17	0	-0.35	1.00	0	17	29
0.15	31	0.00	1.00	31	0	-0.30	1.00	0	31	50
0.20	48	0.05	0.95	45	0	-0.25	1.00	0	45	69
0.25	66	0.10	0.89	59	0	-0.20	1.00	0	59	86
0.30	87	0.15	0.85	74	0	-0.15	1.00	0	74	101
0.35	110	0.20	0.80	89	14	-0.10	1.00	14	102	132
0.40	134	0.25	0.77	103	39	-0.05	1.00	39	143	175
0.45	160	0.30	0.74	119	72	0.00	1.00	72	191	223
0.48	178	0.33	0.72	128	96	0.03	1.00	96	225	255
0.50	188	0.35	0.71	134	111	0.05	0.95	105	239	267

Table 9-5: Hydraulic analysis: Vertical slot without a sill

Vertical slot without sill							
Slot width (b)		0.15 m					
Channel Width (B)		1.00 m					
Discharge Coefficient (Cd)		0.61					
Drop between pools (DH)		0.135 m					
Length between pools (L)		1.30 m					
Thickness of wall (T)		0.10 m					
Effective length of pool (Le)		1.20 m					
Slope		1/9.6					
H1(m)	**Yc**	**H2(m)**	**H2/H1**	**Q**	**Vs**	**Vol**	**Pv (Watt/m^3)**
0.050	0.033	0.000	0.000	0.0026	0.572	0.011	303
0.100	0.067	0.000	0.000	0.0073	0.809	0.045	214
0.150	0.100	0.015	0.100	0.0134	0.990	0.099	179
0.200	0.133	0.065	0.325	0.0206	1.144	0.159	171
0.250	0.167	0.115	0.460	0.0288	1.279	0.219	174
0.300	0.200	0.165	0.550	0.0378	1.401	0.279	180
0.350	0.233	0.215	0.614	0.0477	1.513	0.339	186
0.400	0.267	0.265	0.663	0.0582	1.617	0.399	193
0.450	0.300	0.315	0.700	0.0670	1.627	0.459	193
0.500	0.333	0.365	0.730	0.0745	1.627	0.519	190
0.550	0.367	0.415	0.755	0.0819	1.627	0.579	187
0.600	0.400	0.465	0.775	0.0893	1.627	0.639	185
0.650	0.433	0.515	0.792	0.0968	1.627	0.699	183
0.700	0.467	0.565	0.807	0.1042	1.627	0.759	182
0.750	0.500	0.615	0.820	0.1117	1.627	0.819	181
0.800	0.533	0.665	0.831	0.1191	1.627	0.879	179
0.850	0.567	0.715	0.841	0.1266	1.627	0.939	179
0.900	0.600	0.765	0.850	0.1340	1.627	0.999	178
0.950	0.633	0.815	0.858	0.1415	1.627	1.059	177
1.000	0.667	0.865	0.865	0.1489	1.627	1.119	176
0.950	0.633	0.815	0.858	0.1415	1.627	1.059	177
1.000	0.667	0.865	0.865	0.1489	1.627	1.119	176

Table 9-6: Hydraulic analysis: Vertical slot with 150 mm sill in slot

Slot with Broad crest sill	
Slot width (b)	0.15 m
Channel Width (B)	1.00 m
Discharge Coefficient (Cd1)	0.90
Discharge Coefficient (Cd2)	0.61
Drop between pools (DH)	0.15 m
Length between pools (L)	1.30 m
Thickness of wall (T)	0.10 m
Effective length of pool (Le)	1.20 m
Slope	1/8.7

H1 (m)	Yc	H2(m)	H2/H1	Q	Qs(l/s)	Vslot	Vol	Pv (Watt/m^3)
0.050	0.033	-0.100	-2.000	0.0026	0.0026	0.572	0.150	25
0.100	0.067	-0.050	-0.500	0.0073	0.0073	0.809	0.210	51
0.150	0.100	0.000	0.000	0.0134	0.0134	0.990	0.270	73
0.200	0.133	0.050	0.250	0.0206	0.0206	1.144	0.330	92
0.250	0.167	0.100	0.400	0.0288	0.0288	1.279	0.390	109
0.300	0.200	0.150	0.500	0.0378	0.0378	1.401	0.450	124
0.350	0.233	0.200	0.571	0.0477	0.0477	1.513	0.510	138
0.400	0.267	0.250	0.625	0.0582	0.0582	1.617	0.570	150
0.450	0.300	0.300	0.667	0.0706	0.0695	1.716	0.630	165
0.500	0.333	0.350	0.700	0.0785	0.0785	1.716	0.690	167
0.550	0.367	0.400	0.727	0.0863	0.0863	1.716	0.750	169
0.600	0.400	0.450	0.750	0.0942	0.0942	1.716	0.810	171
0.650	0.433	0.500	0.769	0.1020	0.1020	1.716	0.870	173
0.700	0.467	0.550	0.786	0.1099	0.1099	1.716	0.930	174
0.750	0.500	0.600	0.800	0.1177	0.1177	1.716	0.990	175
0.800	0.533	0.650	0.813	0.1256	0.1256	1.716	1.050	176
0.850	0.567	0.700	0.824	0.1334	0.1334	1.716	1.110	177
0.900	0.600	0.750	0.833	0.1413	0.1413	1.716	1.170	178
0.950	0.633	0.800	0.842	0.1491	0.1491	1.716	1.230	178
1.000	0.667	0.850	0.850	0.1570	0.1570	1.716	1.290	179

Table 9-7: Range of Head and flow for which various fishway designs will be negotiable in Sabie River

Fishway	Range of head m	Range of flow l/s	Max Pv watt/m^3
Pool and weir without notch	0 - 0.16	0 -115	180
Pool and weir with 300 mmx300 mm notch	0 - 0.40	0 - 143	180
Vertical slot without sill-drop reduced to 135 mm	All heads above 0.15	Flows above 13	180
Vertical slot with 100 mm sill in slot	All heads	All flows	180

Hydrological considerations

The flow in the Sabie River is summarized in Table 9-8.

Table 9-8: Percentage of time that flow is exceeded in the Sabie River:

Department of Water Affairs and Forestry
HYFLOW V135
Output 10/11/2006

Time-Weighted Stream Discharge Duration Analysis of Instantaneous Values. Interval
Sabie River @ Lower Sabie Rest Camp   Discharge (Cumecs) Site X3H015
Percentage of Time that Parameter was Equalled or Exceeded.
Period of Record 10/12/1986 to 12/09/2006

%	Total	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	%
100	0.02	2.15	1.06	0.69	0.97	0.43	0.45	0.02	0.41	0.24	0.03	0.08	0.61	100
99	0.30	2.79	1.31	0.82	1.12	0.64	0.55	0.46	0.51	0.28	0.08	0.17	0.82	99
98	0.44	3.28	1.42	1.29	1.22	0.76	0.59	0.52	0.57	0.30	0.14	0.52	1.09	98
97	0.58	3.68	1.78	1.42	1.37	0.83	0.65	0.61	0.61	0.30	0.18	0.74	1.33	97
96	0.68	3.84	2.42	1.72	1.66	0.87	0.74	0.67	0.63	0.32	0.19	0.91	1.74	96
95	0.80	4.15	2.92	2.09	2.12	0.97	0.92	0.72	0.67	0.35	0.21	1.08	1.96	95
90	1.42	5.66	5.59	5.44	4.29	2.92	1.53	0.97	0.85	0.48	0.40	1.49	3.49	90
85	1.91	6.55	6.36	6.87	5.11	4.07	2.49	1.41	1.01	0.71	0.87	1.74	4.41	85
80	2.69	7.40	7.17	8.06	6.91	4.73	2.93	1.77	1.49	1.08	1.27	2.00	5.26	80
75	3.62	8.58	8.88	9.13	8.27	5.44	3.32	2.74	1.72	1.56	1.44	2.33	6.14	75
70	4.25	9.47	10.12	10.95	9.30	6.04	4.04	3.72	2.17	1.83	1.63	2.71	7.58	70
65	4.77	10.64	11.81	14.59	9.99	6.69	4.40	4.11	2.55	2.03	1.85	3.47	8.50	65
60	5.37	12.58	13.98	17.47	10.63	7.32	4.73	4.29	3.20	2.28	2.11	4.13	9.05	60
55	6.19	14.61	15.68	19.13	11.83	7.75	4.96	4.45	3.64	2.66	2.75	4.46	10.04	55
50	7.06	16.47	18.06	21.43	13.55	8.43	5.53	4.66	3.93	3.13	3.26	4.91	10.81	50
45	8.01	19.63	21.03	24.52	15.39	8.98	6.27	4.86	4.27	3.50	3.88	5.31	11.70	45
40	9.24	22.62	25.72	27.56	17.22	9.85	7.09	5.26	4.54	4.02	4.36	6.09	13.03	40
35	10.41	25.60	30.53	31.54	19.35	10.63	7.79	5.69	4.83	4.52	4.92	6.55	14.17	35
30	12.02	29.49	33.24	38.68	20.89	11.61	8.82	6.43	5.22	5.37	5.31	7.25	15.53	30
25	14.34	33.66	37.09	45.68	23.93	12.71	10.39	7.05	6.39	5.83	5.77	8.42	17.69	25
20	17.72	38.33	42.56	52.96	27.04	14.83	11.44	8.70	7.06	6.51	6.65	9.85	24.77	20
15	23.44	44.93	50.21	64.65	29.51	16.68	12.51	9.39	7.77	7.17	7.55	11.53	32.00	15
10	32.14	52.29	68.32	82.02	34.71	20.03	13.22	10.38	9.56	8.66	9.57	17.46	44.08	10
5	50.22	80.23	169.43	118.15	43.58	24.63	14.50	11.40	12.31	13.97	12.67	30.28	61.46	5
4	56.77	93.88	183.20	136.75	46.61	26.12	14.82	11.50	14.66	14.88	13.94	42.36	68.96	4
3	67.03	103.48	256.71	155.64	52.50	27.63	15.54	12.10	17.30	15.19	14.22	53.24	75.01	3
2	88.27	131.84	331.39	172.90	57.50	28.68	16.53	12.46	17.57	16.09	15.45	59.34	87.98	2
1	137.82	155.15	584.58	283.71	68.87	32.69	18.31	12.79	18.27	17.63	19.55	84.81	105.43	1
0	1353.23	544.29	1353.23	837.82	126.77	55.17	20.89	13.77	19.65	24.73	36.28	182.04	296.51	0

It is normally acceptable for the fishway not to operate at very low or very high flows. Let us accept that for the lowest 10% and highest 10% of flows in summer, no migration will be possible. A fishway that can operate effectively between flows of 5 m^3/s and 80 m^3/s will ensure that for more than 80% of the time in summer migration will be possible.

To evaluate the water levels associated with these flows at a proposed barrier, these flows must be translated to water levels at the barrier. A weir with a spillway width of 50 m is proposed at the site. The discharge over the spillway is given by the following formula:

$$Q = 2/3\ C_d\ b\ (2g)^{0.5}\ H_1^{1.5}$$

with $C_d = 0.61$

The relationship between water level and flow is shown in Table 9-9:

Table 9-9: Spillway hydraulics: 50 m wide spillway in Sabie River Relationship between head and discharge

Spillway Hydraulics	
H1	Q
m	m^3/s
0.05	1.01
0.10	2.85
0.15	5.23
0.20	8.06
0.25	11.26
0.30	14.80
0.35	18.65
0.40	22.78
0.45	27.19
0.50	31.84
0.55	36.74
0.60	41.86
0.65	47.20
0.70	52.75
0.75	58.50
0.80	64.45
0.85	70.58
0.90	76.90
0.95	83.40
1.00	90.07
1.05	96.90

Flows of 5 and 80 m^3/s will therefore translate to water levels of 0.15 m and 0.95 m above the crest of the spillway of the weir.

In comparing the data from Tables 9-7, 9-8 and 9-9, the flow rates in the Sabie River for which the various fishways will be negotiable is summarized in Table 9-10.

Table 9-10: Percentage of time in summer (January to March) that fishway will be negotiable

Fishway	Range of head (Table 9-6)	Range of flow in Sabie (Table 9-9)	Max velocity	Percentage in range for summer (Table 9-8)
	(m)	(m^3/s)	(m/s)	%
Pool and weir without notch	0 - 0.16	0 - 6	1.7	10
Pool and weir with 300 mmx300 mm notch	0 - 0.40	0 - 23	1.7	60
Vertical slot without sill	>.15	>5	1.6	90
Vertical slot with 150 mm sill in slot	>0	All flows	1.7	100

In the above table it has been assumed that the inlet level of the fishway will be the same as the crest of the barrier.

From the above it is clear that the two vertical slot options will be negotiable for a much higher percentage of the time in summer when most migration will take place. The highest flow that can be accommodated in this fishway will depend on the height of the sidewalls of the fishway. If the walls are made 1 m high for instance, a head of 1 m can be accommodated and the fishway will start overflowing when the flow in the Sabie River is 90 m^3/s (Table 9-9). This flow is only exceeded for 4, 5 and 8% of the time in January, February and March respectively (see Table 9-8).

Research in South Africa has not established whether the use of a sill improves the performance of the vertical slot fishways. Although a sill helps to create a pool and reduces turbulence at low flows, tests with small fish indicate that if rocks are placed on the bottom of the fishway some species manage to move through the fishway at very low flows, even if a sill is not used. The rocks seem to slow down the flow and form a continuous riffle which appears to replicate hydraulic conditions favoured by these small fish. When a sill sloping in the flow direction was moved the rocks downstream washed away forming fast flowing water along the down slop of the sill. In some tests with relatively steep fishways the fish seemed to struggle to move over the sills under these circumstances.

Until more information becomes available it is recommended that no sill be placed in the slots and that at least two layers of rock (various sizes but not larger than 152 mm) be placed along the bottom of the fishway to form a continuous slope. If it is found during monitoring that a sill is required, it should be a simple matter to add a sill at a later stage.

The size, especially the width of the fishway used in this example, is much smaller than the size normally used in the past in South African fishways when targeting adult fish. Such a small fishway may become overcrowded during mass migrations of larger fish such as labeos and yellowfish. It will also be more prone to blocking by large floating debris. If a larger fishway is needed, the length and width of the pool must be increased to ensure proper flow patterns and acceptable turbulence levels. The drop between the pools cannot be increased in this case since the velocities will become unacceptable. The slope of such a fishway will therefore have to be flatter. If in the above example a 2m wide vertical slot fishway is used, the slot will be 300 mm wide and the pool 2,4 m long. With a drop between the pools kept at 150 mm, the slope of the fishway will become approximately 1/16. The turbulence levels in such a fishway will be below 110 watt/m^3.

If a wider range of fish sizes than specified for this fishway must be accommodated, the slope of the fishway will also have to become flatter. Fishways with such flat slopes can become very expensive and also difficult to fit into the available space, especially at high barriers. An alternative design that does not require such flat slopes will be discussed at the end of this chapter (Section 9.6).

9.5 Kowie Ebb and Flow Weir

9.5.1 *Biological considerations influencing fishway design*

The fish and macrocrustaceans (prawns, crabs) known to attempt to migrate past the Kowie River Ebb and Flow Weir (located at the tidal limit of the Kowie River estuary), as well as their swimming and migratory characteristics, are given in the Table 9-11. This information is used to provide the preferred design, size and hydraulic characteristics of the fishway proposed at this barrier.

Table 9-11: Details of size, migratory ability and behaviour of species to be catered for at the Kowie River Ebb and Flow Weir.

Required Information	Best available knowledge
Target migratory species	Freshwater eels *(Anguilla spp. 2-3 species)* Freshwater mullet *(Myxus capensis)* Flathead mullet *(Mugil cephalus)* Cape Moony *(Monodactylus falciformis)* River goby (*Glossogobius calidus*) Freshwater prawns (*Macrobrachium spp.)* Freshwater swimming crab *(Varuna litterata)*
Reason for migration	Post-larvae and juveniles of nearly all species migrate upstream from marine or estuarine spawning areas into freshwater zones , mainly for feeding and to escape predation
Size range (length) to be catered for	Eels - elvers - 5 mm to 10 mm Mullet - 20 mm to 150 mm Moonies - 25 to 80 mm Gobies - 25 to 60 mm Prawns and crabs - megalopa larvae, ca. 10 mm carapace length)
Migratory behaviour	Elvers & crustaceans: These swim in shallow water on edge of current and crawl or climb round obstacles using the wetted surface on the edge of the flow (splash-zone) Fish: Prefer to swim in shallow water around barriers to migration, jumping as last resort
Swimming speed of weakest or smallest species	Elvers: burst speed of 0.6 to 0.9 m/s Prawns and crabs: no data, suspect ca. 0.6 m/s Mullet (>25 mm) can be taken as the relevant “critical” species for determining fishway design at the Kowie Ebb and Flow Weir: A mean velocity of 1.2 m/s over the weirs is acceptable. Shallow areas on the sloping fishway weirs at the edge of the flow will have lower velocities, which can be exploited by the small fish. Gobies can be considered as climbers, as they can use the “splash zone” or rock substrate to migrate upstream. In addition, gobies are not considered important migrants in this system.
Turbulence levels negotiated by weakest swimmer targeted	Mullet (25 mm and larger): ca. 150 to 200 watts/m^3
Jumping/crawling ability of weakest/smallest species	Elvers, macrocrustaceans (and river goby): can crawl up rough, wetted surface at slope of ca 1:2

Required Information	Best available knowledge
Recommended fishway design	Sloping weir fishways are known to pass both small fish and crawling species in South Africa. This design is thus the preferred option - provided the hydrological and hydraulic considerations at the site can be met.
General Recommendations	Sloping weir fishways are not easily clogged with floating debris, unlike small vertical slot fishways. The use of vertical slot fishways by crawling biota even with a substrate of rocks and pebbles, has yet to be demonstrated in South Africa. Although fish as small as 12 mm may be migrating upstream at the Ebb & Flow Weir, for practical purposes it is considered justified to only cater for fish over 25 mm in length. The rapid growth of the smaller fish to over 25 mm (within 1 or 2 months) will then allow them to negotiate the fishway. In terms pool size in relation to the maximum size of migrating fish, over 90% of fish are expected to be under 100 mm in length. In practice, however, the fishway pools need to be large enough to ensure that suitable turbulence levels prevail over a range of flows for the smaller, weaker-swimming fish (i.e. under 150 to 200 watts/m^3). The minimum width of the pools is based on ensuring a wetted “splash zone” on the laterally sloping weir over the recommended variation in flow depth down the fishway, and is not based on fish size

9.6 Fishway design Kowie River

9.6.1 *Design criteria*

Maximum velocity for small mullet is taken as 1.2 m/s (see Table 9-12 above).

For Gobies, crabs and elvers provide wetted surface (sloping weir) or bed strata (vertical slot).

Largest fish to be catered for is 150 mm.

Max turbulence allowed is 150 watt/m^3.

It should be noted that the above design criteria are those which would allow the most economical fishway to be built without significantly reducing its effectiveness for the migratory biota at the site under consideration. These criteria could be adjusted to be less demanding, if considered necessary. Thus, fishway dimensions which provide lower velocity and turbulence values (i.e. smaller drops between pools, less steep fishway slope, larger pools, etc.) would naturally be more than acceptable, although more expensive. This would have the added advantage of allowing smaller (<25 mm), weaker-swimming fish to negotiate the fishway.

9.6.2 *Fishway Dimensions*

Consider sloping weir and vertical slot fishways to cater for creeping and crawling species.

The maximum drop to keep the velocity below 1.2 m/s is 0.075 m or 75 mm.

The minimum effective pool length is L_e =375 mm, i.e. 2.5 times length of largest fish.

The minimum weir thickness T = 2 x drop = 0.15 m or 150 mm.

The side slope of the sloping weir is ¼.

The minimum distance between the pools, L = 375+150=525 mm.

The maximum fishway slope = 75/525 =1/7.

The minimum width of fishway is 300 mm, i.e. 2 x length of largest fish.

The minimum pool depth is 300 mm.

These minimum requirements lead to a fishway that is very small. More practical dimensions for a suitable sloping weir and vertical slot fishway are chosen below:

Sloping weir:

- Drop between pools: 75 mm
- Effective pool length: 450 mm
- Weir thickness: 150 mm
- Distance between pools: 600 mm
- Fishway slope = 75/600 = 1/8
- Side slope of sloping weir: ¼
- Fishway width: 600 mm. This width will allow a variation of flow depth of 150 mm while providing an exposed wetted surface over the weir
- Pool depth at start of flow 300 m

Vertical slot:

- Drop between pools: 75 mm
- Slot width: 75 mm.
- Fishway width: 75x6.63 =500 mm
- Effective pool length: 75x8.11 = 600 mm
- Wall thickness of structure separating pools: 50 mm
- Distance between pools: 650 mm
- Slope = 75/650 = 1/8.7
- Sill height in slot: 75 mm
- Rock strata on bottom to level of sill

Fishway hydraulics

The hydraulic analysis along the lines of the analysis for the fishways in Chapter 7 was done and the results for the fishways are shown in Table 9-12 and 9-13 and summarized in Table 9-14.

Table 9-12: Results of hydraulic analysis for the sloping weir:

Sloping weir						
Channel Width (B)		0.50 m				
Pool Depth (D)		0.30 m				
Side slope of weir		¼				
Discharge Coefficient (Cd)		0.61				
Drop between pools (DH)		0.075 m				
Length of weir (T)		0.60 m				
Thickness of weir (T)		0.15 m				
Effective length of pool (Le)		0.45 m				
Slope		1/8.0				
H1 (m)	**Qf (l/s)**	**H2 (m)**	**K**	**Qs (l/s)**	**Volume (m^3)**	**Pv (watt/m^3)**
0.02	0.2	-0.055	1.000	0.2	0.076	2
0.04	0.9	-0.035	1.000	0.9	0.082	8
0.06	2.5	-0.015	1.000	2.5	0.087	21
0.08	5.2	0.005	1.000	5.2	0.092	41
0.10	9.1	0.025	0.988	9.0	0.098	68
0.12	14.4	0.045	0.966	13.9	0.103	99
0.14	21.1	0.065	0.941	19.9	0.109	135
0.15	25.1	0.075	0.928	23.3	0.111	154

In this fishway the weirs will start flowing over their full width when the flow in the fishway is 23 l/s. The turbulence level will be close to the allowable value of 150 watt/m^3 at this stage.

Table 9-13: Results of analysis for vertical slot

Slot with Broad crest sill	
Slot Width (b)	0.075 m
Channel Width (B)	0.50 m
Sill Height (m)	0.075 m
Discharge Coefficient sill (CD1)	0.90 m
Discharge Coefficient slot (CD2)	0.61
Drop between pools (DH)	0.075 m
Length between pools (L)	0.60 m
Thickness of wall (T)	0.10 m
Effective length of pool (Le)	0.50 m
Slope	1/8.0

H1 (m)	Yc (m)	H2 (m)	H2/H1	Q (m^3/s)	Qs (m^3/s)	Vslot (m/s)	Vol (m^3)	Pv ($watt/m^3$)
0.050	0.033	0	0	0.0013	0.0013	0.572	0.026	36
0.100	0.067	0.025	0.250	0.0036	0.0036	0.809	0.041	65
0.150	0.100	0.075	0.500	0.0067	0.0067	0.990	0.056	87
0.200	0.133	0.125	0.625	0.0103	0.0103	1.144	0.071	106
0.250	0.167	0.175	0.700	0.0139	0.0139	1.213	0.086	118
0.300	0.200	0.225	0.750	0.0166	0.0166	1.213	0.101	121
0.350	0.233	0.275	0.786	0.0194	0.0194	1.213	0.116	123
0.400	0.267	0.325	0.813	0.0222	0.0222	1.213	0.131	124
0.450	0.300	0.375	0.833	0.0250	0.0250	1.213	0.146	126
0.500	0.333	0.425	0.850	0.0277	0.0277	1.213	0.161	127
0.550	0.367	0.475	0.864	0.0305	0.0305	1.213	0.176	127
0.600	0.400	0.525	0.875	0.0333	0.0333	1.213	0.191	128

In this fishway the turbulence levels will remain below 130 $watt/m^3$ over the entire range of water levels in the river.

Table 9-14: Comparison of flow range for which the sloping weir and vertical slot fishways will be negotiable in Kowie River

Fishway	Range of head mm	Range of flow l/s	Max Pv $watt/m^3$
Sloping weir	0 -150	0 -23	150
Vertical slot with 50 mm sill in slot	All heads	All flows	130

The sloping weir fishway will operate up to a head of 150 mm after which the weir will flow over its full width, not providing a sloping wetted surface for the creeping and crawling species. The vertical slot will operate for all water levels and turbulence levels will remain below 130 $watt/m^3$ throughout.

Hydrological considerations

The flow rates exceeded for given percentages of time in the Kowie is given in Table 9-15.

Table 9-15: Flow exceedance in Kowie River

Percentage of time flow is exceeded	70	60	50	40	30	20	10	5	2
Flow (m^3/s)	0.000	0.008	0.023	0.055	0.126	0.287	0.732	1.722	4.163

This table indicates that for 30% of the time there is no flow in the river, for 40% of the time the flow is below 8 l/s and for 5% of the time the flow exceeds 1722 l/s. A fishway that will operate from the start of flow in the Kowie, up to a flow of 1.7 m^3/s, will only be non operational due to high flows for 5% of the time

To evaluate the water levels associated with these flows at a proposed barrier, these flows must be translated to water levels at the barrier. A weir with a spillway width of 20 m is proposed at the site. The discharge over the spillway is given by the following formula:

$$Q = 2/3\ C_d\ b\ (2g)^{0.5}\ H_1^{1.5}$$

With $C_d = 0.61$

The relationship between water level and flow is shown in Table 9-16.

Table 9-16: Relationship between water level and discharge for 20 m weir in the Kowie River

H1	Q
m	M^3/s
0.01	0.04
0.02	0.10
0.03	0.19
0.04	0.29
0.05	0.40
0.06	0.53
0.07	0.67
0.08	0.82
0.09	0.97
0.10	1.14
0.11	1.31
0.12	1.50
0.13	1.69
0.14	1.89
0.15	2.09
0.16	2.31
0.17	2.53
0.18	2.75
0.19	2.98
0.20	3.22

For a depth of flow over the weir of 130 mm, the flow in the river will be 1.69 m^3/s (see Table 9-14). This flow rate will only be exceeded for 5% of the time (see Table 9-13). Both the fishways will thus be negotiable for most flows in the river and from hydrological considerations there is nothing to choose between these two fishways.

The inlet of both these fishways can be placed approximately 50 mm to 60 mm lower than the crest of the weir. This will ensure that at low flow in the river the first flows go through the fishways, attracting migrating fish to the fishway.

This analyses show that a very small fishway can meet all the hydraulic criteria if only small fish are targeted. Small sloping weir fishways have been used in South Africa with success (i.e. existing fishway at Ebb and Flow in the Kowie - see photo) and fish have been observed migrating through these at slopes as steep as 1/5 with turbulence levels between 200 and 250 watt/m^3. A major advantage of this fishway is that it tends to be able to remain free from debris for long periods of time, especially if the sidewalls of the fishway are kept low to allow the fishway to overflow during high flows.

Tests with small vertical slot fishways have shown that at lower flows the stronger swimmers such as small Moonies and Mullet can negotiate this fishway successfully, even at slopes of up to 1/5, especially if rock strata are placed on the bottom. Hydraulically the vertical slot fishway is preferred for the swimming species but the ability of the creeping and crawling species to negotiate this fishway design has not been proven in South Africa. There is also a major concern about the possibility of debris blocking the narrow slots in these fishways.

9.7 Twin Channel Fishways

9.7.1 *Introduction*

If a wide range of fish sizes must be accommodated in one fishway, the slope of the fishway can become very flat. The weak swimmers require small drops between the pools (75 to 100 mm, see Table 9-9 and 9-8) whereas the larger fish require a long pool (effective pool length of at least 2.5 times the longest fish catered for, see Section 7.3.2). Slopes flatter than 1/20 can be required if drops must be limited to 75 mm and fish up to 600 mm must be accommodated. In Australia slopes of as flat as 1/30 have been constructed to accommodate the wide range of swimming abilities and fish sizes present in some of their rivers (Mallen-Cooper (1997).

In many cases it will be cheaper to build two separate fishways, one catering for the small fish (weak swimmers) where small drops and short pools are used, and one catering for large fish where large drops and long pools are employed. To investigate the possibility of a fishway that will deal with a wide range of fish sizes, as well as with a large variation in water levels upstream of the barrier, the “twin channel” vertical slot fishway (Rossouw *et al.,* 2007) was developed. This fishway was aimed at the typical size range and swimming abilities of fish species in South Africa’s inland rivers.

9.7.2 *Twin Channel vertical slot fishway*

The twin channel vertical slot fishway concept incorporates two channels adjacent to each other, both contained in one structure. Analysis showed that channel widths of 1.0 m and 0.5 m will be sufficient to cater for most migrating species in South Africa’s inland rivers. Such a fishway will therefore be a combination of the vertical slot fishway described in Sections 9.3.2 and 9.5.2. The hydraulic analysis of these two fishways is given in Tables 9-6 and 9-13. Because each channel caters for a smaller range of fish sizes, the slope of this fishway can be steeper than the examples given in Tables 9-6 and 9-13.

In discussions with the engineers at DWAF, it became clear that if a relatively wide wall is used to separate the two channels, construction and access for maintenance and monitoring will be simplified. A 500mm wide separation wall was proposed. It was further proposed to remove the separation wall in areas where the water level in adjacent pools was the same. The resulting fishway is shown in Figure 9-1.

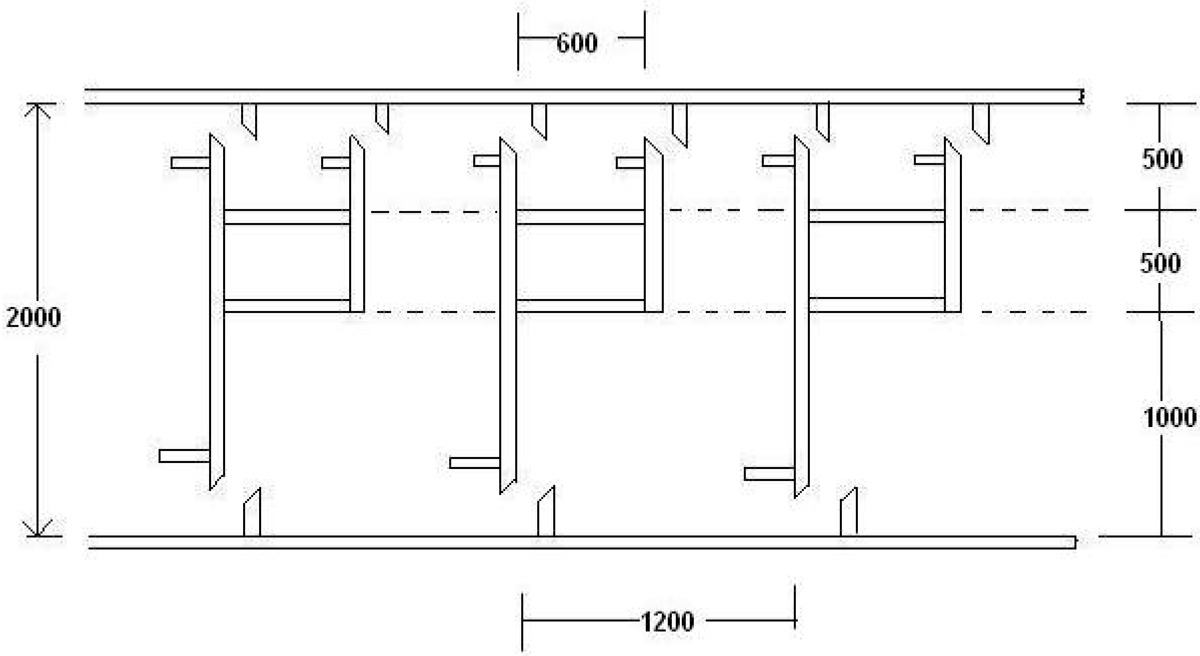

Figure 9-1: General Design

DWAF constructed two models of this fishway. The first model was a small scale model to confirm the anticipated hydraulic characteristics. Once this was established, a full scale model was built and calibrated in their hydraulic laboratories in Pretoria. A photo of this model is shown in Plate 9-1.

Plate 9-1: Various views of the full-scale Twin Channel Vertical Slot fishway model.

Hydraulic analysis of the proposed fishway shows that at a slope of approximately 1/7, this fishway will cope with all three categories of fish shown in Table 5-5. This is illustrated in Table 9-17.

Table 9-17: Velocity and Turbulence in Twin Channel Vertical slot fishway at slope of 1/7:

Channel	Width	Length	Drop	Slope	Velocity	Turbulence
	(m)	(m)	(m)		(m/s)	(watt/m^3)
Small	0.5	0.6	0.085	1/7	1.3	170
Large	1.0	1.2	0.170	1/7	1.8	210

Fish smaller than 40 mm and weak swimmers should therefore be able to comfortably negotiate the small channel whereas the pools in the larger channel are long enough to allow for fish of up to 480 mm in length to move through at turbulence levels and velocities well below their capabilities.

9.7.3 *Tests with full scale model in DWAF laboratories*

A number of hydraulic calibration tests as well as limited tests with fish were performed in the DWAF hydraulic laboratories in Pretoria (Rossouw *et al.,* 2007). In these tests the twin channel vertical slot fishway was built into the standard 1/5 downstream slope of a typical DWAF rump gauging weir. The slope of the fishway was therefore 1/5, i.e. considerably steeper than the 1/7 slope described above. The idea was to see how well the fish will cope with such a steep slope which can easily be fitted into any new Crump weir structure.

In the DWAF tests, an Ogee sill was constructed in each slot to ensure that the pools are filled with water at the start of flow. Rocks were placed in the pools up to the level of the crests of the sills.

The hydraulic analysis of the DWAF model is shown in the Table 9-18.

Table 9-18: Velocity and Turbulence in Twin Channel Vertical slot fishway at slope of 1/5:

Channel	Width	Length	Drop	Slope	Velocity	Turbulence
	(m)	(m)	(m)		(m/s)	(watt/m^3)
Small	0.5	0.6	0.120	1/5	1.5	260
Large	1.0	1.2	0.240	1/5	2.2	330

The drop between the pools and therefore the velocity in the wider channel exceeds the allowable values for large fish in Table 5-5. The velocity in the narrow channel exceeds the allowable value for very small fish. The turbulence values in both channels exceed the allowable value for large fish. This fishway at such a steep slope therefore does not comply with the norms specified in this guideline. Tests with small portable models of this and other vertical slot and sloping weir fishways in the field and in the laboratories, however, revealed that many species, especially when they are on a migration run, negotiated fishways with hydraulic conditions that far exceeded the velocities and turbulence levels specified in Table 5-5.

The tests in the DWAF full scale model revealed the following (Rossouw *et al.,* 2007):

- The hydraulic calibration of the model agreed closely to the theory. This allows the theory to be used with confidence in the design of the fishways. It also allows the inclusion of this fishway in gauging weirs without any compromise to the accuracy of the gauging weirs.
- The rocks near the crest of the Ogee sill washed down into the downstream pool, exposing the steep downstream slope of the sill (Plate 9-2). This made it difficult for the fish to negotiate the sills, especially in the wider channel with the higher drops. Most of the fish that succeeded in moving up the fishway therefore made use of the narrow channel. It was thought that the effective pool length in the wider channel was insufficient for the fish to be able to negotiate the drop of 240 mm.
- Although some fish made it through the fishway, many showed unwillingness to attempt moving upstream. This was probably caused by stress due to poor water quality and the fish not being in a migratory mode.

Plate 9-2: Sloping sills and substrate incorporated into a modified design.

9.7.4 *Tests with a portable twin channel vertical slot model*

A 1/2.5 scale model of the twin channel vertical slot model was constructed to be able to test the performance of the design in the field. In this model the channels were 200 mm and 400 mm wide with slot widths of 30 mm and 60 mm respectively. A series of tests were performed with migrating fish in the Kowie River (Plate 9-3 to 9-5) (Rossouw *et al.,* 2007) as well as a few tests at an aquarium in Stellenbosch. The slope used in all these tests was 1/5, leading to a drop between pools of 50 mm and 100 mm (velocities of 1.0 m/s and 1.4 m/s).

Plate 9-3: Fishway set up on the lower shelf at the base of the Kowie River weir.

Plate 9-4: Fishway channel showing stones on bottom at low flows (large fishway channel).

Plate 9-5: Fishway channel at high flow (18.9 l/s)

In the tests in the Kowie River with rock strata on the bottom 60 to 80% of freshwater mullet (*Myxus capensis*) and Cape moonies (*Monodactylus falciformis*) of between 35 mm and 60 mm, made it through fishway in 20 – 30 minutes at flows between 2.9 l/s and 11.6 l/s. Turbulence levels were between 200 and 260 watt/m^3 during successful tests. Limited tests at Jonkershoek indicated that 87% of Berg River Redfins (*Pseudobarbus burgi*) of 50 to 80 mm in length made it up this fishway.

If we convert the result of the small portable model to that of a full scale fishway with slots of 75 mm and 150 mm, a slope 1/5 and drops between the pools of 125 mm and 250 mm (velocities 1.6 to 2.2 m/s), we can expect that fish of 60 mm to 100 mm should move through fishway in 30 to 45 minutes at flows of 29 l/s to 115 l/s. Turbulence levels will be between 320 and 410 watt/m^3.

It can therefore be concluded that the twin channel vertical slot fishway shows great promise as a fishway that will cope with a wide range of fish sizes at a relatively steep slope for a wide range of water levels upstream of the barrier. At a 1/5 slope, such a fishway can be built into standard DWAF Crump weirs, but at this slope the velocities and turbulence levels will exceed the levels recommended in these guidelines. To reduce the velocities and turbulence levels to those recommended in the guidelines, slopes of between 1/8 and 1/10 will be more appropriate. Tests with the portable model do however indicate that most of the stronger swimmers will be able to deal with the 1/5 slope.

10 SUMMARY, RECOMMENDATIONS AND CONCLUDING REMARKS

In these guidelines the following information has been supplied:

- Protocols to establish the need for a fishway (Figure 2-2) and the priority for a fishway (Table 2-2) have been developed.
- The advantages and disadvantages of various fishway types have been discussed (Table 2-6).
- The swimming abilities of coastal and inland fishes in terms of fishway design parameters have been summarized (Table 5-4 and Table 5-5).
- The hydraulic calculations required in the design of fishways are presented in Chapter 7.

As part of this project many fishways were visited and analyzed. Many South African fishways are considered ineffective for the following reasons:

- Poor placement of the fishway entrance, resulting in fish having difficulty in finding the entrance. This is a very common mistake in existing South African fishways. Proper placement of the entrance is considered the most important parameter in the design of the fishway.
- Many fishways have been designed mainly for large fish with drops between the pools of 300 mm and the fishway entrance only reachable during high flows.
- The pools in many of the fishways are too short, resulting in high turbulence levels in the pools and high vertical velocities where the incoming jet impinges on the weirs at the downstream end of the pools.
- Due to problems during construction the design of the fishways are often altered during construction, resulting in one small pool or one large drop which forms a bottleneck in the fishway and makes the structure ineffective in passing the target species.
- A lack of maintenance of the fishway often results in debris blocking parts of the fishway. Regular maintenance and designs aimed at keeping debris from entering the fishway are essential to maintain their long-term effectiveness.
- The effectiveness of most fishways is unknown because of a lack of monitoring. In many cases the need for monitoring fish movement through the fishway was not considered in the fishway design and quantitative monitoring of these fishways is often impossible after construction. In addition, these monitoring data will facilitate the development of increasingly effective fishway designs suitable for the migratory behaviour of indigenous species and the particular hydrological conditions found in South African rivers.

Based on the results of this study the following recommendations can be made:

- There are strong indications that many South African fish species can overcome velocities and turbulence levels much higher than quoted in the literature. It is strongly recommended that the twin channel vertical slot fishway as described in Section 9.6, constructed at a slope of 1/5, be built into a Crump fishway in order to test its effectiveness under natural conditions. This fishway should be fitted with a properly designed monitoring system and a detailed monitoring programme should be undertaken over a period of at least two years. If such a fishway proves successful it will open the way for cheaper fishway designs in South Africa.

- In order to successfully implement a fishway provision programme in South Africa, it will be necessary to quantify the extent to which natural migrations are already blocked by man-made instream structures. The protocols referred to earlier to establish the need for and priority of a fishway at an instream barrier could be used to help identify priority sites for fishway provision throughout the country.
- Research into the migratory needs of the weaker swimmers should be undertaken. Virtually all the species tested in field tests during this project proved to be relatively strong swimmers which would probably cope with velocities and turbulences far exceeding the values recommended in these guidelines. The cost of a fishway is largely determined by the weakest swimmers to be catered for and therefore the abilities of these weaker swimmers, as well as the necessity of these species to migrate, should be established as a matter of urgency.

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APPENDIX A

INVENTORY GIVING DETAILS OF ALL FISHWAYS IN SOUTH AFRICA (AUGUST 2006)

(KNP = Kruger National Park). WMA = Water Management Area; NC = not yet constructed; UC = under construction; ND = no data; ? = information not yet obtained by author). For "Pool and Slot" design = see text.

River system (tributary)	WMA & coordinates	Date built & owner	Barrier name, description & height	Design of fishway	Condition & problems	Monitoring data
Limpopo System, Luvuvhu R.	WMA: 2 S 22^{O} 43' 36" E 30^{0} 47' 44"	2003 DWAF	Xikundu weir; Gauging & diversion weir	Pool and weir with staggered notches in weirs	Operational	Been monitored since June 2004 by Univen
Limpopo/ Luvuvhu R. Latinyande trib.	WMA: 2 S 23^{O} 03' 18" E 30^{0} 14' 42"		A9H007 Gauging & diversion weir;	Single pool and huge drop, not designed as a fishway	ND Non-functional	ND
Limp, Luv (Nzhelele river)	WMA: 2	Private (Marimane reserve)	Weir	Pool and weir	Functional	P. Fouche. M. Angliss
Limp. Luv. Nwanedi River	WMA: 2	Private (Popalin Ranch)	weir (irrigation)	Pool & weir	Functional	None
Olifants	WMA: 2	DWAF (after 2000)	Mamba	Pre-barrage	Monitoring difficult	none
Olifants	WMA: 2	planned	Balule	?		
Inkomati		KOBWA	Nonyane fishway	near natural	Monitoring difficult	none
Limpopo/ Luvuvhu R Nzhelele River	WMA2 S 22^{o} 52,824" E 30^{o} 06,619"	DWAF	Rabali Gauging & diversion weir	Pool & slot with staggered notches (vertical slot type) with downstream slope	New and operational, Afrikon	Monitored by Univen in Sep 2004
Olifants system; Shingwedzi R	WMA: 2 S 23^{O} 13' 04.6" E 31^{0} 13' 27.5"	1982 KNP	Silwervis Dam; 7 m high	Pool & weir with staggered notches with no downstream slope	Requires removal of sediment: Not effective, baffle design needs to be changed	Limited data, but observations have confirmed design problems
Olifants system; Shingwedzi R.	WMA: 2 S 23^{O} 08' 34.7" E 31^{0} 27' 46.3"	1992 KNP	Kanniedood Dam; cement wall; 8 m high	Pool & weir with staggered notches; steep fishway gradient of 12,7 to 14,2, large pools	Functional, effective, looks well maintained,some minor changes needed	Excellent data, 18 species plus large numbers of small fish (<50 mm) used fishway

River system (tributary)	WMA & coordinates	Date built & owner	Barrier name, description & height	Design of fishway	Condition & problems	Monitoring data
Olifants system; Letaba R; Tsende tributary	WMA: 2 S 23^{O} 31' 24.7" E 31^{0} 23' 52.0"	1976; upgraded in ? KNP	(Mopani) Pioneer Dam, Concrete buttress; 12.5 m	Natural, using rock on river bank plus formal pool & weir with staggered notches	Functional; effective, some modification needed	Limited monitoring data; internal report available
Olifants system; Letaba River	WMA: 2 S 23^{O} 45' 38.3" E 31^{0} 29' 57.6"	? KNP	Mingerhout weir; concrete; 1 to 2 m high	Pool and weir with staggered notches	Appears functional, particularly for large fish	?
Olifants system Letaba R.	WMA: 2 S 23^{O} 42' 08.9" E 31^{0} 12' 59.9"	2002 DWAF	Black Heron (B8H034); guaging weir;	Pool and weir plus natural rock channel	Yellowfish move, being rebuilt after 2000 floods	Barrages and berms required for small fish
Olifants system Letaba R	WMA: 2 S 22^{O} 50' 16.8" E 31^{0} 38' 16.8"	1970 KNP	Engelhardt Dam; cement wall; 13 m high	Pool & submerged orifices	Functional; effective, some modification needed, serious flood damage in Feb. 2000	Excellent data collected; internal reports
Olifants system; Timbavati R.,	WMA: 4 S 24^{O} 13' 48.1" E 31^{0} 37' 59.2"	199? KNP	Piet Grobler Dam; 165 m long crest; 8 m high,	Pool & weir, staggered notches,	Functional; needs some modification; repair needed as serious flood damage in Feb 2000	Some data after 1993
Olifants system; Olifants R.	WMA: 4 S 24^{O} 11' 02" E 30^{0} 49' 26"	1999 DWAF	Oxford Weir (B7H007) Gauging weir	Sluicing flumes (no separate fishway)	ND	ND
Crocodile River at Pelindaba		2004 DWAF	Kalkheuwel – Crocodile River at Pelindaba	Combined pre-barrage slot and pool	ND	ND
Olifants system; Wilge River, at Waterval	S25 ^{O}.57'879 E29 ^{O}12'747	2005 DWAF	Xusterstrrom	Pool and sloton left bank operates from 300 l/s. Attraction flow required. At high flow all water should pass through fishway	ND	ND Info from Dr. Pieter Wessels (DWAF)
Inkomati system; Sabie River; Sabani Trib.	WMA: 5	? DWAF	Mac-Mac, Gauging weir, crump design (EMMET)	Baffle blocks on downstream face high tailwater due to rocks and sill??	ND Considered non-functional due to design, but more data needed	ND
Limpopo system; Sand River	WMA: 5 S 22^{O} 45' 30" E 29^{0} 36' 51"	2001 DWAF	Waterpoort (A7H001); Gauging weir, crump	Vertical slots	Not working no water	ND

River system (tributary)	WMA & coordinates	Date built & owner	Barrier name, description & height	Design of fishway	Condition & problems	Monitoring data
Inkomati system; Sabie River	WMA: 5 S 24^{O} 58' 10.3" E 31^{0} 30' 55.1"	2002) DWAF	Kruger Gate (X3H021); gauging weir	Pre-barrages: Sluicing flume (large canal with sloping sides) plus crump weir (no separate fishway). A series of pre-barrages and bi-channel fishway to make a new pool and barrages to raise tail water	Low flows through by-pass channels, high flows direct by-pass. Steps possibly too high. Maintenance visits to rectify.	ND
Inkomati system; Sabie River	WMA 5	Not DWAF	Hoxani	Sloping baffles with pool and weir	Functional. Human predation	Francois Roux
Inkomati system; Sabie R.	WMA: 5 S 25^{O} 07' 21.10" E 31^{0} 55' 27.5"	5/10/01 KNP	Lower Sabie Road-bridge causeway	Rock-ramp: Old: Semi-natural, cement on natural rock; has been replaced by new large rock ramp fishway	Old fishway partially functional; New Rock-ramp fishway appears effective	Some data (DWAF 1999); 17 migratory species in old fishway; No data on rock-ramp fishway
Inkomati system; Sabie River	WMA: 5 S 25^{O} 08' 57.5" E 31^{0} 56' 27.3"	Sept 2001 DWAF	Lower Sabie weir Gauging weir (X3H015)	Pool and weir, wide notch, forward sloping baffle on west bank;	Newly completed; ND	ND
Inkomati system; Crocodile River	WMA: 5 S 25^{O} 21' 48.4" E 31^{0} 57' 23.1"	mid –2001 DWAF	Ten Bosch Gauging weir (X2H016)	Pool & slot, wide, forward sloping baffle; also, tail-water pool; baffles on downstream face. Pre-barrages on low crest and pool and slot on left bank	Not yet functional - ND. Operates only at high flow Pool and slot operates at 4.5m^{3}/s Nest 12 months will rectify for low flow to meet Mozambique requirements	ND
Inkomati system; Crocodile River	WMA: 5 25^{O} 24' 06.6" E 31^{0} 36' 22.90"	mid- 2001 DWAF	Riverside Gauging weir (X2H046)	Pool, weir/ vertical slot combination on south bank	Newly finished; ND	ND
Inkomati system; Crocodile River	WMA: 5 S 00^{O} 00' 00.0" E 00^{0} 00' 00.0"	1995 Private	Leopard Creek; 1 – 2 m high weir	Natural type/pool & notched weir on south bank, plus 4 pool & notched weir type fishways along the length of the weir	Appears functional, prone to debris blockage (water hyacynth)	No hard data; appears to work
Inkomati system	WMA: 5 S 25^{O} 26' 10" E 31^{0} 58' 56"	? DWAF	Komatipoort (X2H036); Gauging weir	Pool & weir, forward sloping baffle, rock pool with 2 slots Left bank pool and vertical slot Right bank a series of prebarrages for higher flows	ND	Francois Roux confirms working
Inkomati system	WMA: 5 S 26^{O} 02' 07" E 30^{0} 59' 51"	1995 DWAF	Hoogenoeg (X1H001) Gauging weir	Pool and weir	1partly functional. Other broken	only B. mar through. (J. Engelbrecht)

River system (tributary)	WMA & coordinates	Date built & owner	Barrier name, description & height	Design of fishway	Condition & problems	Monitoring data
Inkomati System; Komati River	WMA: 5 S 25^{O} 26' 47.9" E 31^{0} 57' 21,2"	KOBWA	Lebombo Gauging Weir, horizontal crump Height ca 1.2 m	Pool and weir, alternate notches with forward-sloping baffle, very gentle channel slope	Well-designed, good condition, should be effective. Functional	F. Roux
Inkomati System; Komati River	WMA: 5 S 25^{O} 27' 04.4" E 31^{0} 57' 06.2"	KRIB	M'weti Weir, horizontal weir crest Height 4.68m m	Pool and weir, alternate notches with forward-sloping baffle, gentle channel slope	Well-designed, good condition, but entrance located far downstream away from base of weir. Small modification required	F. Roux
Inkomati System; Komati River	WMA: 5 S 25^{O} 43' 30.5" E 31^{0} 46' 50.8"	KRIB	Walda Weir, horizontal weir crest Height ca 7,5 m	Pool and weir, very steep slope of about 1:3, not folded back with entrance about 20m downstream of weir wall	Badly designed, much too steep, not effective most of the time (possibly for small fish at very low flows?)	not possible to monitor
? Palala River	WMA: ? ?	199? ?	Farmer's weir; 4 m	Pool & Weir	ND	ND
Pongola System; Banzi Pan	WMA: 6 ?	19??; KZN Wildlife	Ndumu Game Reserve	? ND	No data – suspect damaged and non-functional	No data
Nhlabane System	WMA: 6 ?	1998; R' Bay Minerals	Nhlabane Weir at head of estuary; concrete wall of 6.5m ht with crest gates	Pool and Weir: variable depth sloping baffle design; 1:12 slope; a 50 mm steps and 95 pools (500 x 900 x 550mm) in total	Well maintained, very effective in passing of fish and macro-invertebrates; tripping of crest gates on weir problematic	Detailed monitoring programme started in 2001, good data, over 20 species of fish plus macrocrustaceans can use fishway
Mzingazi River	WMA: 6 S 28^{O} 46' 28.1" E 32^{0} 04' 18.1"	2000 RB Mun.	Mzingazi Saltwater barrier; cement weir, ca. 1.8 m	Basic sloping channel (1 m wide) through wall round side weir; operational at high tide only	Functions well and appears effective (Dec. 2001), but only for short period over tidal cycle	?
Tugula System; Thaka R.	WMA: 7 ?	1977 Local M	Martins Dam (Wakkerstroom); 6 m	Pool & Weir with notches (modified)	Badly designed, too steep, needs major modification	Some data from 1995
Tugela System; Mooi River	WMA: 7	DWAF	Mearns Weir Diversion Weir	ND. Ramp for eels?	ND Considered as non-functional	ND
Hluleka River	WMA 12 S 31^{0} 49' 27" E 29^{0} 18' 05"	2002 G5	Causeway on access road at head of estuary; ca 1 m	Variable depth pool & weir plus separate eel/prawn ramp	Gentle slope, good design and should be effective	ND

River system (tributary)	WMA & coordinates	Date built & owner	Barrier name, description & height	Design of fishway	Condition & problems	Monitoring data
Mtata River	WMA: 12 S 31^{O} 33.163" E 28^{0} 44.762"	2002 DWAF	Umtata Weir; Gauging Weir	Ramps for eels on both sides of downstream face of weir	ND, considered non-functional. Eel-ramps poorly-designed, operated over limited range of flows, weir totally submerged during high floods	ND
Mbanyana R.	WMA 12 S 32^{0} 12' 14.2" E 28^{0} 52 40.7"	2002 G5	Cwebe water supply scheme; 0.5 m high wall	Variable depth pool & weir plus separate eel/prawn ramp	Gentle slope, good design thus should be effective	ND
Nqabara R.	WMA 12 S 32^{0} 15' 35'.2" E 28^{0} 46' 31.4"	2003 G5 DWAF	Dwesa water supply scheme: ca. 1,2 m	Variable depth pool and weir plus separate eel/prawn ramp; fishway projects 16 m into upstream pool	ND Gentle slope, good design thus should be effective	
Great Kei	WMA: 12 ?	1989; DWAF	Fort Harden; lower Great Kei; crump gauging weir	Series of parallel canals on downstream face at 90^{0} to river flow connected by escape routes	Non-functional. ; Rapid flow over weir crest a problem. Will place new fishway in near future..	Initial observations show small fish can only use lower section of fishway
Haga-Haga River	WMA: 12 S 32^{0} 45' 13.20" E 28^{0} 14' 53.2" ?	1995; Great Kei DM	Haga-Haga weir; concrete wall; 3.4 m high	Pool and Weir (variable depth baffle); slope 1:5, 80 mm head between pools (300 x 450 x 280 mm)	Functional but requires removal of debris and maintenance required, serious erosion of river bank below weir	No detailed monitoring, but small fish seen to use fishway successfully.
Nahoon River	WMA: 12 S 32^{0} 57' 54.7" E 27^{0} 54' 55.3"	1990; Buffalo City MM	Abbotsford Causeway; 1.4 m high	Pool and Weir (variable depth baffle); slope 1:6; 90 mm head between pools (300 x 500 x 300 mm)	Baffles drowned-out at higher flows and thus not suitable for climbers, needs extension into low tide level of estuary	Some monitoring data: effective for small fish from >20 mm, pipe under causeway may be a potential barrier
Keiskamma R.	WMA: 12 S 33^{0} 11' 08.0" E 27^{0} 23' 28.1"	2003 DWAF	Gauging Weir (R1H015); at tidal limit of estuary	Cement tower with submerged orifice on downstream side	Poor design and badly sited - far from main flow over sharp-crested weir - needs re-design, non-functional in present state. Will replace with sloping baffle fishway in near future.	No data – but considered priority barrier with significant impact on catadromous species
Vaal		DWAF	Goosebay weir		Data, Rauecon	
Orange/Vaal	WMA: 13 ?no locality data available	?	Botshabelo Dam Needs confirmation, based on hear-say	Not a conventional design	Considered non-functional for small fish due to large drop between fishway and river.	ND

River system (tributary)	WMA & coordinates	Date built & owner	Barrier name, description & height	Design of fishway	Condition & problems	Monitoring data
Orange R main channel	WMA: 14 S 31^{O} 03' 52" E 23^{0} 41' 47"	1989; DWAF	Mark's Drift Weir; (D3H008) gauging and water diversion; 4.2 m	Pool & weir; slope 1:10	Functional, but not very effective at medium and lower flows	Observations, no hard data
Orange R. main channel	WMA: 14 29^{O} 02' 36" E 23^{0} 50' 13"	1989 DWAF	Douglas Weir (CR003); gauging and diversion; 6.29 m	Pool and weir; slope 1;2	Non-functional. Much too steep, completely non-functional as fishway	Observations – serious design faults, no fish movement possible
Orange R. main channel	WMA: 14 S 28^{O} 46' 05" E 20^{0} 43' 14"	1992 DWAF	Neusberg weir (D7H014); gauging and diversion weir;. 7.4 m	Vertical slot; slope 1:10	Functional, appears effective in passing both large and small fish; but locating entrance a problem	Limited data from 1994/1995; more monitoring required
Great Fish River	WMA: 15 S 31^{O} 54' 11" E 25^{0} 28' 56"	1991 DWAF	Hermanuskraal (Q1H001); diversion weir; 6 m	Pool & weir (downstream section) plus pipe	No recent information; exit reported silted up	Report 1995; lower section passes larger fish
Kowie River	WMA 15 S 33^{O} 32' 39.0" E 26^{0} 46' 52.3"	1992 P. Alfred Munic.	Ebb & Flow weir; concrete causeway, ca 3 m	Modified, crudely built variable depth baffle pool and weir; slope ca. 1:6	Good condition; used successfully by small fish at low flows, needs design modifications	good data recorded in unpubli. Report (Bok & Cambray 1995
Swartkops River	WMA 15 S 33^{O} 45' 09.0" E 25^{0} 20' 31.3"	2002 E.Cape DRPW	Bulmers Drift causeway, ca 1.5 m	Natural rock ramp/pool & weir type for small catadromous fish and climbers	No sampling to date	Appears a bit steep, does not operate at extremely low flows
Gamtoos system; Geelhoutbos R.	WMA: 15 ?	1990; DEAET	Geelhoutboskloof weir; Concrete weir; 1 m high	Pool and weir (variable depth baffle) for small (100 mm) fish	Weir damaged in 1994; leaking badly, needs repair	Initially functional, seen to pass small fish; little data
Kouga River	WMA: 15 S 33^{O} 47' 26" E 24^{0} 01' 50"	1990 DWAF	Gauging weir (L8H005), crump design	Pool & weir (no pool depth!)	Non-functional. Wrong design;. Bass at site in main channel, therefore fishway not required	No data; observations at low flow
Groot River (Oos)	WMA: 15 S 34^{0} 01' 55.8" E 24^{0} 11' 45.5"	1998 DWAF	Rooiwal Gauging weir (K8H006); crump design	Channel with flat v-shaped baffles and tower fishway with entrance on downstream side	Non-functional. Tower may function at high tailwater pool levels. DWAF will change design.	No data
Gourits system; Olifants R.	WMA: 16	1998 Local Mun.?	Bridge on gravel road to Gamkaberg reserve,; ca. 2 m high	Pool and notched weirs with vertical edges & low side-walls	Good condition; Design problems as water falls in arc, not effective at high flows, should be effective at low flows	ND to date
Olifants R. Boskloof trib.	WMA: 17 S 32^{0} 33' 59.5" E 19^{0} 03' 04.1"	1999 Private	Farmers weir; near Citrusdal; 3.0 m	Pool and weir for small fish (<200 mm)	Functions well at low flows for small fish	Some recent data (Dean Impson, WCape Conservation)

River system (tributary)	WMA & coordinates	Date built & owner	Barrier name, description & height	Design of fishway	Condition & problems	Monitoring data
Berg River System. Platkloof River	WMA: 19 S 32^{0} 51' 10" E 18^{0} 42' 05"	2003 DAD	Goedverwaght, Piketberg; Platkloof weir; Dept. Agriculture	Pool and weir (variable passage depth)	Early 2003, design problems at exit and entrance	ND
Eeste River	WMA: 19 S 33^{0} 56' 35" E 18^{0} 50' 45"	1948; Provincial Admin.	Stellenbosch Weir; 2 m	Pool and weir	Non-functional, state of disrepair	No data available
Berg R. System, Little Berg	WMA: 19 S 33^{O} 11' 05" E 19^{0} 09' 19"	1951; DWAF	Diversion weir (G1H021); 5 m	Pool and weir with notches	Non-functional, state of disrepair; channel sediments totally blocking entrance to fishway	No hard data available, some descriptive reports after construction
Seekoeivlei	WMA 19 S 34^{0} 03' 55" E 18^{0} 30' 15"	1998: City of cape Town	On Rondevlei spillway	Pool and weir with notches, 13 cm drop between pools	Functional, barrier in river bed to Rondevlei spillway affects upstream migration	ND