The Investigation and Specification of Flow Measurement Structure Design Features that Aid the Migration of Fish without Significantly Compromising Flow Measurement Accuracy, with the Potential to Influence the Production of Suitable British Standards

R&D Technical Report W6-084/TR1

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Statement of Use
This report describes Phase 1 of National R&D Project No. W6-084. It comprises the results of a literature search, a questionnaire and discussions with Environment Agency officers all of which contributed to the definition of the Phase 2 laboratory testing programme.

Key Words
Calibration, fish biology, fish passage, flow measurement, hydrometry, weir.

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EXECUTIVE SUMMARY

This document forms the Technical Report to the Environment Agency's R&D project W6-084, commissioned in July 2002.

The objectives of the overall project are *"The investigation and specification of flow measurement structure design features that aid the migration of fish without significantly compromising flow measurement accuracy, with the potential to influence the production of suitable British Standards."*

This research project is not concerned with the hydraulic performance of basic flow measurement structures which are to be found in British and International Standards. It is concerned with the adaptation or augmentation of Standard gauging structures to aid the migration of fish and is intended to ensure that these adaptations do not significantly degrade the accuracy of the structure as a flow measurement device. The research will ultimately provide specifications for fish migration adaptations or augmentations which can be introduced without significantly affecting flow measurement performance.

This Technical Report on Phase 1 of the project gives the results of a literature review of readily available information. It also contains the results of a questionnaire and some follow-up interviews with interested parties. A complementary Laboratory Proposal report (not released to public) has been prepared which interprets the findings of this Technical Report in terms of priorities for future laboratory work in Phase 2, and is summarised within this report. Thus the aim of Phase 1 is to review current knowledge in order to define the most useful and productive way forward. In particular it provides the justification for future, accurate, hydrometric modelling of possible solutions in Phase 2.

Phase 1 has, in summary, provided the following information:

Hydrometry

1. There is general agreement within the Environment Agency that low to medium flows should be measured with uncertainty levels no greater than +/- 5%. For medium to high flows this figure could be stretched to +/- 10%.
2. The accuracy of routine current meter calibrations in the field is generally lower than the accuracy attainable at Standard flow measurement structures.
3. The usage of Standard flow measuring devices within the Environment Agency remains extensive (>1000 installations), particularly the use of Crump, flat-V and compound structures.
4. The Environment Agency view of accuracy requirements is not necessarily the worldwide, international view. This is of relevance when promoting the results through British and International Standards. Historically, countries in which water shortages are common have argued for higher accuracies in flow measurement than currently required by the Environment Agency.

Fish Biology and swimming capabilities

1. There is extensive information on swimming capabilities of fish but the subject is complex and the data is neither comprehensive nor precise. Early work was concentrated on salmon and sea trout. More recently there is a greater emphasis on freshwater and coarse fish.

2. The swimming capabilities of fish depend upon a number of factors including:
   - species
   - length (the age of an individual fish or the collective adult size of a particular species)
   - water temperature
   - water depth
   - water velocity
   - turbulence
   - distance to be negotiated
3. A distinction is made between "burst" speed and "cruising" speed. Burst speed is generally anaerobic swimming while cruising or sustained swimming is aerobic. Burst speed seems to be the most relevant figure for passage over or around gauging weirs. Both burst and cruising speeds depend on the size of fish, all other things being equal.
4. As a broad generalisation, salmon and sea trout have high burst speeds, typically in the range 2.0 m/s to 3.5 m/s for mature fish. Freshwater fish have lower burst speeds, typically in the range 1.0 m/s to 1.5 m/s for mature fish. Velocities on the downstream face of gauging weirs may reach 4.0 m/s. Thus, weirs present far more of a barrier to freshwater species than to salmon and sea trout.

Fish passage over or around river structures

1. There are many references to "one-off" fish pass types but the choice appears to be narrowing to three commonly used devices. These are, pool and traverse, Denil (or a derivative) and Larinier (or a derivative).
2. Scale models have been used to assess the relative merits of the different types of fish pass. These have been carried out at relatively small scales to facilitate rapid, economical construction and ease of modification. These models have provided flow characteristics which are adequate for designing fish passes but not for hydrometric purposes.
3. Smaller scale models have also been used to investigate new ideas on adaptations to measuring weirs. They have been of limited value because they cannot simulate aeration of the flow and their hydrometric performance is impaired by fluid property effects.
4. Some hydraulic and fish monitoring tests have been carried out at field installations, including looking into downstream conditions and the factors which attract fish towards fish passes.

There are three main categories of potential solutions to the fish passage problem:

- bypass channels which could be much longer than the gauging structure in the direction of flow and which might take the form of a pool and traverse fish pass, a Denil fish pass (or derivative), a Larinier fish pass (or derivative) or a semi-natural channel.
- fish passes which are combined with a Standard gauging structures to form compound units. These may utilise pool and traverse, Denil or Larinier fish passes which would be separated from the main gauging section of the structure by divide walls of some type.
- adaptations of Standard gauging structures in the form of fish "aids" on the downstream face of the weir, the easement approach. The solution being tested on the Moors River at Hurn is an example of this approach. The introduction of a

Larinier or Denil fish pass to the downstream face of weirs is unlikely to be successful based on past experience.

Bypass channels and compound units
In the first two categories, flows down the fish pass are separated from flows over the main gauging structure. The proportion of flow taken by the fish pass can be determined / designed but this proportion will vary as the river flow varies because of the different rating curves for the gauging section and the fish pass section. This assumes that monitored and controlled variable level intakes to fish passes are not a practical proposition. The overall percentage uncertainty in the measured river flow will depend on the percentage uncertainties in the flows measured by the gauging weir and the fish pass and the proportion of the total flow taken by each. Thus, if the uncertainties in the measured fish pass flows are large and the proportion of flow taken by the fish pass is also large then the overall uncertainty will be unacceptable from a hydrometric point of view. On the other hand, if the uncertainty in the fish pass flow is not much higher than the gauging weir and the fish pass takes a small proportion of the flow then the situation becomes more acceptable to the hydrometrist.

The Phase 2 testing will need to look at the basic uncertainties associated with fish passes and will need to be augmented with a desk study to formulate design methods which will ensure that the overall uncertainties of the system are acceptable. It will not be necessary to model the gauging weirs, only the fish pass sections of any compound arrangement. Indeed, it may only be necessary to model the head of each type of fish pass because this determines its hydrometric performance. The greatest challenge will be to avoid high uncertainties at the gauging section brought about by relatively high discharges through the fish pass section and consequent low heads at the gauging section.

Adaptation of Standard gauging structures, the easement approach
Fish passage aids of various types have, and are, being tried. They offer one possible solution to the fish passage problem.

Salient points from the questionnaire / consultation exercise
The questionnaire was formulated jointly by the consultant and the Project Board. Replies were evaluated by the consultant and are fully discussed in Section 1 of Chapter 3.

The replies to the questionnaire, the workshop, and the discussions during the consultation process were useful in that they helped to identify current issues and gave an opportunity for Environment Agency personnel and other experts to give their views. Inevitably the views were subjective and, in some cases, contradictory. Thus, in consultation with the Project Board, the consultant sifted responses and identified those issues upon which there is a broad degree of agreement. These are listed in Section 2 of Chapter 3.

Key issues which have not already been reported above and which need to be addressed in future studies include:

- the need to develop methods for "retro-fitting" fish pass aids because of the large numbers of existing flow measurement structures.

- the need to address the problem of trash being caught in fish passes with consequent changes to head / discharge relationships.
- the need to minimise afflux (the difference between upstream and downstream water levels) over flow measurement structures because peak velocites are closely related to afflux.
- the need to ensure that any truncation of the downstream face of a flow measurement structure is submerged by the tailwater.
- the need to minimise aeration because of the reduced ability of fish to navigate and swim under such conditions.
- the need to minimise large scale turbulence and flow convergence both of which disorientate fish.
- the need to provide a diversity of flow conditions locally, which fish are able to exploit.
- the need to attract fish towards the downstream outlet from any fish pass.
- the need to provide easy approaches to fish passes to minimise the amount of anaerobic swimming that is required.
- the need to provide suitable flow conditions upstream of the fish pass such that fish are not swept back over the flow measuring structure.

Proposed laboratory tests

The Phase 2 testing will need to model the proposed solution, possibly with sectional models, and seek adaptations that have little or no effect on the hydrometric performance of the basic weir.

The details of the Phase 2 testing needs to take into account the types of weir which are of the greatest value to, or see the greatest usage in, hydrometry. It will also have to incorporate those fish passes or adaptations that have a successful track record and are welcomed by the fisheries interests. On present evidence, the ranges are:

Weirs:	Two-dimensional triangular profile (Crump)
	Flat-V
	Compound
Fish passage aids:	Pool and traverse fish pass
	Denil (or derivative) fish pass
	Larinier (or derivative) fish pass
	Adaptations to Standard weirs (easements)

Details of the proposals for laboratory testing are based upon these conclusions and are given in the Laboratory Proposal report (not released to public), and summarised below.

The recommended projects for Phase 2 are:

Proposal	Value for money & Urgency	Notes
1. Desk study of the combined uncertainties associated with the introduction of fish passage aids at Standard flow measurement structures.	High, High	This is an important study which will: • enhance understanding of the hydrometric implications of the introduction of fish passage aids at flow measurement structures. • provide guidelines for the design of fish passes vis-à-vis the performance characteristics of the flow measurement structure.
2. Review of the problems of trash at fish passes and ways of minimising accumulations.	High, High	This is an important study, which should be carried out as a matter of urgency such that any lessons learned can be incorporated in any of the design solutions modelled in Phase 2.
3. Laboratory tests to provide an accurate hydrometric calibration of a Larinier fish pass.	High, Medium	This study will consider the basic calibration of the Larinier fish pass and also possible adaptations at the upstream end to improve hydrometric performance. It will provide information for existing installations and design information for new installations.
4. Laboratory testing of a Larinier and/or a Pool and Traverse fish pass with a submerged orifice upstream intake set alongside a flow measurement structure (non-specific).	High, Medium	This study will look at a combined fish pass/flow measurement installation in which the fish pass is placed alongside any Standard flow measurement structure. Flow measurement through the fish pass could be achieved by a variety of means. Fish counting would also be feasible.
5. Laboratory testing of a Larinier and/or a Pool and Traverse fish pass with a submerged orifice upstream intake set midstream at a flat-V weir.	Medium, Low	This study is similar, in some respects, to study 4 and will look at a combined fish pass/flow measurement installation in which the fish pass is installed midstream within a flat-V weir. The interaction with flows over the flat-V weir, particularly downstream flow conditions, will need to be investigated.
6. Fundamental requirements for the near-crest arrangements for baffles on the downstream face of a measuring weir.	High, High	The baffle arrangements on the "Hurn" type easement are designed to reduce velocities on the downstream face and to create a spatial diversity of flow conditions. The upstream baffles are those which potentially affect hydrometric performance. This study will provide a limited amount of basic information about the requirements for the location of the most upstream baffle in relation to its size.
7. Testing of a limited range of "finalised" Hurn type adaptations to flat-V weirs.	High, Medium	There is a problem with developing general design and performance data for "Hurn" type easements. This is because the size, spacing and location of baffles are related to fish size, not weir size. Hence easements on large weirs are not necessarily geometrically similar to easements on small weirs. This study will thus investigate a limited range of typical arrangements. Generalised information will have to be derived by interpolation.

Following discussions with the Environment Agency Project Board, Studies 1, 2, 3, 4 and 6 will be progressed as Phase 2 of this R&D project.

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LIST OF FIGURES

1. INTRODUCTION

This research project is not concerned with the hydraulic performance of basic flow measurement structures which are to be found in British and International Standards. It is concerned with the adaptation of Standard structures to aid the migration of fish and is intended to ensure that these adaptations do not significantly degrade the accuracy of the structure as a flow measurement device. The research will provide specifications for fish migration adaptations which can be introduced without significantly affecting flow measurement performance.

In its proposal HR Wallingford identified three key issues which were important in securing a successful outcome from the project:

Communication and understanding
There is an understandable difference between the aspirations and requirements of hydrometric and fisheries interests. Flow measurement structures require a water level difference between the upstream and downstream reaches in order to function. This water level difference introduces the potential for high adverse velocities as far as the passage of fish is concerned. It is important, therefore, that both parties understand each other’s problems.

Accuracy requirements for flow measurement
The accuracy requirements for flow measurement vary with the usage of the data. Generally speaking, low and medium flows require high accuracy because of the requirement to monitor and share water in situations where supply is limited and ecological damage could occur due to abstraction or discharge. Flood flows need less precision.

Standard specifications for gauging structures generally quote the accuracy of the coefficient of discharge but this is not the accuracy of the measured flow. The location, quality and maintenance of the structure, the condition and the maintenance of both the upstream and downstream channels, the zeroing of the water level gauge and the accuracy of the water level recording apparatus also influence the accuracy of the measured flow. Coefficients of discharge need to be measured and quoted in Standards to an accuracy of between 1% and 3% in order that the user may achieve measured flows to an accuracy of between 5% and 10%.

Under these circumstances it is necessary to agree what, if any, deviation from the Standard coefficient of discharge is permissible when introducing fish adaptations. The EA wishes to have the results promoted through British and International Standards and in doing this it must be realised that the Environment Agency requirements regarding the accuracy of flow measurement is not the only one to be considered.

Fish performance and requirements
The swimming performance of fish depends on many factors including:

- species
- length (the age of an individual fish or the collective adult size of a particular species)
- water temperature

- water depth
- water velocity
- turbulence
- distance to be negotiated.

It is thus a complex subject with many variations. The data is neither comprehensive nor quantitative. Hence it is necessary to reach an agreed consensus on the hydraulic parameters which are acceptable from a fisheries point of view before moving on to Phase 2 of this project which will involve large scale testing of the most promising devices.

The Environment Agency terms of reference give the following project objectives:

Overall Objective
To produce proposed amendments/additions to British Standards design features of flow measurement weirs and compound weir structures to aid the migration of fish without significantly compromising flow measurement accuracy.

Specific Objectives
- To research and consult, review and report on the *range* of possibilities which exist for the adaptation of measurement structures to aid the migration of fish, covering a range of weir types and potential baffle, composite pass or bypass options.
- To prioritise the hydraulic investigation of the above, and recommend a costed programme of laboratory work that best serves the Agency's immediate needs for new/revised design standards for new and reconstructed gauging structures to aid the passage of fish.
- To carry out laboratory testing of the highest priority proposals, building on the results of previous R&D work, and to refine design features such that fish passage is assisted without significantly affecting the accuracy of flow measurement.
- To quantify the impact of fish passage aids on flow measurement accuracy and reliability.
- To produce a technical report that summarises the experiments, incorporates proposed amendments and additions to existing British Standards for gauging weirs or construction guidelines, and gives recommendations for future work.
- To promote the inclusion of these amendments and additions into British Standards through participation in the work of Standards committees – an ongoing process, the timescale of which is dictated by the Standards organisations.

This Technical Report relates to the following ongoing or recently completed Environment Agency research projects:

- **Child S, Woods-Ballard B, Clare-Dalgleish A and Sayers P** 2002. *Review of good practices for hydrometry.* Environment Agency Draft Technical report W6(00)07.
- **Clough S C and Turnpenny A W H** 2001. *Swimming speeds in fish: Phase 1.* Environment Agency Technical report W2026/TR1.
- **Joint National Hydrometry and Fish Pass Group** 2001. *Guidance on the design and construction of Crump and Flat-V gauging weirs in relation to fish passage.* Environment Agency memo.
- **National Rivers Authority** 1995. *Hurn weir gauging station: re-appraisal of options to facilitate the upstream migration of Dace.* National Rivers Authority, project no. C5200.
- **Phillips G and Clarke C** 2001. *Weirs, flow measurement and fish passage: action on reconciling the conflicts.* Environment Agency memo.
- **Turnpenny A W H, Lawton K and Clough S C** 2002. *Fish passage at flow gauging stations in England and Wales. Stage 1: Literature review and regional survey.* Environment Agency R & D Technical Report W6-029/TR1.
- **Turnpenny A W H, Lawton K, Clough S C, Hanson K, Ramsay R, Osborne G and Kitson N** 2002. *Fish passage at flow gauging stations in England and Wales. Stage 2: Fish pass physical model evaluation and field studies.* Environment Agency R & D Technical Report W246.
- **Turnpenny A W H, Blay S R, Carron J J and Clough S C** 2000. *Literature review of swimming speeds of freshwater fish.* Environment Agency R & D Technical Report W2-026/TR2.
- **Walters G A** 1996. *Hydraulic model tests on the proposed fish pass structure for Hurn gauging weir, Dorset.* Exeter Enterprises Ltd.
- **Walters G A** 1996. *Hydraulic model tests on the proposed fish pass structure for Hurn gauging weir, Dorset: supplementary report.* Exeter Enterprises Ltd.
- **Walters G A** 1997. *Hydraulic model tests on the proposed fish pass structure for Hurn gauging weir, Dorset: supplementary report no. 2.* Exeter Enterprises Ltd.

This Technical Report gives the results of a literature review of readily available information. It also contains the results of a questionnaire, workshop discussions, and some follow-up interviews with interested parties. A complementary Laboratory Proposal report (not released to public) has been prepared which interprets the findings of this Technical Report in terms of priorities for future laboratory work, and is summarised within this report.

2. LITERATURE REVIEW

2.1 Introduction

This literature review builds on the extensive studies carried out and commissioned by the Environment Agency in recent years, some of which are ongoing. These studies have also included literature reviews and extensive consultation. Some have involved model testing and field trials.

In addition to this in-house and commissioned research we have searched the literature to establish what work has and is being done internationally.

Studies can generally be assigned to one of the following categories:

- Hydrometric practice, with particular reference to gauging structures
- Fish biology and swimming capabilities
- Fish passage over or around river structures

This chapter is laid out such that each of these aspects is dealt with separately. A later section of this report discusses the interactions between the three aspects in the context of the aims and objectives of this project.

In the case of the Environment Agency in-house and commissioned work we have sought not to duplicate effort. Where Environment Agency reports are available we reproduce the executive summary and provide commentary on the salient aspects. The international literature is dealt with more fully.

2.2 Hydrometry

2.2.1 British International Standards

The British Standards Institute (BSI) participates in the activities of both the International Standards Organisation (ISO) and the European Standards Bureau (CEN). To date CEN has not taken an active interest in flow measurement using flow measurement structures, CEN 318 being primarily interested in velocity area techniques and instrumentation. The international community, on the other hand, is actively interested in flow measurement structures and there are more International Standards than British Standards covering this field. Generally speaking BSI prefers to promote Standards through the international route and then to subsequently accept the documents as dual numbered British Standards. Until recently the dual numbering involved a designated part number of the BS 3680 series. The new policy is to retain the original ISO number only. Thus in future we will not have the neat arrangement whereby we can refer to the BS 3680 series as covering all Standards relating to open channel flow measurement.

There are many British and International Standards relating to flow measurement structures. These Standards are given in Table 1.

Table 2.1: International & British Standards for flow measurement structures (as at December 2002)

International Standard	British Standard (BSI/CPI/113 Hydrometry)	Flow Measurement Structure
ISO 1438/1:1980	BS 3680:Part4A:1981	Thin plate weirs
ISO 4360:1984	BS 3680:Part4B:1986	Triangular profile weirs
ISO 4359:1983	BS 3680:Part4C:1981	Long throated flumes
ISO 14139:2000	BS 14139:2000	Compound gauging structures
ISO 3846:1989	BS 3680:Part4E:1990	Rectangular broad crested weirs
ISO 4374:1989	BS 3680:Part4F:1990	Round nose horizontal crest weirs
ISO 4377:1990	BS 3680:Part4G:2002	Flat-V weirs
ISO 8368:1999	BS 3680:Part4H:1999	Guidelines for the selection of structures
ISO 8333:1985	BS 3680:Part 4I:1986	V shaped broad crested weirs
ISO 3847:1977		End depth method
ISO 4362:1999		End depth method (non-rectangular channels)
ISO 9826:1990		Parshall and SANIIRI flumes
ISO 9827:1992		Streamlined triangular profile weirs
ISO 13550 (FDIS)		Vertical underflow gates

2.2.2 Environment Agency R&D Review of Good Practices for Hydrometry (W6(00)07)

Child S, Woods-Ballard B, Clare-Dalgleish A and Sayers P 2002. *Review of good practices for hydrometry*. Environment Agency Draft Technical report W6(00)07.

The Environment Agency has commissioned an R&D Project, R&D W6A, "Review of Good Practices for Hydrometry". According to the Project Brief, the main overall objective is:

"To provide the Environment Agency with a review of hydrometric Good Practice. This will involve the production of an objective, cost benefit analysis of hydrometric inputs to the provision of data which meets the needs of the Agency and minimum levels of inputs for all hydrometric data types will be identified."

The work, which commenced in August 2000, was awarded to Hydro-Logic Ltd. working in association with HR Wallingford. This report describes the work that has been undertaken and the main findings of the review.

The main phases of the work undertaken follow:

1. Survey of data user requirements.
2. Survey of data providers to assess current practices.
3. Literature review.
4. Analysis of findings of 1 – 3 above.
5. Development of quality and cost analysis models and data decision analysis tools to assess the benefits and costs of different hydrometric practices

6. Use of models to analyse impacts of different hydrometric practices on data quality and costs
7. Recommendations on hydrometric practices based on the analysis referred to in 4 and 6 above.

A considerable amount of information and a variety of opinions were obtained from the survey of data user requirements. While most users of hydrometric data were not dissatisfied with the overall standard of service provided it was generally felt that it could be improved. The majority of users were of the opinion that data should be accurate to at least ± 10% and most users of hydrometric data felt that a data return of less than 95% was unacceptable. It was apparent from the discussions with users, and providers that in most regions the quality control of data could be improved, many users felt that there was insufficient Metadata available.

All the hydrometric providers consulted indicated that they undertook hydrometric activities in accordance with the hydrometric manual, British Standards and other accepted practice. However, despite efforts to obtain national consistency, it was clearly apparent that there are differences in current practices between Regions and even within Areas. These differences relate mainly to the inputs required for certain activities, the frequency of routine inspection and maintenance visits, calibration of instruments or installations and the quality control of data. A few of the divergences in practice could be partially explained by physical and other differences between Regions. However, the many of the differences identified were due to historic reasons and individual opinions. For most activities, no reasons were identified as to why a consistent national approach should not be adopted.

The literature review indicated that very little research had been undertaken on the impacts of different hydrometric practices on data quality. Most of the literature was concerned with the costs and benefits associated with variable quality or no hydrometric data, and the data requirements for various hydrological studies.

The cost implications and benefits of the recommended hydrometric practices are analysed and discussed in the report. It is believed that from a national perspective the implementation of the recommended good practice should result in an overall improvement in data quality for a relatively small increase in costs. This does not mean that the same conclusions will apply equally across all Regions. It has not been possible to provide an overall, absolute estimate of the national cost implications of implementing the recommended good practice guidelines. This is because each Region and even Areas within Regions currently adopt different practices for some items of work i.e. for some items one or more Regions may already be adopting the recommendation, whereas others may not.

Commentary
Data accuracy, perceptions and requirements are discussed in Section 3.5.2 of the Project Report. The most relevant data, as far as the current research is concerned is given in Table 2.2, taken from this reference.

Table 2.2: Data accuracy, perceptions and requirements

	Current	Ideal	Satisfactory	Worst acceptable	Remarks
Water resources and water quality related activities					
Instantaneous flows (one-off and calibration measurements)	+/- 5% - 25%	+/- 5%	+/- 5% - 10%	+/- 15%	Most correspondents think that current meter gauged flows are well within 10%.
Continuous flows (volumes)	+/- 5% - >100%	+/- <5%	+/- 5% - 10%	+/- 10%	Some rated sections or structures susceptible to high levels of weed growth can grossly over-estimate flow.
Flood related activities					
Instantaneous flows (one-off and calibration measurements)	+/- 15% - 30%	+/- 5%	+/- 10%	+/- 20%	Problems of undertaking current meter gauging under flood conditions not always fully understood.
Continuous flows (volumes)	+/- 10% - >100%	+/- 5% - 10%	+/- 10% - 15%	+/- 20%	Problems of non-modular flow, rating curve extension etc. not always recognised.

Water resources and water quality related activities are mainly concerned with low and medium flows. Flood related activities are concerned with the high end of the flow range. Hence, in very broad terms the Environment Agency is aiming for uncertainties in measured low and medium flows of around 5% and uncertainties at the high end of the flow range of around 10%.

The actual uncertainty in flow measurement using the published performance data for Standard weirs and flumes depends on a number of factors, including the accuracy of the coefficient of discharge, the accuracy of the head measurement, the accuracy of the surveyed dimensions of the weir or flume, whether the weir or flume has been adequately maintained, whether the flow conditions are modular or drowned, etc. etc. There is no unique answer to the question "How accurate is a weir or flume?". However, the Standards give a methodology for computing the overall accuracy of flow measurement and also worked examples. These may not be totally representative but the examples given in the relevant Standards for three of the more widely used weirs give the following overall uncertainties in flow measurement:

Triangular profile (Crump) weir:	+/- 2.0% (modular),	+/- 7.5% (drowned).
Flat-V weir:	+/- 3.5% (modular),	+/- 4.0% (drowned).
Compound triangular profile weir:	+/- 3.2% (modular),	+/- 10.0% (drowned).

In all three cases the estimates for the drowned flow condition assume that the downstream conditions are sensed with a crest tapping, not a downstream gauge - which would make the uncertainty much greater.

Broadly speaking well maintained weirs of these three types produce uncertainties in measured flows of 2% to 5% in the modular flow range and 5% to 10% in the drowned flow range.

2.2.3 DETR R&D extending the scope of BSI, ISO and CEN Standard Specifications for Open Channel Flow measurement structures

Spaliviero F and White W R 1998. *Review of Standards and Current Usage.* HR Wallingford. Report No. SR 532

The Summary and Conclusions from this report are reproduced below:

Summary

The performance data given in existing flow measurement Standards for open channel flow measurement structures are qualified by strict limitations which are imposed because the original supporting research did not anticipate the more extensive range of conditions and the newer construction materials used today by the water industry and the civil engineering profession. Commonly used gauging structures often operate outside the limits specified in the Standards and this can lead to gross inaccuracies in measured flows.

The Department of the Environment, Transport and the Regions (DETR) partly funded this research project to extend the range of conditions in which a stage-discharge relationship for a particular structure can be predicted, thereby extending the scope of Standards. Additional financial contributions came from HR Wallingford, the Environment Agency, the Scottish Environment Protection Agency (SEPA) and Yorkshire Water plc.

Information available in the flow measurement Standards was summarised and the key experimental limitations were highlighted. Additionally a review of the current usage of flow measurement structures was undertaken. This was based on documents such as registers of gauging structures, reports of studies undertaken for Water Service plc's and asset surveys undertaken for the Environment Agency. Individual experts and operators of structures were also consulted to identify the areas where the Standards needed extending.

The information from the review of flow measurement Standards and the review of current usage was drawn together in order to decide what laboratory tests might be undertaken to provide information which would enable the Standards to be extended to cover more of the structures in common use. The experimental work, which commenced in January 1999 is covered in Report SR 564, see below. Inevitably, only the priority issues were be covered by this project because of the limited finance available.

Detailed conclusions from the work were as follows:

Review of Standards

The review of flow measurement Standards showed the following areas where there is obvious scope for extending their coverage:

- provision of performance data at very low heads.
  This might benefit the measurement of low flows but would demand very high accuracy in the geometry of the structure and in the measurement of head. Such research would benefit laboratory uses of gauging structures but would not benefit field installations.
- provision of performance data when the h/P ratio (or approach Froude number) exceeds current limitations.
  There are strong economic and environmental reasons for installing gauging structures at the lowest practical elevation. This, combined with the limitations on h/P and the modular limit required to avoid drowning, restricts the maximum flows which can be measured. Research to raise permissible h/P ratios would benefit field measurements, including existing installations where siltation upstream of the structure has reduced the height of the weir below its original design value.
- provision of performance data for an extended range of h/L vales.
  This relates specifically to certain broad crested weirs and flumes. Research would benefit both laboratory and field installations. However, the amount of testing may be prohibitive.
- provision of performance data for compound structures without divide piers
  This would benefit many field installations in the UK, all important to the assessment of UK water resources.
- provision of drowned flow data for additional types of structure
  This would again benefit many UK field installations.

Review of current usage

The review of current usage provides two types of information. First it gives some guidance on the extent of usage of the individual types of measuring structure. Second it identifies areas where the structures do not comply with Standard specifications.

In terms of the extent of usage the following conclusions can be drawn:

- Thin plate weirs are used extensively in laboratories. They are also used in the field where sediment movement is minimal eg to measure outflows from sewage works.
- Triangular profile Crump weirs are extensively used in the field and play a major role in measuring flows in UK rivers. They are also used in compound form, with and without divide piers to separate adjacent crest sections. Laboratory installations are not uncommon.
- Flat-V weirs are also used extensively in the field and provide an alternative to compound weirs where an extended range of flows are to be measured.
- Long throated flumes are used in both the laboratory and in the field although their application in the field is restricted to relatively small rivers. They are particularly common in wastewater applications.
- Broad crested weirs of all types are less common but are found both in the laboratory and the field
- The Essex weir is used in many small rivers in Anglia. It is not found elsewhere.

In terms of non-compliance with Standards the following conclusions can be drawn:

- In many cases the approach conditions to the structure are non-compliant.
- In many cases structures drown at an early stage either because the structure is too low or because tailwater levels are higher than anticipated.
- In many cases structures have been built for water resources purposes and hence are designed to measure low to medium flows whereas now they are being used to estimate flood flows.
- In some cases the upstream head measurement is too close to the structure.
- In many field installations sediment deposition has reduced the effective weir height and the installation no longer stays within h/P limits.
- Many structures show variations from the Standard specifications which define their required geometry. This includes basic dimensional requirements, surface finish and such items as truncation of the weirs and invert levels/slopes in flumes.
- Many compound weirs have no divide piers between adjacent crest sections.
- Some structures are of a type which has never been considered for Standardisation eg Essex weirs.

Recommended laboratory tests
The most pressing requirements, taking into account both the extent of usage and the extent of non-compliance with Standards are:

- to extend the range of h/P ratios.
- to evaluate the performance characteristics of compound weirs without divide piers.
- to extend the availability of drowned flow performance data.

White W R, Whitehead E and Forty E J 2000.*Extending the Scope of Standard Specifications for Open Channel Flow measurement structures.* HR Wallingford. Report No. SR 564.
White W R 2001. *Standard Specifications for Flow Measurement Structures*. Proceedings of the Institution of Civil Engineers, Water and Maritime Engineering, **148**, 3, September.

The HR Report No. SR 564 and the summary paper published in the Proceedings of the Institution of Civil Engineers covered the laboratory testing identified in HR Report No. SR 532. The results identified amendments which would enhance the following Standards:

- BS 3680:Part 4A:1981 Thin Plate Weirs.
- BS 3680:Part 4B:1986 Triangular Profile Weirs
- BS 3680:Part 4D:1981 Compound Gauging Structures.
- BS 3680:Part 4E:1990 Rectangular Broad Crested Weirs.
- BS 3680:Part 4H:1999 Guidelines for the selection of structures.

BS 3680 Parts 4A and 4E are currently being revised by BSI / CPI 113 / SC2. These will be published initially as British Standards. New uncertainties sections, in line with the new ISO standard "Guidance for the statement of Uncertainty in Measurement", GUM, have been developed. The proposals were discussed by ISO in Bern in

September 2002. Ultimately the GUM requirements will require all flow measurement Standards to be revised.

Part 4B requires more fundamental changes and will be dealt with by the sub-committee in due course.

Part 4D has been dealt with by providing additional information in the UK Foreword of BS ISO 14139:2000 which was published in June 2000. This stresses the need for divide piers to separate the different crest sections of compound weirs.

Consideration of BS 3680:Part 4H:1999 awaits finalisation of other Standards.

2.3 Fish biology and swimming capabilities

2.3.1 Environment Agency R&D Swimming speeds in fish (W2-026)

Turnpenny A W H, Blay S R, Carron J J and Clough S C 2000. *Literature review of swimming speeds of freshwater fish.* Environment Agency R & D Technical Report W2-026/TR2.

This study was carried out as a precursor to the experimental work at Fawley, see below. The authors of the report quote more than 80 references on the swimming capabilities of freshwater fish but unfortunately much of the data is qualitative.

In an effort to maximise the value of the work in the context of the UK freshwater fisheries interests the report reviews specifically the available data for the "project" species:

- brown trout *(Salmo trutta L)*
- chub *(Leuciscus cephalus L)*
- dace *(Lueciscus lueciscus L)*
- roach *(Rutilus rutilus L)*
- elver *(Anguilla anguilla L)*
- barbel *(Barbus barbus L)*
- perch *(Perca fluviatilis L)*
- pike *(Esox lucius L)*

The literature review concluded that, in general, the data was limited in quantity and lacked a systematic scientific approach.

Commentary
The comprehensive list of references in this report remain of great value as a bibliography for those wishing to read around the subject. The review helped the authors to formulate a systematic laboratory investigation of fish performance, see below.

Clough S C and Turnpenny A W H 2001. *Swimming speeds in fish: Phase 1.* Environment Agency Technical report W2026/TR1.

The conclusions / recommendations from this report is reproduced below:

1. The present study has dealt with a small number of freshwater fish species found in Britain, and has been limited in size range up to about 30 cm fish length. There is a regulatory and conservation interest in a much wider range of species, including small epibenthic species such as bullhead (*Cottus gobio L*) and stoneloach *(Barbatula barbatula L)* and other cyprinid and percid species, and migratory species such as lampreys and shads. It is recommended that a prioritised list of these should be drawn up for future testing.
2. In view of the good performance of the methods used here, it is recommended that the same methods should be used in future studies. Our experiences with fish condition at high summer temperatures in particular indicate that at least a modest level of temperature control of facilities would be helpful.
3. For species which are particularly sensitive to handling or of high conservation merit, consideration should be given to setting up a portable test facility that can be used on the riverbank. This would eliminate much of the stress associated with handling and transport and would enable the fish to be returned direct to source.
4. It was noted during the endurance swimming tests some fish completed the full 200 minutes (of testing) even at the highest velocities. For future studies it would be useful to have a flume facility which offered maximum speeds in excess of 1.4 m/s. A modification to the existing Fawley endurance flume, replacing the paddle wheel with an impeller, would allow much higher velocities to be generated.

Commentary

This study represents a major exercise in the study of fish swimming capabilities using good experimental facilities and techniques. The study covered selected British freshwater fish:

- brown trout *(Salmo trutta L)*
- chub *(Leuciscus cephalus L)*
- dace *(Lueciscus lueciscus L)*
- roach *(Rutilus rutilus L)*
- elver *(Anguilla anguilla L)*

The conclusions and recommendations give little information concerning the burst and swimming speeds of the fish tested, nor is there any explanation as to the broader implications of the work to fish of different species or size. However, data is presented elsewhere in the report. The work refers to the computer programme SWIMIT, the output from which supplies some of the results quoted in the body of the report.

The report implies that both the endurance and burst speeds are relevant to the passage of fish through fish passes and over weirs. They are also shown to be relevant to approach conditions.

Examples of recorded endurance speeds include a range of 0.5 m/s to 0.7 m/s for 15 cm dace, chub, roach and elver and 1.0 m/s to 1.2 m/s for trout. These figures are much less that the known hydraulic conditions met at fish passes and flow measurement structures where velocities are typically in the range 2.0 m/s to 3.5 m/s. This illustrates that anaerobic "burst" swimming is almost always required if fish are to migrate.

Burst speeds are discussed in the main body of the text both in terms of absolute values and also in terms of body lengths per second. The results, in terms of body length per second, show similarities in form with earlier work by **White W R** 1966 and **Beach MH** 1984. In terms of absolute values burst speeds increase at a modest rate with increasing fish length but the effect of temperature is not very significant in the range 10 degC to 15 degC. The burst speeds for chub, dace, roach and trout generally lie within the range 1.0 m/s to 1.5 m/s. The results for trout seem anomalous in that there is little difference between burst and endurance speed.

Ladle M 2002. *Review of Flow needs for Fish and Fisheries.* Environment Agency Technical report W159.

The Executive Summary of this report is reproduced below:

Background
The present decline in stocks of salmon associated with a succession of low flow years has generated an urgent requirement for understanding of the aspects of river flow which induce fish migration. This study was initiated by the Environment Agency to review the literature dealing with fish migration in relation to river flows and to examine available fish (salmon) counter data sets with a view to the possibility of developing a standard methodology to deal with flows and fish migration.

In relation to its influence on fish populations, flow cannot be considered to operate in isolation from other factors. For example, low summer flow is often associated with high temperature. The salmon, which is the main object of this study, has a complex life history strategy which involves a variable number of years of river (parr) life and several possible tactics in the marine phase (1 SW, 2SW, 3SW etc). This makes interpretation of data much more difficult and emphasises the need for long data runs.

Objectives
- To review the current literature concerning the relationship between river flows and migration, river flow and stock levels and river flow and fish catches. Also to consider Environment Agency data and methodologies used in this area. The limitations of this being set by the availability of information.
- To review literature and knowledge on the relationships between river flows and salmonid/coarse fish migration and angling success. By far the greatest bulk of this deals with salmon.
- To inspect data from fish counters and flow recorders on the Rivers Frome, Tamar, Usk, Lune, Kent and Coquet and to present graphical and statistical approaches to analysis of this data.
- If possible to classify rivers in such a way that a simple relationship between flow types and run patterns may be demonstrable.
- To identify gaps in knowledge and, where possible, provide proposals to address the gaps.

Results
- The original core idea, of examining salmon migration in relation to flow in different rivers and integrating the information from counters on different rivers to explore the possibility of a standard modelling procedure has been achieved.

- In reviewing the literature, the relationship of salmon migration rates to river flows, the units of measurement used to define flow requirements, the methodologies established for setting flows required for salmon migration, known patterns of salmon migration, the influences of flow on the behaviour of salmon, the impact of variations in annual flows on the numbers of salmon migrating, the possible effects on other salmonids and their relevance to migration of Atlantic salmon, eel and coarse fish migration have been considered.
- There is little information on the influences of flow on post-emergent fry but a growing number of publications concern parr habitat - some of which deal with flow. Information on salmon smolts is very limited, as is that on coarse fish populations. Although it is widely felt that there are strong relationships between catches of salmonid fish and river flow there are few scientific studies.
- Environment Agency data and methodologies are currently limited by the availability of information. Representative data from existing fish counters have been included. By far the most information on the relationships between river flows and salmonid/coarse fish migration and angling success deals with salmon
- Data from fish counters and flow were obtained and examined, clearly showing that only on the Dorset River Frome does there appear to be an easily accessed, adequate long-term (IFE) data set. Detailed graphical and statistical approaches to analysis of this and other data were applied. There is a uniformity of pattern in seasonal migration of salmon with superimposed inter-river differences. Even if the data were available, the differences between rivers are likely to render a generalised approach difficult.

2.3.2 International references

Beach M H 1984. *Fish pass design – criteria for the design and approval of fish passes and other structures to facilitate the passage of migratory fish in rivers.* Lowestoft, Ministry of Agriculture Fisheries and Food, Directorate of Fisheries Research, Fisheries Research Technical Report No. 78, 46 pp.

The pioneering work by the Ministry of Agriculture, Fisheries and Food encompassed fish biology and swimming capabilities as well as fish pass design. The work was carried out with some collaboration from the Hydraulics Research Station which provided expertise in the hydraulics of gauging weirs. This reference summarises the work in a concise design guide.

The report distinguishes between "burst" speeds and "cruising" speeds. It argues that burst speeds are the most important as far as fish passage around obstructions are concerned and suggests that burst speed is a function of fish length and muscle-twitch contraction time. This model was calibrated by considering measurements of muscle contraction times for six species of fish with a range of lengths within each species.

The report also provides some information on "endurance times", these being the time for which fish can sustain their maximum swimming speeds.

The coverage of this reference, in terms of fish pass design, are explained in Section 2.4.5.

White W R and Hartley W G undated (1966). *Experiments to compare the passage of fish over two triangular profile Flat-Vee weirs.* Report No. INT 67, Hydraulics Research Station, Wallingford, Berkshire, England, 48 pp.

This study was carried out at the time when the flat-V weir was being developed as an alternative to the compound weir where accuracy of flow measurement is essential over a wide range of flows. The original concept was that the flat-V weir should have a 1:5 downstream slope, the same as the two-dimensional Crump weir. The hydraulic arguments for this were strong because of the neat, strong and predictable hydraulic jump which forms on such a slope. However, the Hydraulics Research Station was asked to consider a steeper downstream slope by the Water Resources Board on the grounds that any shortening of the structure would reduce construction costs. The question then arose as to whether the two alternatives were comparable in terms of the passage of fish.

The two weirs were designed to be comparable in terms of their hydrometric performance and were installed in series in a large flume. Rainbow trout were used as the guinea-pigs. The flat-V weir with the 1:5 downstream slope was shown to be more satisfactory than the 1:2 downstream slope, due mainly to the lower degree of flow convergence on the downstream face and the less confusing conditions at the point where the fish were required to start their ascent.

The reference, based on a simplified analysis of fish biology and an accurate analysis of the hydraulics, that fish burst speed should be proportional to the square root of the length of the fish, all other parameters being equal. This form of the relationship fits in reasonably well with the data presented by **Beach M H** 1984 and **Turnpenny A W H, Blay S R, Carron J J and Clough S C** 2000.

2.4 Fish passage over or around river structures

2.4.1 Environment Agency R&D Fish passage at flow gauging stations in England and Wales (W6-029)

Turnpenny A W H, Lawton K and Clough S C 2002. *Fish passage at flow gauging stations in England and Wales. Stage 1: Literature review and regional survey.* Environment Agency R & D Technical Report W6-029/TR1.

The summary and conclusions from this report is reproduced below:

Summary
The effective management of water systems or catchments requires the accurate and reliable measurement of river discharges. The data are used for a wide range of purposes, including abstraction licensing, flood control and prevention, river regulation, habitat conservation and discharge licensing. To permit accurate and reliable flow measurement it is common practice to construct a weir, conforming to BS3680. The Environment Agency operates a large network of flow gauging stations throughout England and Wales.

It has long been recognised that any form of weir may create a potential barrier to the ascent of migratory fish in river systems, and fish passes have been developed as a solution to this problem. Only more recently, in the past decade or so, has attention been paid to the non-migratory freshwater fishes, including brown trout (*Salmo trutta*) and coarse fish. The free movement of all fish species within river systems is now recognised as an important conservation objective. Providing a habitat continuum along a river system encourages optimal habitat use and allows faster recovery after hostile events such as pollution incidents, flash floods or drought.

R & D Project No. W6-084 was set up in two stages. Phase One, reported here, was to provide a technical review of the subject and to assess the extent and importance of fish passage problems associated with flow gauging stations in England and Wales. This was done by literature review, questionnaires to Agency Fisheries and Water Resources (Hydrometry) staff and by setting up Regional meetings to discuss the issues. The findings, along with a database of information referring to individual gauging stations, are reported here. Phase Two deals with solutions, based on physical hydraulic modelling of various fish pass designs and field studies of existing fish passes associated with gauging stations.

Conclusions

1. The Environment Agency operates over fifteen hundred flow gauging stations, of at least 13 different types. These are used for assessing and monitoring water resources, for flood prediction and management and for aquatic habitat protection. Details of some 1,536 stations were recorded in the present survey; possible fisheries problems were associated with 260 of these (18%).
2. The gauging weirs were divided into three head difference categories (<0.5 m, 0.5-1.0 m and >1.0 m). Head difference data were provided for two-thirds of these (949). The frequencies of the low-to-high head categories were 53%, 27% and 20% respectively. Fishery problems were associated with all categories, although for the lower-head stations, problems were associated primarily with coarse fish. Most problems were related to Crump (33% of all problems) and Flat-V gauging stations (22% of all problems).
3. In most Agency Regions it was stressed that where gauging stations are considered to be a significant problem, the problem was nevertheless small in relation to other industrial and water supply weirs which generally greatly outnumber gauging weirs. Consequently, although 260 out of 1,536 sites were identified as potentially problematical in the present survey, a rather smaller number might merit remedial action until such times as neighbouring weirs were removed or made passable. Nevertheless, it is important for the Agency to set a good example to others, which may mean taking action even where neighbouring weirs will continue to constrain fisheries.
4. A review of literature and opinions of Fisheries Staff around the Agency identified several types of problem that arise from barriers to fish movement in rivers. These include: loss of access to habitat, especially spawning habitat; alteration of habitat and biological community structure above and below weirs; increased predation risk for fish that are held up above or below obstructions; prevention of recolonisation of denuded areas following pollution, flooding or drought incidents; and reduction of population unit size for fisheries management. Recent research indicates that impacts on population genetics are generally undetectable, either because timescales since industrialisation have been too short or because there is generally sufficient leakage to prevent genetic drift.

5. The ability or otherwise of fish to ascend gauging weirs is determined mainly by the required swimming speeds and endurance to counter the flow. Ascent is made more difficult at all types of weir by the acceleration and thinning of flow towards the bottom of the weir slope. This is exacerbated in designs where there is severe turbulence, especially in the Flat-Vee configuration, which features flow converging on the centreline and disorientating levels of turbulence in the tail pool. All easement and dedicated fish pass methods attempt to provide flow conditions that make ascent for target species easier. These conditions do not need to prevail all year round, but only when the target species are likely to be on the move upstream. Fisheries departments need to clarify these requirements for each and every structure.
6. A number of fish pass designs are used within the Agency, including pool-and-traverse, Larinier and Denil (plain baffle and Alaskan) passes. These have different merits and there were strong Regional preferences, based both on local historical practice and differing requirements. Overall, the Larinier pass was considered to be the first choice for further evaluation, owing to its suitability for a wide range of species and its debris handling performance. Other preferred fish passes were the pool-and- traverse type and the plain-baffle Denil. Designs such as the vertical-slot pass may be worth considering in the future but there is no experience of this type of pass in the UK at present.
7. Accumulation of debris was considered to be a key factor determining the accuracy of gauging the fish pass component of flow. Denil passes were, for reasons of their susceptibility to weed accumulation, considered to be unsuitable in some lowland areas. Generally, however, the problem was not considered insurmountable, as all Areas sent out staff regularly to clear fish passes (Fisheries) and gauging weirs (Water Resources). If the frequency needed to be stepped up to cope with fish passes on gauging stations, then the extra effort would need to be costed into capital projects of this type.
8. Easement methods, including baffle cascades and Larinier sections on Flat-Vee and Crump weirs were also of wide interest, as they represent relatively simple, low-cost and possibly retro-fittable solutions. Although there is some anecdotal evidence of successful fish passage, there are no data on failure rates. Most methods still require scientific evaluation but this is outside the scope of Phase Two of the present Project. Construction of rock chutes and deepening of tail pools on gauging weirs have been used as easements, especially on salmonid rivers, but this can alter the modular flow range; the method is most widely used on disused gauging weirs and on non-gauging weirs.
9. The standard of accuracy for most gauging stations is ±5% of the calibration on average or ±10% for any spot reading, depending on the purpose of the gauging station (e.g. flood defence or water resources). In rare cases, required average values as low as ±2% were cited. The required accuracy for gauging within the fish-pass element of a compound structure depends on whether the pass is used for high-flow or low-flow gauging, or both, the proportions of flow carried relative to that in the main weir and whether the pass can be boarded up when not in use. Within the context of Phase Two of this Project, the need is to define what accuracies can be achieved with the selected fish pass types, after making any improving modifications. Users can then factor these figures into the overall accuracy calculations for the scheme.
10. Blockage by debris would, potentially, have a significant impact on gauging accuracy. This is largely controllable through regular maintenance, especially

following high flows or e.g. weed-cutting, although the frequency of maintenance might need to be increased over that used at present. Most methods of screening or deflecting debris at fish pass upper entrances were reported to be ineffective and the development of improved techniques for this purpose is seen as being of high value to the present Project.

11. It is apparent that varying gauging standards occur across the Regions of the Agency. There may be a case for harmonising standards where differences result from historical practice rather than Regional need. For example, in Regions where it is not normal practice to perform manual calibrations periodically but to rely on rating curves, it may be more difficult to introduce fish passage structures that could alter ratings, or more costly to build structures that guaranteed no impact on ratings (e.g. with extended upstream wing-walls).
12. For Phase Two of the Project, it is recommended that modelling is carried out on the following fish pass types:
    1. Plain-baffle Denil pass at 20% slope;
    2. Larinier pass at 15% slope;
    3. Pool-and-traverse pass (standard configuration, as per Beach, 1984).
13. The Phase One study identified a number of candidate sites that might be suitable for field investigations. These are locations where fish passes and gauging stations already coexist. The aim would be to look at the hydrometric characteristics of fish passes in these structures for comparison with laboratory findings from fish pass scale models.

Commentary

This literature review and regional survey provides a comprehensive picture of the perceived problems within the Environment Agency relating to the passage of fish over river structures. The most salient points are as follows:

- Gauging weirs are only part of the problem, they are outnumbered by other "industrial usage" weirs. However, gauging weirs are, in the main, the responsibility of the Environment Agency which considers it should show an example in trying to minimise the adverse effects of weirs on fish migration.
- The free movement of all types of fish has now become an aim within the Environment Agency.
- Fish are confronted with challenging conditions at gauging weirs in terms of high velocities, low depths and high degrees of turbulence. This applies to both the gauging weirs and the downstream approach conditions.
- Larinier fish passes seem to be the preferred type because they are suitable for many fish species and they are less prone to the accumulation of debris than other types. Denil (plain baffle) and pool and traverse types are also considered acceptable under suitable conditions.
- The accumulation of debris at the head of fish passes affects flow measurement accuracy.
- Easement methods such as fish pass adaptations on the downstream face of gauging weirs are also considered worthy of further investigation.

Conclusion 11 suggests there are varying gauging standards across the Regions of the Environment Agency. It implies that those regions of the Environment Agency which calibrate gauging structures in the field have more flexibility in introducing fish passes because a gauging weir / fish pass combination can be calibrated in the same way as a straightforward weir. It should be realised that to obtain an accuracy in a field calibration which approaches that of a well built and well maintained Standard gauging structure, using Standard equations and coefficients, requires specialised techniques and equipment, see **White W R** 1975. The specialised field calibrations reported in this reference show that Standard equations and coefficients are confirmed for field installations if enormous care is taken with the fieldwork.

Consideration of those British and International Standards which deal with routine current meter rating and the development of rating curves clearly indicate higher uncertainties than those which deal with Standard gauging structures. Therefore the only sound justification for using field calibrations and not using Standard equations and coefficients is where the structure for some reason does not comply with Standard specifications. Examples might be a compound weir without divide piers or a weir with non-Standard upstream or downstream slopes.

Turnpenny A W H, Lawton K, Clough S C, Hanson K, Ramsay R, Osborne G and Kitson N 2002. *Fish passage at flow gauging stations in England and Wales. Stage 2: Fish pass physical model evaluation and field studies.* Environment Agency R & D Technical Report W6-029/TR2.

The relevant sections of the Executive Summary from this report are reproduced below:

Objectives
Stage 2 of the Project is concerned with solutions. The key objectives of Stage 2 were:

1. to investigate the effect of installing fish passes at flow measurement structures on flow gauging accuracy and reliability;
2. to evaluate the effect on fish passage if changes in commonly used designs were required to achieve adequate flow gauging performance;
3. to evaluate additional maintenance costs and needs if fish passes were to be installed within gauging structures;
4. to estimate the extra costs of installing fish passes at gauging structures.

Three types of fish pass were investigated, based on popularity of use within the Agency. These were:

- the plain-baffle Denil pass;
- the Larinier (‘super-active baffle’) pass and
- the pool-and-traverse pass.

Methods
The study was in two parts and involved a laboratory phase with scale models of the fish passes and a field phase in which examples of existing fish passes of the three types were monitored hydraulically.

In the laboratory studies, models of each of three types of fish pass were constructed at one-third scale and hydraulic measurements were made to develop rating curves and to define attainable accuracies. This work was carried out in the physical hydraulic modelling facilities of ABP Research Ltd in Southampton, using a 30m long by 1.5m wide flume, using a recirculating, pumped flow system. Flow measurement was by an ultrasonic, time-of-flight flow meter fixed to the pump discharge and capable of an accuracy of ±1%. A series of replicated flow versus head measurements was made and the results were analysed statistically to calculate rating curves by linear regression analysis and to determine the mean and spot error attainable with each fish pass configuration.

Performance was judged against criteria that a mean accuracy of ±5% of the calibrations, with up to 10% error on spot readings. Where initial trials did not meet the performance criteria, the upstream arrangement in the pass was modified to reduce upstream turbulence. This was only necessary in the Denil and Larinier-type passes and was achieved by removing baffles near to the crest. The tests were then re-run with the modified arrangement. Additionally, two alternative crest arrangements were tested with the Larinier design. One ('Larinier 1') had a shallow-sloping (1:20) sill above the crest, typical of an arrangement used with fish counting electrodes, and the second ('Larinier 2') had a triangular profile crest with a 1:2 upstream slope, more typical of a Crump-type gaugin*g* weir.

Field Studies

The field investigations were carried out on a plain-baffle Denil pass (River Test, Conagar Bridge, Southampton), a Larinier pass (River Colne, Staines) and a pool-and traverse pass (South Park, Darlington). All of these sites have Environment Agency gauging weirs within 50m upstream. At each pass, a period of level monitoring was carried out in the headrace of the pass using an Orphimedes level logger. Spot measurements of flow within the passes were also made, except in the case of South Park, which has an internal Agency flow gauge that runs continuously. Contemporaneous data were obtained for the adjacent Agency flow gauges. Statistical analysis of the data was used to compare the variability (coefficients of variation) associated with the monitored fish pass headrace levels and the contemporaneous flow data. This was to establish whether data obtained by gauging the fish passes would be subject to higher variability than would be the established gauging stations.

Results

In the laboratory studies, rating curves were established for all the fish pass types. For each fish pass type it was possible to achieve performance within the specified limits in one configuration or another, although in some cases the performance was degraded below the limits when operated at head levels of less than the minimum design operating value. Normally this would not be a problem if the fish pass invert level is properly specified, although it could compromise hydrometric measurements at extreme low flows. The removal of upstream baffles on Larinier and Denil passes does, however, increase the velocities against which fish must swim by a small margin (typically 11-13%) and could decrease fish passage efficiency in some cases.

In general, the field investigations showed that quite stable conditions existed within the headraces of all three types of fish pass, with coefficients of variation less than those calculated from the adjacent gauging stations. The coefficients of variation were calculated as the daily standard deviation of the 15-minute flow measurements divided by the daily mean flow measurement, averaged over a period of a few weeks; they provide a comparative indication of short-term fluctuations in measured flow values. The findings suggest that factors such as upstream turbulence caused by baffle hydraulics and wind-induced wave action were not a serious problem in the data series examined. In the cases of the Denil and Larinier passes, however, the entrance invert levels were well drowned and flows were not at extreme lows, hence the baffles were well submerged at all times.

Conclusions and Recommendations

1. The findings from the hydraulic modelling studies indicate that all three types of fish pass tested (excepting the unmodified Denil pass) would be capable of meeting the accuracy criteria of the mean lying within ±5% of calibration and spot readings lying within 10%, other than at low flows, i.e. below the normal minimum design flow for a fish pass. The best performers were the Larinier 2 (triangular crest) design and the pool-and-traverse pass. Within the normal design head range for a fish pass, both of these met the accuracy criteria without modification and therefore without compromising fish ascent efficiency. A conventional Larinier fish pass design will allow accurate flow gauging, provided that suitable upstream conditions are provided (laminar flow, 1:2 upslope). However, in all cases further investigation is required to assess gauging performance at flows lower than fish-pass design values.
2. Removal of the two topmost baffles in either the Denil or Larinier passes improved gauging performance but at the potential expense of fish passage efficiency. Velocity increases of the order 11-13% were indicated when the baffles were removed. However, in many situations, where an ample margin for fish ascent existed, this may not reduce passage efficiency significantly. The choice of fish pass and baffle configuration must therefore be determined on a case by case basis, balancing the need for gauging accuracy against fish passage efficiency.
3. The gauging performance of fish passes in the field at levels of accuracy found in the laboratory will depend on site conditions (as for other types of gauge) and particularly the ability to maintain them in clean and clear condition. When clear, the field observations made on operating fish passes in this study suggest that headrace conditions do remain stable and suitable for gauging. This is likely to require more maintenance effort than would be involved in standard gauging station maintenance, owing to the greater propensity of narrow channels and baffled structures to blockage and accumulation of debris. On the fisheries side, fish pass maintenance is normally carried out only during the fish migration season and not year-round. The extra maintenance costs are likely to be highly site-specific but could be reduced with joint Fisheries/Water Resources maintenance programmes and by careful initial siting and design.
4. There is scope for developing automated systems based on a velocity-level comparator method that would enable alarm signals to be sent to monitoring centres when partial or complete blockages occurred. This would allow immediate action to be taken and data for the period to be marked as suspect. It is recommended that such systems should be investigated.
5. Deterioration of gauging performance can be expected when the upstream level falls below the minimum design operating level of the fish pass, especially with baffled types, and consideration should be given to this aspect where lower flow gauging is critical. Low flow gauging is critical at some Agency sites and it is recommended that further modelling of low flow scenarios should be undertaken.
6. Typical construction costs for a retro-fitted integral fish pass within or adjacent to a weir range from £30-50k, but this may rise by a further £30k with obtaining planning consents and meeting current Agency policy on environmental assessment of new projects. £70k-80k is now a typical cost for such structures within Thames Region. Bypass-type structures are much more costly, perhaps by a factor of three.

The extra cost of building a bypass structure to avoid interfering with gauging performance of a standard gauging structure should be weighed against the extra cost of regular field calibration of non-standard structures. In reality, costs are highly site-specific and would need to be considered on a case by case basis.

7. Installation of fish passes will probably affect the performance of a gauging structure in relation to the passage of water, hence there will be more backwater effects than with commonly used gauging structures. It should not inevitably affect the quality and accuracy of data.
8. The rating curves developed here are more accurate than those generally used in fish pass design, which are intended only for sizing purposes. The equations given here for the prototype-dimensioned passes can be scaled to other common fish pass sizes, provided that the three-dimensional geometry of the passes remains in proportion.

Commentary

This report describes the results of tests on three types of fish pass carried out at 1/3rd scale. The most salient conclusions are:

- that all three types are capable of providing flow measurement accuracy of +/- 5% for calibration and +/- 10% for spot readings except at flows below the normal design flow for the fish pass - but see below.
- that the Larinier 2 (with adaptation at the head) performed best from a hydrometric point of view.
- that the passage of fish is made marginally more difficult by adaptations at the head of fish passes where fish may be reaching the limit of their endurance.
- that flow measurement through fish passes at low flows needs further investigation.
- that fish passes introduced in parallel with existing gauging structures change flow frequencies through the gauging structure and will, in general, reduce the accuracy of the gauging structure itself.

Conclusion 8 needs qualification. The facilities used for this investigation are excellent for comparative tests between different types of fish pass. They do not, however, have the precision required for hydrometric work, particularly if results are to feed through to Standards.

The basic facilities do not have a constant head tank in the water supply pipework and hence steady flow cannot be guaranteed. The claimed accuracy for flow measurement is +/- 1% or better but this is a manufacturer's claim and has not been verified. The overall accuracy is, of course, also influenced by the precision of the dimensions of the model structures and of the upstream head measurement. In these tests head measurements were made with point gauges to a claimed accuracy of +/- 1 mm which compares with +/- 0.01 mm required and previously used for hydrometric work.

2.4.2 Environment Agency R&D The Hurn gauging station – baffle effectiveness (W6A(02)01)

National Rivers Authority 1995. *Hurn weir gauging station: re-appraisal of options to facilitate the upstream migration of Dace.* National Rivers Authority, project no. C5200.

The flat-V weir was constructed in 1987 on the Moors river at Hurn in Dorset. The weir was designed to measure low and medium flows with a low water afflux of marginally under 1.0 m. It was a Standard design according to BS3680: Part 4G. Shortly after construction the Area Fisheries Officers expressed concern that the weir posed a serious obstacle to migrating coarse fish, particularly Dace. The weir was not thought to be a serious problem to salmonids or (larger) trout.

As a result it was decided to investigate various ways of facilitating the passage of fish and the following were considered:

- the replacement of the weir by an electromagnetic gauging station.
- a by-pass channel.
- a chute type fish pass.
- drowning out of the weir.
- lowering of the weir.
- Denil fish pass set into the weir.

It was concluded that an Alaskan Model A Denil fish pass would be the most effective, although most types of fish pass had not been tested vis-à-vis coarse fish performance. The fish pass was constructed on the centre line of the downstream face of the weir in 1991. The solution was not successful and Dace were observed to find difficulties both within the fish pass and on the downstream face of the measuring weir. Upstream stocks did not recover and a revised solution was sought. Possibilities included:

- do nothing - but start monitoring fish.
- replace the Denil with a vertical slot pass.
- replace the Denil with a Larinier fish pass.
- construct a by-pass channel.
- replace the weir with an electromagnetic gauging station.
- construct a cascade downstream of the weir crest.

It was decided to remove the Denil fish pass and to construct a cascade downstream of the weir crest. It was suggested that such a design could be flexible and that different arrangements could be installed at different times of the year to cope with varying flows. (This seems highly suspect in the light of more recent experience.) It was acknowledged that the proposed solution method was novel and that model studies should be carried out to look at flow patterns and velocities induced by the proposed cascade.

Following model testing, see below, the stop-log cascade was installed at Hurn in 1996.

Walters G A 1996. *Hydraulic model tests on the proposed fish pass structure for Hurn gauging weir, Dorset.* Exeter Enterprises Ltd.

Model studies of the cascade were undertaken by Exeter Exterprises Ltd at Exeter University. The objectives were:

- to optimise the design of the cascade in terms of velocities and depths.
- to measure velocities through the cascade and to compare them with the velocities which occur without the cascade.
- to determine whether the proposed cascade would have any significant effect on the use of the weir as a gauging structure.

Some changes were made to the arrangement of the stop logs on the downstream face of the weir to reduce velocities and to provide more uniform depths between the stop logs. Velocities predicted for the Hurn weir were generally in the range 1.5 m/s to 2.0 m/s. The model suggested that the modular calibration of the weir would be unaffected up to 6 m^3/s but that the coefficient of discharge would fall thereafter.

Walters G A 1996. *Hydraulic model tests on the proposed fish pass structure for Hurn gauging weir, Dorset: supplementary report.* Exeter Enterprises Ltd.

Prior to the construction of the Hurn weir, further changes were suggested. Instead of timber stop logs it was decided to use recycled plastic members. There were also minor changes to the slots and notches within the main members. The tests confirmed that these changes produced some improvement in flow conditions over the downstream face of the weir. At this stage no further hydrometric testing was undertaken.

Walters G A 1997. *Hydraulic model tests on the proposed fish pass structure for Hurn gauging weir, Dorset: supplementary report no. 2.* Exeter Enterprises Ltd.

Following the two sets of testing in 1996, the weir at Hurn was constructed. Unfortunately the cascade as built differed from the cascade as tested and further model studies were commissioned to look at the performance of the as built cascade. The tests looked at:

- the hydrometric performance of the weir with the as built cascade.
- flow conditions through the as built cascade.

The conclusions were that the error in construction had not affected the flow calibration of the structure and that flow conditions over the cascade were only marginally affected.

Commentary

The model studies at Exeter University were carried out at a relatively small scale.

The model showed none of the aeration characteristics of the Hurn weir. Figure 2.1 shows the model operating at low flow and at a discharge above the V-full capacity. In neither case does the model show any aeration. Figure 2.2 shows the prototype Hurn weir with extensive aeration of the flow - a very different situation both hydraulically and in terms of fish migration. , See **May R W P** 1991, **Nagar S et al.** 1977**, Wood I R (Ed)** 1991.

Due to the small scale and lack of weighing or volumetric flow measurement facilities, the results for the weir calibration are not up to the required accuracy for Standardisation.

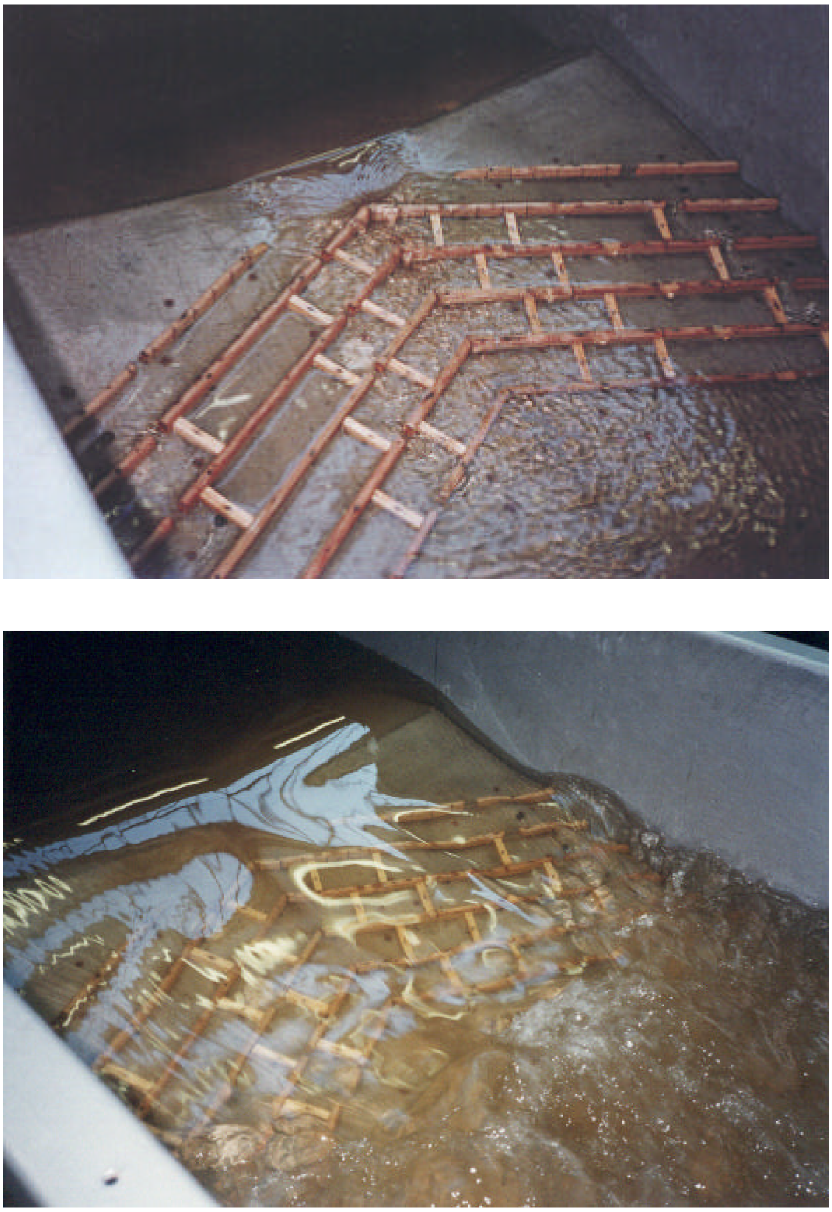

Figure 2.1: Model of Flat-V weir, Moors River, Hurn, Dorset

Figure 2.2: Flat-V weir, Moors River, Hurn, Dorset

2.4.3 Environment Agency R&D Low-cost solutions for improving fish passage at Crump-type weirs (W6A(91)01)

The objectives of this R&D programme, which started in 2002 and is complementary to the current study, are as follows:

- to identify and model potential solutions for improving fish passage conditions on sloping weirs.
- to describe the effects of scale, and of changing physical variables, e.g. slope, baffle dimensions, depth, etc.
- to identify the implications for gauging accuracy and reliability where such structures are used for hydrometric purposes.
- to identify and apply the most promising solutions in carefully identified field situations.

- to produce technical design guidance.

Ayres S A. *Low-cost solutions for improving fish passage at Crump-type weirs.* Cranfield University. Submitted paper, destination unknown.

This paper reports preliminary work on a research project to develop low-cost solutions to the Crump weir, and similar shallow-sloping weirs, in order to facilitate fish passage. A typical site was identified in the field and a 1:5 scale model was fabricated for laboratory experimentation. In order to test a multiplicity of trial baffle arrangements quickly and cheaply, the baffles are to be modeled using Lego bricks. Several most promising alternatives will be identified, using water depth and velocity as the fish passage criteria at this stage. Further investigation of the detailed flow structure will be carried out on the selected baffle configurations together with studies of air entrainment. In parallel with the model studies, some analysis will be carried out using existing databases of Crump weirs that have been identified as posing problems for fish passage.

Sarkar M D, Rhodes D G and Armstrong G S 2001. *Modification of Crump weir to facilitate fish passage.* Cranfield University. Proceedings, 29th IAHR Congress, Beijing.

The low-flow section of a compound Crump weir was modeled at 1/5 scale to investigate the effect of low-cost modifications to the downstream face to improve fish passage. These consisted of baffles with a slot at each wall, and the arrangement was varied in terms of baffle spacing and slot width. Measurements at the 95 percentile low-flow indicated that the modifications, though not yet a satisfactory solution, offer potential that merits further work.

Commentary
The objectives of this project are wide-ranging and the study is at an early stage. Hence only preliminary observations can be made.

It is not clear from the papers whether the Cranfield model is a true 1:5 scale model of the Brimpton weir ie both height and width are scaled or whether the model is a sectional model where the height is scaled but not the width. Interpretation of some aspects of the data are therefore difficult. However, useful comments can be made on some aspects of the modelling in relation to the objectives of the project.

The discussion of scaling and the effects of surface tension and viscosity are a little confused. Flows over Crump weirs are predominantly Froudian ie the effects of gravity are overriding. As far as flow measurement is concerned, surface tension becomes significant at heads below about 25 mm. This is because the curvature of the upper nappe at the weir crest becomes affected by surface tension - it tightens up and restricts flow. This is why there is a head correction factor in the Standard formulae for Crump and other types of weirs. Viscosity, as expressed by Reynolds number, affects the turbulence on the downstream face and contributes to the degree of aeration at objects placed upon the downstream face. Typically, small models show far less turbulence and aeration than the prototypes they seek to mimic - the model of the Hurn weir at Exeter University clearly shows this effect. Aeration is an extremely complex subject and its planned study in this project is ill-conceived, see **May R W P** 1991, **Nagar S et al.** 1977**, Wood I R (Ed)** 1991.

Early tests are concentrating on the 95 percentile low flow. This correspond to a model flow of 2.97 l/s. The corresponding head is around 19 mm and hence the hydrometric performance is in the range which is affected by surface tension. More serious, though, is that flow conditions across the downstream baffles being tested will show little resemblance to the prototype.

Tests to date are specific to the Brimpton weir. The work will have to find a far more fundamental understanding of the physics if the results, presented through the Technical Design Guide, are to be of widespread value.

Due to the small scale and lack of weighing or volumetric flow measurement facilities, the results for the weir calibration are not up to the required accuracy for Standardisation.

2.4.4 Environment Agency Memoranda

Phillips G and Clarke C 2001. *Weirs, flow measurement and fish passage: action on reconciling the conflicts.* Environment Agency memo.

This memo, dated 5 December 2001, announced closer co-operation between the hydrometric and fisheries interests within the Environment Agency in the form of a joint National Hydrometry and Fish Pass working group. The Group had its inaugural meeting on 30 April 2001.

The Group's overall aim is to improve fish passage at river flow gauging weir sites, while not compromising the accuracy of flow and level measurement. In particular it aims to eliminate or minimise any impacts on fish migration at new gauging stations, and to improve fish passage at existing gauging stations where it is considered necessary to do so. This will be accomplished through the following strategies:

- promotion and guidance of Research and Development
- implementation of Research and Development outputs
- development of jointly agreed Agency Guidelines for construction of gauging stations where they might impinge significantly on fish migration

The Joint National Hydrometry and Fish Pass Group have since issued a position statement which says how these objectives will be met.

Joint National Hydrometry and Fish Pass Group 2001. *Guidance on the design and construction of Crump and Flat-V gauging weirs in relation to fish passage.* Environment Agency memo.

The Joint National Hydrometry and Fish Pass Group have issued the following guidelines:

The following design criteria relate to the mean daily flow condition for the period of the year when upstream fish passage is required. These periods will vary locally and be specific to the site location, the river and the species concerned. The relevant periods should be confirmed with Fisheries & Ecology staff. In the absence of good information, the relevant inclusive periods of the year will normally be:

Coarse fish: March - June
Trout: September - November
Eel: April - August
Salmon & Sea trout: April - December

The design criteria below relate to the more common fish species, special considerations may apply in the case of rare or SAC listed species (e.g. shad, bullhead, lamprey, etc.).

1. The maximum difference in level between crest level and the downstream tail water level is to be not greater than 0.5 m for Crump weirs and 0.3 m for Flat V's.
2. The maximum velocity should be no more than 3.5 m/s on the downstream face of the weir immediately upstream of the hydraulic jump.
3. The mean approach velocity in the stilling basin must be no more than 0.7 m/s for migratory salmonids (including trout) or 0.3 m/s for coarse fish.
4. The stilling basin should have a minimum depth of 300 mm below tail bed level.
5. The hydraulic jump is to form on the face of the weir, not in the stilling basin.
6. It is desirable to truncate the downstream face of the weir. Where it is truncated the toe of the weir must be drowned, and the hydraulic jump must form up-stream of the truncation.
7. The tail stilling basin must be a minimum of 3.0 m in length downstream of any truncation, or of the bottom of the weir slope.
8. The designer must produce the necessary calculations to show that the requirements above are met, and these should be included in the Environmental Impact Assessment that is carried out for the site.
9. Where particular design features other than those above need to be included to accommodate fish passage, consultation with the National Fish Pass Group will be required.

Commentary
Item 1:
This criterion is not met at many existing gauging structures. For new structures it will often imply that operation in the drowned flow range is necessary. Greater uncertainties in flow measurement are inevitable, particularly if downstream gauges are preferred to crest tappings.

Item 2:
This velocity is common on Crump and Flat-V weirs. It occurs, under modular flow conditions, between 1.0 m and 2.5 m downstream of the crest dependent upon the flow. The distance increases as the flows diminish.

Item 8:
It is assumed that the designer should also show that his design, which complies with these guidelines, meets his requirement for flow measurement accuracy. See comments on Item 1 above.

2.4.5 International references

Beach M H 1984. *Fish pass design – criteria for the design and approval of fish passes and other structures to facilitate the passage of migratory fish in rivers.* Lowestoft, Ministry of Agriculture Fisheries and Food, Directorate of Fisheries Research, Fisheries Research Technical Report No. 78, 46 pp.

The pioneering work by the Ministry of Agriculture, Fisheries and Food encompassed fish biology and swimming capabilities as well as fish pass design. The work was carried out with some collaboration from the Hydraulics Research Station which provided expertise in the hydraulics of gauging weirs. This reference summarises the work in a concise design guide.

General recommendations for fish pass structures are:

- the flow velocity through the structure should not exceed the burst speed of this fish wishing to move from one reach to the next.
- since endurance time is limited, the approach to the structure should be as easy as possible with adequate take-off depths.
- downstream water levels should be prescribed and maintained.

Having described the general principle of fish pass design, the reference then goes on to consider in detail the following types of structures:

<u>Flow control</u>
- Flood relief channels
- Sluices

<u>Flow measurement</u>
- Crump weir (BS 3680: Part 4B)
- Flat-V weir (BS 3680: Part 4G)

<u>Fish passes</u>
- Pool and traverse
- Denil

In all cases comments are made on flow conditions within or over the structures and information is given on their hydraulic calibration characteristics.

Boiten W 1991. Hydraulic design of pool type fishway with V-shaped overfalls. *Delft Hydraulics, Publication no. 449.*

The first pool-type fishway with V-shaped overfalls was constructed in the Netherlands about 20 years ago. Since that time the variety in designs has increased considerably: in some cases the pool dimensions are very large, in other cases they are far too small. In order to optimise the hydraulic design of the pool-type fishway with V-shaped overfalls, the Dutch Ministry of Agriculture and Fisheries requested Delft Hydraulics to undertake model studies, which were carried out in close co-operation with the Agricultural University of Wageningen.

The objective of the paper is to present the hydraulic characteristics of this pool-type fishway. This fishway, with V-shaped overfalls, is today applied throughout the Netherlands, especially in small rivers: sometimes in the river itself, in other cases as a by-pass of the main river. The model studies resulted in practical design rules which satisfy the boundary conditions determined by the migrant and river characteristics.

The paper concludes with design rules and recommendations for the improvement of the presented fishway.

Commentary
An important finding of the study was the conclusion that the design of any fishway will only be successful, if it results from a close dialogue between the responsible water authority and his advisors on the one side, and the experts in the field of fish migration on the other hand. Although some data is given on the hydrometric performance of this type of fishway which enables a crude calibration to be derived, no claim is made that they may be used, as a matter of course, as flow measurement installations.

Boiten W 1992. *Literature survey on fishways.* Delft Hydraulics, Report Q 1507, 82pp.

This literature survey includes all the papers given at the International Symposium on Fishways '90 in Gifu. In addition it includes other international publications and provides some analysis and categorisation of the types and applicability of the different types of fishways.

In this reference migratory fish is classified according to their environment - salt water or fresh water - where they remain during a part of their life, and according to the direction they go when migrating. The following fish species were identified:

Potadromous	Migratory fish that permanently remain in fresh water.
Anadromous	A fish which spawns in fresh water and migrates to sea to complete most of its growth. (Salmonids)
Catadromous	Fish which spawns at sea and migrates to fresh or brackish water to complete most of its growth and maturity. It spends most of its life in fresh water and migrates to sea to breed.
Diadromous	Migratory between salt and fresh water, including anadromous and catadromous.
Amphidromous	Migrating from sea to fresh water or fresh water to sea at regularly definable stages not related to breeding.
Oceanodromous	Migratory fish that remain in marine water.

The reference suggests that fishways can be defined as hydraulic structures which facilitate upstream and downstream migration of certain fish species in rivers where natural or manmade obstructions - waterfalls, dams, hydropower stations, pumping stations, watermills and weirs - prevent free migration. The main purpose of fishways is to provide acceptable flow conditions for migrating fish. Acceptable flow conditions cover the flow pattern, flow velocities, desired drop in waterlevel, rest places etc.

Based on the literature survey, fishways are classified as follows:

- Pool and weir fishways
  Consist of a sloping or a stepped channel (rectangular or trapezoidal cross-section) partitioned into pools by weirs. Flow over the weirs is plunging (free flow) or streaming. The energy is dissipated in the pools provided the pools have sufficient volume.

  Pool and weir fishways can be subdivided into many subtypes, mainly depending on the weir geometry, such as:
  - central rectangular notches pool and traverse)
  - lateral notches
  - V-shaped weirs
  - V-shaped with a rectangular notch pool and chute
  - lateral notch with sloping ramps
  - any notch or weir with orifices at the bottom.

- Vertical slot fishways
  Consist of a sloping or stepped rectangular channel partitioned into pools, separated by vertical slots.

  Many different subtypes can be distinguished:
  - single jet slots
  - double jet slots
  - baffle and slot

- Denil fishways
  These consist of a sloping rectangular channel with closely spaced baffles on the sides and the bottom. Due to the high energy dissipation, flow is highly turbulent. The main flow has a reduced velocity. The baffles can be placed vertically or under a certain inclination.

- Culvert fishways
  Consist of a sloping pipe flowing partly full with regularly spaced baffles at the bottom.

- Eel pipes
  These pipes are roughened by brushes.

- Fish locks
  Allow a small numbers of fish to pass over a high dam. In Switzerland and France Borland fish locks have been applied. In Japan double-gated locks are used in large barriers (Nagara River).

- Fish elevators
  Small numbers of fish are carried across high dams or weirs. They are used in the U.S.A., Russia and many other developed countries.

- Screens
  These are used to keep the migrating fish away from turbines, pumping stations and weirs. Several types are used, such as drum screens and guidance screens.

- Miscellaneous structures
  Many alternative solutions have been applied, such as:
  - undershot gates
  - flapgates
  - revetment blocks at the bottom
  - pools in an inclined channel

The reference deals with literature on a variety of subjects dealing with migratory fish, such as:

- various types and subtypes of fishway designs
- various fish exclusion systems for turbine intakes and pumping stations
- selection of the best location of a fishway in a river or a dam
- fish physiology, including the capacities of many fish species
- monitoring techniques to measure fish migration.

Experiences with fishway design and operation from about 20 different countries - North America, Europe and the Far East - are presented. The following conclusions were drawn:

1. Although more than 500 papers and publications were reviewed the outcome is very incomplete. The amount of current literature on upstream and downstream migration facilities, fish behaviour and monitoring techniques is very extensive.
2. The selection of the most appropriate fishway design for given boundary conditions is still under discussion. This means that presently existing designs still are subjected to modifications and that new designs are being developed, both for fishways and exclusion systems, for adult and for juvenile fish.
3. The success of a fishway depends highly on its situation in the river or dam. The importance of attraction flow is often times underestimated or completely neglected.
4. The literature on fish capacities - cruising speed, sprint speed and leap height - is far from unanimous. Reliable tables of capacities for a variety of fish species would be welcome to prevent overdesign or underdesign of fish migration facilities.
5. New monitoring techniques are still under development to improve the determination of the effectiveness of the migration facilities.

Fjellheim A and Raddum G G 1996. *Weir building in a regulated west Norwegian river: long term dynamics of invertebrates and fish.* In Regulated Rivers, Research & Management, Wiley, ISSN 0886 9375.

In the period 1975-1990 long-term studies of succession and dynamics of invertebrates and fish were conducted in a weir basin area in the strongly regulated River Ekso. During the years of the study, the invertebrate community in the basin was subjected to great changes. In the first years after weir building, biomass was greatest in the riffles due to a higher abundance of lotic species like the mayfly, *Baetis*, blackflies and many stonefly larvae. The biomass of oligochaetes and chironomids was similar both in the riffles and in the deeper and more lentic weir basin. In the following years the biomass of lentic chironomid species increased dramatically in the basin. In 1984 the fauna was dominated by *Stictochironomus pictulus.* In 1988 another species, *Chironomur melanotus,* also became very abundant. At this time net benthic animal production in the basin had increased 10-fold compared with *1975-1976.* A high flow situation during the summer of 1989 altered the weir basin community dramatically. The mean autumnal biomass decreased 4.5 times compared with 1988, dominant lentic species disappeared and lotic/semi-lotic species like the stoneflies *Amphinemura sulcicollis, Leuctra fusca* and *Capnia pygmaea* increased in density.

Prior to regulation the density of brown trout in the riffle, which later constituted the weir basin area, was 2.5 individuals per 100 m^2. During the first years after regulation and weir building, fish density increased to 11.1 individuals to 100 m^2. In 1983 a density of 23.0 trout to 100 m^2 was achieved. The trout were stunted and showed marked tendencies towards food depletion. During 1984-1985 most of the brown trout population of the basin were removed and used as stock material in the reservoirs of the hydropower station. This resulted in a higher growth rate in the remaining weir basin population. The strong reduction in trout density was followed by major immigration of small (2+ and 3+) trout from the surrounding riffles to the basin. The trout population was now harvested, while a small population of adult spawners was retained.

The paper concluded that weir basins increase the area of pool habitats in strongly regulated rivers, and are of major benefit for trout populations, especially by segregating size classes and increasing winter survival. The presence of intermittent riffle sections is also very important, both as spawning and nursery areas and for fish food production.

Commentary
This is one of the rare examples where river structures have been shown to be of value to fisheries interests, although in this case (and often in river fisheries that are otherwise featureless) low weirs have been used to increase habitat diversity.

Guiny E, Ervine D A and Armstrong J D 2000. *Integrating hydraulics and biology to investigate movements of salmon through fish passes.* New trends in water and environmental engineering for safety and life, Maione, Majone Lehto and Monti (eds), Balkema, Rotterdam, ISBN 90 5809 138 4.

The installation of hydroelectric dams may seriously affect the fish resources of river ecosystems by inhibiting spawning migrations. However, fish passes facilitate these migrations and if efficient may ameliorate adverse effects of dams. Salmon approaching and moving through passes need to locate and traverse the entrance of each section of the pass. The research described in this paper combines biological and hydraulics expertise to investigate the water flow dynamics and attractiveness of different design of entrance in a scaled-down model.

The entrance of the pass has been recognised as a particularly important part of the system (**Bonnyman G A** 1953, **Clay C H** 1961, **Rainey W S** 1991, **Struthers G** 1993, **Uedda M** 1990). The location of the entrance is critical. Ideally, upstream migrating salmon should be attracted directly to the entrance and should not be distracted by other flows, for example, the tailrace from the turbines in generating stations. Both hydraulic and biological aspects of fish passage have to be considered together to ensure that entrance flows and entrance designs of fish pass readily attract fish.

A valuable approach to studying movements of salmon through fish passes is to track remotely the behaviour of large numbers of wild fish in natural situations (**Gowans A** et al. 1999). This approach may allow assessments of the efficiencies of fishways and may provide insights into the proportions of the migrating populations that actually move upstream and the proportions that find the entrances of fishways. However, the behaviour of salmon in the wild is influenced by so many factors that research based only on field surveys may not establish clearly the behavioural mechanisms that enable approaching fish to locate passes efficiently. Furthermore, field studies generally do not permit an experimental analysis of how modifying aspects of fish pass designs influences the behaviour of fish. A method that is complementary to field studies is the use of scaled-down model passes coupled with observations of juvenile salmon (**Stuart T A** 1962). We used such a system to compare the hydraulic characteristics of two types of fish pass entrance: weirs and submerged orifices. Small stream-dwelling salmon (commonly termed "parr") move upstream when displaced downstream (**Huntingford F A** et al. 1999). This paper describes a study which used this behaviour to encourage salmon parr to attempt to locate and move through fish pass entrances.

The authors conclude that the synergy of combining the disciplines of biology and hydraulics to develop good fish passes. The results presented are at an early stage of analysis, but it is clear that variations in the way water is used can have a large influence on the way fish respond to the presence of passes. When more results are available the authors consider that they will be better able to understand how different designs can best be matched to local requirements and what the trade-offs are between cost and performance.

Guiny E, Ervine D A and Armstrong J D 2000. *Fish passes at dams and weirs.* Scottish Hydraulics Study Group, 13th Annual Seminar, 30 March, Environmental River Engineering, Technical Papers.

Guiny E, Ervine D A and Armstrong J D 2000. *Optimum design of fish passes - combining biology with hydraulics at the laboratory scale.* Proceedings of the international symposium on environmental hydraulics, Tempe, Arizona, USA, 5-8 December.

Guiny E, Ervine D A and Armstrong J D 2000. *Hydraulic and biological aspects of fish passes for dams.* Paper submitted to the ASCE Journal of Hydraulic Engineering.

The above three papers result from a collaborative study between the Freshwater Fisheries Laboratory, Pitlochry and the University of Glasgow.

These papers investigate the efficiency of weirs, orifices and vertical slot fish passes using a model fishpass and juvenile salmon. One model at Almondbank, Perth, is used for behavioral studies, while an identical flume at the University of Glasgow is used for hydraulic measurements including velocity patterns and turbulent structure. Both Sets of results are combined to throw new light on the preferences of salmon as they negotiate a fish pass.

Four basic types of openings were tested: weirs, orifices, vertical slots and combinations over five biological series of tests. Designs were generally tested for two discharges, 0.012 m^3/s and 0.02 m^3/s.

Salmon parr were able both to locate and pass easily through the orifices or the slots. They were also capable of passing over the weirs but were more reluctant to do so. Pilot experiments, in which groups of fish were allowed up to 24 hours to pass, confirmed that weirs did not constitute a physical barrier to passage for the size of fish used. The slow response of parr at weirs might be due to the fact that jumping at falling water is likely to be risky due to the possibilities of damage and of attracting predators and is also likely to be expensive in energy terms.

Commentary
The weirs used in these studies were thin plate devices with a falling nappe on the downstream side. They were not Standard designs.

Guiny E, Ervine D A and Armstrong J D 2000. *Preferences of mature male brown trout and Atlantic salmon parr for orifice and weir fish pass entrances matched for peak velocities and turbulence.* Proceeding of the international symposium "Fishways 2001", Reykjavik, Iceland, 19-22 September.

The authors describe a study which claimed to test directly whether salmon and trout preferred to move up-stream by swimming through an orifice or over a weir.

The study used a flume which was fed by natural river water. Roughly half way along the flume a partition was introduced which contain a rectangular orifice and a rectangular notch weir. The authors suggest that design of the experiment was well balanced in terms of hydraulics because both the maximum velocities and turbulence were similar between the weir and orifice.

The study used adult brown trout and small male salmon that had matured at the parr stage (before migrating to sea). The size of the model fish pass was such that it could be considered full scale for the trout (which in many cases spawn in very small streams). However, the system was effectively a scaled-down structure for anadramous adult salmon, analogous to experiments by **Stuart T A** 1962.

There was little mixing of water between the two sides of the flume. Under these conditions, all the mature parr and 95% of the brown trout selected the orifice over the weir. The results of this experiment differ from those of **Stuart T A** 1962 who observed that salmon parr attracted to orifices could not pass through them. This difference may be a function of the experiment designs because although Stuart considered a wide range of types of weir he looked only at one orifice. The design of weir used in the present study incorporated features that Stuart found to be favourable to the upstream migration of salmon. Flow from the orifice was more directional and extended further into the observation chamber than that from the weir and is likely to have provided a stronger cue to approaching fish.

The authors claim that the results of the present study have direct application to the design of passes for brown trout, which often spawn in streams of similar dimension or smaller than the experimental channel. The implication is that submerged passes are likely to be better options than weirs for passing fish. However, an additional practical consideration is the problem of build up of trash (**Gowans A** et al 1999), which may be more serious in orifices than weirs and may necessitate additional maintenance.

Commentary
The conclusions drawn from this work are broad and sweeping. Orifices are better than weirs! This single set of results from a particular weir / orifice arrangement cannot justify such a conclusion. For example, in this particular experiment the flow through the orifice was three times that over the weir. Surely this influenced choices being made by the fish under test. It is also unwise to generalise from thin plate weirs with a falling nappe to all types of weir.

Again, the weirs used in these studies were not Standard designs. There is also some doubt as to whether the behaviour exhibited by juvenile fish can be taken as reflecting the behaviour of adult fish.

Hydraulics Research Station 1976. Fish pass at Chester weir. *Report no. EX 737.*

This paper describes a model study which was used to investigate the fish counting facilities at Chester weir on the River Dee. The original fish pass involved a series of rectangular tubes through which the fish swam, their presence being detected electronically. It was not satisfactory and an alternative was required.

The weir at Chester forms the tidal limit of the River Dee and downstream water levels are, therefore, subject to considerable variation. At the time of high water downstream, the water level at the original fish pass exit was raised considerably, and thus the discharge and velocity were reduced through the original fish counter. The normal reaction of fish was to swim against the current and pass through the counting tubes only once. However, with high tailwater levels and the associated reduction in flow fish were observed to linger within the counting tubes. The records of fish movement in this case were therefore of little value.

A weir of Crump profile was considered as a suitable alternative to the original tube counter arrangement as the fish would not normally pass the measuring section more than once. Furthermore the Water Data Unit, for whom this investigation was conducted, had developed a fish counting instrument which may be embedded within the concrete crest of such a weir. Its operation was, however, sensitive to changes in depth and to the effects of the proximity of a hydraulic jump close to the measuring section.

A hydraulic model was therefore constructed to examine the design and performance of the new fish pass arrangements.

Commentary
This probably represents the first application of a fish counter comprising a Standard Crump weir with metal resistivity strips on the downstream face.

Kamula R 2001. *Flow over weirs with application to fish passage facilities.* Department of Process and Environmental Engineering, University of Oulu, Finland.

Fishways have been studied at the University of Oulu since the early 1980's in close co-operation with biologists and engineers. Until 1996, experimental facilities of the laboratory were located in an old-fashioned, inappropriate and impractical building. In 1996 a new experimental hall was taken into use and the possibilities for hydraulic studies improved considerably. Fishway studies at the University of Oulu have arisen from practical problems, and most of the model studies were conducted for existing or designed structures.

This PhD thesis from the University of Oulu calls upon much of the work carried out there in the last 20 years. The main aim of the thesis is to create a common dimensionless scaling equation for fishway structures and establish a new design procedure. In addition, flow patterns below different fishway types were studied and weir flows over a chain of weirs and a single weir were considered. During her studies Riitta Kamula visited Edmonton for six months and worked with Professors Rajaratnam of the University of Alberta and Katopodis of the Freshwater Institute.

The authors view is that there is not one special fishway type that is superior over the others. There are three basic types: the vertical slot, the Denil, and the pool-and-weir fishway. Each has merits in certain locations and for certain species of fish. Of the three basic types, pool-and-weir fishways are suitable for sites where the upper and lower water level are almost constant, and where there is enough space. Pool-and-weir fishways can be modified to tolerate water level fluctuations to some extent by forming the weir crest or adding notches or orifices. Denil fishways are suitable for sites where the space is a limiting factor and the slope of the fishway would become steep. Denil fishways tolerate water level fluctuations better than pool-and-weir fishways, and may carry a large amount of water. According to this study, the attraction of Denil fishways to fish may be weak, although with improvements and a preceding entrance pool the situation could be improved. Vertical slot fishways are suitable for sites where water level fluctuations are extensive, and where a large number of fish species with varying swimming ability is in concern.

The author suggests that entrance conditions are actually more important for the proper operation of a fishway than the actual fishway type, especially when it comes to fish passage. One important point is that flow pattern both inside the fishway and at the fishway entrance should be clear and concise. All this does not, however, mean that the exit is of minor importance. On the contrary, it is important to locate the fishway exit far enough from possible water intakes in order to avoid unnecessary migration back downstream.

The basis of this study has been to create a general procedure and model to predict flows in fishways in several fishway structures for design purposes. The longitudinal distance between the weirs or baffles, *L,* is used for scaling distances and water depths. As a measure of discharge, the water depth at the weir was chosen. However, the use of a general equation for different fishway types and different flow stages contains uncertainties. It is noted that it is not actually possible to create a precise equation for fishway flows which covers several fishway types and, in pool-and-weir fishways, both plunging and streaming flows. However, the procedure can be used to roughly estimate discharges and water depths in designing fishways.

The author suggests that the results of the studies can be used in determining the most appropriate solution for the fishway entrance at different sites and for different fish species. Because the nature of the flow from different fishway types differs so, special attention should be paid to the flow pattern below the fishway entrance. The thesis suggests guidelines for this provided by biologists (presumably within the University).

Commentary
This work provides some generalised information for calculating flow conditions in the more common types of fishpass and also some advice on downstream conditions which attract fish to the pass. The generalised formulations for the flow conditions are a long way short of providing the sort of accuracy required for hydrometric purposes.

Katopodis C and Rajaratnam N 1997. *Denil fishways of varying geometry*. ASCE Journal Hydraulic Engineering, **123** (7), 624-631.

This paper presents the results of an extensive laboratory study aimed at improving the design of Denil fishways. For the standard design of the simple Denil, an equation was developed between the dimensionless discharge and the relative depth of flow over a large range of conditions. The normalised velocity distributions in the centerplane of the Denil were found to have certain shapes depending upon the depth to width ratio. For non-standard designs of the Denil fishway, based on the results of about 660 experiments, a method was found to predict not only the relation between the dimensionless discharges and relative depths but also the normalised velocity profiles in the centerplane of the Denil. The coefficient of friction between the central stream in the Denil and the circulating water on the sides as well as the bottom has been evaluated along with the equivalent Manning's *n* for the Denil fishway.

The authors claim that these results are important in extending the depth range of the standard Denil Fishpass as well as making changes to the standard design for passing different species of fish.

Commentary
This is one of numerous papers from the "Alberta School" where the hydraulics and effectiveness of Denil fish passes have been studied in great depth, see Rajaratnam et al. below.

Larinier M, Porcher J P, Travade F and Gosset C 1992. *Passes à Poissons. Expertise, conception des ouvrages de franchissement.* Collection 'Mise aux Point'. Conseil Supérieur de la Peche, Paris. ISBN 2-11-088083-X, 336 pp.

Larinier M, Travade F and Porcher J P (2002) *Fishways: biological basis, design criteria and monitoring.* Environment Agency, Cemagref. ISBN 92-5-104665-4.

The authors outline in this book the basic principles which can be used as a guide for planning fish passage facilities at dams or obstructions. The first part addresses the negative effect of barriers across rivers on natural fish population, contributing to the reduction of abundance and even the extinction of species. French statutory legislation on fish passage at obstructions is given. Functional features and design parameters are described for different types of fish facilities, focusing on the advantages, the limits and the cost of each type: pool type fish passes, baffle fish passes, fish locks, fish elevators natural bypass channels, pre-barrages. Stress is laid on the importance of the location of the fishway, hydraulic conditions and the flow discharge at the entrance. Special mention is made of fish facilities for shad, young eels and elvers. Various monitoring techniques to evaluate fish passage efficiency are presented (trapping, automatic counters, video recording, telemetry). Fish passage through culverts, rock weirs and at estuarine obstruction are addressed. Downstream migration problems at hydroelectric power plants are discussed in the last part: evaluation of fish mortality in spillways and hydraulic turbines, design of fish screening and alternative behavioural diversionary techniques used to prevent entry of downstream migrants into intakes. Special mention is made of the most popular technology in France, *i.e.* surface downstream bypasses associated with conventional trashracks, focusing on their design criteria, advantages and limits.

Individual chapters in this comprehensive book are as follows:

Chapter	Title	Authors
1	Fishways: Biological basis, limits and legal considerations	J P Porcher and F Travade
2	Fishways: General considerations	M Larinier
3	Biological factors to be taken into account in the design of fishways, the concept of obstructions to upstream migration	M Larinier
4	Location of fishways	M Larinier
5	Pool fishways, pre-barrages and natural bypass channels	M Larinier
6	Baffle fishways	M Larinier
7	Fish locks and fish lifts	F Travade and M Larinier
8	Fish passage through culverts, rock weirs and estruarine obstructions	M Larinier
9	The design of fishways for shad	M Larinier and F Travade
10	Fishways for eels	J P Porcher
11	Designing fishways, supervision of construction, costs, hydraulic model studies	J P Porcher and M Larinier
12	Monitoring techniques for fishways	F Travade and M Larinier
13	Downstream migration: Problems and facilities	M Larinier and F Travade

Moore K, Furniss M, Firor S and Love M 1999. *Fish passage through culverts: an annotated bibliography.* Six rivers national forest watershed interactions team, Eureka CA.

This bibliography includes 96 annotated citations on culvert design for fish passage, risk analysis, and fish swimming ability. This collection is a subset of a larger bibliography on culverts and sizing, repair, maintenance, installation, failure, hydraulics, and hydrology. Authors' abstracts were included if available, if not, each paper was read and abstracted.

This work was funded, in part, by the San Dimas Technology and Development Center of the USDA-Forest Service. See also: Copstead, Moore, Ledwith and Furniss. 1998.

Water/road interaction: An annotated bibliography. Water/road interactions technology series. USDA Forest Service, Technology and Development Program.

Commentary
This is a specialised paper covering the passage of fish through culverts. Publication of the 96 annotated citations would distort the balance of this report. Specialists seeking further information should consult this reference.

Odeh M (Ed) 1999. *Innovations in Fish Passage technology.* American Fisheries Society Publication, 224 pp.

This book discusses state-of-the-art-technology currently being used to assist migratory fishes in their innate effort to migrate, and to help them mitigate natural and man-made obstructions that they find on the way to their feeding and habitat areas in the oceans and their spawning grounds in rivers. It contains studies conducted to understand the viability, through fish behaviour, of innovative engineering designs constructed to give fish an alternative route to passage through hydropower turbines on their way back to the ocean. It also contains a study on the passage of non-salmonid fishes, which has recently become an important and challenging task to accomplish in the US and abroad. Understanding the relationship between hydraulic phenomena and how they injure fish has become essential to designing "fish friendly" engineering structures. The final chapter explores how cavitation (a pressure-related fluid flow phenomenon that occurs in turbines and at dam spillways) can injure fish.

Rajaratnam N and Katapodis C 1984. *Hydraulics of Denil fishways.* ASCE Journal Hydraulic Engineering, **110** (9), 1219-1233.

This paper presents the results of an experimental study on the hydraulics of simple Denil fishways. For the Standard Denil, the characteristic velocity profile that exists in the fully developed flow region is found. A rating curve is developed for the Standard Denil, which would be very useful in the design of Denils over a range of slopes and discharges. A number of other interesting and practical features of the Denil fishways are found. Some results are also obtained for some "non-standard" Denil designs.

Rajaratnam, N, Katopodis C and Flint-Petersen L 1986. *Hydraulics of two-level Denil fishway*. ASCE Journal Hydraulic Engineering, **113**, 5, 670-674.

In practice, some Denil fishways are sometimes built with the depth to breadth ratio greater than three and these fishways, with their higher velocities, present a greater challenge to migrating fish. One remedy for these large depth to breadth cases is to introduce a roof, parallel to the bed, so that the lower level will have a depth to breadth ratio of three. Then so long as the discharge does not exceed the flow capacity of the lower Denil, it will act like a simple Denil. If, on the other hand, the discharge is larger, then the lower Denil will act as a conduit and carry part of the flow. The rest will be carried by the upper Denil, acting as a simple Denil with a much smaller depth to breadth ratio. With this two-level arrangement, the larger velocities that would have existed in the absence of the roof will be avoided, and the fish passing capacity of the fishway will be improved. This paper (technical note) presents the results of an experimental study performed on such a two-level Denil with a depth to breadth ratio of three for the lower section.

Rajaratnam N, Van der Vinne G and Katapodis C 1986. *Hydraulics of vertical slot fishways.* ASCE Journal Hydraulic Engineering, **112** (10), 909-927.

This paper presents the results of an experimental study on the hydraulics of vertical slot fishways. Seven designs, including some conventional designs, were tested. A conceptual uniform flow state was defined for which a linear relation was found between the dimensionless flow rate and relative flow depth. Non-uniform flow of the Ml and M2 types were analysed using the Bakhmeteff-Chow method. Some observations were also made on the velocity profiles at the slot and circulation patterns in the pools.

Rajaratnam N, Katopodis C and McQuitty N 1989. *Hydraulics of culvert fishways II: slotted-weir culvert fishways.* Canadian Journal of Civil Engineering, **16**, June, 375-383.

This paper presents the results of an experimental study on the hydraulics of culvert fishways with a slotted-weir baffle system. Six designs with two baffle heights and three spacings were tested. A flow equation has been developed to predict the flow depth for any given discharge, diameter, and slope. The barrier velocity that would exist at the slot in the baffles has also been predicted in a general manner. This relatively simple slotted-weir baffle system was found to match the performance of the more complicated but frequently used offset baffle system of similar dimensions.

Rajaratnam N and Katopodis C 1990. *Hydraulics of culvert fishways III: weir baffle culvert fishways.* Canadian Journal of Civil Engineering, **17**, August, 558-568.

This paper presents the results of a laboratory study of culvert fishways with weir-type baffles. Baffles with heights equal to 0.15 and 0.10 times the diameter *(D)* of the culvert were studied with longitudinal spacings of 0.6D and 1.2D. Equations have been developed to describe the relation between the discharge, slope, diameter, and the depth of flow. It was possible to predict the barrier velocity that would exist at the baffles. The performance of the weir baffles has been found to be as good as that of the slotted-weir baffles.

Rajaratnam N and Katopodis C 1997. *Hydraulics of resting pools for Denil fishways.* ASCE Journal Hydraulic Engineering, **123** (7), 632-638.

This paper presents the results of an exploratory laboratory study on the hydraulics of fish resting pools that are built between two Denil fishways, making a full turn or arranged in a folded-back pattern. These experiments show that the flow from the Denil entering the pool diffuses as a surface jet, with an increased growth rate, possibly because of the circulation and turbulence in the pool. This diffusing jet impinges on the backwall and dives into the pool. The flow formation in the vicinity of the outflowing Denil appears to occur in a relatively small region. The energy dissipation in the pool is significant. To provide some resting areas for fish ascending the multiple Denils, it is necessary to provide some depth below the common invert of the two Denils. Some suggestions are made for determining the size of these resting pools.

Shamloo H, Rajaratnam N and Katopodis C 2000. *Hydraulics of simple habitat structures.* Journal Hydraulic Research, **39**, 4.

Habitat structures are built in rivers to provide feeding and resting areas for fish. This paper presents the results of a laboratory study on the flow and erosion around simple habitat structures. Hemispheres with diameters from 74 mm to 130 mm were placed on smooth, rough as well as erodible beds and Froude number of the approaching flow was in the range of 0.07 to 0.60. The depth to body height ratio was found to be the important parameter and was varied from about 0.6 to 4.3. Four different regimes of flow were found, which were classified based on the relative depth. Downstream of the body, there was a recirculation region (closed wake) which was followed by an open turbulent wake. The structure of flow in this open wake was analysed in two layers using the concept of the wall wake. In the plane of symmetry, the inner layer was analysed using the law of the wall whereas the outer layer was analysed using the wake equation of Schlichting. The variation of the velocity in the transverse direction was also analysed using the concept of similar profiles. Some observations were also made on the nature of erosion around the hemisphere placed on erodible beds of two sand sizes. It was found that the pattern of erosion was different for the different flow regimes. The maximum equilibrium clear water scour depth occurred in front of hemispherical bodies.

Thorncraft, G and Harris, J H (2000*). Fish passage and fishways in New South Wales: a status report.* Office of conservation, NSW fisheries, Sydney, Cooperative research centre for freshwater ecology, Technical report 1/2000.

The seven broad categories of fishways that have been used or considered in New South Wales are the pool type (including vertical-slot), Denil, lock, trap-and-transport, rock-ramp, bypass, and eel fishways. Of the 55 species of native freshwater fish living in New South Wales, 32 are at present known to be migratory and to require free passage to sustain populations. Barriers to fish passage, of which there are known to be 4308 in New South Wales streams, can cause local extinction or greatly reduce fish abundance and diversity. Dams, weirs and other structural barriers physically impede fish movement, whilst behavioural barriers such as cold-water pollution or acid drainage either deter fish from attempting to migrate or else inhibit their swimming ability.

The State Goverment Fisheries Department, NSW Fisheries, has regulatory responsibility for protecting fisheries resources, including provisions for fish passage. Since 1985 NSW Fisheries has developed extensive research knowledge about fishways technology and the migrations of inland and coastal freshwater species. Experience has shown that, to build successful fishways, engineering expertise must be combined with fish-biology expertise.

The authors consider that there have been many problems in the history of fishways and fish passage in south-eastern Australia, and lack of knowledge, inappropriate fishway designs, inadequate resources and poor maintenance have taken their toll in the past. Fortunately, the situation has improved greatly over recent years, but the continuing need for improved fishway designs and reduced fishway costs emphasises the requirement for ongoing research and development. Better knowledge remains an urgent priority, especially in the areas of migratory fish behaviour, fishway hydraulics and design, and innovations such as prefabricated modular fishways and less-expensive fishway designs.

Winstone A J, Gee A S and Varallo P V 1985. *The assessment of flow characteristics at certain weirs in relation to the upstream movement of migratory salmonids.* Journal of Fish Biology, **27 (Supplement A**), 75-83.

A major problem in relation to the rehabilitation of Atlantic salmon and sea trout into many industrial rivers in South Wales is the presence of large abstraction weirs which can, under certain flows, constrain the upstream migration of fish. A method is presented whereby the constraints at two weirs on the River Afan were assessed by relating the swimming capacities of different sizes of fish and the flows needed to stimulate upstream movement to the distribution of flows and current velocities. The 'gateways' for fish to ascend the weir are calculated, and their significance in relation to historical flow data and the requirement for remedial action are assessed.

This paper presents a method whereby the constraints on the upstream passage of sea trout, *Salmo trutta* L., at a Crump weir and the effects of water abstraction at another weir on the River Afan were quantified and the requirement for remedial action assessed.

Commentary
The authors of this paper assessed the swimming capabilities of migratory salmonids using mainly the recommendations of **Beach M H** 1981, **Beamish F W H** 1978 and **Gray J R** 1957. However, in their comparison of swimming capabilities versus flow conditions they made the simplifying assumption that fish could swim at 10 lengths per second. This rule of thumb gives over-optimistic swimming speeds for the larger fish and distorts the results. Also, there is no consideration of depths of flows which can also provide challenges to migrating fish.

This is one of the rare papers which considers flow frequencies in rivers and, by implication, indicates certain preferential flow conditions which are attractive to migrating fish.

Yasuda Y, Ohtsu I, Hamano T and Miya Y 2001. *A proposed fishway to facilitate the upstream and downstream migration of freshwater shrimps and crabs*. Proceedings, 29th IAHR Congress, Beijing.

The authors consider that for fish, freshwater shrimps, and crabs, weir and drop-structures without fishways are obstacles to both upstream and downstream migrations. In particular, it is important for diadromous shrimps and crabs to migrate upstream over drop-structures from estuaries where their larvae develop and metamorphose to juveniles. A fishway for shrimps and crabs should be required in drop-structures in order to conserve the local populations of such aquatic animals. This paper proposes a type of fishway for shrimps and crabs that has a stepped channel with a trapezoidal cross-section. The effect of this fishway on the upstream migration of freshwater shrimp is discussed on the basis of experimental results concerning flow fields. Also, changes in the number of freshwater shrimps and crabs migrating upstream via the fishway during a 24-hour period are evaluated.

3. QUESTIONNAIRE AND CONSULTATIONS

3.1 Questionnaire

3.1.1 Response characterisation

A questionnaire was sent out to 34 people; 25 of these were Environment Agency employees, 1 was a SEPA employee, 7 were academics or consultants, and 1 represented the British Canoe Union. The complete list of questionnaire recipients is given in Appendix A. Of the 34 recipients, 16 completed forms were received by HR Wallingford, which represents a response rate of 47 %.

A summary of the expertise areas of the respondents is given in Figure 3.1 below.

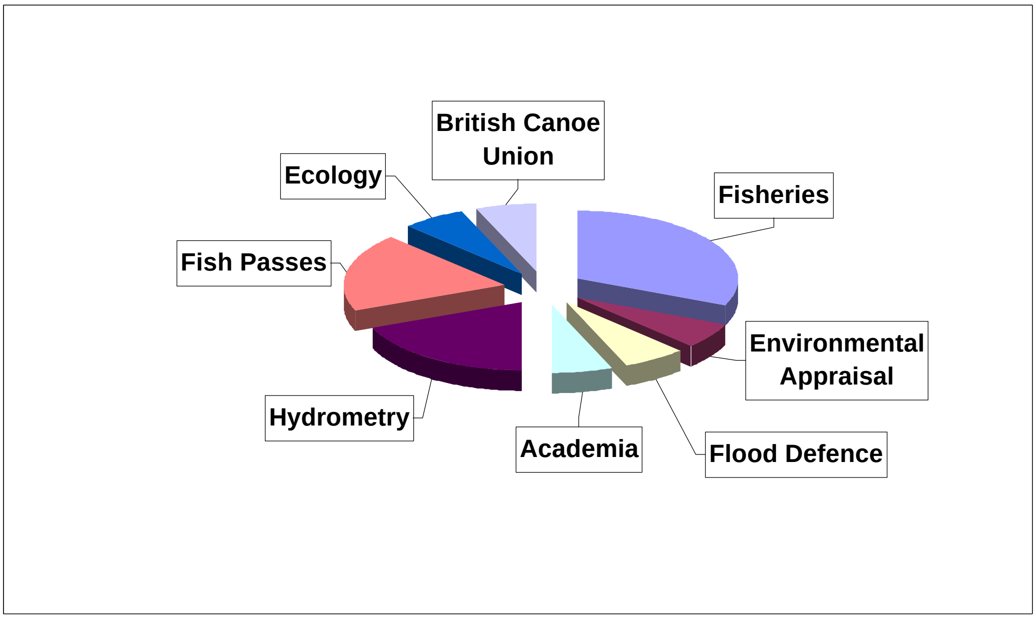

Figure 3.1: Expertise consulted

It should be emphasised that the responses summarised in this Section are essentially raw text taken directly from the returned questionnaires. Inevitably many of the views are subjective and, in some cases, contradictory. In Section 3.2, the responses have been sifted and reviewed in order to present an agreed viewpoint.

3.1.2 Value of different gauging structures for flow measurement

Question:
'Which of the following types of gauging structure do you perceive as having the greatest value in terms of flow measurement:
(a) Thin plate weirs
(b) Horizontal triangular profile weirs
(c) Flat-V weirs
(d) Flumes
(e) Compound gauging structures
(f) Rectangular broad crested weirs
(g) Round nose horizontal crest weirs
(h) V shaped broad crested weirs

(i) End depth method
(j) Trapezoidal broad crested weirs
(k) Parshall and SANIIRI flumes
(l) Streamlined triangular profile weirs
(m) Vertical underflow gates

Many of the recipients were unable to answer this question due to their experience being in fisheries or fish passes, rather than hydrometry. Recipients were asked to rank their favoured options, from 1 (favoured option) to 6 (least favoured option).

Figure 3.2 summarises the responses. The horizontal bar indicates the average value attributed to a particular solution. The vertical bar indicates the complete range of responses e.g. from the maximum to minimum rank given. Many recipients had no experience of some of the gauge types.

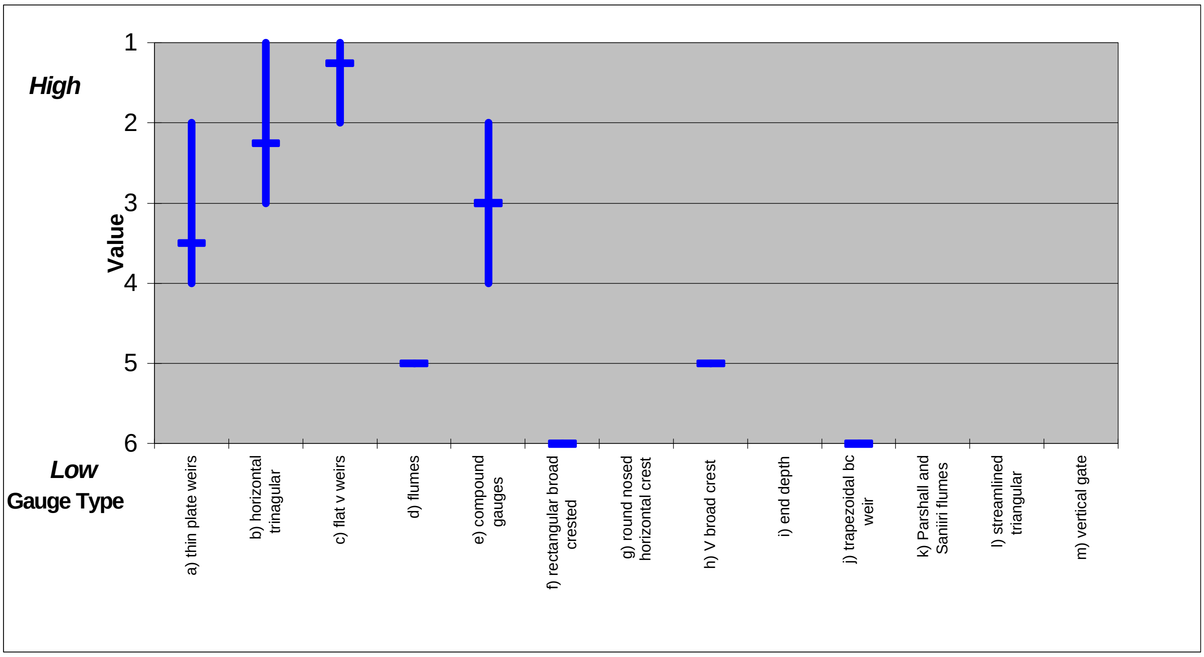

Figure 3.2: Perceived value of structures for flow measurement

The Flat-V weir was the most favoured, followed by the horizontal triangular profile weir. Compound gauging structures and thin-plate weirs were also popular. Although not specified on the list, ultrasonics were mentioned by two recipients. Specific comments are given in the following table:

Gauging weir	Comments
a) Thin plate weirs	• Good accuracy at low flows • Problems with high head losses • Range of flow measurement limited
b) Horizontal triangular profile weirs	• Good accuracy over a range of flows • No central pier complications • Low head losses
c) Flat-V weirs	• Versatile • Sensitive at low flow heads • Low head loss • Good accuracy over a range of flows • Use of upstream and downstream levels to measure drowned flows
d) Flumes	• Self-cleansing properties (useful where debris loads are high) • Minimum head-loss • Good accuracy over a range of flows
e) Compound gauging structures	• With correct combination, flow range capabilities can be high
f) Rectangular broad-crested weirs	• Only appropriate for large rivers
g) Round nosed horizontal crest weirs	• Little / no experience
h) V shaped broad-crested weirs	• Moderate accuracy over range of flows
i) End depth methods	• Little / no experience
j) Trapezoidal broad-crested weir	• Moderate accuracy if good approach and exit
k) Parshall and Saniri flumes	• Little / no experience
l) Streamlined triangular profile weir	• Little / no experience
m) Vertical underflow gates	• Little / no experience

3.1.3 Gauging structure types that are most problematic to the free movement of fish

Question:
'Which of the following types of gauging structure do you perceive as being most problematic to the free movement of fish?'

The list of structure types was then the same as in the previous question.

Two of the recipients were unable to answer this question. Recipients were asked to rank the structure types, with '1' representing the most problematic, through to '6' being the least difficult.

Figure 3.3 summarises the responses.

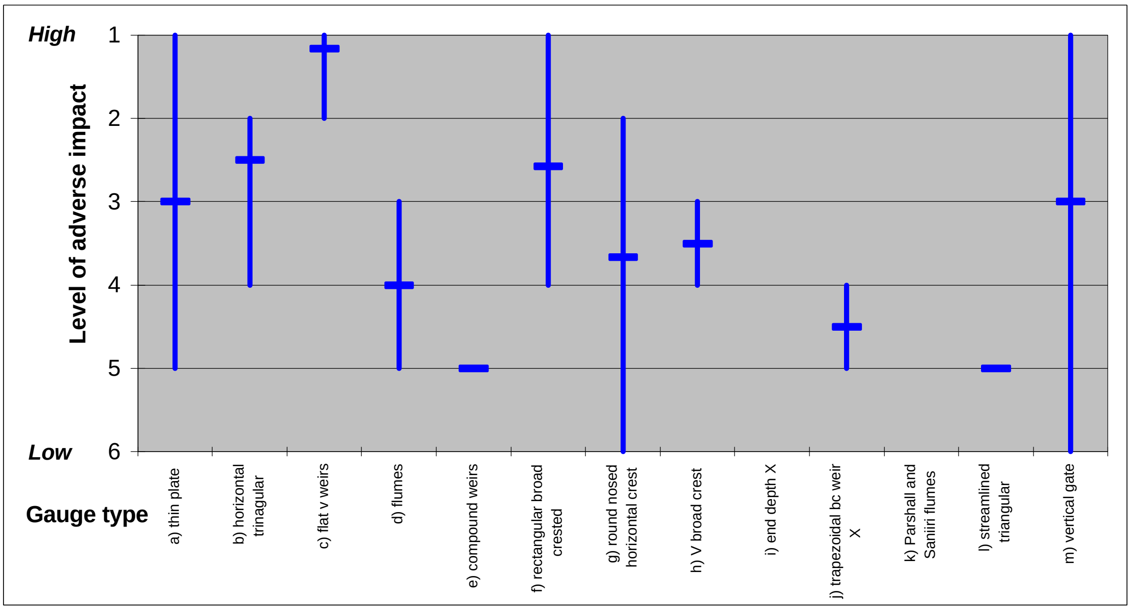

Figure 3.3: Perceived extent to which fish passage is compromised by gauging structure

The range of responses probably reflects different people's experience with different structure types. In very general terms, flat-V weirs were seen to significantly compromise fish migration behaviour, and thin plate, horizontal triangular and rectangular broad-crested weirs were all seen to have high levels of problematic characteristics. Compound weirs, streamlined triangular weirs and trapezoidal broad-crested weirs were seen as less problematic.

Specific comments are given in the following table:

Gauging weir	Problematic Characteristics
a) Thin plate weirs	• Thin flow over plate • Aerated nappe • Large differences between upstream and downstream levels • Vertical face • Insufficient depth of water below crest
b) Horizontal triangular profile weirs	• High velocities over the crest and d/s • Large differences between upstream and downstream levels • If low heads ensured, then can allow fish passage
c) Flat-V weirs	• High velocities • Convergence of waters downstream • Large difference between upstream and downstream levels
d) Flumes	• High velocities
e) Compound gauging structures	• Can be designed out. Has potential to pass a wide range of fish
f) Rectangular broad-crested weirs	• Vertical downstream face • Thin flow over wide crest • Aerated nappe apron • Large difference between upstream and downstream levels
g) Round nosed horizontal crest weirs	• Thin flow on crest • High velocities • Vertical downstream face • Large difference between upstream and downstream levels
h) V shaped broad-crested weirs	• Vertical downstream face • Large difference between upstream and downstream levels
i) End depth methods	
j) Trapezoidal broad-crested weir	• Thin flow over crest • High downstream velocities
k) Parshall and Saniri flumes	
l) Streamlined triangular profile weir	• High velocities are a problem
m) Vertical underflow gates	• High velocities • Vertical component of flow prevents passage

3.1.4 Gauging structure types that are most accommodating to the free movement of fish

Question:
'Which of the following types of gauging structure do you perceive as being most accommodating for fish passage?'

The list of structure types was then the same as in the previous question.

Two of the recipients were unable to answer this question. Recipients were asked to rank the structure types, with '1' representing the most accommodating, through to '6' being the least accommodating.

Figure 3.4 summarises the responses.

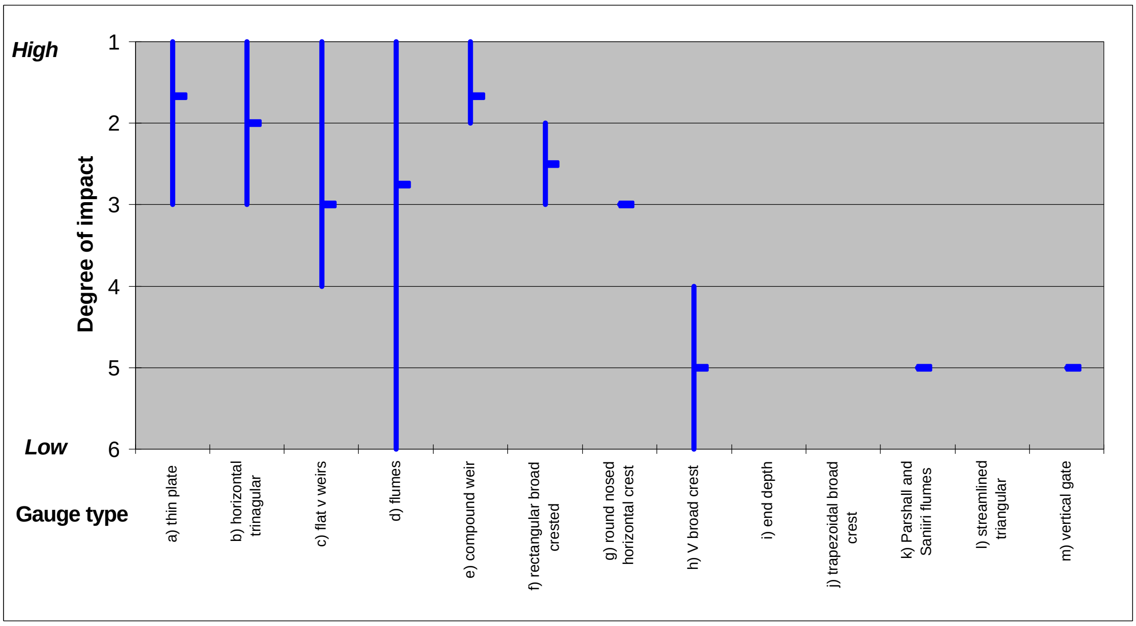

Figure 3.4: Extent to which gauging structure can accommodate fish passage

This plot appears to contradict the results given in the previous question. However, the responses are qualified by comments given in the following table. The levels indicate the opportunities for accommodating fish passage, dependent on specific design characteristics. It is possible that some of the recipients were not fully aware of the geometry of the structures listed.

Gauging weir	Comments
a) Thin plate weirs	• Good if no vertical fall of water (bottom of V drowned) • Used in Holland for slow swimming species • Need small change between upstream and downstream levels, so that the fish do not have to jump far
b) Horizontal triangular profile weirs	• Opportunities dependant on head/tailwater level ratio • Can pass if deep water on crest and moderate head difference
c) Flat-V weirs	• Possible if head loss across structure is low
d) Flumes	• Best for fish because of steady flow conditions and limited gradient • Needs to be deep enough for swimming, have a low head loss, and low velocities
e) Compound gauging structures	• Has the potential to provide fish passage in structure without a jump • Opportunities dependant on head/tailwater level ratio • Needs good depth of water on downstream slope • Allows passage over reasonable flow range
f) Rectangular broad-crested weirs	• Opportunities dependant on head/tailwater level ratio, and depth over crest
g) Round nosed horizontal crest weirs	• Opportunities dependant on head/tailwater level ratio, and depth over crest
h) V shaped broad-crested weirs	• Opportunities dependant on head/tailwater level ratio, and depth over crest
i) End depth methods	
j) Trapezoidal broad-crested weir	
k) Parshall and Saniri flumes	
l) Streamlined triangular profile weir	
m) Vertical underflow gates	• Passage possible if sufficient depth and vertical /horizontal velocities constrained

3.1.5 Fish types to be considered for fish passage at gauging structures

Question:
'Which of the following types of fish need to be considered, and in what circumstances:
1. ***Seawater & Euryhaline fish?***
2. ***Migratory salmonids?***
3. ***Other Anadromous/Catadromous fish?***
4. ***Freshwater fish?'***

To clarify the terminology in this question:

- '***Euryhaline***' is a term denoting those fish that inhabit either fresh or salt water at any given time/opportunity.
- '***Anadromous***' fishes are those that spend all or part of their adult life in salt water and return to freshwater streams and rivers to spawn.
- '***Catadromous***' fishes live in fresh water and go to sea to spawn e.g. eels.

The results are summarised in Figure 3.5:

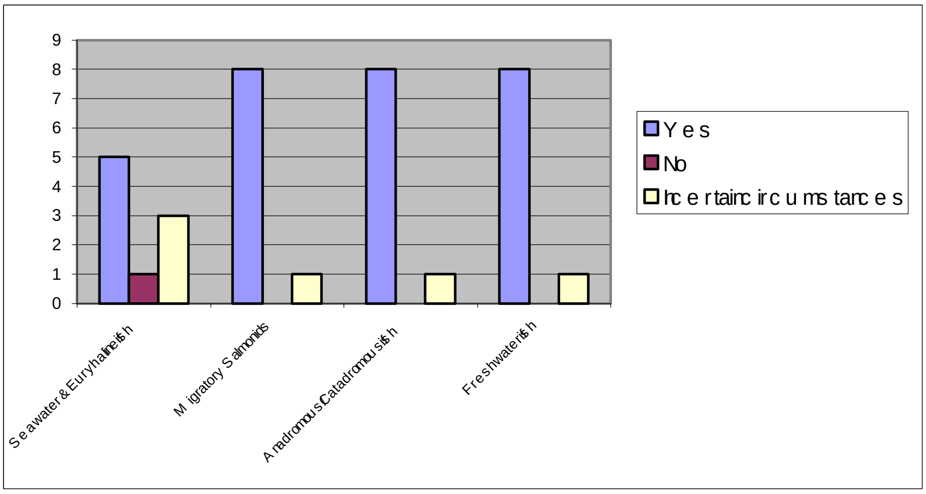

Figure 3.5: Fish types that should be considered for fish passage at gauging structures

Specific comments are given in the following table:

Fish Type	**Comments**
1) Sea water and Euryhaline fish	• All fish need to migrate to some degree, to extend range and genetic structure • Structures have the potential to segregate populations, lowering the gene pool • Mullet and flounders make long 10km migrations into rivers in South West • Lampreys are important • These fish need access to certain important habitats at key life cycle stages
2) Migratory Salmonids	• Must be considered wherever present as they need to move upstream to spawn. This is a statutory

Fish Type	Comments
	requirement. Population size depends on access to breeding/feeding sites and winter shelter areas
3) Other Anadromous / Catadromous fish	• Shad, lampreys, eels all need to migrate to feed, reproduce etc. Most are biodiversity plan species
4) Freshwater fish	• Must be considered wherever present • All fish need to migrate to some degree to extend their range and genetic structure • Review of the Fisheries Act identified migratory needs of all fresh water fish should be considered in the future. The Act will be amended next year

3.1.6 Swimming ability of fish

Question:
'What is your view of the relative swimming capabilities of the following species of fish?'

The results are shown in the following Figure 3.6.

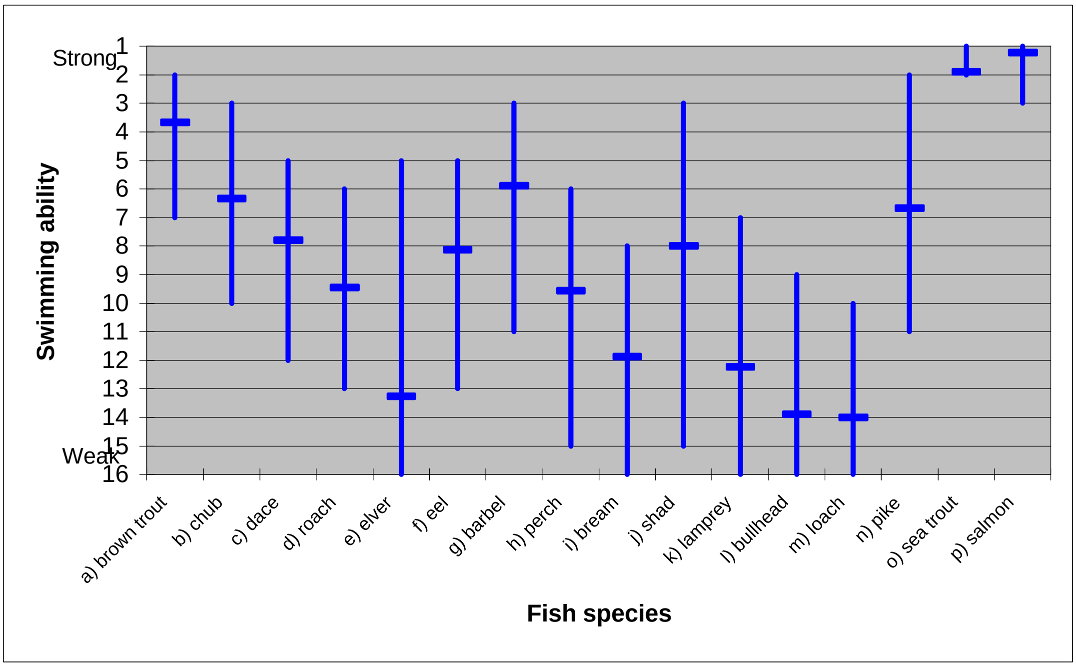

Figure 3.6: Swimming ability of each species of fish

The results indicate that salmon and sea trout have the highest swimming speeds, closely followed by brown trout. Chub, barbel, dace, roach, shad, eel, perch and pike are medium speed swimmers, with elver, loach, bream, bullhead and lamprey being classified as the slowest swimmers.

Specific comments are given in the following table:

Comments
• It depends on the distance over which speeds are measured. Pike are very good at short bursts. White muscle species tend to be good at short bursts but red muscle species can cope with longer distances. Sea trout have high burst speeds but poor endurance capacity. • Some species and smaller individuals are clever at exploiting diverse water velocity or boundary layer conditions for their speed. • It is often not the speed that is the critical characteristic. The channel configuration is also critical in many situations. Bottom swimming species like Barbel need continuity of substrate to negotiate any barrier. • What about minor species e.g. minnow and sticklebacks?

3.1.7 Effectiveness of fish pass types in expediting passage of fish

Question:
'What is your view on the effectiveness of the following means of expediting the passage of fish?'

The results are summarised in the following table. Some comments appear to be contradictory, reflecting different site-specific experiences with different structure types.

Structure Type	Comments
a) Pool and traverse fish pass	• Effective for large salmonids, and possibly Chub • Good for a range of species as it reduces heads between pools • Could be designed to complement flow structure • Not all species jump or move at the surface which limits the appeal of this structure • Effectiveness limited by sensitivity to small changes in head water level • Most effective and widely used, applicable to all species • Good for some coarse fish. Needs a shallow gradient and correct pool size • Insufficient data to get a good impression of the relative merit of this pass type under various river conditions and for various species
b) Vertical slot pool Pass	• Can easily cope with large range in both head and tail water levels • High velocities between slots likely to discourage some fish • Effective for salmonids • Most useful type, for a wide range of species • Expensive and needs significant space

Structure Type	Comments
	• Poor at low flows • Not as flexible as pool and traverse structure • Insufficient data to get a good impression of the relative merit of this pass type under various river conditions and for various species
c) Denil fish pass	• Too turbulent for many species • Effective for (large) salmonids and possibly Chub, limited use for other species unless the slope is minimal • Can withstand a range in head and tail water levels • Useful where longitudinal space is limited because it can be built at a relatively steep slope • Not as effective as pool and traverse structure • Used internationally • Good value • Insufficient data to get a good impression of the relative merit of this pass type under various river conditions and for various species
d) Larinier fish pass	• Very effective pass for a range of fish size and species • Posseses a diverse velocity profile suiting broad range of fish sizes • Can accommodate a modest increase in head and tail water levels • Relatively wide and shallow making it easy to drown the tail effectively • In general, good for salmonids but debatable for others • Pass most often advised for England & Wales • Data shows it is good for a range of species • Used throughout the Thames region but limited evidence of effectiveness • Good for coarse fish if sufficiently shallow • Good value
e) Adaption of structure e.g. Hurn baffle solution	• Appears effective for a range of species and sizes of fish • Unproved but lots of potential. Currently it is used at 3 sites and some planned in Wales South East Area for 2003 • Model study of baffle on crump weir results promising • Effective for salmonids but possibly not other species

Structure Type	Comments
	• Needs to produce smooth flow up to crest
f) Pre-barrage	• Good if it increases depth and reduces swim distance, not if it forms additional barrier • Simple means of expediting fish passage where there are only modest head differences to be overcome • It alters the approach conditions to increase depth and lower approach velocities to put any swim or jump within the capability of the target species • Can be designed to be effective for a range of sizes and species • Better approach than adaptation of triangular weir
Additional comments	• Uneven rocks are better than a weir • The most effective seems to be the pool-drop approach. BCU white water courses at Teeside and Holme Pierrepont are also fantastic fish passes. Padiham is expected to validate this

3.1.8 Availability of data to support the conclusions drawn in the previous question

Question (which refers to previous question):
'Is data available to validate your views?'

The results are summarised in the following table:

Available data
• Observations from Skip Bridge weir, salmon captured from the Don for the first time in 150 years • Radio tracking and PIT tagging at Stamford Bridge Denil pass • Other studies in UK, Holland, Denmark • Physical model studies are being undertaken in October 2003 on baffle arrangement • Model measurements - see Sarker et al., (2001), 29th IAHR Congress, Theme B, 371-377 • Data obtained during management of fish pass R&D project (Paul Power) • Blakes lock (Thames) has data from use of a Larinier pass which has a trap at the head. Fish passage through the pass has been monitored for several years. 16 or more different species of fish from 10-100 cm have used the pass. There is uncertainty over smaller fish because of the mesh size of the trap. • Bypass channel at Penton Hook has shown to be successful for all species. Fawley Aquatics producing a report on this soon • At Sheepbridge on the River Loddon, fish have been shown to use the bypass. Used flume to gauge the bypass channel • A simple baffle system has recently been installed at Kyle Flat-V Gauging Weir in NE Region. Validation work should be carried out during spring 2003 • Very little data on fish species apart from salmonids

3.1.9 Solutions that have been tried in addition to those already listed

Question:
'Are you aware of any other successful solutions that have been trialled?'

The results are summarised in the following table:

Comments
• Baulk passes and low cost solutions • Rock chute on River Don • Natural by-pass (Denmark) • Thin-plate weirs (Holland) • Fish lifts in Scotland • Roughened downstream face • Baulks, rock-ramps, by-pass channels, lifts, submerged orifice passes, eel passes • Removal of structure and installation of a multi-path ultrasonic gauge at Skip Bridge on the River Nidd • Natural bypass channel at Penton Hook, successful for all species of fish

3.1.10 Tried solutions that have failed

Question:
'Are you aware of trialled solutions that have failed?'

The results are summarised in the following table:

Comments
• Poorly designed/located versions of Pool and traverse fish passes and Denil fish passes • Baffles at Skip Bridge • Larinier at Crimple and Kirkham - too long, steep and wide • Ham weir - small face • Attempts to use lower sections of Denils sunk into flat-V weirs in North West and Anglian regions

3.1.11 Suggestions for modifications to the solutions that may help improve either fish passage or flow measurement accuracy

Question:
'Do you have any suggestions for modifications to the above methods, which may help improve either fish passage performance or flow measurement accuracy?'

The results are summarised in the following table:

Comments
Modifications to improve fish passage • Diversity of velocity is important so natural bypasses and flat-V's over even crests are good • Reduce jump heights in pool and traverse • Allow slot boards • If baffles are used on the weir face, then they must be drowned at the tail in the same way as baffles of fish passes are • Bypass channels to exit at the foot of the weir to reduce turbulence • Bypass conduits are not good ***Modifications to improve flow measurement accuracy*** • Measure flow down Denils to add to weir flow ***Both*** • Pool and traverse structures designed in tandem with flow measurement structures would seem the best option to maintain high quality flow data with fish passage. But this would have cost and space implications • Tailor flow over a Crump weir to facilitate fish passage • The solution is dependent upon the site. A large watercourse may be insensitive to flow loss through a bypass fish pass. May be possible to use ultrasonic gauge in the pass • Use BS profile at crest of structure and then introduce proven fish pass below point of interference • Consider making the whole gauging weir a fish pass. A long V-crest with a critical flow should have no effect on metering and with bottom baffles to slow the boundary layer will allow fish passage. This design would enable canoeists to shoot the weir safer. It would be safer for the public and cheap to build

3.1.12 Features that encourage fish to use fish pass structures

Question:
'Which features, in your view, encourage fish to use fish pass structures?'

The results are summarised in the following table:

Comments
• Significant pass flow compared to the whole flow at the site • Location of pass entrance. This needs to be well-defined and the water must be baffled or turbulent, not laminar. There must be adequate flow to attract fish (especially salmonids) • If most of the turbulence is beneath the main weir and not the fish pass, it is likely to attract fish to the wrong place • The funnelling to and from outlet and inlet • Operation at entrance, and location where fish will find it • Attractive velocity profiles • Noise (resulting from head drop and/or turbulence) • Need for a distinguishable velocity jet in which the target species of fish can swim with comfort • Submerged downstream face • Avoidance of truncation, forcing fish to leap into shallow water • Minimum weir heights • Compound weir crests should include a low flow section with swimming depth • Avoid V-crest Crump weirs that produce disorientating eddies • On line structures (based on experience of using diversion channels during construction) • Make the fish passes bigger and reduce the spatial intensity of power dissipation from the flow

3.1.13 Features that discourage fish to use fish pass structures

Question:
'Which features, in your view, discourage fish to use fish pass structures?'

The results are summarised in the following table:

Comments
• Inadequate flow, excess flow, incorrect entrance design, competing local flows • Excessive turbulence and velocities (fish dis-orientated, cannot rest, or creates insufficient water density) • Vertical components of flow, eddies which align fish in opposite direction • Poorly located entrances • Excessive jump heights and/or vertical walls at approach • Shallow, fast flowing (< body depth), as fish prefer to be unseen during migration • Steep slopes • Inappropriate type of pass for the target fish species • Insufficient attraction to pass entrance (e.g. entrance obscured by weir spill) • Off line structures (based on experience of using diversion channels during construction)

3.1.14 Tendency of fish pass structures to have an adverse impact on flow gauging accuracy

Question:
'Do the fish pass structures tend to have an adverse impact on flow gauging calibration (flow structure accuracy)?'

The results are summarised in the following table:

Comments
• Yes • It is difficult to measure flows through fish passes at low flows and when debris has accumulated on the pass. The R&D (Fish passes at gauging structures) describes this, but also suggests that the discharge relationship is stable at depths above the normal hydraulic operating range of fish passes • The question is whether the degree of impact is acceptable. This raises a fundamental question about how accurate the measurement really needs to be in the first place • Larinier baffles are essentially sharp-crested weirs, so should in theory give a good head-discharge relationship • Any fish pass will have an adverse impact on flow gauging accuracy if flow in the pass is not measured accurately. The impact will vary according to the relative flows in the main channel and the fish pass. Likely to become less important at high flows

3.1.15 Tendency of fish pass structures to have an adverse impact on flow gauging station reliability and/or maintenance needs

Question:
'Do the fish pass structures tend to have an adverse impact on flow structure reliability and/or maintenance?'

The results are summarised in the following table:

Comments
• Baffles will tend to catch debris • Bio-fouling should be avoidable through use of appropriate materials for baffle construction • Fish passes generally comprise a narrower channel which will have a greater tendency to become blocked • The Hurn type seems to have little impact on reliability and maintenance • Bypass fish passes may need regular cleaning at the inlet end if flow measurement takes place there • Evidence has shown that fish passes collect trash and debris, and are generally poorly maintained. Unless there is a change in attitude to commit to regular maintenance (there do not appear to be regular maintenance schedules at present) there will be a lack of confidence for inclusion within gauging structures

3.1.16 Methods for adjustment of gauge calibration for the fish pass structure

Question:
'In your experience, how is the gauge calibration adjusted for fish passage structures?'

The results are summarised in the following table:

Comments
• Estimate flow at certain stages and add it on to Q-H relationship for main structure

3.1.17 Acceptability of ultrasonic or electromagnetic technologies as alternatives to other flow measurement structures

Question:
'Are technologies such as ultrasonic or electromagnetic acceptable alternatives to structures?'

The results are summarised in the following table:

Comments
• Cost may be a precluding factor • Cost of getting electricity to remote sites is a major consideration when evaluating electronic options • Ultrasonics are relatively cheap and accurate. Electromagnetics are expensive. • At certain locations, they are the best option but they tend to be expensive to build and not as accurate, robust or reliable (flow data failure is higher and there is a high skilled maintenance requirement) • From a fisheries point of view they tend to be a more acceptable option than hard infrastructure. However, the ultrasonic sound frequency must not occur in the same range as the hearing frequency of Shad where they are present • From a hydrometrics point of view, they may not be acceptable due to above reasons and technical aspects e.g. where insufficient water depth, high aeration, high suspended solids etc. • Almost invariably preferred option. Though still some local habitat issues associated with channelisation, dredging, keeping clear for gauging. These are relatively easy to mitigate for

3.1.18 Environment Agency requirements for measurement accuracy of low/medium and high flows

Question:
'What overall accuracy of flow measurement do you perceive as the EA requirement for:
1. ***Low flows?***
2. ***Medium flows?***
3. ***High flows?'***

The results are shown in the following Figure 3.7.

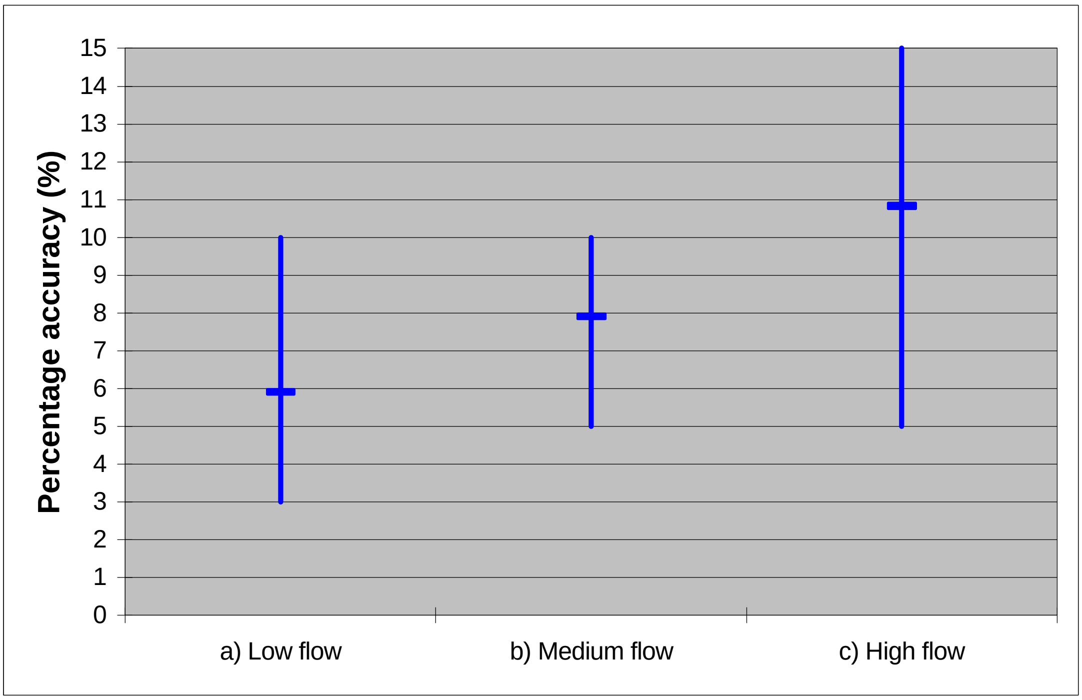

Figure 3.7: Environment Agency accuracy requirements for flow measurement

3.1.19 Problems with obtaining financing for fish pass structures

Question:
'Are there any problems with providing financial justification and/or finance for capital works to aid the passage of fish over gauging weirs?'

The results are summarised in the following table:

Comments
• Not if anglers threaten to sue for loss of amenity • Justification is easy as economic benefit values are available (e.g. for salmonids – increased or lost production). Cash is less certain, even with benefit: cost ratios significantly above unity • Justification easier for salmonids than other species • Easier to get funding for salmonids on SAP rivers failing targets, than on other rivers • Unlikely to be problems with 'justification' due to flow gauge and fish pass seen as environmentally sound proposal. Increased costs of compound structures will inevitably increase the promotion of alternative flow techniques (ultrasonic, electromagnetic). This should also force clients to focus on quality of data that they really require • Most Agency structures are owned by Water Resources. Fisheries is funded by FER who have more restrictions on budget than Water Resources. Main issue is to get funding from Water Resources under the Agency 'Making it Happen' and local contribution strategies • Yes there are problems providing financial justification because of anecdotal evidence. The issue is not yet being dealt with, start of R&D process. • Existing legislation allows for application for funds for salmonids as allowing free passage is a statutory requirement. Future legislation should make this possible for all freshwater fish

3.1.20 Issues with maintenance associated with fish pass structures

Question:
'Who takes responsibility for maintenance of fish passes? Have you experienced problems with maintenance issues?'

The results are summarised in the following table:

Comments
• Maintenance should be the responsibility of the pass owner, and the department that paid for it. It is, however, a grey area • Adhoc. Fisheries enforcement and EWF do some. Limited amounts done • This should be a Fisheries function • Expect hydrometry staff would be responsible to maintain the pass when an integral flow gauge • Fisheries department – but there are disputes within the Enviroment Agency as to who is responsible and who should pay • The disputes mean that they are not maintained on a regular basis

3.1.21 Critical issues to be addressed if the study is to be successful

Question:
'In general terms, what do you see as the critical issues that need to be addressed in the present study if it is to be successful?'

The results are summarised in the following table, under 3 headings. It should be highlighted that recipients tended to use this question to highlight critical issues in general, rather than considering whether they would be appropriate for inclusion within this study specifically.

Comments
General • Reaffirming that new (and, in time, existing) structures should not have adverse impact on environment • To design a compound measurement/fish pass structure that provides defined, known and consistent flow measurement performance combined with facilitating passage of target species of fish • To decide whether some specific forms of technical fish passes can or cannot be used in compound weirs to achieve both fisheries and hydrometric aims. If so, how. Larinier and pool & traverse are best prospects for achieving this • Exploration of funding streams particularly for retrospective incorporation of fish passes. Water Framework Directive may be of assistance here
Flow Measurement • Assessing effects on flow measurement accuracy of range of fish pass solutions • Promoting low cost additions to weirs and electronic solutions. There is a growing range of electronic solutions for flow measurement, not all of which are ultrasonic • To identify a minimum flow at which the solution should facilitate fish passage • To define a tolerable level of interference with hydrometric function e.g. a) no effect on head-Q for modular flow, b) no effect on differential head-Q for non-modular flow • Find means to ameliorate negative effects of existing weirs whilst retaining gauging quality. To describe in detail the means of achieving such retrofit • Hydraulic study of pool & traverse, and Denil passes to enable them to be designed as hydrological gauges – particular attention being paid to top baffles, impact of successive baffles/traverses and turbulence ***Design Characteristics*** • Considering submerged entrances to fish passes to mitigate debris collecting/ maintenance problems • To ensure that any composite structure does not collect debris and thus add to maintenance needs of structure ***Fish Passage*** • Whatever combination of gauge/fish pass is chosen, it must be effective for fish passage in the wild. Laboratory testing would not be sufficient for this • Any new method must be thoroughly field tested in order to fully assess the

impact on the gauging capability of an amended structure. It is also vital that information on fish populations are gathered well in advance of any field trial so that the effects can be assessed post modification. It is also vital that any laboratory flow testing is carried out in such a way as required to meet BS and ISO standards requirement • Test some different passage options under controlled range of conditions for different species of fish. Pay particular attention to making the passes easy for fish to find. Don't concentrate only on sustained swimming and burst speeds of fish in laminar flow if there is substantial turbulence in the systems of interest • Review the conceptual approach to the passage of fish. It is making life easy for the fish to pass both up and downstream that must be considered. Fish will take the line of least resistance, hence use the whole weir

3.2 Summary of the salient points from the questionnaire and additional consultations

The replies to the questionnaire, the workshop, and the discussions during the consultation process were useful in that they helped to identify current issues and gave an opportunity for Environment Agency personnel and other experts to give their views. Inevitably many of the views were subjective and, in some cases, contradictory. Thus, in consultation with the Project Board, the consultant sifted responses and identified those issues upon which there is a broad degree of agreement.

This section of the report gives the results of this exercise.

3.2.1 Value of different gauging structures for flow measurement

Gauging weir	Comments
a) Thin plate weirs	• Good accuracy at low flows • Problems with high head losses • Range of flow measurement limited
b) Horizontal triangular profile weirs	• Good accuracy over a range of flows • No central pier complications • Low head losses
c) Flat-V weirs	• Versatile • Sensitive at low flow heads • Low head loss • Good accuracy over a range of flows • Use of upstream and downstream levels to measure drowned flows
d) Flumes	• Self-cleansing properties (useful where debris loads are high) • Minimum head-loss • Good accuracy over a range of flows
e) Compound gauging structures	• With correct combination, flow range capabilities can be high
f) Rectangular broad-crested weirs	• Only appropriate for large rivers
h) V shaped broad-crested weirs	• Moderate accuracy over range of flows
j) Trapezoidal broad-crested weir	• Moderate accuracy if good approach and exit

3.2.2 Gauging structure types that are most problematic to the free movement of fish

Gauging weir	Problematic Characteristics for Fish
a) Thin plate weirs	• Thin flow over plate • Aerated nappe • Large differences between upstream and downstream levels • Vertical face • Insufficient depth of water at tail • Poor approach conditions
b) Horizontal triangular profile weirs	• High velocities over the crest and on face • Thin flow on face • Large differences between upstream and downstream levels
c) Flat-V weirs	• High velocities • Convergence of flow downstream • Large difference between upstream and downstream levels • Insufficient depth of water at tail • Poor approach conditions
d) Flumes	• High velocities
e) Compound gauging structures	• Poor approach conditions
f) Rectangular broad-crested weirs	• Vertical downstream face • Thin flow over wide crest • Aerated nappe • Large difference between upstream and downstream levels • Insufficient depth of water at tail • Poor approach conditions
g) Round nosed horizontal crest weirs	• Thin flow on crest • High velocities • Vertical downstream face • Large difference between upstream and downstream levels
h) V shaped broad-crested weirs	• Vertical downstream face • Aerated nappe • Large difference between upstream and downstream levels
j) Trapezoidal broad-crested weir	• Thin flow over crest • High downstream velocities
l) Streamlined triangular profile weir	• High velocities
m) Vertical underflow gates	• High velocities • Vertical flow components

3.2.3 Gauging structure types that are most accommodating to the free movement of fish

Gauging weir	Accommodating Characteristics for Fish
a) Thin plate weirs	• Base of V drowned • Limited difference between upstream and downstream levels
b) Horizontal triangular profile weirs	• Limited difference between upstream and downstream levels • Reasonable depth of water on crest and face
c) Flat-V weirs	• Limited difference between upstream and downstream levels
d) Flumes	• Steady flow conditions • Limited gradient • Adequate depth (to allow for fish to pass up flume) • Low velocities • Limited difference between upstream and downstream levels
e) Compound gauging structures	• Potential to provide fish passage in low flow section of structure without a jump • Adequate depths of water on downstream slope • Limited difference between upstream and downstream levels
f) Rectangular broad-crested weirs	• Limited difference between upstream and downstream levels • Reasonable depth of water on crest and face
g) Round nosed horizontal crest weirs	• Limited difference between upstream and downstream levels • Reasonable depth of water on crest and face
h) V shaped broad-crested weirs	• Limited difference between upstream and downstream levels • Reasonable depth of water on crest and face
m) Vertical underflow gates	• Adequate depth of flow • Constrained vertical / horizontal velocities

3.2.4 Fish types to be considered for fish passage at gauging structures

Fish Type	Comments
1) Sea water and Euryhaline fish	• All fish need to migrate to some degree, to extend range, mix and maintain a robust genetic structure • Structures have the potential to segregate populations, lowering the gene pool • Mullet and flounders make long 10km migrations into rivers in South West • Lampreys are important • These fish need access to certain important habitats at key life cycle stages
2) Migratory Salmonids	• Must be considered wherever present as they need to move upstream to spawn. This is a statutory requirement. Population size depends on access to breeding, feeding sites and nursery sites
3) Other Anadromous / Catadromous fish	• Shad and lampreys all need to migrate to feed, reproduce etc. Most are biodiversity plan species
4) Freshwater fish	• Must be considered wherever present • Some are biodiversity plan species • All fish need to migrate to some degree to extend their range, mix and maintain a robust genetic structure • Review of the Fisheries Act identified migratory needs of all fresh water fish should be considered in the future. The Act is expected to be amended shortly

3.2.5 Swimming ability of fish

Comments
• It depends on the distance and time over which speeds are measured. White muscle is used anaerobically for relatively short bursts, while red muscle is used aerobically for lengthy periods and longer distance swimming. • Some species and smaller individuals are clever at exploiting diverse water velocity or boundary layer conditions for their speed. • It is often not the speed that is the critical characteristic. The channel configuration is also critical in many situations. Bottom swimming species like Barbel need continuity of substrate to negotiate any barrier, i.e. the behaviour of different species has to be taken into account.

3.2.6 Effectiveness of fish pass types in expediting passage of fish

Structure Type	Comments
b) Pool and traverse fish pass	• Good for a range of species as it reduces heads between pools • Not all species jump or move at the surface which limits the appeal of this structure • Effectiveness limited by sensitivity to small changes in head water level. • Needs a shallow gradient and correct pool size
b) Vertical slot pool Pass	• Can easily cope with large range in both head and tail water levels • High velocities between slots likely to discourage some fish – particularly small individuals • Effective for migratory salmonids and a wide range of other fish species • Expensive and needs significant space • Poor at low flows – requires significant minimum discharge
c) Denil fish pass	• Too turbulent for many species • Can withstand a range in head and tail water levels • Useful where longitudinal space is limited because it can be built at a relatively steep slope • Used internationally • Good value
d) Larinier fish pass	• Very effective pass for a range of fish size and species • Can be juxtaposed to enable large attraction flows • Possesses a diverse velocity profile suiting broad range of fish sizes • Can accommodate a modest increase in head and tail water levels • Relatively wide and shallow making it easy to drown the tail effectively. • Pass most often advised for England & Wales • Data shows it is good for a range of species • Good value
e) Adaption of structure e.g. Hurn baffle solution	• Unproved but lots of potential. Currently it is used at 3 sites and some planned in Wales South East Area, 2003 • Model study of baffle on crump weir results promising • Needs to produce smooth flow up to crest
f) Pre-barrage	• Good if it increases depth and reduces swim distance, not if it forms additional barrier • Simple means of expediting fish passage where there are only modest head differences to be overcome.

3.2.7 Suggestions for modifications to the solutions that may help improve either fish passage or flow measurement accuracy

Comments
• Increase diversity of velocity profiles • Reduce jump heights • Allow slot boards • Drown baffles • Submerged inlets

3.2.8 Features that encourage fish to use fish pass structures

Comments
• Significant proportion of pass flow compared to the whole flow at the site • Location of pass entrance. This needs to be well-defined (located where it is easily and quickly located by fish), and the water jet must be distinct and not broken by cross-flow or otherwise masked. There must be adequate flow to attract fish (especially salmonids) • Turbulence at the inflow to attract fish. • Attractive velocity profiles • Noise (resulting from head drop and/or turbulence) • Correctly submerged tail in the case of baffle passes • Minimum weir heights

3.2.9 Features that discourage fish to use fish pass structures

Comments
• Inadequate flow, excess flow, incorrect entrance design, competing local flows • Excessive turbulence and velocities (fish dis-orientated, cannot rest, or creates insufficient water density) • Turbulence beneath the main weir (which attracts fish to the wrong place) • Truncation or aeration, forcing fish to leap into high velocity shallow water where they are easily disorientated or exposed to side forces • Vertical components of flow, eddies which align fish in incorrect directions • Poorly located entrances • Excessive jump heights and/or vertical walls at approach • Shallow, fast flowing (< body depth), as fish prefer to be unseen during migration

3.2.10 Tendency of fish pass structures to have an adverse impact on flow gauging station reliability and/or maintenance needs

Comments
• Baffles will tend to catch debris • Bio-fouling may be enhanced • Narrower channels will have a greater tendency to become blocked • Bypass fish passes may need regular cleaning at the inlet end if flow measurement takes place there

3.2.11 Critical issues to be addressed if the study is to be successful

Comments
• Define tolerable level of interference with hydrometric function e.g. a) no effect on head-Q for modular flow, b) no effect on differential head-Q for non-modular flow • Design of a compound measurement/fish pass structure that provides defined, known and consistent flow performance combined with passage of target species of fish. • To decide whether some specific forms of technical fish passes can or cannot be used in compound weirs to achieve both fisheries and hydrometric aims. If so, how. Larinier and pool & traverse are best prospects for achieving this • Find means to ameliorate negative effects of existing weirs but keeping gauging quality. To describe in detail the means of achieving such retrofits.

3.3 Consultations

Consultations were undertaken with Dr David Rhodes and Susan Servais of Cranfield University, and also with the Scottish Environment Protection Agency (SEPA). The outcome of these consultative meetings is discussed in the following sections.

3.3.1 Visit to Cranfield University

A visit was made to the Royal Military College of Science, Cranfield University, by HR Wallingford on 13 December 2002. The purpose of this visit was to discuss and view laboratory work being undertaken by Dr David Rhodes and Susan Servais to develop low-cost modifications to Crump-type weirs in order to improve fish passage while preserving their hydrometric function. The team is currently investigating a baffle arrangement on a 1:5 scale model of a Crump weir by measuring free surface profiles and velocity distributions at selected locations.

The visit will ensure that the two projects progress in parallel, producing complementary results for the hydrometric and fisheries communities.

3.3.2 Visit to SEPA, Edinburgh

A visit was made by HR Wallingford to the Scottish Environment Protection Agency (SEPA) in Edinburgh on 22 January 2003. Discussions were held with Drew Aitken and Neil McLean, both employed in the Hydrometry Department.

The law governing the provision of fish passes in Scotland is described in "The Salmon (fish passes and screens) (Scotland) Regulations 1994." Guidance on the application of these regulations is given in *Notes for guidance on the provision of fish passes and screens for the safe passage of salmon* published by The Scottish Office Agriculture and Fisheries Department in 1995, ISBN 0 7480 3105 Y. These regulations apply to salmon and sea trout only. SEPA considers that the EU Water Framework Directive will dictate that other species of fish are considered in future.

For flow measurement, SEPA's gauging stations are predominantly of the velocity area type but there are a few flat-V weirs, a few trapezoidal flumes and several non-Standard devices in use. Few of the structures have fish passes or fish passage aids. Hydrometric structures are outnumbered by weirs introduced for industrial purposes. It is felt that many of these structures inhibit fish movement.

Although SEPA did not respond to the Questionnaire sent out as part of this study, its content was discussed during the visit to Edinburgh. SEPA was broadly in agreement with the responses previously obtained by HR. Exceptionally, SEPA considers that long throated trapezoidal flumes should be added to the list of structures that are important from a hydrometric point of view.

SEPA has targets for flow measurement accuracy, which are dependent upon the flow rate. An uncertainty level of +/- 5 per cent is stipulated between the 20 percentile and 90 percentile flow rates. Outside these limits the stipulated uncertainty is relaxed to 10 per cent, this being realistically achievable under these high and low flow conditions, using velocity area techniques.

4. DISCUSSION AND CONCLUSIONS

The objectives of the overall project are *"The investigation and specification of flow measurement structure design features that aid the migration of fish without significantly compromising flow measurement accuracy, with the potential to influence the production of suitable British Standards."*

The aim of Phase 1, the work described in this Technical Report, is to review current knowledge in order to define the most useful and productive way forward. In particular it provides the justification for future, accurate, hydrometric modelling of possible solutions in Phase 2.

So what has Phase 1 told us and how does this influence priorities for Phase 2?

Hydrometry

1. There is general agreement within the Environment Agency that low to medium flows should be measured with uncertainty levels no greater than +/- 5%. For medium to high flows this figure could be stretched to +/- 10%.
2. The accuracy of routine current meter calibrations in the field is generally lower than the accuracy attainable at Standard flow measurement structures.
3. The usage of Standard flow measuring devices within the Environment Agency remains extensive (> 1000 installations), particularly the use of Crump, flat-V and compound structures.
4. The Environment Agency view of accuracy requirements is not necessarily the worldwide, international view. This is of relevance when promoting the results through British and International Standards. Historically, countries in which water shortages are common have argued for higher accuracies in flow measurement than currently required by the Environment Agency.

Fish Biology and swimming capabilities

1. There is extensive information on swimming capabilities of fish but the subject is complex and the data is neither comprehensive nor precise. Early work was concentrated on salmon and sea trout. More recently there is a greater emphasis on freshwater and coarse fish. Much of the work was ad hoc observation from trials done for other purposes and was not reported in a sound scientific manner.
2. The swimming capabilities of fish depend upon a number of factors including:
   - species
   - length (the age of an individual fish or the collective adult size of a particular species)
   - water temperature
   - water depth
   - water velocity
   - turbulence
   - distance to be negotiated
3. A distinction is made between "burst" speed and "cruising" speed. Burst speed is generally anaerobic swimming while cruising or sustained swimming is aerobic. Burst speed seems to be the most relevant figure for passage over or around gauging weirs. Both burst and cruising speeds depend on the size of fish, all other things being equal.

4. As a broad generalisation, salmon and sea trout have high burst speeds, typically in the range 2.0 m/s to 3.5 m/s for mature fish. Freshwater fish have lower burst speeds, typically in the range 1.0 m/s to 1.5 m/s for mature fish. Velocities on the downstream face of gauging weirs may reach 4.0 m/s. Thus, weirs present far more of a barrier to freshwater species than to salmon and sea trout.

Fish passage over or around river structures

1. There are many references to "one-off" fish pass types but the choice, in the context of this study, appears to be narrowing to three commonly used devices. These are, pool and traverse, Denil (or a derivative) and Larinier (or a derivative).
2. Scale models have been used to assess the relative merits of the different types of fish pass. These have been carried out at relatively small scales to facilitate rapid, economical construction and ease of modification. These models have provided flow characteristics that are adequate for designing fish passes but not for hydrometric purposes.
3. Smaller scale models have also been used to investigate new ideas on adaptations to measuring weirs. They have been of limited value because they cannot simulate aeration of the flow and their hydrometric performance is impaired by fluid property effects.
4. Some hydraulic and fish monitoring tests have been carried out at field installations, including looking into downstream conditions and the factors which attract fish towards fish passes.

There are three main categories of potential solutions to the fish passage problem:

- bypass channels which could be much longer than the gauging structure in the direction of flow and which might take the form of a pool and traverse fish pass, a Denil fish pass (or derivative), a Larinier fish pass (or derivative) or a semi-natural channel.
- fish passes which are combined with a Standard gauging structures to form compound units. These may utilise pool and traverse, Denil or Larinier fish passes which would be separated from the main gauging section of the structure by divide walls of some type.
- adaptations of Standard gauging structures in the form of fish "aids" on the downstream face of the weir, the easement approach. The solution being tested on the Moors River at Hurn is an example of this approach. The introduction of a Larinier or Denil fish passes to the downstream face of weirs is unlikely to be successful based on past experience.

Bypass channels and compound units

In the first two categories flows down the fish pass are separated from flows over the main gauging structure. The proportion of flow taken by the fish pass can be determined / designed but this proportion will vary as the river flow varies because of the different rating curves for the gauging section and the fish pass section. (Assuming that monitored and controlled variable level intakes to fish passes are not a practical proposition). The overall percentage uncertainty in the measured river flow will depend on the percentage uncertainties in the flows measured by the gauging weir and the fish pass and the proportion of the total flow taken by each. Thus, if the uncertainties in the measured fish pass flows are large and the proportion of flow taken by the fish pass is also large then the overall uncertainty will be unacceptable from a hydrometric point of view. On the other hand, if the uncertainty in the fish pass flow is not much higher than the gauging weir and / or the fish pass takes a small proportion of the flow then the situation becomes more acceptable to the hydrometrist. Responses from the questionnaire illustrated a lack of appreciation of the hydrometric concerns by fisheries interests, a factor which needs to change if combined flow measurement structures / fish passage aids are to meet with general consent.

The Phase 2 testing will need to look at the basic uncertainties associated with fish passes and will need to be augmented with a desk study to formulate design methods which will ensure that the overall uncertainties of the system are acceptable. It will not be necessary to model the gauging weirs, only the fish pass sections of any compound arrangement. Indeed, it may only be necessary to model the head of each type of fish pass because this determines its hydrometric performance. The greatest challenge will be to avoid high uncertainties at the gauging section brought about by relatively high discharges through the fish pass section and consequent low heads at the gauging section.

Adaptation of Standard gauging structures, the easement approach
In the third of the categories, the easement approach, fish passage aids of various types have, and are, being tried. They offer one possible solution to the fish passage problem but they have yet to be proven in the field.

Salient points from the questionnaire / consultation exercise
The questionnaire was formulated jointly by the consultant and the Project Board. Replies were evaluated by the consultant and are discussed in Section 1 of Chapter 3.

The replies to the questionnaire, the workshop, and the discussions during the consultation process were useful in that they helped to identify current issues and gave an opportunity for Environment Agency personnel and other experts to give their views. Inevitably the views were subjective and, in some cases, contradictory. Thus, in consultation with the Project Board, the consultant sifted responses and identified those issues upon which there is a broad degree of agreement. These are listed in Section 2 of Chapter 3.

Key issues which have not already been reported above and which need to be addressed in future studies include:

- the need to develop methods for "retro-fitting" fish pass aids because of the large numbers of existing flow measurement structures.
- the need to address the problem of trash being caught in fish passes with consequent changes to head / discharge relationships.
- the need to minimise afflux (the difference between upstream and downstream water levels) over flow measurement structures because peak velocities are closely related to afflux.
- the need to ensure that any truncation of the downstream face of a flow measurement structure is submerged by the tailwater.
- the need to minimise aeration because of the reduced ability of fish to navigate and swim under such conditions.
- the need to minimise large scale turbulence and flow convergence both of which disorientate fish.

- the need to provide a diversity of flow conditions locally which fish are able to exploit.
- the need to attract fish towards the downstream outlet from any fish pass.
- the need to provide easy approaches to fish passes to minimise the amount of anaerobic swimming that is required.
- the need to provide suitable flow conditions upstream of the fish pass such that fish are not swept back over the flow measuring structure.

Proposed laboratory testing

The Phase 2 testing will need to model the proposed solution, possibly with sectional models, and seek adaptations that have little or no effect on the hydrometric performance of the basic weir.

The details of the Phase 2 testing needs to take into account the types of weir which are of the greatest value to, or see the greatest usage in, hydrometry - the Crump weir, the flat-V weir and the compound weir are candidates. It will also have to incorporate those fish passes or adaptations that have a successful track record and are welcomed by the fisheries interests. On present evidence the ranges are:

Weirs:	Two-dimensional triangular profile (Crump) Flat-V Compound
Fish passage aids:	Pool and traverse fish pass Denil (or derivative) fish pass Larinier (or derivative) fish pass Adaptations to Standard weirs (easements)

For reference purposes, typical pool and traverse, Denil and Larinier fish passes are shown in Figures 4.1, 4.2 and 4.3. Figures showing variations of these solutions are presented in Appendix B. Details of the proposals for laboratory testing are based upon these conclusions and are given in the Laboratory Proposal report (not released to public), and summarised below. The recommended projects for Phase 2 are:

Proposal	Value For money & Urgency	Notes
1. Desk study of the combined uncertainties associated with the introduction of fish passage aids at Standard flow measurement structures.	High, High	This is an important study which will: • enhance understanding of the hydrometric implications of the introduction of fish passage aids at flow measurement structures. • provide guidelines for the design of fish passes vis-à-vis the performance characteristics of the flow measurement structure.
2. Review of the problems of trash at	High, High	This is an important study, which should be carried out as a matter of urgency such that any

Proposal	Value For money & Urgency	Notes
fish passes and ways of minimising accumulations.		lessons learned can be incorporated in any of the design solutions modelled in Phase 2.
3. Laboratory tests to provide an accurate hydrometric calibration of a Larinier fish pass.	High, Medium	This study will consider the basic calibration of the Larinier fish pass and also possible adaptations at the upstream end to improve hydrometric performance. It will provide information for existing installations and design information for new installations.
4. Laboratory testing of a Larinier and/or a Pool and Traverse fish pass with a submerged orifice upstream intake set alongside a flow measurement structure (non-specific).	High, Medium	This study will look at a combined fish pass/flow measurement installation in which the fish pass is placed alongside any Standard flow measurement structure. Flow measurement through the fish pass could be achieved by a variety of means. Fish counting would also be feasible.
5. Laboratory testing of a Larinier and/or a Pool and Traverse fish pass with a submerged orifice upstream intake set midstream at a flat-V weir.	Medium, Low	This study is similar, in some respects, to study 4 and will look at a combined fish pass/flow measurement installation in which the fish pass is installed midstream within a flat-V weir. The interaction with flows over the flat-V weir, particularly downstream flow conditions, will need to be investigated.
6. Fundamental requirements for the near-crest arrangements for baffles on the downstream face of a measuring weir.	High, High	The baffle arrangements on the "Hurn" type easement are designed to reduce velocities on the downstream face and to create a spatial diversity of flow conditions. The upstream baffles are those which potentially affect hydrometric performance. This study will provide a limited amount of basic information about the requirements for the location of the most upstream baffle in relation to its size.
7. Testing of a limited range of "finalised" Hurn type adaptations to flat-V weirs.	High, Medium	There is a problem with developing general design and performance data for "Hurn" type easements. This is because the size, spacing and location of baffles is related to fish size, not weir size. Hence easements on large weirs are not necessarily geometrically similar to easements on small weirs. This study will thus investigate a limited range of typical arrangements. Generalised information will have to be derived by interpolation.

Following discussions with the Environment Agency Project Board, studies 1, 2, 3, 4 and 6 will be progressed as Phase 2 of this R&D project.

This Phase 1 review has identified several fish passage aids which were judged either not successful in terms of aiding fish migration or requiring no further research at this stage. Some fish passage aids, e.g. pre-barrages, do not impinge on flow measurement using Standard structures so long as their design does not infringe the requirements for the flow measurement structure.

The following types of fish passage aids are therefore *not* considered for further work in Phase 2:

Structure type	**Comments**
Denil fish pass	• Generally thought to have limited usage in the UK because Denil fish passes are mainly of value in steep rivers, and there is a limit to the range of fish types that would could use the pass successfully.
Pre-barrage	• Good value if the pre-barrage increases depth and reduces swim distance but not if it forms additional barrier. • Can be used without further research so long as the hydrometric properties of the Standard structure are not affected.
Bypass channels • Rock chutes (e.g. River Don) • Natural by-pass (e.g. Penton Hook, Denmark) • Thin-plate weirs (Holland)	• Not thought worthy of testing from a fisheries point of view • Would need Standard flow measurement structure at the upstream end if used as part of a flow measurement system
Adaptations to Standard weirs • Roughened downstream face • Baulks	• Performance from a fisheries point of view still under investigation • Limited amount of research suggested at this stage
Fish lifts (e.g. Scotland)	• Useful under specific circumstances • Not of direct relevance to the current research project
Specific types of fish pass • Submerged orifice (with free fall to pass) • Eel passes	• Not of direct relevance to the current research project
Replacement of flow measurement structure • Ultrasonic • Electromagnetic • Velocity area station	• Not of direct relevance to the current research project

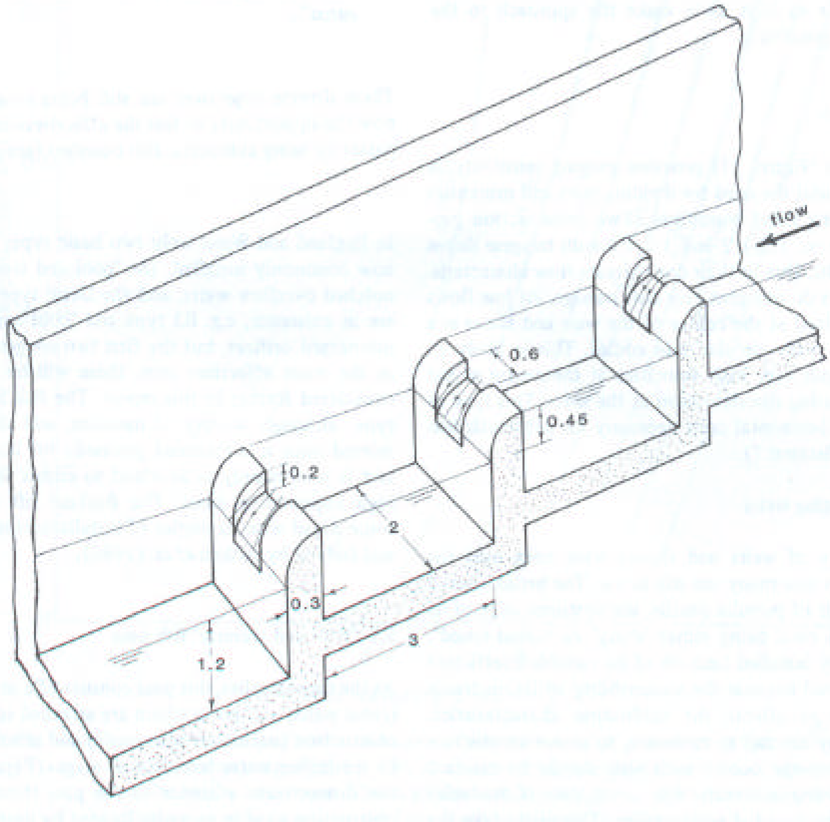

Figure 4.1: Pool and traverse fish pass

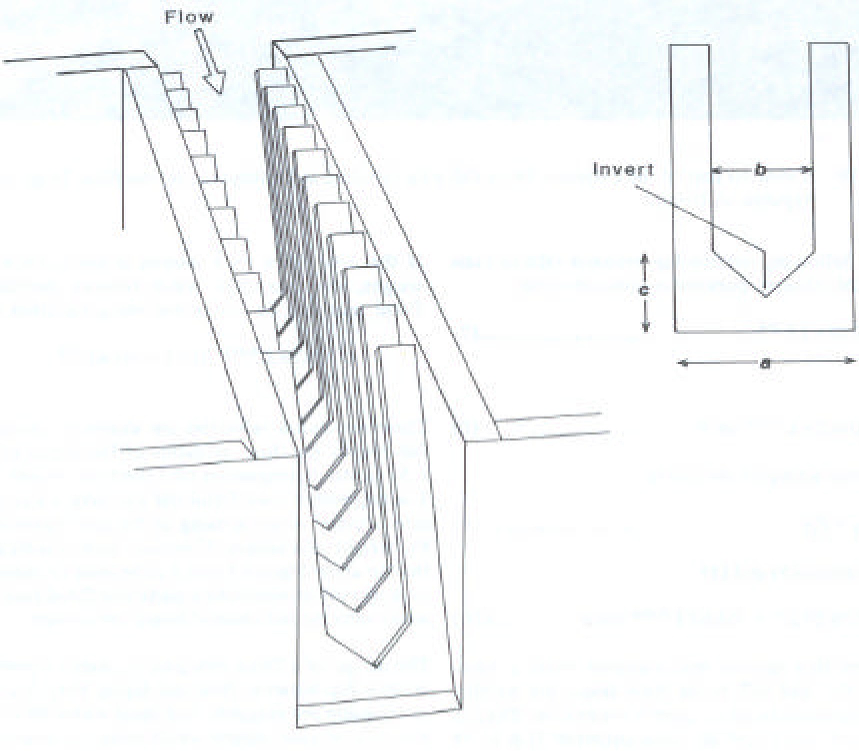

Figure 4.2: Denil fish pass

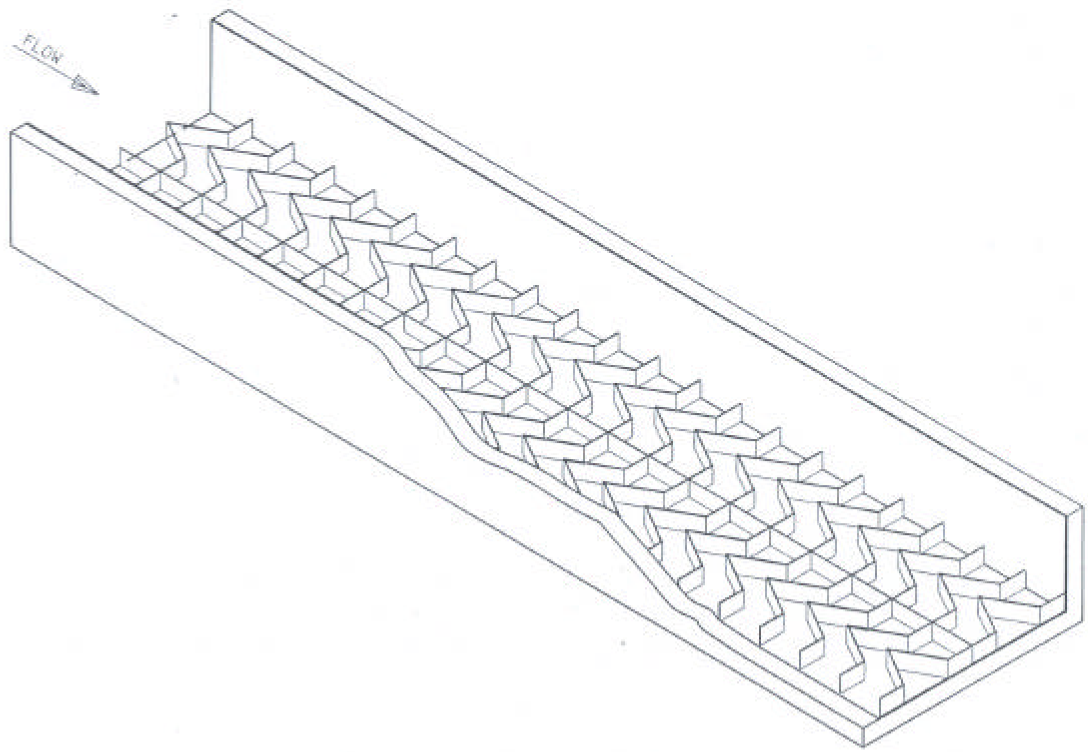

Figure 4.3: Larinier fish pass

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APPENDICES

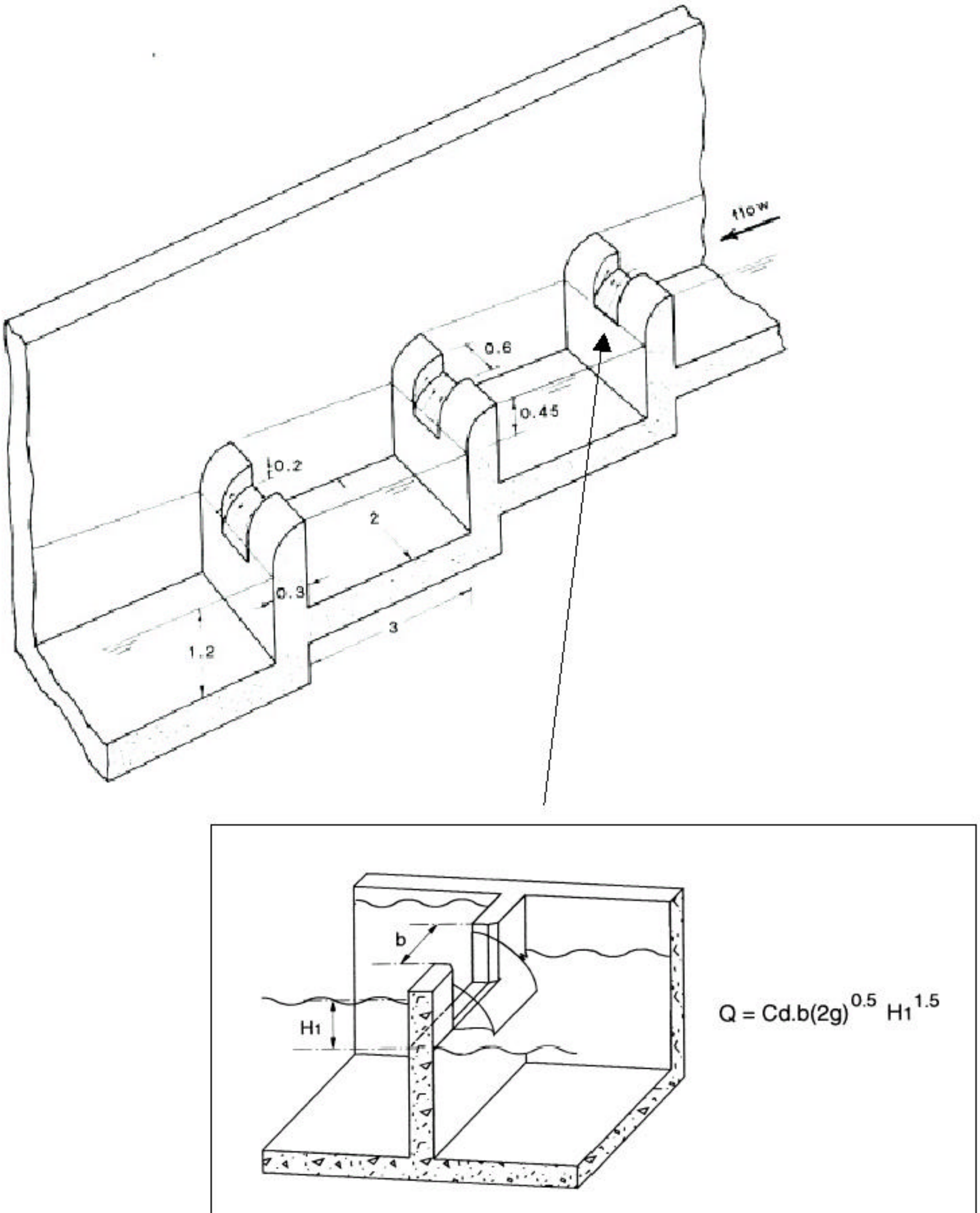
APPENDIX A

Consultees

Name	Address	Questionnaire Response	Workshop Attendee	Additional Meeting
Adrian Fewings	EA, Southern		✓	
Steve Axford	EA, North East	✓	✓	
Phil Rippon	EA, North East			
Peter Kerr	EA, North East	✓		
Keith Kendall	EA, North West	✓	✓	
Ben Bayliss	EA, North West	✓	✓	
Miran Aprahamian	EA, North West			
Chris Lawson	EA, South West			
Andy Strevens	EA, South West	✓	✓	
Ed Sharkey	EA, Midlands			
Tim Jacklin	EA Midlands			
Chris Marsh	EA, Midlands			
Chris Reeds	EA, Anglian			
Chris Randall	EA, Anglian		✓	
Eddie Hopkins	EA, Thames		✓	
Steve Sheridan	EA, Thames	✓	✓	
Roger Wren	EA, Thames		✓	
Roger Davis	EA, Thames			
Peter Gough	EA, Wales	✓		
Dr Martyn Lucas	University of Durham			
Helen Samuels	Halcrow, South West			
Mike Beach	Fisheries Consultant	✓	✓	
David Rhodes/ Susan Servais	Cranfield / Shrivenham	✓	✓	✓
Chris Katapodis	Department of Fisheries & Oceans, Winnipeg, Canada			
Michael Larinier	Institut de Mecaniques des Fluides, Toulouse, France	✓		
Chris Hawkesworth / George Parr	British Canoe Union	✓	✓	
Project Board				
Richard Iredale	EA, Midlands	✓	✓	
Rachel Tapp	EA, Midlands			
Alastair Picken	EA, Midlands			
Greg Armstrong	EA, Wales	✓	✓	
Dave Stewart	EA, North East	✓		
Nigel Reader	EA, South West	✓	✓	
Paul Power	EA, Thames	✓	✓	
Drew Aitkin	SEPA, Edinburgh			✓
Malcolm Beveridge	FRS Freshwater Laboratory, Scotland	✓		

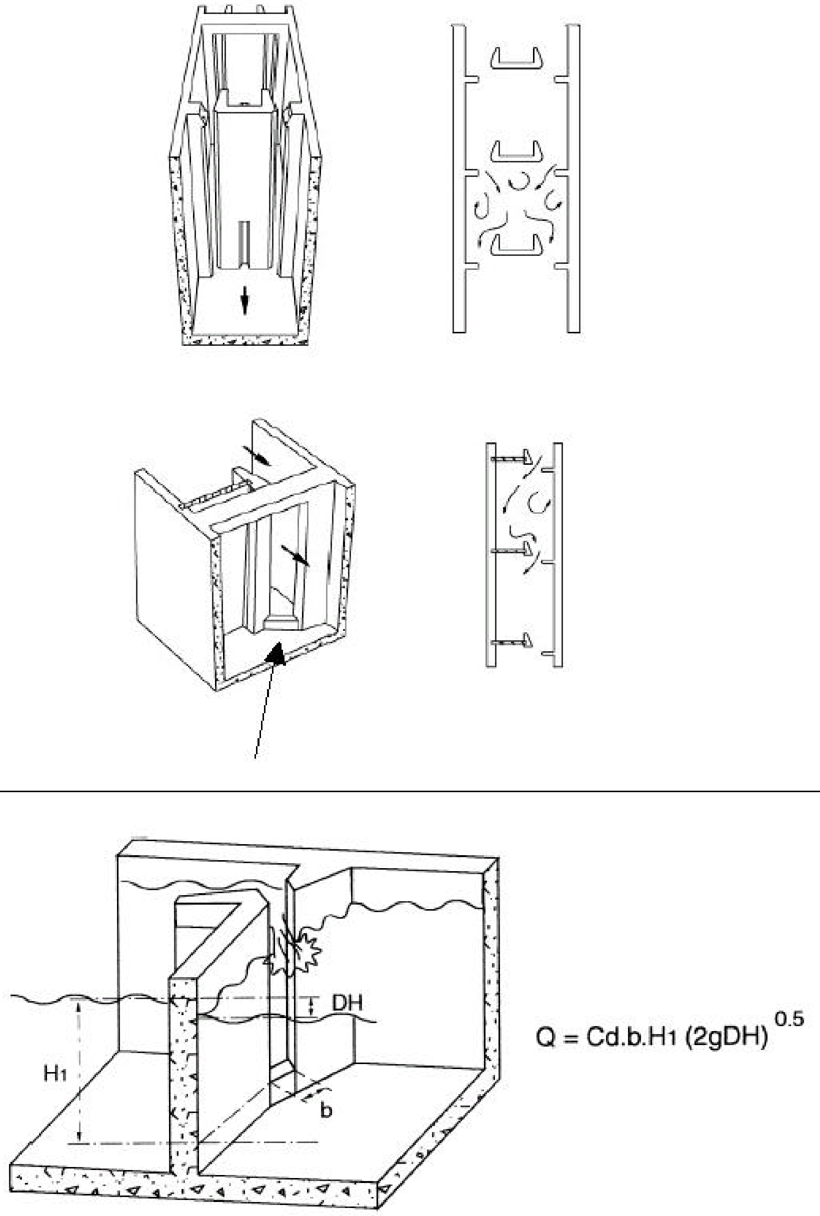
APPENDIX B

Figures showing typical fish passage structures



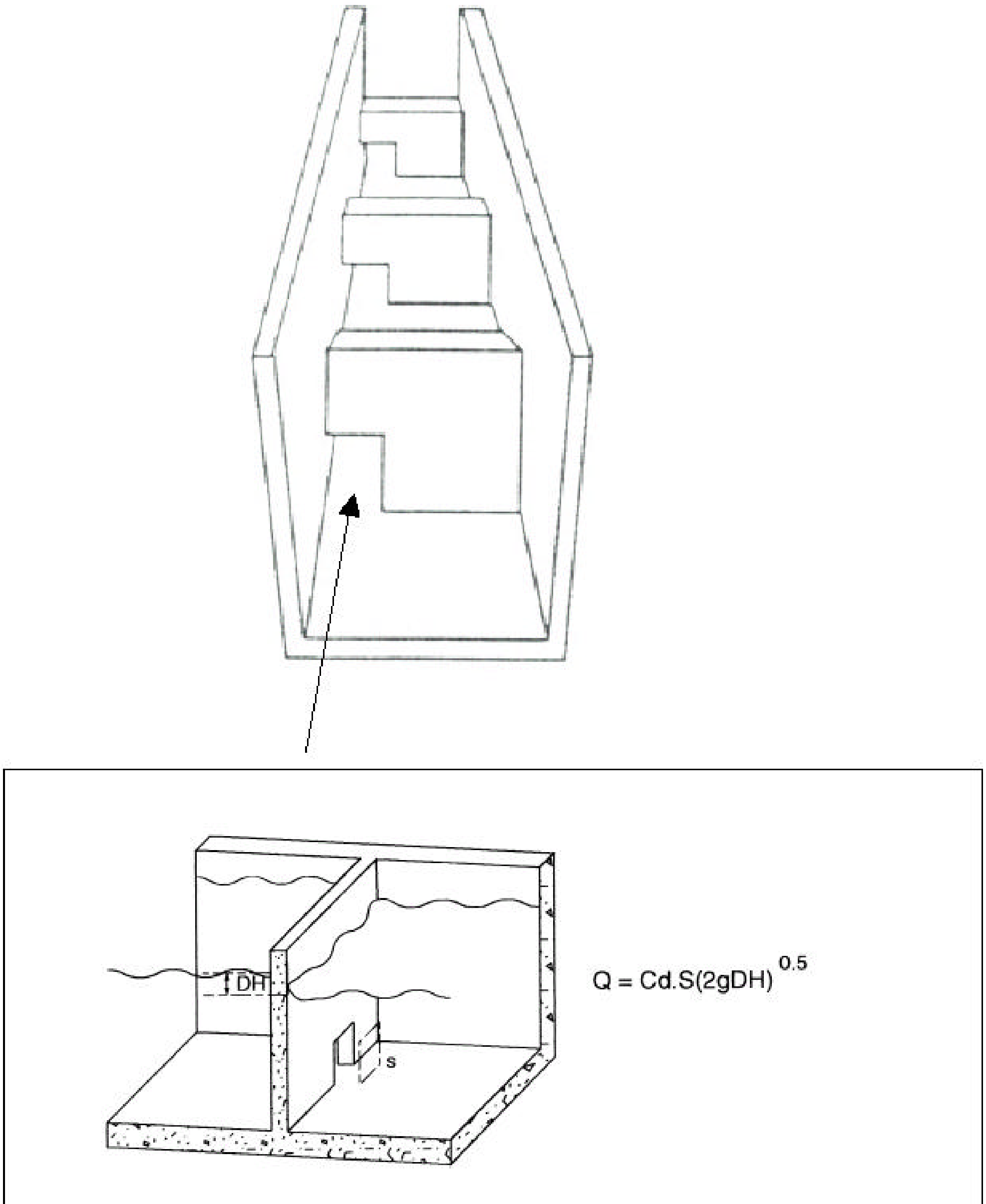
Generalised geometric characteristics and discharge equation for a pool and traverse pass
(downstream pool level lower than invert of the notch)
(After Larinier, 1992)

Figure B.1:
Schematic diagram of a typical Pool & Traverse fish pass with notched traverse and plunging type flow. Dimensions given are the recommended minima for large migratory salmonids (After Beach, 1984)



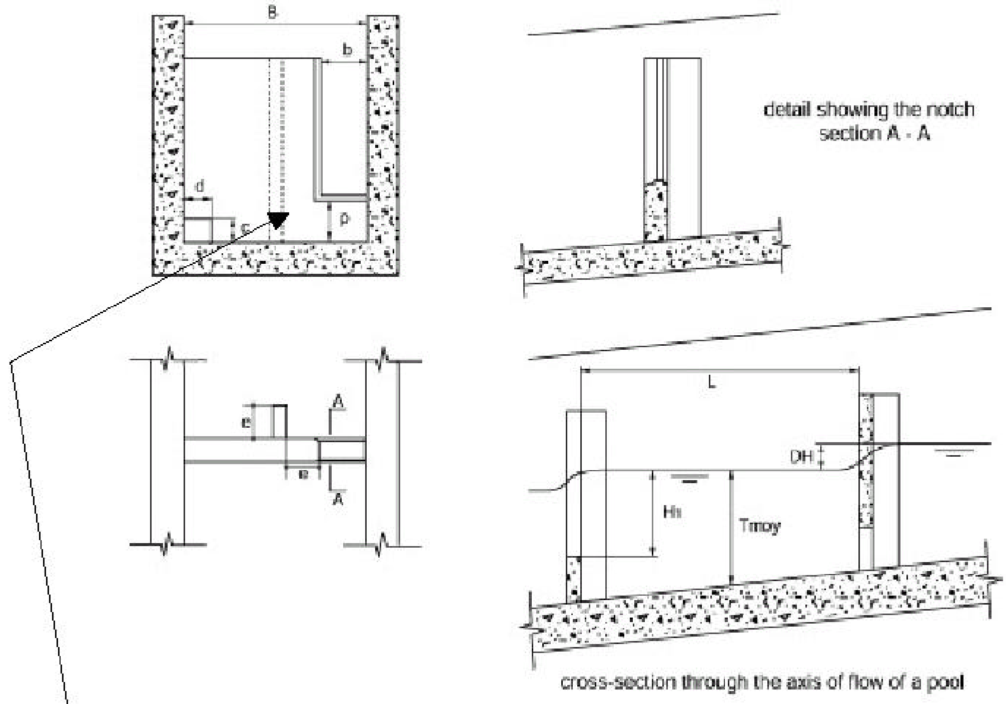
Generalised geometric characteristics and discharge equation for a vertical slot pass (After Larinier, 1992)

Figure B.2:
Single and paired vertical slot passes (after Larinier, 1992a)



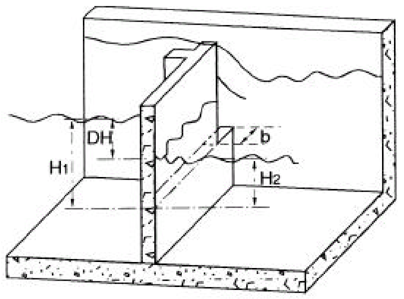
Generalised geometric characteristics and discharge equation for a submerged orifice fish pass (After Larinier 1992a)

Figure B.3:
Pool and orifice fishway (after Larinier, 1992a)



Q (*) (m³/s)	L (m)	B (m)	Tmoy (m)	b (m)	cXd (mXm)	e (m)	P (m)	H1 (*) (m)
0.175	2.20	1.25	1.15	0.20	0.15x0.15	0.15	0.70	0.60
0.300	2.70	1.50	1.30	0.30	0.20x0.20	0.25	0.80	0.65
0.500	3.15	1.80	1.50	0.40	0.30x0.30	0.35	0.925	0.725
0.700	3.50	2.00	1.65	0.45	0.375x0.375	0.40	0.95	0.85

(*) design head and flow discharge



$$Qn = K.Qd$$

$$K = [1-((H_1-DH)/H_1)^{1.5}]^{0.385}$$

$$Qd = Cd.b(2g)^{0.5}H_1^{1.5}$$

$$H2 = H1 - DH$$

Generalised geometric characteristics and discharge equation for deep slot fish pass (After Larinier 1992a)

Figure B.4:
Characteristics of some deep slot and orifice passes used in France (after Larinier, 1992a)

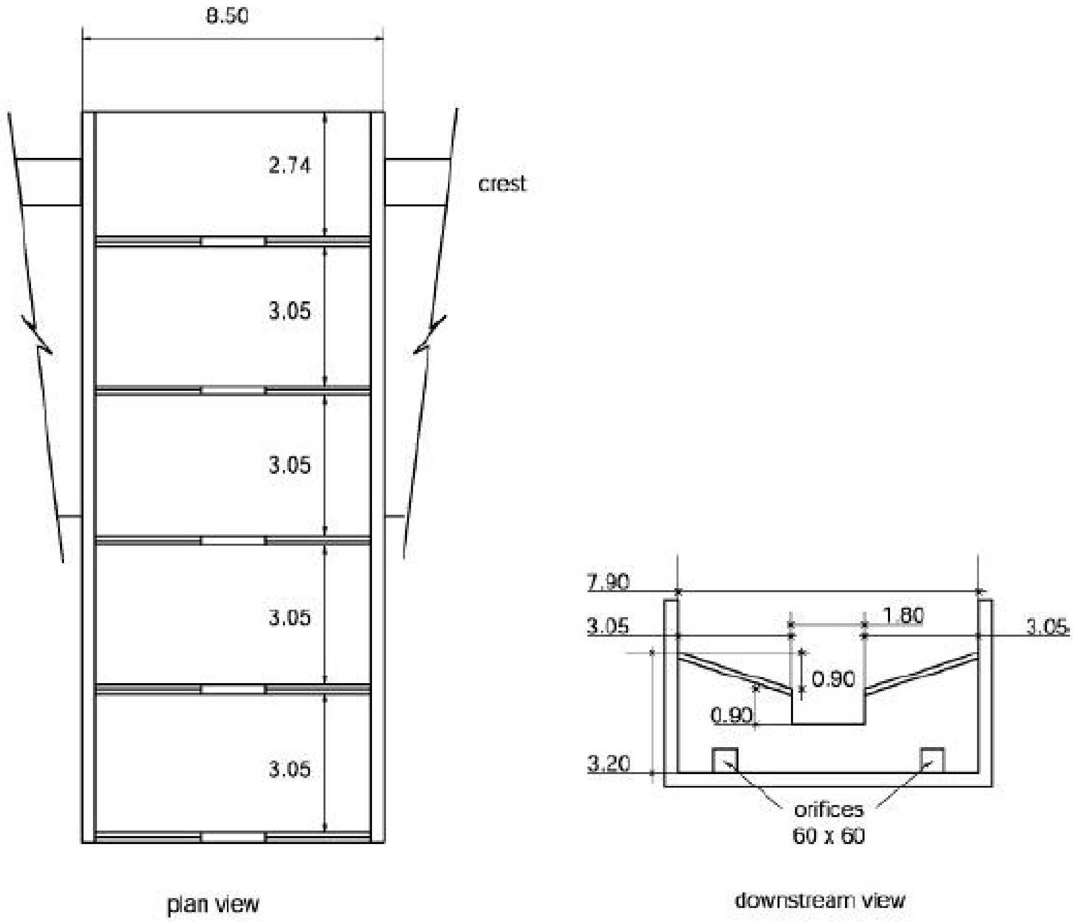
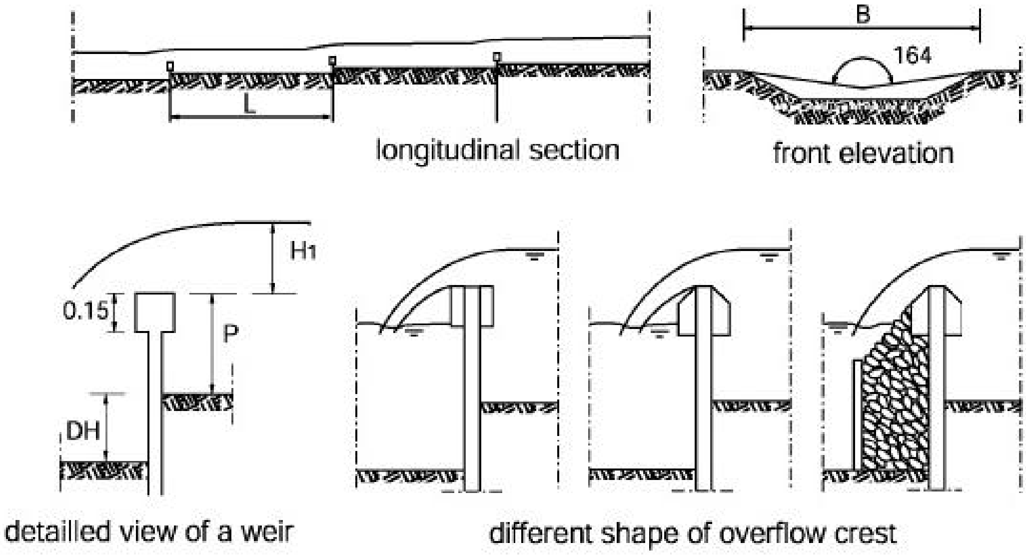


Figure B.5:
Characteristics of a Pool & Chute fishway (after Bates, 1990)



Flow (m³/s) Q ($9.8\ H_1^{2.5}$)	Drop DH ($0.475\ H_1$)	Dimensions (m) L ($14.2\ H_1$)	B ($18.8\ H_1$)	P (m) ($0.76\ H_1$)	Head H_1 (m)
1.14	0.20	6	8	0.32	0.42
2	0.25	7.5	10	0.40	0.53
3.15	0.30	9	12	0.48	0.63
5.51	0.375	11.25	15	0.60	0.79

Figure B.6:
Characteristics of a V-shaped pool fishway used in the Netherlands (after Boiten 1990)

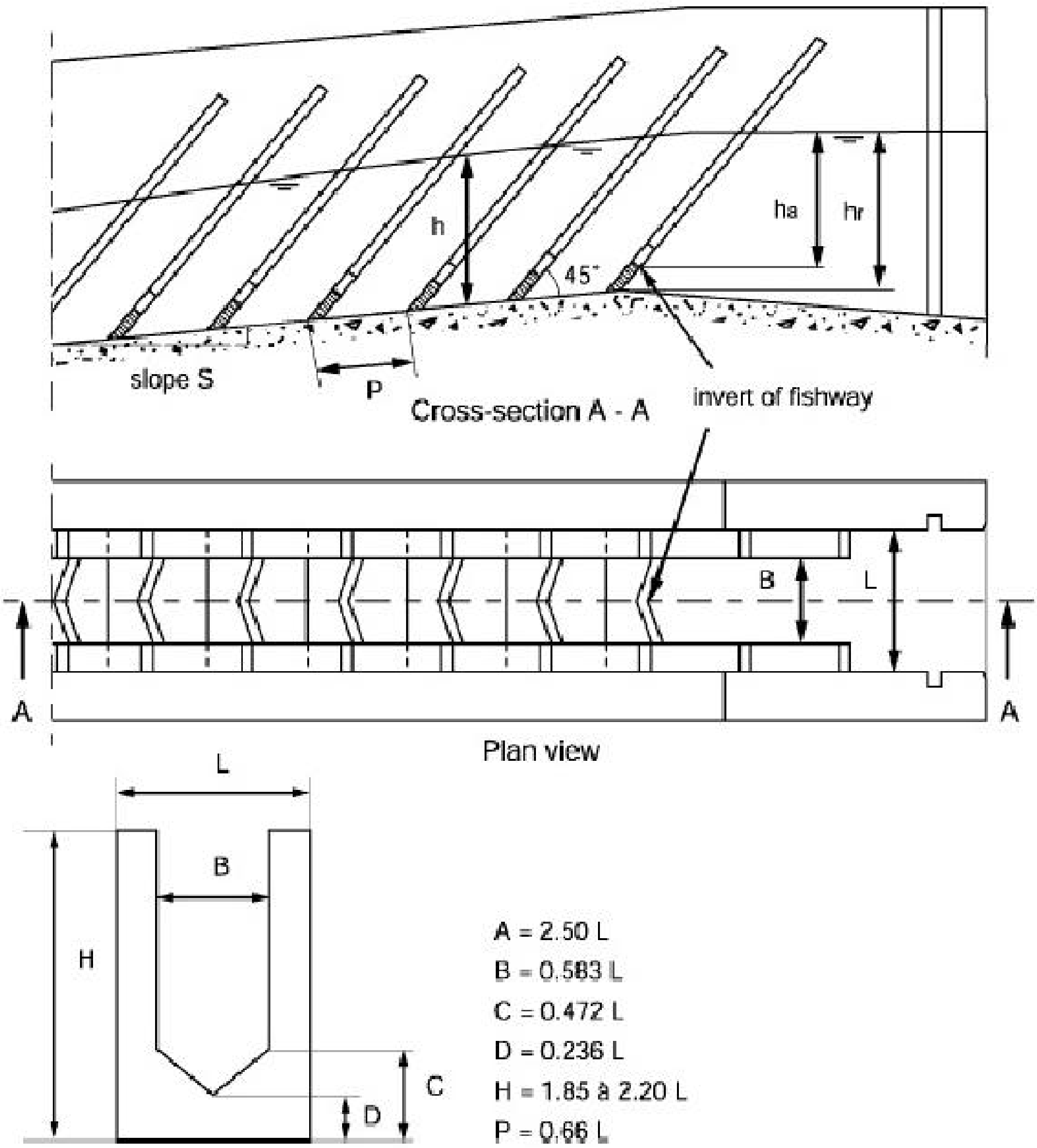


Figure B.7:
Cross-section and geometric characteristics of a plane baffle Denil fishway (after Larinier 1992d)

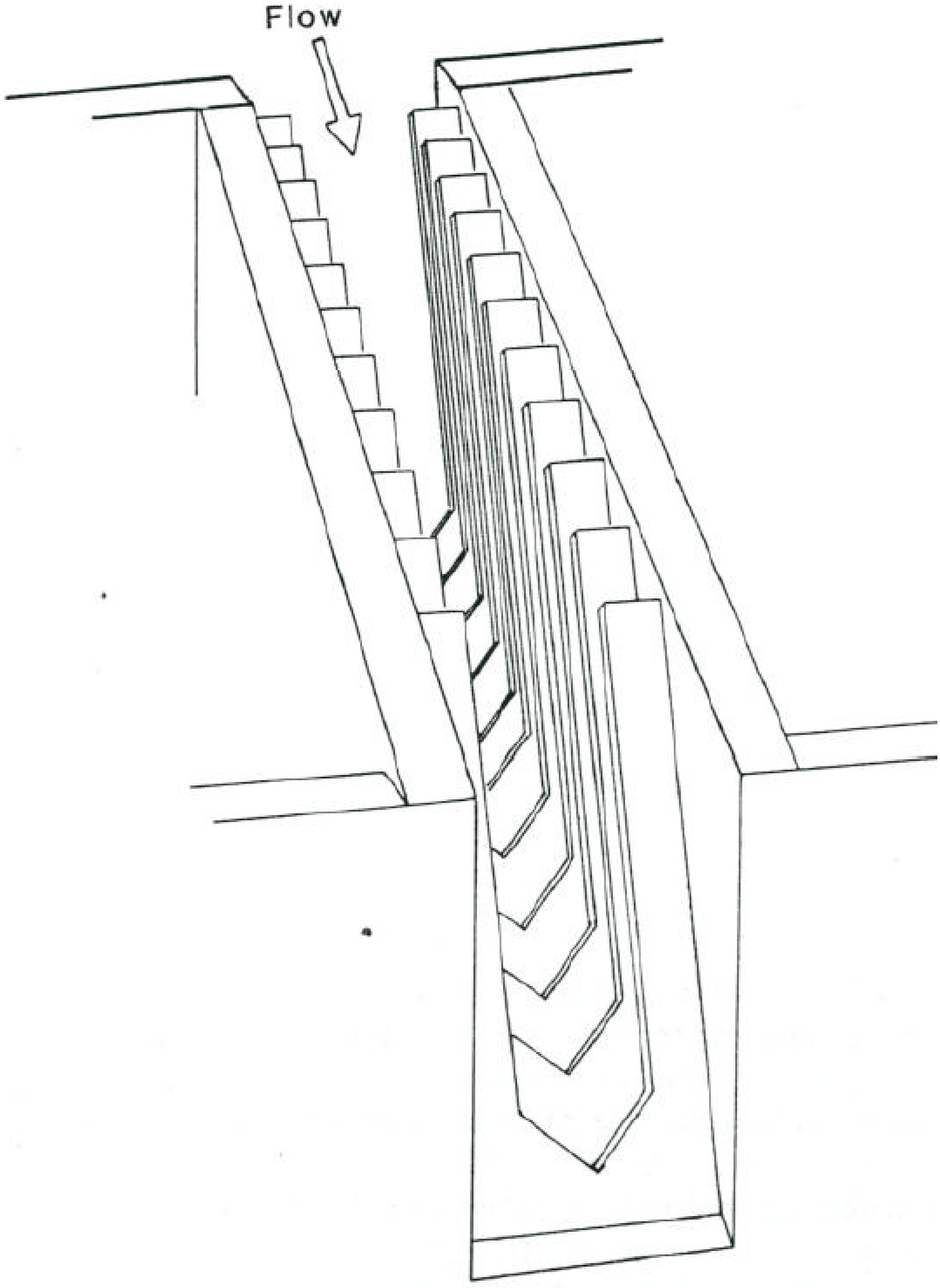


Figure B.8:
Isometric view of a plane baffle Denil fishway (after Beach, 1994)

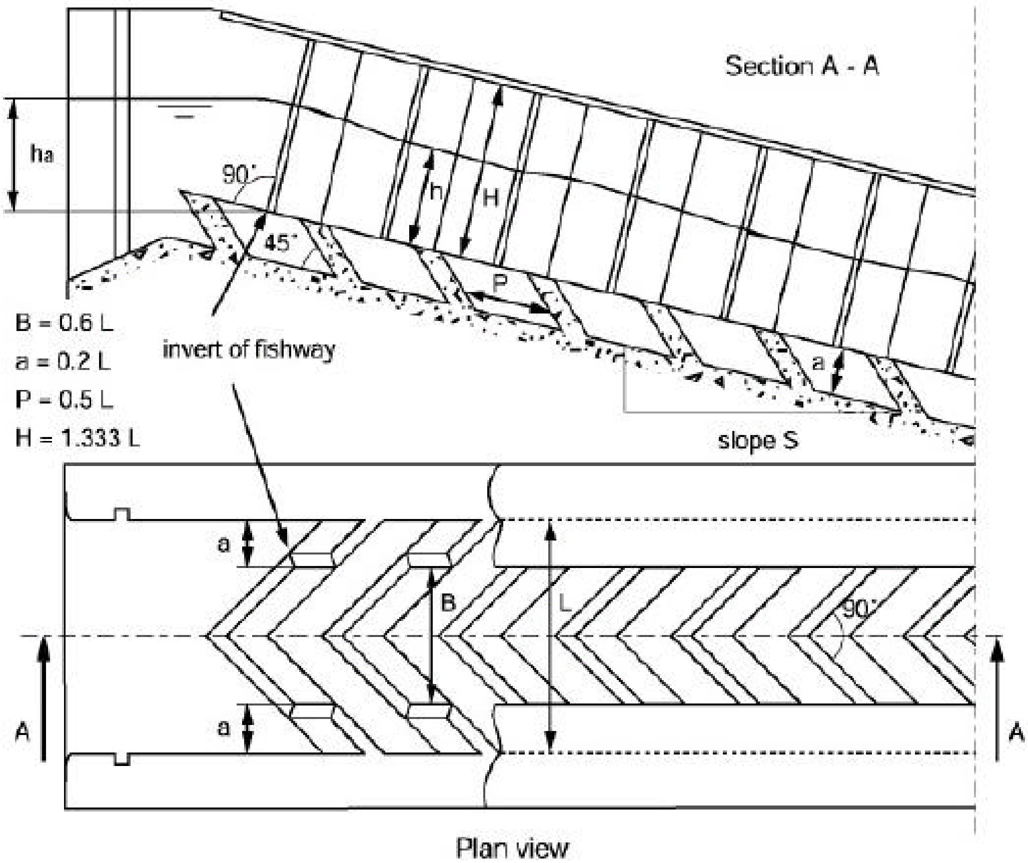


Figure B.9:
Cross-section and plan view of a Fatou baffle fishway (after Larinier, 1992d)

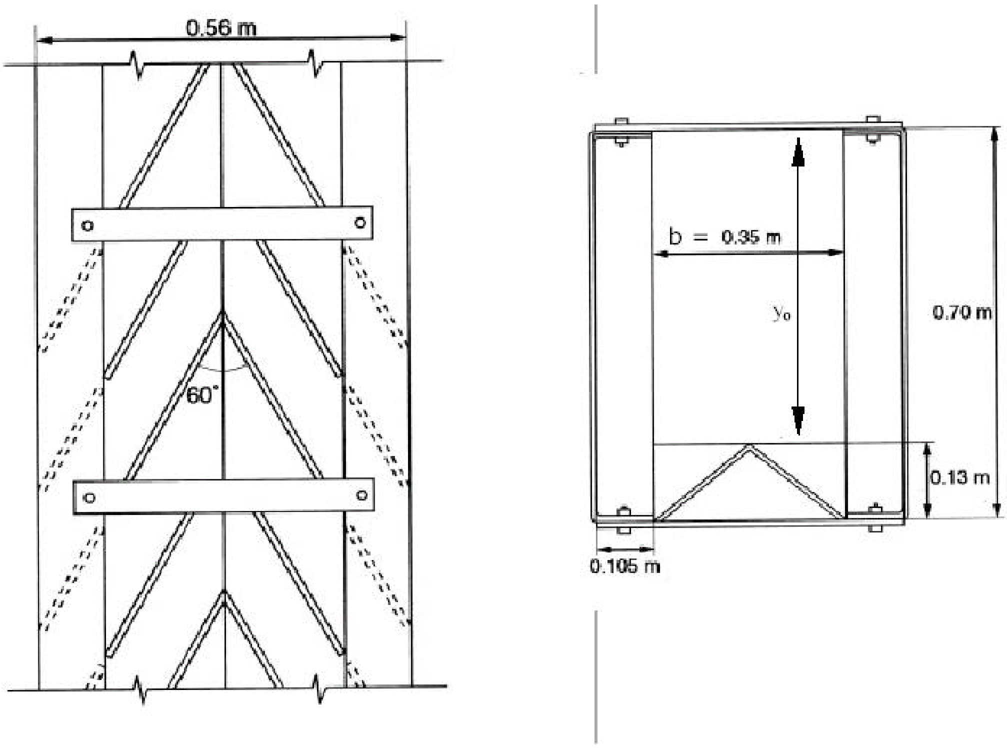


Figure B.10:
Plan and cross-section, giving the geometric characteristics of an Alaskan `A` fishway (after Larinier, 1992d)

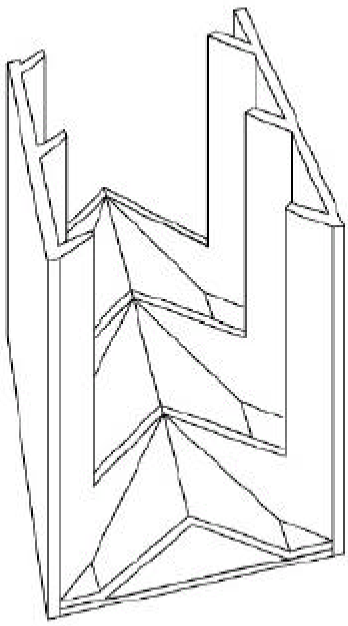


Figure B.11:
Isometric view of an Alaskan `A` fishway (after Larinier, 1992d)

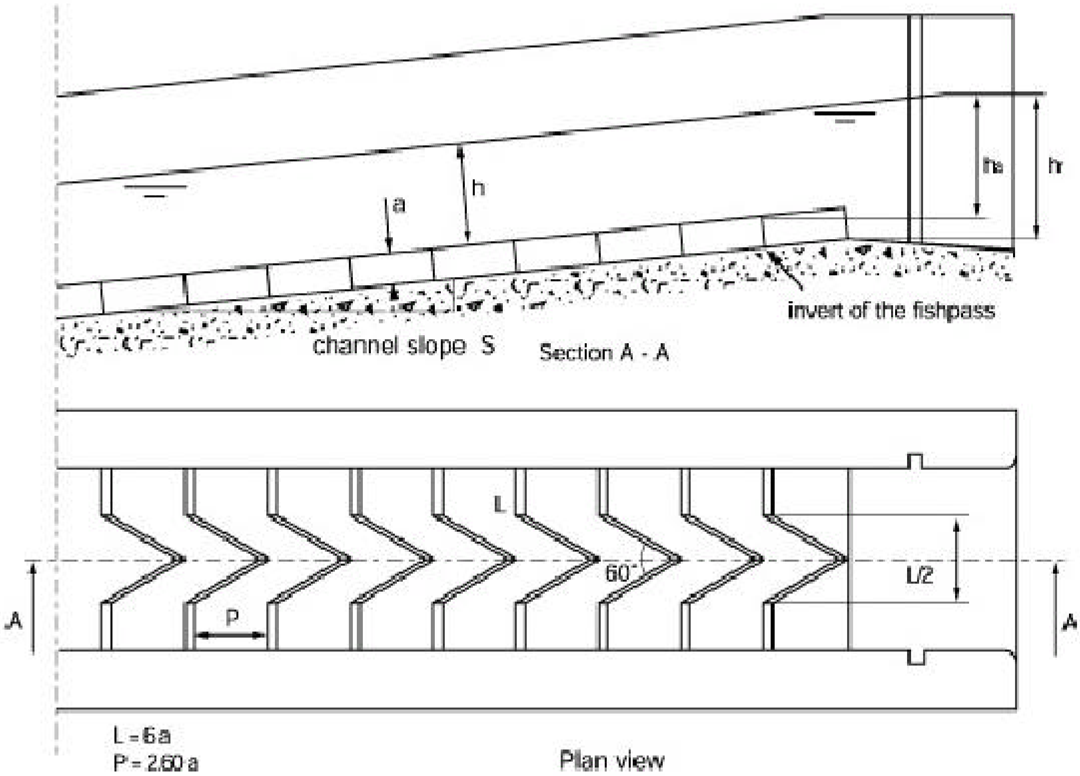


Figure B.12:
Geometric characteristics of a Super-active baffle (Larinier) fish way (after Larinier, 1992d)

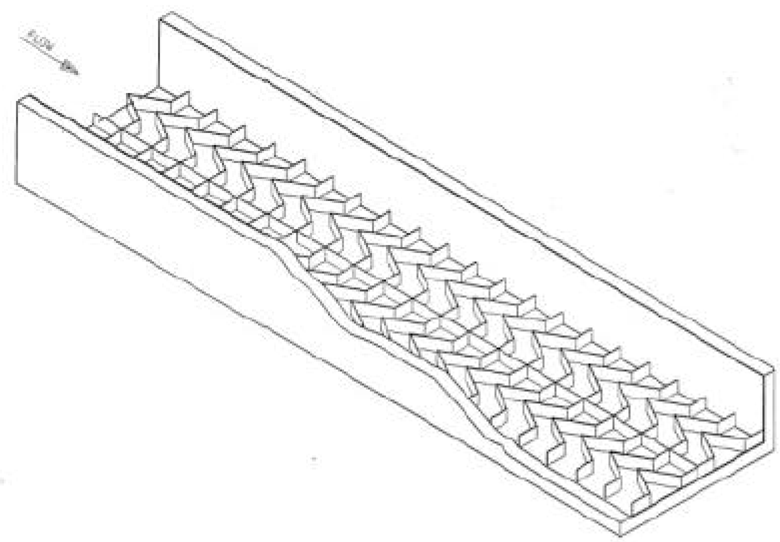


Figure B.13:
Isometric view of a Super-active baffle (Larinier) fishway

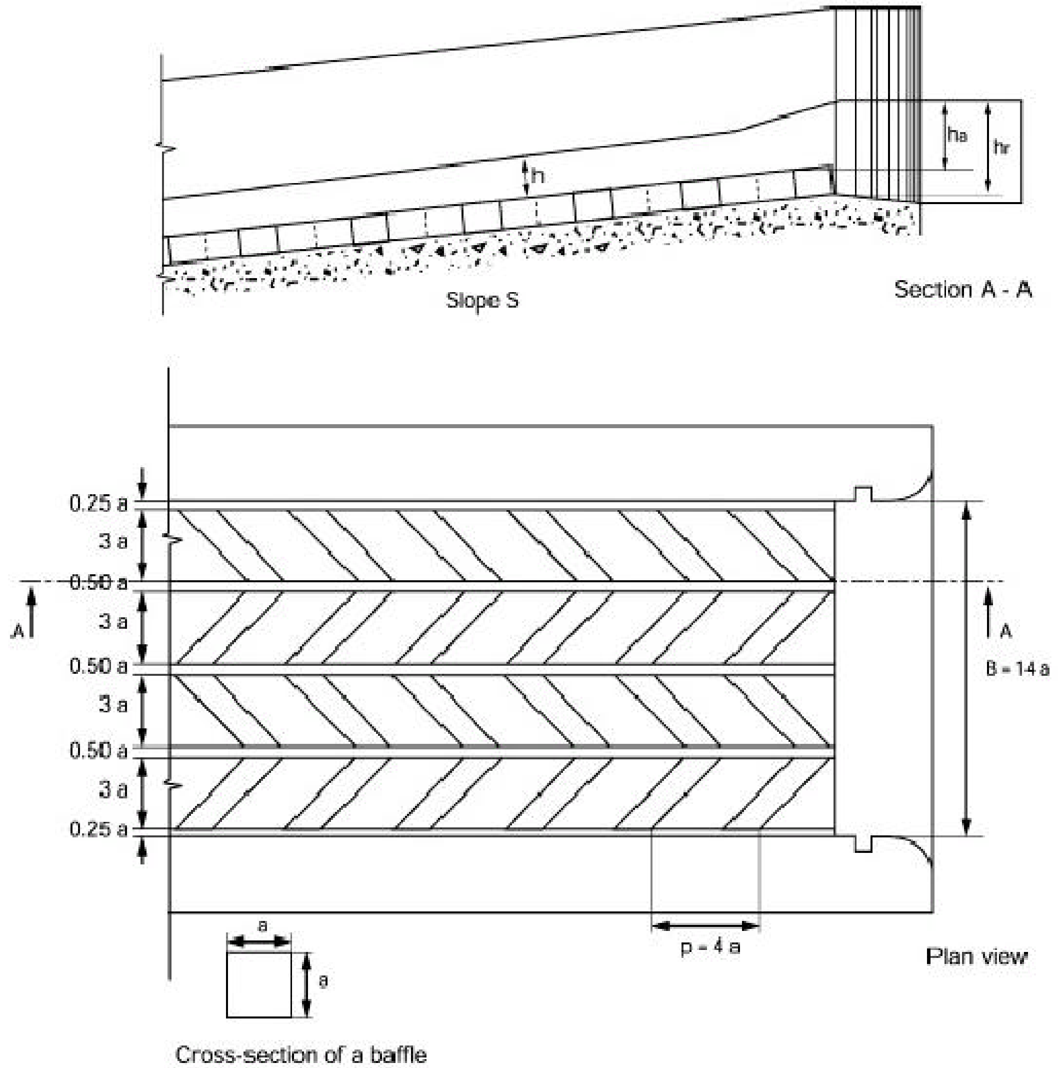


Figure B.14:
Geometric characteristics of a Chevron baffle fishway (after Larinier 1992d)

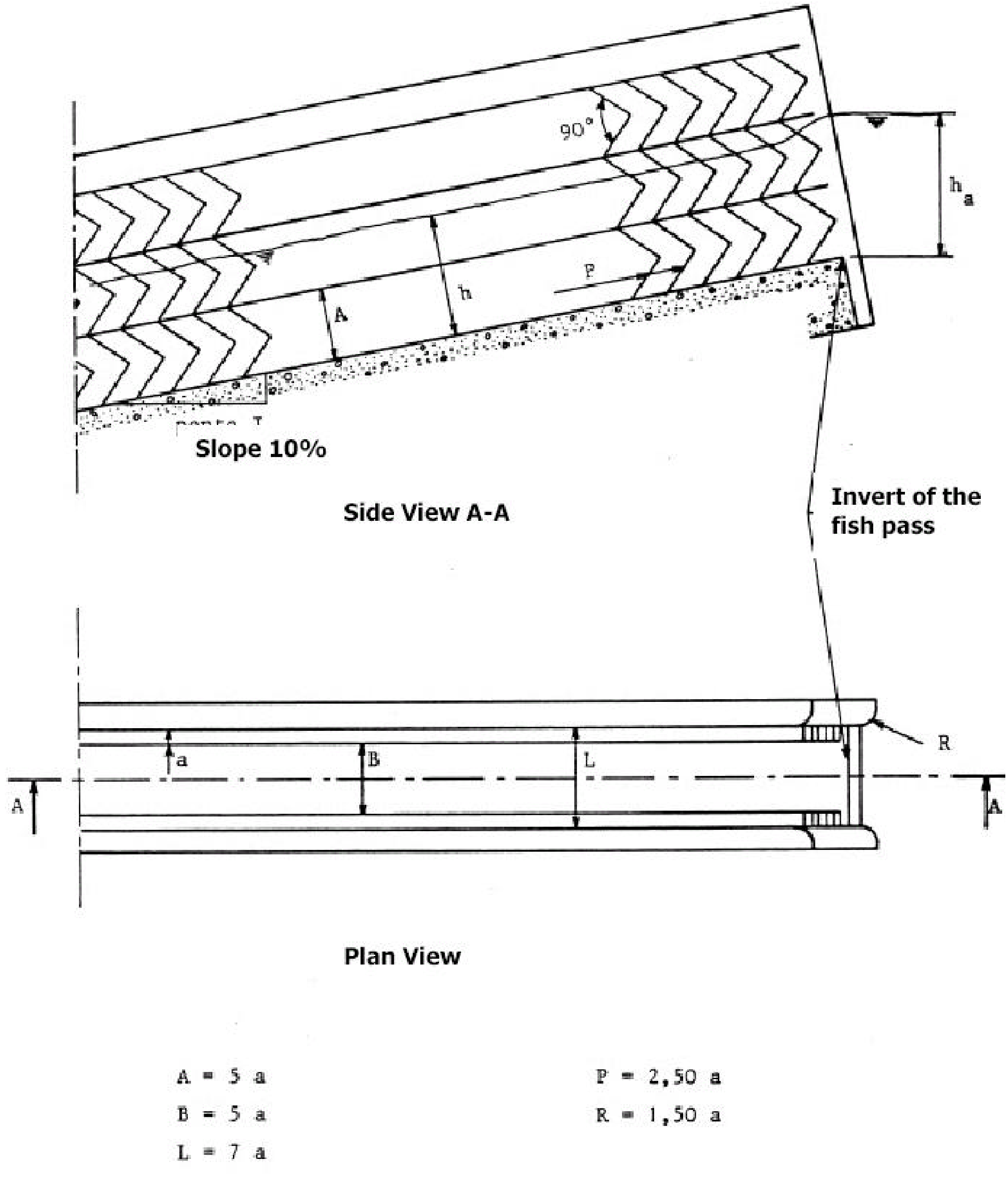


Figure B.15:
Geometric characteristics of a Chevron Side Baffle fishway (after Larinier & Miralles, 1981)

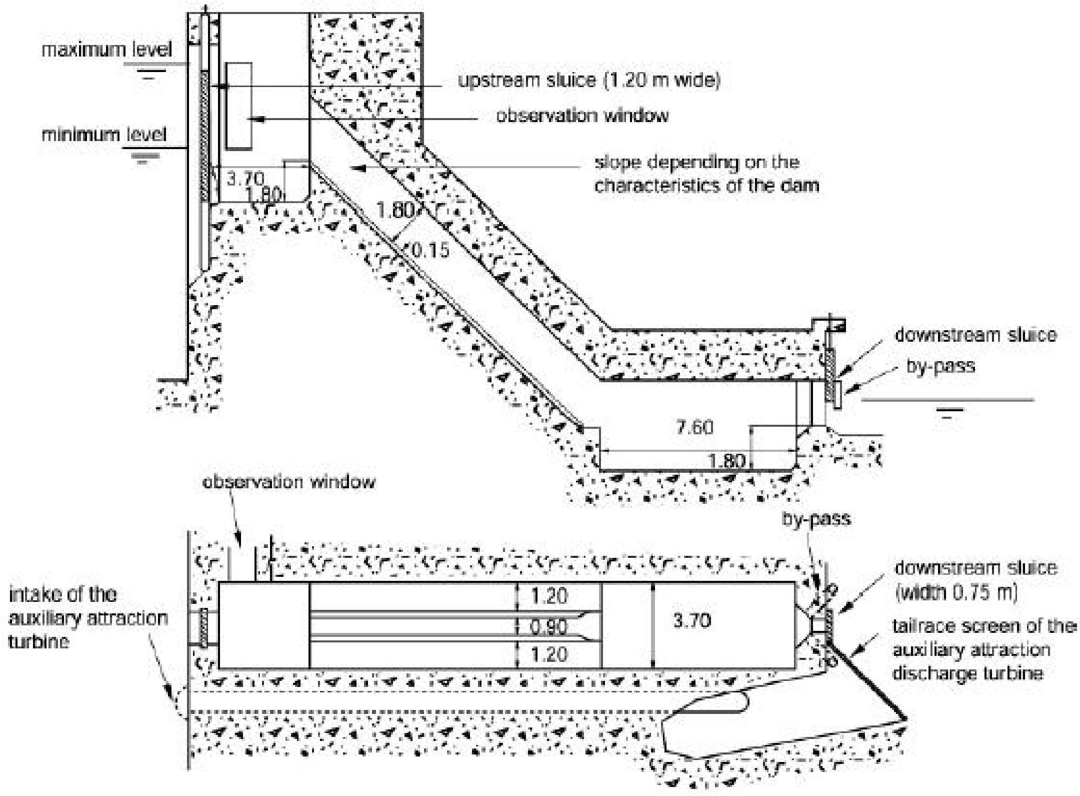


Figure B.16:
The plan and cross-section of a typical fish lock (after Aitken et al, 1996)

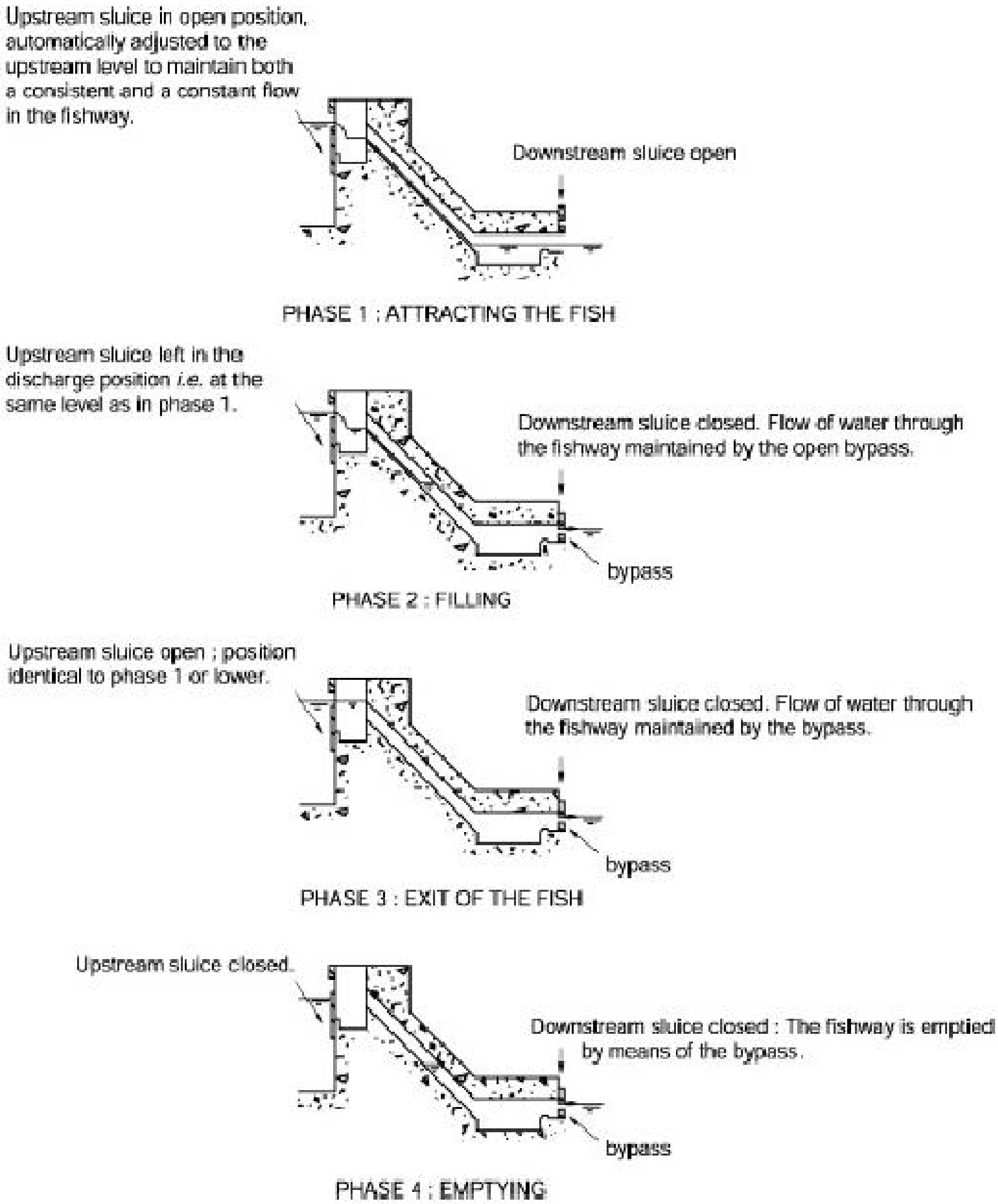


Figure B.17:
The operating cycle of a fish lock (after Travade & Larinier, 1992a)

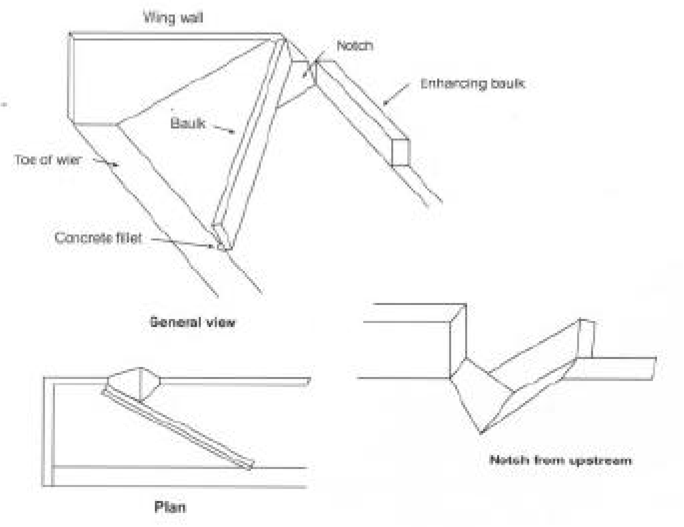


Figure B.18:
Schematic diagram of a Baulk pass (after Fort & Brayshaw, 1961)

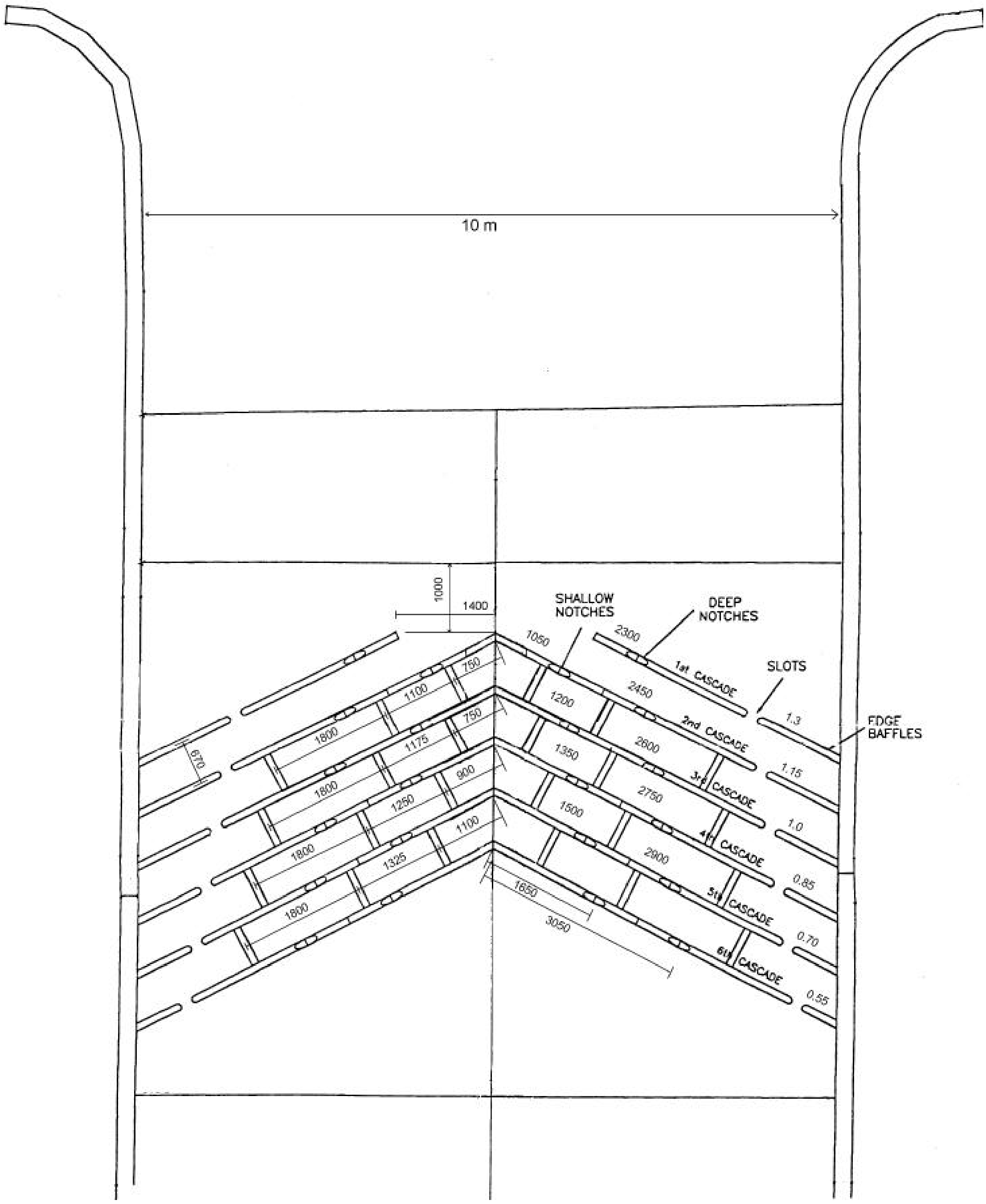


Figure B.19:
Characteristics of the Hurn-type baffle system (After Walters, 1996)

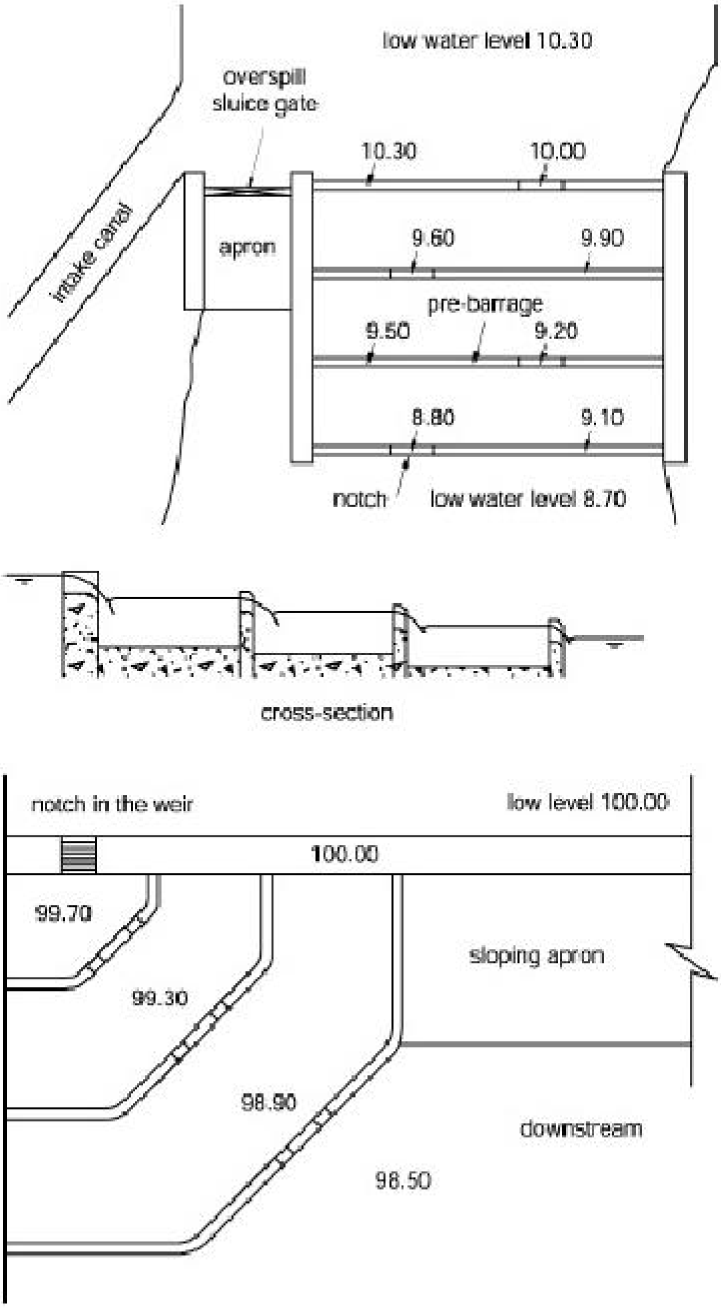


Figure B.20:
Schematic plans illustrating the use of pre -barrages across the whole, or part of the width, of a stream in front of a barrier (after Larinier, 1992a)

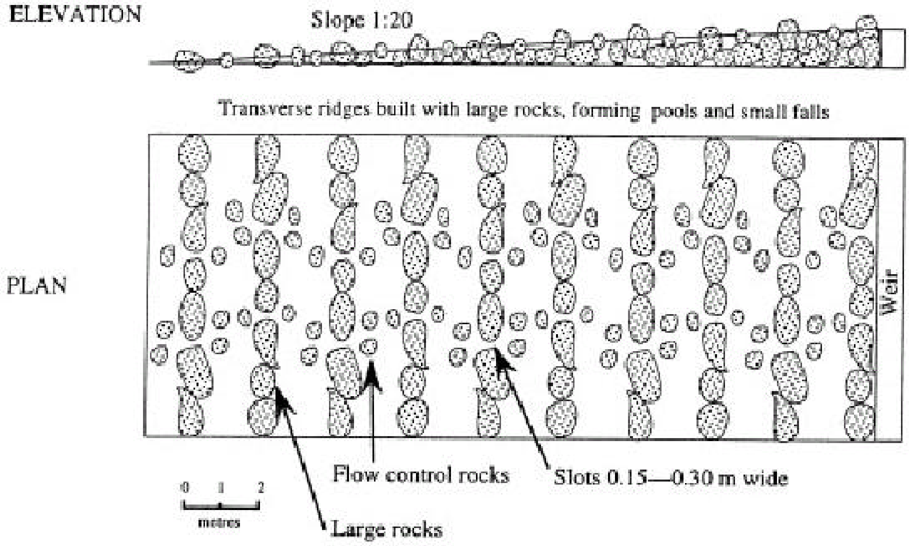


Figure B.21:
The general design layout of experimental rock-ramp fishways in New South Wales, Australia (after Harris et al, 1998)

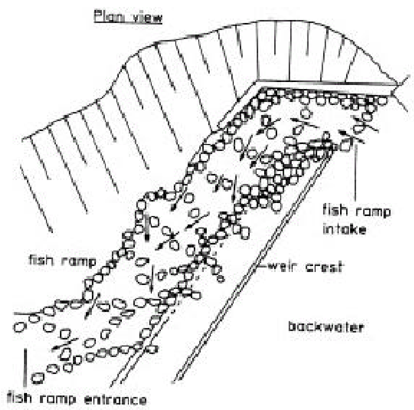
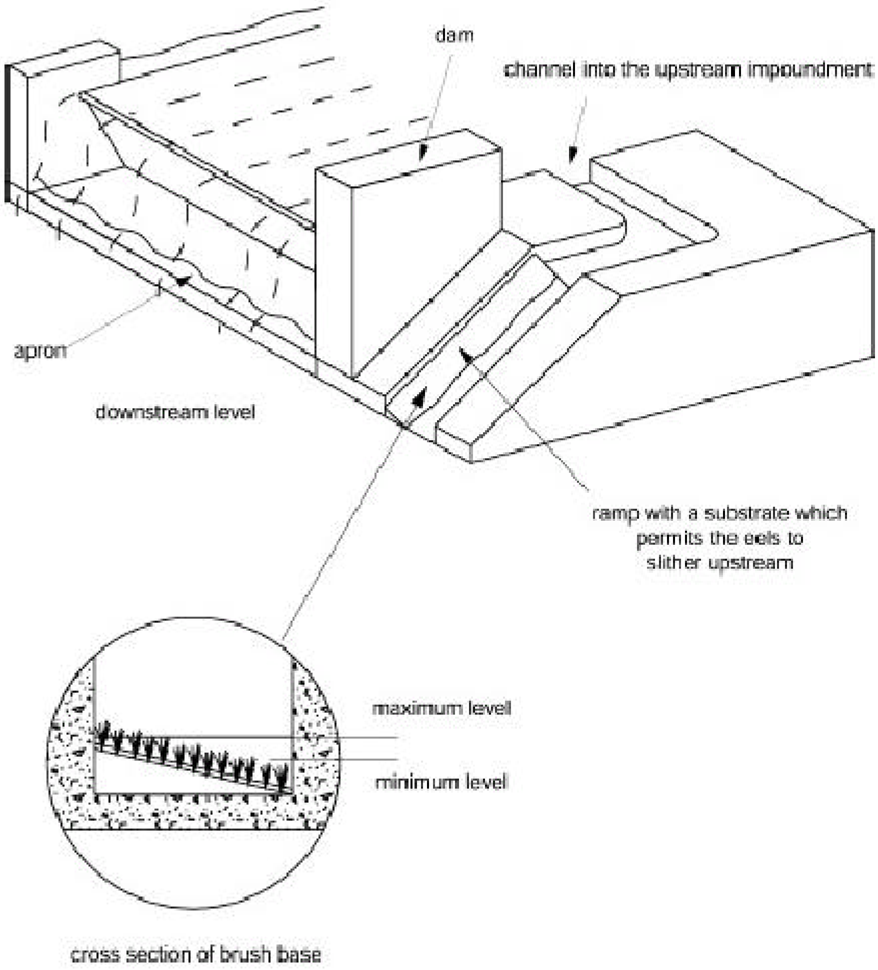


Figure B.22:
Plan view of a fish ramp in the corner of a weir on the Elz River, Germany (after Gebler, 1998)



Typical cross-section of a brush base showing the lateral slope to accommodate some variation in head water level

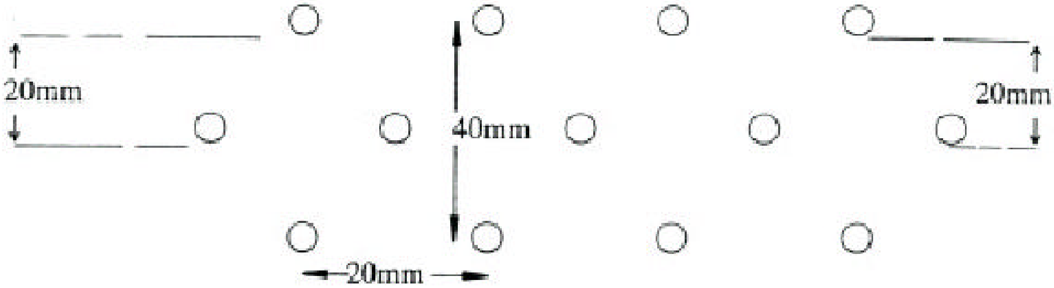


Figure B.23:
Schematic plan of a fishway for elvers and small eels (after Porcher,1992)

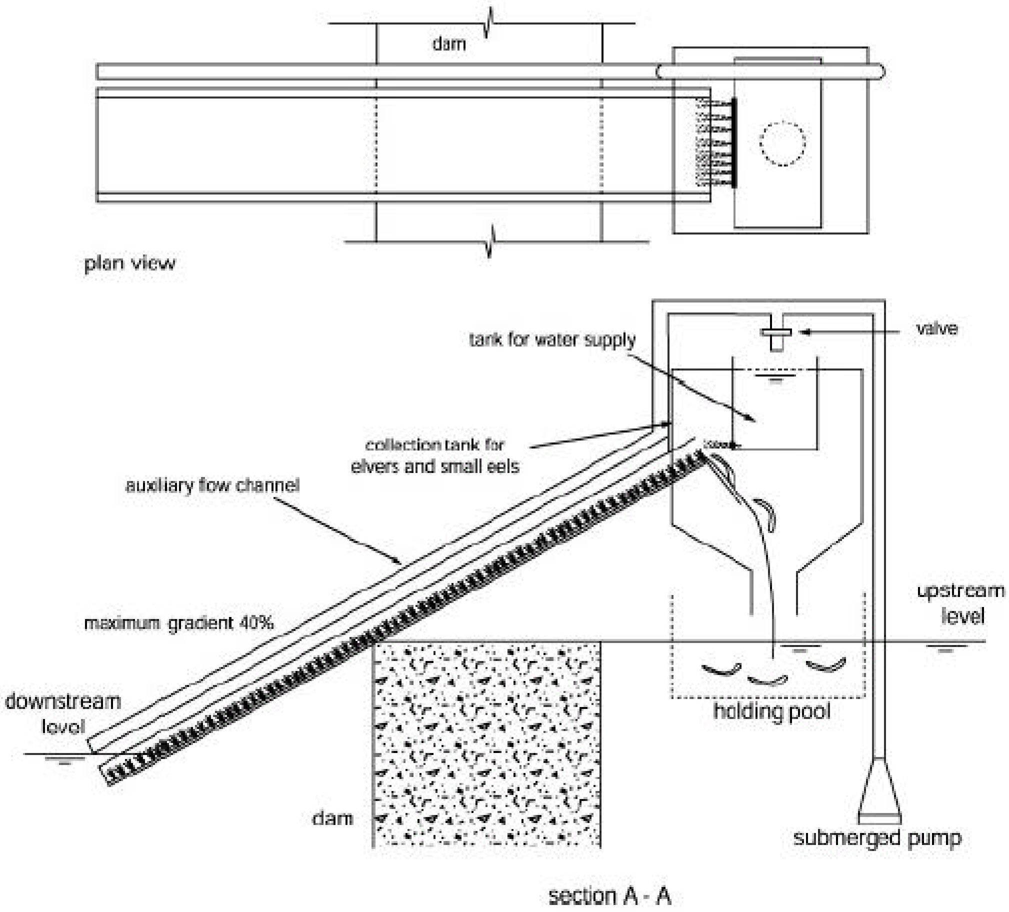


Figure B.24:
Typical configuration of a pass and trap for elvers and young eels (After Porcher, 1992)

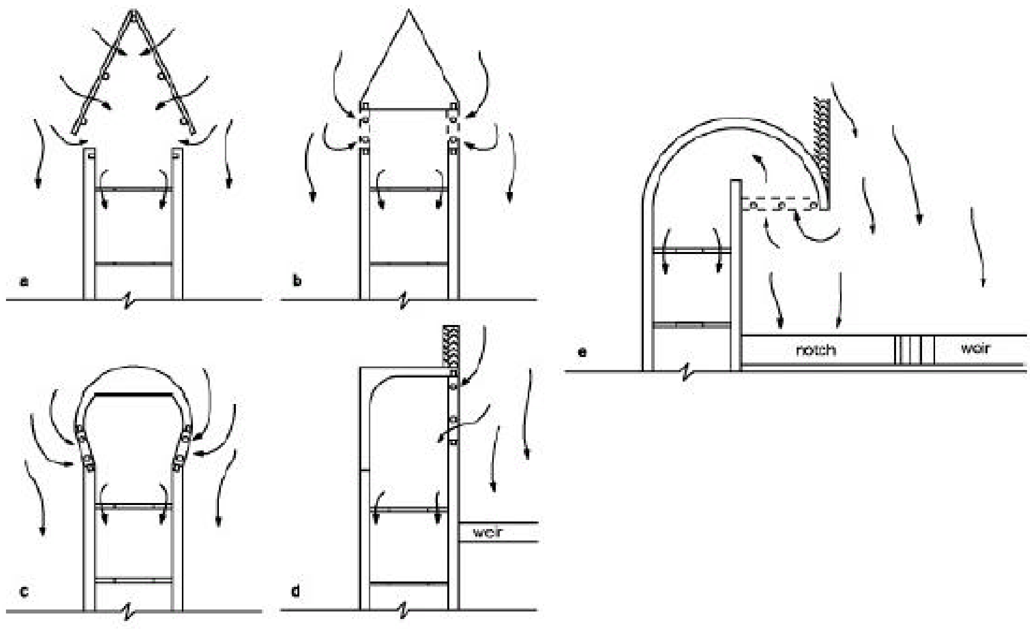


Figure B.25:
Schematic examples of laterally sited fishway exits to help avoid trash problems (after Larinier, 1992c)