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Manual for provision of upstream migration facilities for Eel and Elver

Science Report SC020075/SR2

ENVIRONMENT AGENCY

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This manual sets out design criteria for upstream passage facilities at obstructions for eels and elvers, based upon assessments of the migratory behaviour and ecology of *Anguilla* spp. It is intended for use by fisheries managers with responsibility for or an interest in the management of stocks of eels and elvers. It is largely based upon the R&D Technical Report W2-070/TR1 "Fish pass design for eel and elver (*Anguilla anguilla*)".

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Professor Mike Depledge Head of Science

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EXECUTIVE SUMMARY

1. The overall aim of this study was to produce design criteria and best practice designs for eel and elver passes. A Technical Report (Solomon and Beach 2004) undertook a review of relevant aspects of eel biology and existing passage facilities for eels and elvers. This manual summarises the earlier Technical Report and develops design criteria for passage facilities in a range of situations.

2. Types of obstruction where passage facilities might be required include tidal barrages, tidal flaps, mill weirs, gauging weirs, amenity barrages and weirs, navigation weirs, dams for reservoirs or HEP, diversion dams or weirs, water intake weirs and fish counting structures.

3. Essential first steps of catchment-wide and site specific surveys and evaluation are described and specified.

4. The manual describes fundamental approaches to providing upstream passage facilities as an introduction to the analysis of existing installations. These are channel passes, pass-traps, pumped-supply passes, pipe passes, lifts and locks, easements, and removal of the structure. The fundamental approaches to protection of downstream migrants are also discussed.

5. Biological criteria for design of passage facilities are explored. These include the seasonal timing of migration, effects of water temperature, river discharge, light, tide, lunar cycle and time of day on migratory activity, climbing ability, dispersion and rate of upstream migration, vulnerability to predation, sizes of fish involved, and swimming ability.

6. Based upon the development of biological criteria, a series of detailed design considerations are presented. These include siting of facilities, facilities based on substrates, facilities based on easements and "natural" channels, pipe passes, lifts and locks, upstream outlet arrangements, monitoring facilities, trap and transport, passage of eels through passes designed for other species, attraction flows, maintenance, health and safety considerations, and protection of downstream migrants.

7. An analysis of a number of existing installations is presented, describing the facilities and reviewing factors that aided design and installation, and good and limiting features of design and installation.

8. A series of conceptual designs are presented for various situations including low-head and high head structures, gauging stations, tidal barriers and culverts.

9. Requirements for further investigation are identified.

10. A list is provided of suppliers of eel pass modules and materials used for their construction

1 INTRODUCTION

1.1 Background and Terms of Reference

There is considerable concern regarding the status of the European eel, *Anguilla anguilla*, with recruitment falling throughout its range of distribution. In 2001 it was estimated that recruitment had fallen by more than 90% since the early 1980s (Dekker 2002). While it is likely that there are a number of factors contributing to this decline, including changes in the marine environment and a high level of exploitation, there is no doubt that production is restricted by eels being denied access to areas that they could formerly colonise. Knights and White (1998) quote figures indicating that about 7% (200,000 ha) of the stillwater habitat and 25% (68,000 ha) of the riverine habitat in Europe are inaccessible to eels due to man-made barriers.

The terms of reference for the project were as follows:-

1. To critically review published and unpublished literature on eel and elver passes, taking into account the issues of hydraulics, exit, entrance and approach, installation, robustness, maintenance and location.

2. To critically review the published and unpublished literature on the swimming speed of eel and elver and the factors affecting it.

3. To produce design criteria for eel and elver passes taking into account their installation. Specific, as opposed to generic, designs may be needed for passes situated at gauging stations, at total exclusion tidal barrages and at tidal flaps.

4. To produce design criteria for traps, which can be incorporated into the fish pass.

5. To produce best practice design criteria and costs for the construction and installation of eel and elver passes and traps. Designs will need to ensure that they do not compromise the function of the original structure, specifically passes at sites used to measure flow.

The first four tasks were reported in the Technical Report W2-070/TR1 (Solomon and Beach, 2004). The aim of this document is to fulfil task 5, to produce a stand-alone guidance note on design of passage facilities for eels and elvers. It draws heavily upon the earlier Technical Report and summarises many of the findings of the whole study.

1.2 Types of Situation where Passage Facilities are Required

There are many types of man-made structure which can represent an obstruction, partial or complete, to the free upstream passage of elvers and eels. These include:-

Tidal barrages
Tidal flaps
Mill weirs
Gauging weirs
Amenity barrages and weirs
Navigation weirs

Dams for reservoirs and hydro-electric plants
Diversion dams or weirs
Water intake weirs
Fish counting structures
Culverts

Early in the project it became apparent that the optimal design for any particular situation was heavily site-specific, depending upon the function and form of the structure concerned, the range of hydraulic conditions it experiences during the period when passage is required, and its location in the watershed. For this reason it is not possible to specify detailed designs to cover a range of sites; rather, the design has to be tailored to each situation. That said, there are many generic principles and designs of facilities that can be adapted to specific situations. For this reason, the end product of this work is a series of design criteria and conceptual designs rather than detailed plans for construction. The manual uses extensive examples of existing installations, considering critical design features and aspects of the individual installations that are successful and, just as importantly, those that are less successful.

2 ASSESSMENT AND SURVEY – ESSENTIAL FIRST STEPS

2.1 Overall Assessment of Obstructions in a Catchment Context

The extent to which any particular structure represents an obstruction, and the potential solutions to allow passage, are highly site-dependent, and will vary with hydraulic head drop, form of the structure, hydrodynamic conditions upstream and downstream, condition of the structure, and presence of edge effects which may represent conditions more benign for eel passage than the main flow. Many structures may represent an obstruction of varying severity depending on prevailing river flow and its associated hydraulic conditions. Further, the impact of any particular obstruction on the eel population within the catchment will depend upon the area and quality of potential habitat upstream, and on presence of further obstructions both upstream and downstream. Addressing eel passage issues therefore involves step by step processes of both catchment-wide assessment and detailed survey of individual sites, followed by identification of priority actions and detailed planning of individual facilities.

As discussed above, addressing problems for passage of eels and elvers is a whole-catchment process. For example, there will be less advantage providing access past a structure which opens up only a small area of habitat than one which gives access to a large area. Similarly, there is little point in engineering potential passage if there are impassable structures downstream – unless these downstream structures are also to be addressed in the foreseeable future. It is therefore important that any programme of installation of eel passage facilities is based on an overall catchment plan for the species. Such an approach has been taken by Evoy and Martin (2000) who assessed obstructions to eel and elver migrations in the rivers of the South part of the English Lake District. They classified all structures according to the level of problem they represented:- 1 (no obstruction), 2 (slightly difficult), 3 (moderately difficult), 4 (very difficult) and 5 (impassable). This allowed identification of the structures for priority attention (construction of elver and eel passes) as well as a range of other actions. Steinbach (2003) undertook a similar exercise for the Loire catchment in France. He used a very similar five-point scale (plus a category zero for obstacles that had been removed) to assess the level of obstruction represented by over a thousand structures in this large catchment. Usefully, this latter publication included photographs of examples of obstructions in each category.

Some smaller catchments may represent a simple issue, with a single obstruction perhaps at or near the tidal limit. In such cases it may be felt that little assessment is required, but even here decisions will need to be taken on priorities for action. In contrast to migratory salmonids we are not dealing with individual river stocks, but a single marine stock that enters many freshwater and brackish habitats to feed and grow. Thus it is likely to be more effective overall to give priority to addressing a problem structure on another river if the potential area opened up represents a larger or more productive habitat.

While prioritising obstructions for attention based upon the perceived level of benefit is recommended, it is most important that all opportunities are optimised whenever a structure is installed, repaired or modified. It is likely to be very much cheaper to undertake appropriate engineering for a future eel pass at such a time than to do so retrospectively. Thus even if the benefit of allowing passage or eels and elvers may be limited, or if there are other barriers upstream or downstream that are currently impassable, consideration should be given to incorporating eel passage facilities at any site where work is being undertaken. This need not involve a full pass at this stage; provision of one or more channels into which an eel pass could later be installed will suffice; these can be blocked off with stop logs or other means for the time being, and represent minimal cost. These comments apply equally to consideration of other species of fish; indeed, all species present or likely to be present in the future should be considered when planning fish passage facilities at individual sites or on a catchment basis. It is therefore recommended that provision be made for later installation of passage facilities for all species whenever a structure is built, rebuilt, modified or repaired, as long as this can be done at reasonable cost. Suggestions for appropriate engineering are made later in Section 7.8.

The first stage of the planning process is the catchment-wide assessment. This should be map-based and should show all potential obstruction to free movement of eels and elvers, and other relevant environmental issues such as water quality problems. Onto this should be added all available information regarding the distribution, abundance and size structure of eel populations throughout the catchment. Such information can be gathered from fish surveys (e.g. by electric fishing or netting), other biological surveys, fish-kill assessments, collections from intake screens, anglers catches, and commercial catches (e.g. eel racks or fyke nets). In well-studied catchments it is likely that enough information will be available to allow a good assessment of the dispersion of various sizes of eel and identification of major obstructions to free access. In other situations some further investigation might be required to complete the assessment. Electric fishing surveys below and above potential obstructions can be particularly useful in this respect. For example, Feunteun *et al* (1998) examined the situation throughout the catchment of the River Frémur in France. They found mean populations of 0.66 eels per m^2 in the 400 metres downstream of obstructions, with less than one-third that level in the 400 metres upstream – and in some cases, zero population upstream. Operation of a temporary pass-trap at the appropriate time of year is also a sound approach; this could provide important information regarding the need for permanent facilities, the number and size range of eels needing passage, and the optimal location for the entrance for the permanent installation.

The quantity and quality of the potential habitat upstream of the obstruction is also likely to affect prioritisation of sites for action and the cost-effectiveness of any proposed action. It is the area of water and the type of habitat that will dictate the potential productivity rather than the catchment area. In general, lowland areas with extensive drainage channels will be much more productive than steeply sloping upland areas. Knights and White (1998) list the following criteria for ideal eel habitat:-

- Shallow and warm water, optimum 18-25^{o}C, with more than 300 days per year over 10^{o}C
- Eutrophic (but not excessively dystrophic) conditions
- Attached/emergent vegetation cover between 25 and 75%
- High densities of benthic invertebrate prey

It would be useful to have a habitat assessment tool for eel populations, to provide at least a semi-quantitative measure of the potential of the habitat represented by any particular drainage area. This is likely to have inputs based upon, *inter alia*, catchment and wetted area, elevation, slope, seasonal temperatures, water chemistry and quality, vegetation and cover, distance from the sea, and overall biological productivity. Development of such a tool is beyond the scope of this study but it is recommended that consideration is given to addressing this as a separate study.

Once the catchment assessment has identified which obstructions are causing real truncation of distribution it will be possible to prioritise those for prompt attention, and commence surveying of individual sites.

2.2 Site Surveys

Before facilities for individual sites can be specified it is important that the site is surveyed and that the full range of hydraulic conditions that occur there are assessed. There are a number of examples of eel and elver passage facilities which are ineffective because of wrong assumptions regarding such hydraulic conditions as headwater level and tailwater level ranges during the period when elvers and eels are migrating, or where inadequate allowance was made for withstanding very high flows.

Information that should be gathered includes:-

- Range of river discharge during the season of operation proposed (Section 4.2)
- Flow-frequency relationship during the operating season (exceedence hydrograph)
- Range of headwater levels and the relationship between headwater level and discharge
- Range of tailwater levels and the relationship between tailwater level and flow
- Hydraulic head difference at various flows
- Area where eels and elvers are known to gather, or are likely to gather, at various flows (may require survey or temporary trap – Section 5.2)
- Size range of eels present immediately below the obstruction, or likely to require passage (Section 4.4)
- Layout of the obstruction, which might suggest a particular approach to provision of passage facilities
- If available, engineering drawings showing appropriate detail of the structure and upstream and downstream bed levels
- Photographs of the structure

Once this survey is completed, consideration can be given to the design criteria for appropriate facilities.

3 FUNDAMENTAL APPROACHES TO PROVIDING FACILITIES FOR EEL PASSAGE

3.1 Fundamental Design Considerations

The fundamental aim is to provide conditions to allow ascent of a hydraulic head drop, either natural or man-made, which is otherwise impassable either at all times or under some conditions, or where ascent is otherwise difficult to the extent that recruitment upstream is sub-optimal. Eels are incapable of jumping, and vertical falls of more than about 50% of their body-length represent a barrier to upstream migration (Knights and White 1998). Their swimming abilities are limited but they are adept at exploiting boundary layers and crawling over rough substrates; elvers are able to climb vertical walls if the substrate is suitable (Section 4.7).

In most cases the following issues are relevant:

1. The fish must be able to locate the appropriate starting point for ascent e.g. the lower entrance of the pass. This may be achieved by constructing the entrance where the fish will naturally congregate, or by providing some attraction mechanism.
2. The fish must be able to enter the facility without undue effort and without causing undue stress.
3. The fish must be able to overcome the head difference within the facility without expending undue effort. In practice this is often achieved by restricting the volume of flow within the pass, restricting the velocity of flow within the pass, and providing a substrate which both slows and disorganises the flow, and allows the fish to achieve a purchase with its body to allow the pass to be ascended by crawling as much as swimming. This approach exploits the natural behaviour of the eel in seeking edge-effects and shallow water in its migrations, as well as its natural climbing behaviour. Another approach used particularly at sites with a high hydraulic head is to trap the fish at the base of the structure and carry them to the head pond.
4. The fish leaving the pass should be deposited in an appropriate area for continued upstream migration, for example where risk of being immediately washed downstream can be minimised.
5. The facility should work under all conditions of head and tail water levels which prevail during the period when fish are migrating at the site, or perhaps more realistically, under conditions that prevail most frequently and for a major part of this time.
6. The fish should be protected from excessive predation at all points of the facility including at the entrance, exit and within the pass.
7. Wherever possible, facilities for monitoring the effectiveness of the pass should be incorporated into the design, for example a trap or counter that can be operated on appropriate occasions. Such traps or counters could also be very useful in monitoring recruitment on a wider scale, and for facilitating wider distribution of the trapped fish to enhance recruitment.
8. Limited funding and other constraints may require that provision of facilities is prioritised, and that designs are cost-effective. It is likely that facilities which allow

passage of a limited size range of eels under restricted conditions will be very much cheaper and less intrusive in visual and engineering terms than those that can allow passage of all eels under all conditions. Such a facility is also greatly preferable to no passage facilities at all, which may be the only alternative where funding is limiting. Targeting the range of conditions under which eels wish to migrate at each site, and providing facilities appropriate for the size of eels at the site, are therefore important. These issues are considered in Section 4.

9. Eel and elver passage facilities, especially those retro-fitted to existing structures, may be very vulnerable to damage by high flows and waterborne debris. Facilities should therefore be designed with this in mind; possible approaches to avoiding such damage include robust construction, siting the facility where it is least exposed to adverse conditions, provision of protecting structures to divert flood flows and waterborne debris, and removal of facilities during the winter. This last option may also facilitate maintenance.
10. Vandalism and theft of eels may be a problem at almost any site. Robust construction and locked covers may help, but a determined vandal may see such features as a challenge. Another approach is to site facilities where the general public does not have access.
11. Human operator health and safety are fundamental concerns for all facilities requiring maintenance, seasonal installation and removal, and especially monitoring.
12. Public safety and liability issues must also be addressed. For example, facilities could represent a danger to children playing nearby and it may be necessary to restrict access or at the very least provide adequate warning notices.

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3.2 Six Basic Approaches

There are six basic approaches to providing upstream passage:-

1. Construct a fish pass, which incorporates a channel that allows the fish to ascend under controlled conditions that are within its capabilities. This commonly involves the use of ramps with a crawling or climbing substrate.
2. Trap the fish and release them above the obstruction. Again, this commonly involves the use of a pass trap with ramps with crawling substrate.
3. Allow the fish to swim through the barrier e.g. through an orifice or pipe; this would normally require some mechanism for restricting water velocity through the aperture
4. Lift the fish either in a fish lock or a fish lift
5. Create conditions at the barrier to allow ascent, for example by roughening the back of a small weir or providing rocks to generate edge effects; in practice this approach merges with 1 above.
6. Removal of the barrier.

Basic features of these approaches are now described; a detailed analysis of design features forms Section 5.

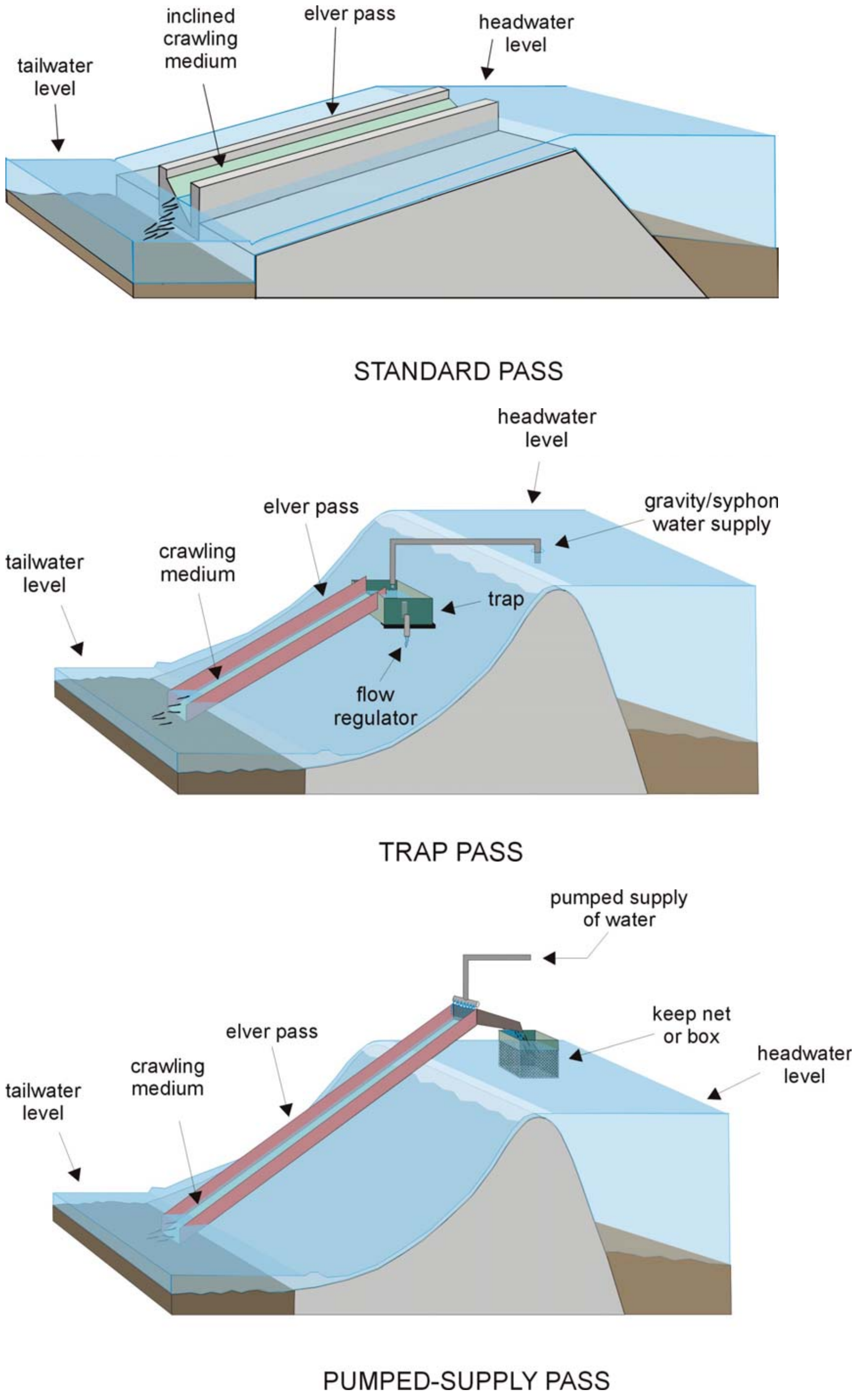

Figure 3.1 The three basic types of substrate-ramp eel passes.

3.3 Facilities Based on Ramps with Substrate

3.3.1 General description

The basic aim of substrate channels or ramps is to provide a sloping waterway carrying a limited discharge, with a substrate to slow the water flow, to provide a purchase for the elvers and eels to exercise their natural crawling and climbing ability, and in some cases to provide cover. Substrates may be natural materials, such as stone or vegetation, or artificial such as bristles or plastic mouldings.

There are three approaches to provision of such facilities (Figure 3.1):-

1. A standard channel pass built into or bypassing an obstruction, with the flow being provided directly by the level in the head pond. It is usual for the substrate to be laterally sloped so that part of it experiences the optimal level of submersion and flow over a range of upstream water levels.
2. A pass-trap, where the ramp does not ascend to the full retained height of the obstruction but instead the eels are retained in a trap box. The flow is usually a gravity supply fed from the retained level in the head pond or by a pump from the tailrace. A range of pre-fabricated pass-traps is manufactured by "Fish-Pass" in France; several such installations are described in Section 6.
3. A pumped-supply pass, where the ramp ascends to a higher level than the full height of the obstruction; the ascending fish are then either retained in a trap or net, or return by gravity into the head pond.

For pass-traps and pumped-supply passes the substrate is usually not laterally sloped as the flow down the ramp is controlled under all conditions.

3.4 Pipe Passes

Pipe passes comprise a pipe that passes through the barrier at some level below the retained water level, in theory creating a direct route of ascent. In practice the pipe usually passes through close to the retained level in order to minimise the velocity of flow through the pipe. A substrate is usually provided within the pipe, both to limit water velocities and to allow the eels to crawl rather than having to swim. A major limitation of pipe passes is the tendency for the substrate to become blocked with debris, requiring removal of the substrate for maintenance. They are most practicable at the outflow from a large impoundment, which acts as a sediment trap for debris so that the water entering the pipe is clear of material that might block the substrate.

3.5 Lifts and Locks

A fish lift comprises a chamber into which the fish are encouraged to swim or climb. Periodically, the chamber is lifted to or above the head-pond level, and the fish are allowed to swim from the chamber or are tipped or drained into the head pond (Figure 3.2).

Fish locks operate in the same manner as a navigation lock. The fish swim into the lock chamber when the lower gate is open. Periodically the lower gate closes and the chamber is filled with water to bring its level up to that of the headpond. An upper gate is then opened and the fish are able to swim out into the headpond.

Both lifts and locks involve a considerable level of engineering but they are well suited to very high head situations where a conventional pass may be impractical.

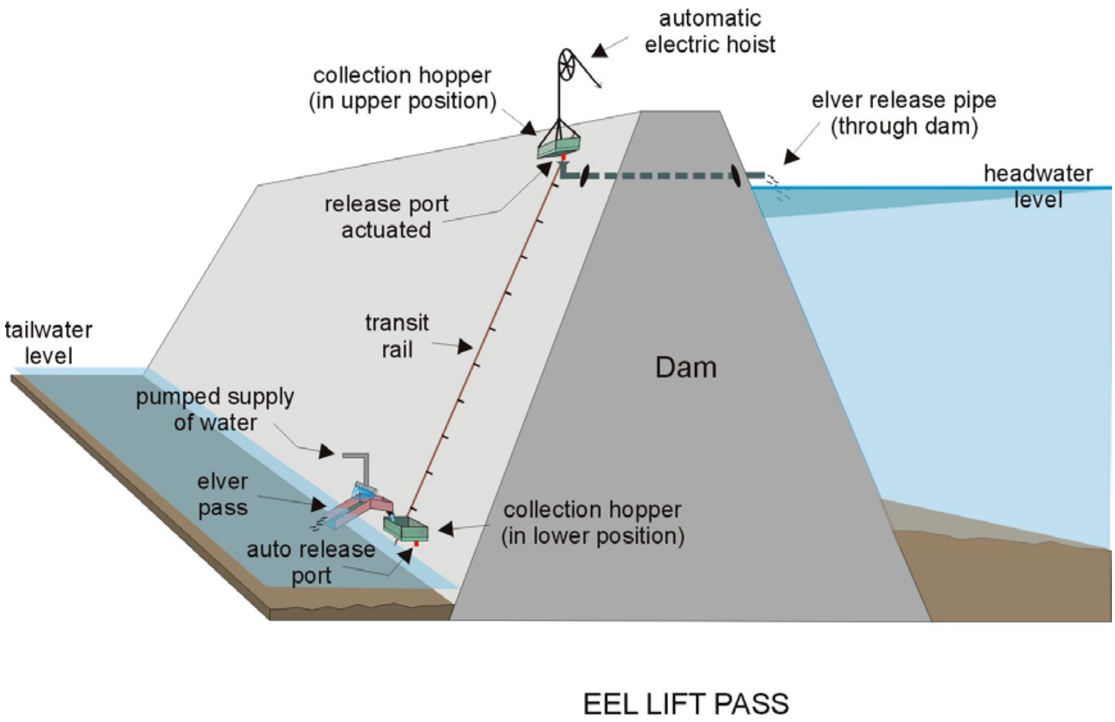

Figure 3.2. The principle of the fish lift

3.6 Facilities Based on Easements

Many obstructions are passable by some eels at some times by virtue of irregularities in flow caused by edge effects, growth of algae or other plants, or features such as cracks and rubble. Eels and elvers are very adept at locating and using zones of reduced flow, and a great deal can be achieved by providing such features in situations where a full-scale engineering solution is not justified or is otherwise inappropriate. For many sites with non-vertical barriers, such as weirs, this is likely to be the most satisfactory solution in terms of simplicity, cost, sustainability and overall effectiveness (Section 5.4).

3.7 Removal of the Barrier

Although this is unlikely to be a viable option in most cases, removal of a disused barrier might be desirable for a number of reasons, including passage of other species and restoration of upstream habitat. The possibility should at least be considered before other major works are planned.

4 BIOLOGICAL CRITERIA FOR DESIGN OF PASSAGE FACILITIES

4.1 Introduction

The aim of this section is to consider aspects of the ecology and behaviour of eels that have a bearing on the design and construction of facilities to provide passage past obstructions. It represents a summary of the findings of the earlier phase of the project; Solomon and Beach (2004) provide full details.

4.2 Season

Virtually all upstream migration is observed within the six-month period April to September inclusive. At or close to the tidal limit the period may be significantly shorter than this, typically April to July inclusive. Facilities should therefore be designed with the flows prevailing during these months in mind. Where convenient, facilities can be withdrawn over the winter months for storage and maintenance, and to prevent damage by floods and ice.

4.3 River Discharge

Many passage facilities for eels and elvers will only operate effectively over a limited range of head and tailwater levels, and thus river flows. It is therefore critically important to match the flows and levels at which facilities will be effective to those prevailing when the fish wish to make use of them.

All available evidence indicates that elvers and eels migrate upstream either without regard to river flow, or migrate to a greater extent at low flows than at high flows. As low flows predominate during the migration season of April to September, because periods of low flow may be of considerable duration in these months, and because periods of high flow are usually of short duration during these months, facilities should be designed to be effective at low flows. Clearly, the ideal would be to have facilities that were effective at all flows, but this is likely to involve considerably greater expense. It is suggested that facilities that allow passage at lower flows which predominate for, say, only half of the April to September period, will be virtually as effective at achieving optimal long-term dispersion as would facilities that were passable at all flows. In this respect eel migration is rather different to that of migratory salmonids. In the latter case movement at any point in a river system may be limited to a matter of days within the season, and any missed opportunity may result in a severe truncation of the spawning distribution and a greatly reduced level of resultant recruitment. Eels, on the other hand, are likely to be able to maximise the opportunity to migrate over a period of several months, and the progress made on any particular day, in any particular month or even in any particular year is unlikely to be critical to the long-term reproductive potential of the population.

4.4 Size of Fish to be Catered For

At or close to the tidal limit the upstream migration will be dominated by elvers (60 to 90mm in length) and 1-group fish (90 to 130mm). However, numbers of fish up to 300mm may also pass upstream at times, and facilities should cater for fish throughout the 60 to 300mm length range. In such situations however, the smaller fish should always be the first priority, as the stock of the whole catchment is dependent upon them. Small eels are willing to climb vertical damp surfaces at times as long as there is sufficient grip, but this activity appears to be restricted to fish of less than 100mm.

Further upstream, the range of sizes of fish that require passage shifts upwards. In most UK situations elvers will not penetrate more than 15-25 km upstream of the tidal limit in their 0-group year, and 1-group fish will dominate with increased numbers of larger fish. In the Upper Severn and Thames, for example, there are few eels of less than 30 cm in length and facilities to facilitate passage there should be designed with this higher length range in mind. In upper reaches, passes installed for other species may well prove to be adequate for the larger eels found there.

We are some way from being able to create a definitive model of the smallest and youngest eels that occur at various points in a catchment. This is partly because the situation appears to vary with the topography; for example the steeper River Dee shows a different pattern of distribution of ages of fish from the River Severn (Aprahamian 1986, 1988). One approach to determining the size range of eels that might wish to effect passage past a structure is to examine the population of fish occurring in the reach immediately downstream. The danger then, of course, is that the size range may be distorted by passage problems downstream, or by the hitherto impassability of the structure under consideration. The safest approach may be to work from downstream to upstream, ensuring that each obstruction encountered is provided with appropriate facilities for passage by eels of appropriate size. Within a year or so the eel population downstream of the next obstruction up river should reflect the size range of fish requiring passage. With modular passes it may also be realistic to change the substrate type to a more appropriate one if the initial assessment proves to be mistaken.

4.5 Water Temperature

Water temperature affects the migratory behaviour and the swimming ability of the fish. Generally there is little activity below about 10^{o}C, with increasing activity with rising temperature up to well over 20^{o}C. Small eels will climb damp surfaces if necessary but only at higher temperatures, typically above 15^{o}C.

4.6 Illumination

There are conflicting reports on the time of day of elver migration, probably reflecting different local conditions. Passage is likely to be required night and day, so covers should be provided in shallow-matrix passes to protect the fish from direct sunlight. Older eels migrate almost entirely at night. It is probably prudent to locate and construct passes so that artificial light does not shine directly upon them, or provide cover to ensure darkness at all points during passage at night. Equally, this aversion to light can be exploited for guiding downstream migrants to safe routes – see Section 5.14.

4.7 Water Flow and Eel Swimming Ability

Many designs of pass for elvers and small eels involve some form of matrix in which the fish is in physical contact, and progress is made by crawling and climbing rather than by swimming. However, at some stage the fish has to swim in open water to approach the pass or leave it at the top. Other facilities will depend on controlling the current speed to a level that the fish requiring passage can swim against. Thus the swimming performance of eels and elvers is likely to be an issue for all upstream passage facilities.

Observations on swimming performance, and climbing behaviour, of elvers and small eels are described by Beach and Solomon (2004), derived from experimental studies and the recently-developed “Swimit” model (Clough and Turnpenny 2001; Clough *et al* 2002). For most purposes the burst speed (the speed that can be maintained for 20 seconds) is probably the most appropriate design criterion to apply, as few situations will require fast swimming to be maintained for longer than that; indeed, in some situations, such as pool and traverse passes and deep slot passes, maximum velocities may only be experienced for a few seconds at most. However, the possibility of periods of fast swimming having to be maintained for longer than 20 seconds must be considered in baffle-type passes, where there are no opportunities for rest between entering and leaving the pass. For elvers of *A. anguilla* burst speeds are of the order of 350 to 600 mm/sec, depending on body length. Burst-speeds for larger eels are of the order of 1.15 m/sec for 200 mm fish, 1.25 m/sec for 400 mm fish, and 1.35 m/sec for 600 mm fish.

The tendency for eels and elvers to be attracted to flowing water, and to gather at the most upstream point below obstructions, provides important pointers to the optimal location of the downstream entrance to passage facilities, and for the provision of an attraction flow, as the volume of water flowing down the pass itself may be very small (Section 5.11).

At times, elvers and small eels (fish less than 10 cm) will climb wetted sloping or even vertical surfaces, especially if they are covered with moss and algae. Although this behaviour is only apparent at temperatures above 15^{o}C it has been exploited to provide passage facilities (see Section 6.6.6) and probably explains the presence of eels upstream of barriers that otherwise appear well beyond the swimming capabilities of small fish.

4.8 Predation

Predation is a major risk for elvers and small eels and they are likely to be particularly vulnerable in passes, and as they approach and enter from downstream and leave the upstream exit. Shallow passes should be covered to prevent bird predation, guarded at each end to prevent the entry of mammalian predators such as mink or rats, and provide adequate cover for fish dispersing from the upstream exit (Section 5.3.11).

4.9 Downstream Migration

The fundamental requirements for downstream passage facilities are quite different to those for upstream migration. Most obstructions that an eel can overcome moving upstream will present little or no obstacle to downstream movement. A major problem can occur, however, where a significant part of the flow is abstracted for water supply or to drive machinery such as hydro-electric power (HEP) turbines, and where any eels going with that part of the flow are likely to be killed or injured, or trapped in a reservoir. For example, it has been calculated that up to 41% of silver eels migrating down the River Meuse in Belgium and the Netherlands are killed by operation of HEP plants (Vriese, 2002). The requirement is to prevent or discourage passage into the intake, and to guide the migrants to a safe bypass route. Approaches to this are discussed further in Section 5.14. An alternative or additional approach of "shutting down" abstraction or generation at times of peak eel migration is discussed below.

The size of eels involved in the downstream migration of maturing fish range from about 280 mm to more than a metre. Based on rather few data for larger eels (Durif *et al* 2003), a fish of 280 mm would require gaps between screen bars of 15 mm or less to prevent passage.

Protection facilities would have to be effective in a wide range of flows including very high discharges, though in many situations a high river flow would mean that the proportion being abstracted or passed through turbines under such conditions may be minor.

From the review described in the Technical Report (Solomon and Beach 2004) it is clear that any facilities for protection of downstream migrants would have to be deployed from June to December inclusive to be fully effective. However, protection of the majority of migrants could be achieved by installation during the peak of the run, lasting about two months. The exact timing of the run peak is likely to vary somewhat between sites and between years, but September through November would appear to cover most fish.

The majority of migration past any particular point may take place during limited hours on relatively few nights, which could perhaps be fairly reliably identified, albeit sometimes at short notice, from information on lunar cycle, discharge, cloud cover etc. Movement is minimal during daylight. Haro *et al* (2003) estimated that, on average, half of the downstream run of eels on a small river in Maine occurred in a 30 day period between September 10 and October 6. There may, therefore, be scope for a degree of protection to be afforded by closing down abstraction or electricity generation at night for limited periods of time. Several attempts to develop the predictive model required for such an approach were reviewed by Rickhus and Dixon (2003); the best was estimated to allow a reduction in mortality of about 50%. Oberwahrenbrock (1999) describes a preliminary model concept for such an early-warning system. Two examples of management based on this approach are recorded on the Shenandoah River in Virginia (Rickhus and Dixon 2003) and at Patea Dam in New Zealand (Chisnall *et al*, 1999). Rickhus and Dixon (2003) suggest that this approach is more likely to be effective on small river systems. A possibly significant advance is the development of a bioassay system called MIGROMAT®, which detects the activity of a group of captive eels held in a flow of river water (Anon 2002). The eels are fitted with short-range transmitters whose movement is monitored. Early results at a site on the Meuse in the Netherlands show that there is a clear correlation between activity of the captive eels and migration activity in the river.

More investigation is needed regarding the depth at which silver eels travel, and optimal design and location of bypass facilities for them.

5 DETAILED DESIGN CONSIDERATIONS

5.1 Introduction

In this section detailed aspects of design for passes for eels and elvers are examined, and approaches to their provision are discussed. This is based largely on an analysis of the installations described in the Technical Report (Solomon and Beach 2004).

5.2 Siting of Facilities

The flow through most elver and eel passes is low compared to that flowing over the obstruction that they are designed to overcome. The siting of the downstream entrance is therefore a critical design consideration. The siting of the upstream exit of the pass is also important to prevent the eels being carried back over the obstruction with the flow, but this is discussed later in section 5.7.

The obvious location for the entrance of the pass is wherever the fish tend to gather at the foot of the obstruction. This can often be determined by observation, or from first principles; close to banks or walls, and quiet corners at the most upstream point below the obstruction are obvious candidates. It may be prudent to employ a temporary portable trap (see Section 6.6) to establish the optimal entrance location. It may be that eels gather in more than one location below a weir, for example close to each bank. This may require more than one pass, or more than one entrance to a single pass. The optimal entrance location may be within a very small area; Solomon and Beach (2004) describe a situation where elvers were gathering in large numbers between the entrance of a ramp pass and the face of the weir, a distance of the order of a metre or two. Provision of alternative facilities with access close to the weir face solved this problem (see section 6.6.6.).

5.3 Facilities Based on Substrate Ramps

5.3.1 Advantages and limitations of different types of installation

The advantages and limitations of the three types of substrate ramp facilities (as defined in Section 3.3) are listed in Table 5.1.

Many different substrates have been deployed, including natural materials, brushes, geotextile matting, rigidly mounted plastic shapes, and concrete mouldings. These are described in the following sections.

5.3.2 Natural substrates

A number of natural substrates have been used in eel passes in the past. These include small tree branches or brushwood, heather, straw and hay (loose or twined into ropes or braids), stones, and wood shavings. However, the review by Solomon and Beach (2004) concluded that substrates of natural materials (with the exception of stones in certain circumstances) are of historic interest only and have no place in modern passes for eels and elvers. This conclusion does not, of course, apply to natural emergent vegetation which can represent an important aspect of passage based on easement (Section 5.4).

Table 5.1. Attributes of different types of substrate-ramp eel pass (see Figure 3.1)

	Standard pass	Pass-trap	Pumped supply pass
Advantages	No separate water supply needed. Resistant to flood damage. Low maintenance. Low manpower requirements.	Pump generally not needed (gravity supply). Migrants are trapped for monitoring and distribution. Not vulnerable to fluctuations in headwater level. May be removed out of season. May be re-located to find optimal location.	Migrants may be trapped for monitoring and distribution, or just allowed to migrate into the headpond. Not vulnerable to changes in headwater level. May be removed out of season. Possible to re-locate.
Limitations	More complex to monitor and trap migrants. Very vulnerable to fluctuations in head-water level.	Dedicated plumbing required. Frequent attention needed, high manpower requirements. May be vulnerable to flood damage and vandalism. Prone to blockage of feed pipe inlet.	Pumped supply required, with dedicated plumbing. Regular attention needed (frequent if trapping), medium to high manpower requirements. May be vulnerable to flood damage and vandalism.

5.3.3 Bristle and brush substrates

Tufts of bristles of various materials have been used to create substrates for eel passes for many years; early references include O'Leary (1971) and Tesch (1977), who records the use of brushes in an eel pass on the Elbe as early as 1964. These early installations often used broom-heads arranged in a suitable array, but nowadays brush mats are made specifically for eel passes using a range of suitable materials, dimensions and spacings for the bristles according to the situation and size of eels to be catered for (Figure 5.1). Typical is the range of bristle mats marketed by the company "Fish Pass" in France.

Figure 5.1 Bristle substrate with nylon bristles fixed to a polypropylene sheet

These are typically 1000 mm by 400 mm polypropylene mats with clumps of bristles about 70 mm in length. Each clump comprises about 25 bristles. The spacing of the bristle clumps is varied according to the size of eels to be passed – either 14 or 21 mm minimum gap. These are used in installations both with and without a lateral slope within the ramp. Panels with mixed spacing are also available, with a zone of closer-spaced clumps up the centre of the panel and zones of wider spaced clumps to each side; these are generally used only where there is no lateral slope within the ramp. The mats can be cut for fitting to particular pass configurations, and the current price from "Fish-Pass" is €131 per 1000 x 400 mm panel for all bristle spacings. For many sites in England mats have been fabricated to a specification produced by the National Rivers Authority. This specification was as follows:- backing boards black polypropylene, 9-10 mm thick, 1000 mm long, and 460 or 1000 mm wide; bristles 1 mm gauge green polyester in clusters to fill 5 mm holes, hand-drawn with stainless steel drawing wire or punch-filled; bristle length 70 mm proud of board; bristle spacing 5 mm holes drilled at 40 mm centres, staggered rows at 20 mm spacing (for eels over 150 mm) or at 25 mm centres with 12.5 mm between staggered rows (for elvers and small eels). The current contact details for companies that provided quotes for supply of boards to this specification in 1994 are listed in Section 8. A number of installations using these substrates are detailed by Solomon and Beach (2004), some of which are described in Section 6 below.

Legault (1991) investigated numbers of eels using three pass ramps with different bristle-tuft spacing (7, 14 and 21 mm) at different slopes (15°, 30° and 45°). The results were somewhat inconclusive (Table 5.2).

Table 5.2 Proportion of small eels (mean length 223 mm) using ramps with different bristle substrates at three different slopes.

	Slope of ramps		
Spacing mm	**15°**	**30°**	**45°**
21	7.6%	35.5%	52.0%
14	61%	52.3%	38.4%
7	31.4%	12.2%	9.6%
Total	100.0%	100.0%	100.0%

Clearly the closest substrate spacing (7 mm) was less used than the wider-spaced ones by this size-range of eels, but the variation with slope defies simple explanation. Interestingly, the mean length of eels recorded at a fish lift at the same site during the same period was 293 mm; clearly, at least one of the passage facilities was size-selective. The fast current speeds in the approach to the fish lift may have discouraged smaller eels from entering, or larger eels may have been less inclined to enter the bristle substrates.

5.3.4 Other synthetic substrates

Many other synthetic substrates have been used for eel passes, including sacks sewn together (Tesch, 1977), discarded trawl netting (Shotzberger and Strait 2002), nylon garden netting and Astroturf (Knights and White 1998), artificial vegetation, trade name "Cassonia" (Eckersley 1982) and geotextile matting (e.g. Enkamat 7020, Dahl 1991; Enkamat 7220, Wippelhauser 2001; Tensar, Matthews *et al* 2001). Enkamat is described by the manufacturer as "a dense three-dimensional permanent erosion prevention mat, made of thick polyamide filaments fused where they cross".

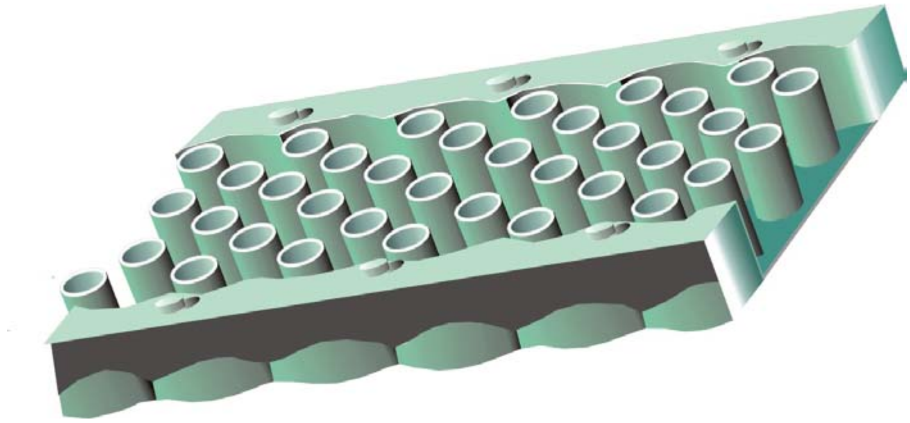

Figure 5.2 Milieu "Eel-ladder" substrate for eels over 15 cm in length

Various thicknesses are available; type 7020 and 7220 mentioned above are 20 mm thick. A limitation of geotextile matting is that the size of eel that can pass through the matrix is limited; Matthews *et al* (2001) mention larger "bootlace" eels which passed their facility late in the season may became tangled in the mesh, and Dahl (1991) refers to larger eels becoming jammed in the Tensar matting when it was used in pipes, and dying there. Voegtle and Larinier (2000) concluded that Enkamat was very "aggressive", causing eels to lose considerable amounts of mucus. They also found it to be size selective, only allowing passage of eels of less than 260 mm. The main use of these substrates would thus appear to be at lower river sites where elvers and small eels predominate.

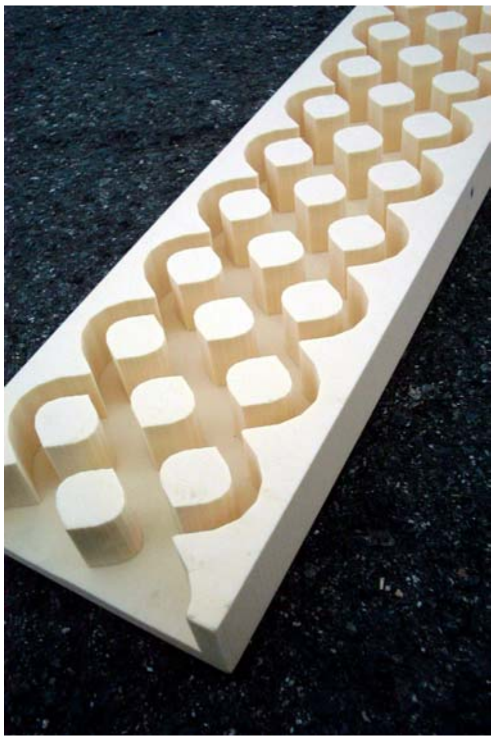

Figure 5.3. Milieu experimental eel pass substrate, machined from solid polyurethane foam.

In recent years some new synthetic substrates have been developed, based upon round solid shapes fixed to a flat bed. These are designed for use without a lateral slope, in pumped-supply passes and pass-traps. One used extensively in North America is called "Eel-ladder" and has been developed by Milieu Inc of Quebec (Figure 5.2). In this case the shapes are open-topped cylinders 50.8 mm in diameter placed in holes in the substrate bed so that the tops project by 101.6 mm. The material is provided in moulded modular channel form so only needs a frame to support it. This substrate is designed for eels of 150 to 750 mm, so is best suited to passes some distance up river. This design has been used with great success in passes at Chambly Dam (Section 6.3.2) and Beauharnois both in Quebec, and a number of other sites in Canada (Solomon and Beach, 2004). Milieu Inc also manufacture a smaller version of this substrate, for elvers and small eels up to 150 mm long. This has studs 25 mm in diameter within a preformed channel 140 mm wide.

Figure 5.4 Plastic eel pass substrate developed by "Fish-Pass" in France, currently under evaluation.

Milieu are experimenting with an adaptation of this smaller substrate, which is machined from a solid block of polyurethane foam. A prototype for elvers and small eels is shown in Figure 5.3. The substrate is designed to be laid in an aluminium channel. Exploration of the need for, and options for, coating of the machined material is continuing.

Another solid plastic substrate, developed by "Fish-Pass" in France, is illustrated in Figure 5.4. It is made of ABS and is supplied in sheets which are designed to be fixed to sloping weir cills. The shapes are dome-topped cylinders, 30 mm in height and with 14 mm gaps. The shape minimises blocking with debris. The optimal operating water depth within the substrate is 2-12 mm, and the optimal slope is up to 35^{o}. This substrate is under evaluation at sites in France.

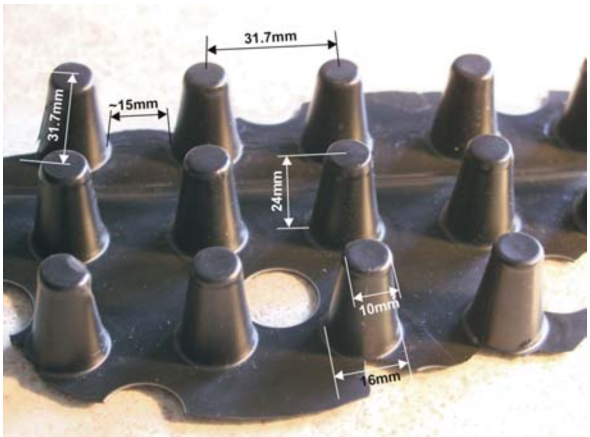

Figure 5.5 "Akwadrain" plastic substrate

Several eel passes in North America have used a plastic substrate with the trade-name of "Akwadrain". This is a plastic moulding designed for vertical drainage against underground walls or walls built into banks. Details are shown in Figure 5.5. The main advantages of this material are the very low cost, and its physical flexibility which could allow it to be draped over weir backs as a temporary installation. The main limitation is its delicate construction; it requires regular replacement in otherwise permanent installations.

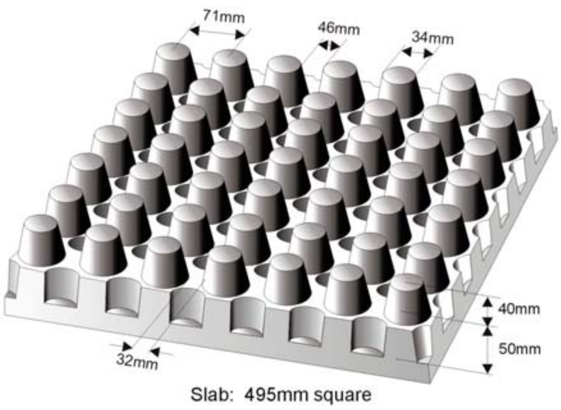

Figure 5.6 "Pelcar" concrete substrate

Experiments have been conducted in France using concrete block substrates, including some manufactured for car parks and walkways to allow grass to grow through. Antoine Legault (pers.comm.) is experimenting with one such called “Pelcar” (Figure 5.6). Voegtle and Larinier (2000) examined the effectiveness of several concrete block substrates, most made specially but also one car park block “Evergreen” (similar to the “Pelcar” slab), and compared their effectiveness with bristle substrates. Tests were conducted at three gradients, 15, 30 and 45°. For most substrates the shallowest slope gave the best results, with the highest level of successful passage and the greatest tolerance to variation in headwater level. Most movement at this slope was by swimming rather than crawling, as long as there was an adequate depth of water (10-20 mm). At steeper slopes most activity was by crawling, with smaller eels in particular finding ascent more difficult. When crawling, the eel needs to derive support from several points, so that the spacing of studs becomes size-specific. The most effective layout of studs was found to be a quincunx (the arrangement of five objects, four in a square with the fifth in the centre, which is, incidentally, the pattern formed by staggered rows of brush bristles described in the specification in Section 5.3.3). For elvers, bristle substrates and a closely-spaced concrete stud substrate were the most effective, because of the level of support provided. For small eels (150 mm) these two substrates plus “Evergreen” gave the best results provided the depth of water was restricted (less than 20 mm at 15°, 10 mm at 30°, 5 mm at 45°). For larger eels, the brush substrate and a larger concrete stud form were the least selective, particularly at the steeper slopes. All substrates were tested also with a lateral slope of 30°, which gave good results with the exception of “Evergreen” at higher gradients. The main potential use for concrete substrates is probably where their great inherent strength is an advantage, such as sites subject to severe floods, vandalism or foot traffic such as canoeists.

5.3.5 Slope

The longitudinal slope of ramps represents a compromise between ensuring restricted water velocities, thus making ascent possible and comfortable for the eels (which suggests a shallow slope), and limiting the length of the installation especially at sites with large hydraulic heads (which requires a steep slope). It is likely that different types of substrate have different optimal slope ranges.

After experimenting with slopes up to 20°, the pass at Moses-Saunders Dam was set at 12° as being “flat enough not to inhibit movement, and steep enough to ensure that an adequate water depth and current were maintained in all sections of the ladder” (Eckersley, 1982); at that time, natural green willow cuttings were being used as a substrate.

Legault (1993) suggests that the longitudinal slope for brush substrates should be not more than 35°.

The Milieu “Eel-ladder” substrate described in Section 5.3.4 is designed to be installed at slopes of up to 55°. Chambly Dam (Section 6.3.2), which uses this substrate, has a slope of 52° for its main run (9.2 m in length). The much longer pass at Beauharnois Dam, using the same substrate, has a slope of 40° for its main section 31 m in length, and 45° for its final section of 2.4 m (Desrochers 2002).

Passes in Maine using Enkamat have ramps at various angles including 43^{o} at Fort Halifax (Section 6.3.1) and 47^{o} at Benton Falls; each of these installations has passed over 200,000 elvers and small eels in a year (Wippelhauser 2002). Enkamat has also been used successfully attached to vertical surfaces for passage of limited numbers of elvers (Section 6.6.6).

5.3.6 Length of pass, and resting facilities

The length of the pass is determined by the height of the structure and the angle of the ramp; the relationship for a range of slopes is indicated in Table 5.3.

Table 5.3 Length per unit head for ramps of different slopes.

Slope ^{o}	Length (m) for 1m of head
10	5.8
15	3.9
20	2.9
30	2.0
35	1.7
45	1.4

Thus for the 35^{o} maximum slope recommended for brush ramps by Legault (1993), the length of the pass would be 1.7 times the head lift of the ramp. The head lift of the ramp would be the same as the head of the weir in a simple pass installation, but a little more where a pumped water supply was used to allow the ramp to extend above the upstream water level to allow for level fluctuations (see section 4.4.9).

Resting places are often incorporated into long passes, especially at a change of direction; these are typically pools or tanks with sufficient volume to considerably reduce the flow velocity, and are often fitted with substrate to provide further protection from the flow. Although no investigations could be identified where the requirement for, and effectiveness of, such provisions had been examined, it is recommended that resting boxes are incorporated at each turn in long passes; they are cheap and simple to include, may simplify engineering and are likely to be helpful to the fish.

The greatest hydraulic heads overcome by ramp passes that could be identified were 27 m at Cathaleen's Fall on the Erne (Matthews *et al* 2001; McGrath 1957) and 25 m at Moses-Saunders Dam on the St Lawrence (Whitfield and Kolenosky 1978; McGrath *et al* 2003b). No information is available regarding the slope and length of the former pass. The pass at Moses-Saunders has a greater head (29.3 m) than the dam as the pass extends above the upstream water level to allow for headwater fluctuation and to allow trapping. At a slope of 12^{o} the pass is 156.4 m in length, the longest eel pass identified in this study. It incorporates eight resting boxes (dimensions not available), one at each change of direction i.e. at approximately 17 m intervals.

The Moses-Saunders pass has worked well, with the minimum time for ascent calculated at 70 minutes. The pass at Cathaleen's Fall did not work well and was replaced with a trap; "although elver were recorded from the tops of the ladders, it is likely that the arduous climb resulted in significant losses" (Matthews *et al*, 2001). It should be noted that the fish at Cathaleen's Fall were predominantly elvers and 1 group eels, whereas those at Moses Saunders were several years older and thus considerably larger, and probably demonstrated greater stamina.

The head (and thus length) of ramp pass-traps at the base of dams or weirs is generally much less than that of the dam itself. The lift needs to be enough to ensure that the trap can operate at all tailwater levels, and low enough so that the trap can be fed by gravity from the headwater level. Other issues are the cost of making the trap with an unnecessarily high lift, and safe, easy access for operation and maintenance.

5.3.7 Width and depth

Most of the substrate ramp passes reviewed by Solomon and Beach (2004) had channels between 300 and 700 mm in width. One design of temporary pass-traps used on a number of rivers was only 100 mm wide (Naismith and Knights 1988, White and Knights 1994), and the pass at Sunbury Weir on the Thames is 1000 mm in width. It is clear that passes of only limited width have been observed to pass relatively large numbers of fish. Most passes are probably operating well below their potential fish capacity. The original single-channel pass at Moses Saunders Dam on the St Lawrence, which was only 300 mm wide, handled over a million sizeable eels per year apparently without undue congestion (Whitfield and Kolenosky 1978; Liew 1982). However, two substrate ramps at a site in Maine, each 300 mm wide, were apparently overwhelmed by a run of elvers in excess of 550,000 (Solomon and Beach 2004). Presumably this was largely a function of timing of the run, with very large numbers moving in a short time.

Most of the narrower ramps are in pass-traps where the flow of water down the pass is regulated and is independent of headwater level, and the substrate is not sloped laterally. Thus the whole width of the substrate is usable at all times. In such situations the depth of the channel may be relatively shallow, with 100-150 mm being typical. Most of the wider ramps are in passes where the substrate is laterally-sloped to allow for changes in headwater level, and thus only a fraction of the substrate is usable at any time (Section 5.3.10). Such channels are inevitably deeper, typically of the order of 300 to 500 mm.

It is therefore suggested that a ramp width of 300 to 450 mm and depth of 100 mm is adequate in most pass traps and pumped supply passes, where the substrate is not laterally sloped. Where elvers predominate and occur only in moderate numbers a narrower ramp may suffice – for example the 150 mm wide elver substrate units produced by Milieu Inc (Section 5.3.4). Where the substrate is installed with a lateral slope, a width of 400 to 1000 mm appears more suitable, or even more if it is necessary to cater for a wide range of headwater levels, with channel depth being dictated by the lateral slope of the substrate bed.

5.3.8 Flow down the pass

Most substrate passes operate most effectively with a surprisingly small volume of flow down the ramp. Here we are considering only the flow within the pass itself; the issue of attraction flow, to help eels and elvers to locate the pass, is discussed below in Section 5.11.

The flow supplied to a range of effective passes is shown in Table 5.4. These are all pumped-supply passes or pass traps, where the volume of flow is under control. In standard passes, including those with laterally-sloped substrate panels, the volume of flow will be determined by the headwater level and is very variable.

These indicate a range of flows from 8.1 to 230 l per minute per metre width, with all but one being less than 66 l per minute per m. Few measurements of water depth are available, but at the lower flow rates there is likely to be just a matter of a few mm of water across the bed of the pass. In a study of the effectiveness of different substrates at different slopes (described in Section 5.3.4), Voegtle and Larinier (2000) noted that restricted water depth was necessary for most efficient passage of small eels, and that this became more critical at higher slopes; best results were obtained with less than 20 mm depth at 15^{o}, less than 10 mm at 30^{o}, and less than 5 mm at 45^{o}. Bristle substrates manufactured by "Fish-Pass" give best results with 2 – 12 mm depth over the bed (A. Legault, pers. comm.).

Table 5.4. Flow down a selection of pumped-supply passes and pass-traps. Full details in Solomon and Beach (2004).

Site	Substrate	Width	Flow l/min	l/min/m width
Moses-Saunders	Cassonia	600 mm	138	230
Chambly	"Eel Pass"	550 mm	36	65.5
Beauharnois (pass-trap)	"Eel Pass"	550 mm	30	54.5
Beauharnois (new pass)	"Eel Pass"	550 mm	24	43.6
Maine "portable passage"	Enkamat	300 mm	10.2	34
Fort Halifax	Enkamat	600 mm	8	13.3
Greenville	Bristle	430 mm	3.5 - 7	8.1 - 16.3
Westfield	Akwadrain	500 mm	20	40

5.3.9 Changes in tailwater level

Changes in tailwater level are easily catered-for by extending the ramp down to and beyond the lowest tailwater level that occurs at the site during low summer flows – this is important, as many elvers and eels are likely to be migrating at such times. At higher tailwater levels part of the ramp will be drowned out but this will not affect performance. Although this is a somewhat obvious requirement, Solomon and Beach (2004) describe sites where the bottom end of the ramp was perched above the tailwater level at low flows.

5.3.10 Changes in headwater level

Variation in headwater level is a more complex problem than variation in tailwater level. The problem is effectively avoided in trap-passes and pumped-supply passes by having the flow down the ramps independent of headwater level (Section 3.2), but it is a major issue for standard passes.

The issue is usually addressed by arranging a lateral slope to the bed of the ramp and thus to the substrate, so that it is progressively inundated by increasing water levels and a different part of the cross-section of the substrate mat is functional for eel passage. In selecting the lateral gradient there is a pay-off between the overall head range over which the ramp will function, and the area that will be available for passage at any particular headwater level. At one extreme, that of no lateral slope, the whole width of the channel would be available for migration but only within a very narrow range of headwater levels. At the other extreme, that of a steep lateral slope, the operating head-range will be greatly increased, but the cross-section area of the ramp that represents effective migration conditions at any time will be considerably less. The situation for a range of lateral slopes for a substrate mat of 700mm wide is shown in Table 5.5; the assumptions made are stated in the caption.

In theory, completely submerged substrate mats ought to offer some possibilities for migration. However, in practice, once the water level rises more than a few cm above the base of the bristles the rate of flow increases markedly, the bristles tend to be flattened by the flow and conditions are unlikely to be suitable for migration of elvers and small eels. Even if there is a small area of the cross-section that offers suitable conditions the small fish are very vulnerable to being swept back downstream if they venture outside this zone. This is particularly critical at the top of the ramp, where accelerating flows into the ramp tend to cut across the substrate so that any elver emerging is likely to be entrained and deposited at the bottom of the pass. This situation is apparent in Figure 6.5. Potential solutions to this are discussed in Section 5.7.

Table 5.5 Effective head-range and effective corridor-width of a 700 mm wide bristle ramp with 70 mm bristles at various lateral slopes. The effective head range is the range of water depths over which water is present at a depth of 7 mm or less over at least part of the mat. The effective corridor is the width of the channel where water is present at a depth of 70 mm or less at any particular water height.

Angle of lateral slope	Effective head range	Effective corridor width
Degrees	mm	mm
0	70	700
10	192	398
20	309	192
30	420	122
40	520	84
45	565	70
50	606	59
60	676	41
70	728	25

An important consideration at this point concerns the range and frequency distribution of headwater levels that are likely to occur during the migration period. On lowland rivers where the levels are closely regulated for navigation (e.g. Thames and Warwickshire Avon), headwater levels may remain within the operating range of passes for the great majority of the time during the season. But what of less regulated rivers? To explore this, gauging station data was sought for three differing un-regulated watercourses in Southern England:-

- the River Asker, a small spate stream in Dorset (East Bridge Gauging Station)
- the Hampshire Avon, a groundwater fed river (East Mills G.S.)
- the Dorset Stour, a river with both surface fed and groundwater fed tributaries (Throop G.S.)

Although the Agency uses a design criterion of allowing effective passage for 90% of the time for salmonids, as discussed in Section 4.3 the requirement for eels and elvers is less stringent. Allowing passage for the drier half of the period between April 1 and September 30 is suggested as a realistic target. The ranges of headwater levels for 50% of the time (between Q100, lowest flow included in the series, and Q50, flow exceeded for 50% of the time in the series), and for 90% of the time (Q100 to Q10), are shown in Table 5.6. For example, the range of headwater levels under which an eel pass would have to operate in order to be effective for the drier 50% of the time between April 1 and September 30 are 38 mm for the Asker, 245 mm for the Stour, and 483 mm for the Avon. These figures, of course, apply only at these gauging station sites; the ranges will be different where the channel is narrower or broader than at these locations, such that an increase in flow would not be associated with the same changes in level. However, they give a good indication of the likely situation on such rivers.

Table 5.6 Some stage height exceedence figures for the period April to September for gauging stations on three rivers in Southern England.

	Stage height or range of stage heights (mm)		
Flow or flow range	**Asker**	**Stour**	**Avon**
Q100	132	194	26
Q95	143	357	333
Q50	170	439	509
Q10	233	598	720
Q100 toQ10	101	404	694
Q100 to Q50	38	245	483

5.3.11 Cover against light and predation

Elvers and eels are vulnerable to predation while they are in shallow water in a situation from which they cannot quickly escape, such as ascending a substrate ramp. Major predators include birds and rats. Many pass-traps and pumped-supply passes are therefore fitted with covers to exclude or discourage such predators – the situation is less critical in standard passes with a lateral slope as the greater water flow provides and element of protection, though it is suggested that it is still good practice to provide covers. Most migration takes place under the cover of darkness, and if there is any local artificial lighting eels may be reluctant to enter the shallow water of a substrate ramp. Light-proof covers are therefore often used, especially at dams or urban installations with extensive lighting. Further, in shallow channels covers can also prevent eels from climbing out of the channel; this is particularly important at installations where any fish leaving the channel are likely to be killed or damaged. Any covers fitted should be easily and safely removed for cleaning and maintenance.

5.4 Facilities Based on Easement and "Natural" Channels

As already discussed, eels are very adept at exploiting edge effects and reduced current speeds in shallow water and around and amongst stones and blocks. A very sound approach to making obstructions passable is to provide such conditions without the engineering requirement or cost of constructing a formal pass. Surprisingly, few examples were identified during this study. It was attempted at Cobham Mill Weir by roughening the weir back but has probably been unsuccessful due to the steepness of the weir back and other hydraulic features (Solomon and Beach, 2004). On weirs with a relatively shallow-sloping downstream face it may be possible just to build-up a rubble ramp by dumping material; the material will act like a substrate ramp, proving areas of low flow, edge effects and crevices. Knights and White (1998) suggest optimal hole/crevice sizes of about 2 mm for "glass eels", 4mm for fish of 15cm, and 7-15 mm for 20-40 cm eels. The material will also encourage the growth of emergent vegetation, providing further diversity for migrating eels and elvers to exploit. This approach can also be useful in making the approach to a ramp pass easier for elvers and small eels.

A further development is the construction of artificial channels with natural features, such as rocks, pools and riffles, to bypass obstructions. This approach to fish passage has been applied to a wide range of species in Germany (Gebler 1998; FAO/DVWK 2002), Austria (Eberstaller *et al* 1998; Mader *et al* 1998) and Denmark (Nielsen, undated). This development has been so successful that Nielsen (undated) states that "nowadays fish ladders are only built in Danish streams if no other solutions are possible". General guidance on this approach is given by Jungwirth *et al* (1998) and Parasiewicz *et al* (1998). The UK lags behind much of Europe in this important development and only one example could be identified in England or Wales; Trudgill *et al* (2003) briefly describe a successful development on the River Don in Yorkshire which has apparently allowed the passage of eels and salmon. It is strongly recommended that this approach is explored as an option wherever passage facilities for eels and other species is required.

5.5 Pipe Passes

Pipe passes have been used in a variety of situations with widely varying hydraulic heads, ranging from less than a metre (eg Section 6.6.5) to more than 65 m (Patea Dam, New Zealand; Clay 1995, Mitchell 1995). Typically pipes of the order of 100 to 200 mm diameter are used (for example see Section 6.6.5). Substrates deployed have included netting (Sections 6.6.5), bottle brushes (Clay 1995) and Enkamat (Dahl 1991; Pedersen 1999).

There are distinct advantages in keeping pipe runs and head losses within pipe passes as small as possible, both in terms of costs and operating complications. The pass at

Garrison Lake, Delaware (Section 6.6.5) uses an open channel approach to bring the elvers close to the crest of the dam, with only a short pipe through the crest itself (Shotzberger and Strait, 2002; Solomon and Beach, 2004). Limitations of a pipe pass on the River Roding are discussed by Solomon and Beach (2004) and include susceptibility to blockage, fixed nature of entrance in a tidal situation, and virtual lack of effective monitoring provision.

The 240 m long pipe pass at the 68 m high Patea Dam, New Zealand (Clay 1995; Mitchell 1995) is not a pipe pass in the same sense as that on the Roding, as the flow is carefully controlled so that only a small trickle of water flows down the pipe. In this respect the pipe is really acting as a substrate ramp with a cover, and would appear to offer little advantage over an open-channel arrangement with removable covers. Problems have arisen with high temperatures due to solar heating killing elvers within the pipe; it was estimated that it was taking elvers two nights and a day to ascend the pipe, leaving them vulnerable to high daytime temperatures, even though they were only moving by night in the nearby stream. The problem was addressed by shading the pipe from direct sunlight. The original bottle-brush substrate has now been replaced with aggregate which is bonded to the base of the pipe with epoxy adhesive; this has reduced maintenance and allows passage of a range of other species including the native *Galaxias*.

Pipe passes would appear to offer no advantage over open-channel designs where deployment of the latter is feasible, and considerable complications in terms of maintenance. Their use is not recommended where a substrate ramp is a viable and cost-effective alternative.

5.6 Lifts and Locks

Only two eel lifts were identified in the site survey undertaken for the Technical Report (Solomon and Beach, 2004), both in France. They were of similar design, and the later one took into account the operating problems experienced at the first, whose deployment has now been suspended. The main problem concerned the "leaky" nature of the hopper, which allowed numbers of small eels to escape during the hauling process. Both lifts use a bristle-substrate ramp to lift the eels through a short hydraulic head to fall into the hopper in its "collect" position; this overcomes any problems associated with variable tailwater level. The hopper is raised once per day. During the lifting cycle (taking a matter of several minutes) any eels ascending the ramp will be returned to the tailwater level, but by arranging for the lift to be undertaken during daylight such activity should be minimal.

The main limitation of a lift system is cost; the second installation in France cost of the order of £60,000 in 1995. Their use is likely to be restricted to high-head sites where their installation is considered to be part of the environmental mitigation package at the time of construction of the dam.

No fish lock systems specifically for eels were identified during the study, but Murphy (1951) commented that eels were seen using the Borland fish lock at Leixlip on the River Liffey in Ireland.

5.7 Upstream Outlet Arrangements

The design of the upstream exit of passage facilities is important, as the fish may be vulnerable both to predation and to being carried back downstream as they emerge from the pass. In some of the passes inspected, conditions at the point where elvers and eels leave the upstream extent of the installation were such that re-entrainment with the downstream flow appeared very likely (for example see Section 6.2.3).

With pass traps this is not really an issue, as the captured eels may be released at a site of the operators choice – though selection of this location may be restricted by logistic constraints. An interesting study has been conducted at Beauharnois Dam on the St Lawrence River in Canada. Marking studies at this and other sites indicated that many eels pass upstream through the pass more than once, apparently having been carried back downstream through the turbines following the initial ascent. A study was therefore undertaken to establish the optimal release location for planning future installations (McGrath *et al*, 2003b). The rate at which tagged eels were recorded below the dam after release upstream indicated that they were vulnerable to being returned downstream from release points some distance upstream, and that this was significantly site-dependent. Using a mark and recapture approach it was found that eels released less than 295 m upstream of the dam showed a rate of return to the tailrace of about 50%, while those released further away showed a return rate of less than 7%. Subsequent experiments with a long release pipe with shallow gradient indicated that it was not practical to flush the eels through with a flow, as they tended to swim against the current. A much better result was obtained using a gentle flow in the opposite direction, such that the eels had to swim against the current to emerge at the upstream end of the pipe (K. McGrath, pers. comm.). It is stressed that these observations were made at run-of-river hydroelectric plant; in situations where the downstream flow passes over the top of a long-crested weir, release a short distance upstream is much less likely to be associated with eels returning downstream.

For pumped-supply passes and lifts, a steep discharge pipe from the top of the facility can be routed to an appropriate release point.

For standard passes the situation is often more critical, as the fish are usually discharged close to the accelerating downstream flow. Re-entrainment can be reduced by providing a refuge for emerging fish in the form of deeper water and/or by extending the climbing substrate down into the headpond, and by installing a wall between the top of the eel pass and other downstream flow for some distance upstream. This wall should extend from the riverbed to above the surface to allow the emerging fish to return safely to deeper water.

5.8 Monitoring Arrangements

Monitoring arrangements are of considerable importance for several reasons. First, they provide input into the assessment of the effectiveness of the installation, which may assist modifications to the structure and operation of the pass and provide design information for other installations. Second, they can provide input for the urgently required overview of eel stocks and recruitment levels, particularly against the backdrop of widespread falling recruitment. Third, if the fish are actually trapped, they can be measured and any samples taken for biological purposes. Fourth, trapping also allows the option of re-distribution of stock upstream or elsewhere (Section 5.9).

The most usual approach to monitoring is through direct trapping of the elvers and eels using the pass. This happens *de facto* in trap passes, and is easily arranged in pumped supply passes. Fitting a trap to a standard pass or pipe pass is a little more complex but by no means impossible.

Surprisingly little attention appears to have been paid to development of the optimal designs for holding facilities within traps. Most installations merely store the captured fish in a darkened box, or where numbers are limited, in a mesh net or sock. Eels are naturally retiring animals when not actively migrating, seeking out cover among rocks, weeds and other structures. Provision of some sort of cover within the trap box would appear to be a sound idea, to prevent the retained animals from continuously trying to escape and exhausting themselves. This may be particularly important where the periods between emptying the trap may be protracted, or where numbers of migrating eels are large. Further experimental investigation of optimal designs is required; one approach might be to provide a matrix of lengths of plastic pipe of appropriate dimensions for the eels being caught at the site; when processing the catch, the matrix could be lifted from the trap box to extract the eels.

Trap design will be highly dependent upon site-specific considerations but some general considerations apply. These include:-

1. The trap must be large enough to hold all elvers and eels that could build up between operator visits. This may involve some level of trial and error as the magnitude and timing of peaks of activity may be difficult to predict.
2. The trap should provide safe refuges for the animals collecting there (see above). Sacking bags and brightly-lit boxes without refuges, from which the animals are constantly trying to escape, are not satisfactory.
3. The design should allow for the easy and safe removal and transfer of the trapped animals (in this context "safe" refers to both the eels and the operator).
4. The trap should be protected from excessive temperatures that might be caused by direct solar radiation, by placing in natural shade or by provision of shading.

Another approach to monitoring is automatic counting. Both resistivity and photocell counters have been deployed on the pumped-supply pass at Chambly in Quebec (Section 4.4.2). Both worked well, and gave counts within 2% of the true number assessed by a manual count. However, the run of eels at this site is of the order of thousands per year of fish averaging 30 cm or so in length. These are readily detected objects generally well separated in time and space; obtaining a reliable count of elvers, which are small, may occur in vast numbers and are not well separated in time and space is altogether a more daunting prospect. Travade and Larinier (2002) show a photograph of a four-tube resistivity counter attached to the outlet from a pass-trap, but give no further details. No automatic elver counting facilities appear to have been developed to date.

Lastly, some idea of the effectiveness of a facility may be obtainable by observation, such as eels actually seen within the pass, a reduction in numbers downstream of the pass, and an increase in numbers upstream of the pass. Although by no means quantitative, such casual observations may be all that is practicable at some sites.

5.9 Trap and Transport

Trapping of elvers and eels at an obstruction low down on the river system offers the opportunity for constructive distribution of releases upstream. This may preclude the need for passage facilities at other obstructions upstream, and may allow optimal dispersion to be achieved. It may also avoid heavy predation, which may occur where predators may learn that the exit from a pass is a productive feeding ground. This approach may be particularly useful at the start of a strategic passage improvement programme.

The principles and practice of such distribution are beyond the scope of this report but Matthews *et al* (2001) describe such activities on the Erne using elvers trapped at Cathaleen's Fall and Cliff. The elvers are released at 30 to 50 sites throughout the catchment, and the target-stocking rate is 1kg per hectare per year.

5.10 Eel Passage Through Other Fish Passes

Existing fish passes may provide adequate facilities for eels in some situations. Fish locks, fish lifts and natural type installations (rocky/vegetation-filled channel) may well pass all sizes of eels. Adult eels are able to use some pool and traverse, vertical slot and baffle-type fish passes if the conditions within them are within their swimming ability. This is likely to be of greatest relevance in the upper parts of larger catchments where only larger eels are present.

Armstrong (1994) records eels successfully passing upstream through a Larinier pass with a mean velocity of 1.3-1.4 m/sec, and Porcher (2002) reports visual evidence of eels passing through fish passes fitted with observation windows. Travade *et al* (1998) report large numbers of 200-300 mm eels using a vertical slot fish pass at Bergerac on the Dordogne River, with a head-loss of 300 mm between pools. However, few used another vertical slot pass at La Bazacle on the Garonne. Although the head-loss between pools was the same at Bergerac (300 mm) the pools were more turbulent (200 W/m^3 compared to 150 at Bergerac) and this was thought to be a factor.

The water velocities predicted in various types of fish pass are summarised in Table 5.7. The slopes and dimensions used in this table are generally those for passes suitable for smaller species such as trout and coarse fish. A 600 mm eel should be able to maintain a burst speed of around 1.4 m/sec for 20 seconds (Section 4.7). An adult eel of this size should be capable of ascending Denil and Larinier passes of moderate length. The situation for pool and traverse and vertical slot passes is rather different, as the fish may have to swim at the maximum velocity in the pass (within the notch or slot) for only very short periods - perhaps less than a second at each traverse. Also, eels are very adept at exploiting boundary layers and zones of reduced flow so may be able to ascend passes where the predicted velocities are greater than the accepted swimming ability of the fish.

For example, in the situation described above for a 300 mm head loss through a vertical slot at a pass at Bergerac, the mean velocity through the slot is predicted at 2.43 m/sec.

Table 5.7. Typical velocities in fish passes

Pass type	Conditions	Velocity (m/sec)[1]	Note
Pool and traverse	300 mm head between pools	2.43	2
Vertical slot	300 mm head between pools	2.43	3
Undershot sluice	600 mm head drop	3.43	4
Plane baffle Denil	Not greater than 20%	1.05-1.40	5
Alaska steep	Not greater than 25%	1.2	6
Larinier	15% slope, 350 mm headwater depth	1.3	7
Baulk		? 2.5	8

Notes on Table 5.7:

[1] The velocity quoted here is the mean velocity across the smallest cross-section of the pass, e.g. within the notch of a pool and traverse pass, or within or over the baffles of a baffle pass.

[2] is a fish pass with a notched traverse with a maximum velocity dictated by the hydrometric head over the traverses. It can accommodate moderate variations in upstream and downstream water levels. The volume of the pools for adequate energy dispersion is related to hydrometric head and volume of flow.

[3] is a fish pass with vertical slots almost the full depth of the inter-pool traverses. This fish pass can accommodate significant variations in upstream and downstream water level variations provided the overall head loss does not increase too much. Energy dispersion is achieved by careful design of notches so that flow jets are directed to provide energy absorption and more tranquil areas for fish to rest. This type of pass is designed mainly for higher flows and is more suitable for salmon (minimum notch width 300mm) but a narrower notch width (200mm) is suitable for trout and coarse fish.

[4] is not a fish pass in the true sense but will afford passage if water velocities, which are dictated by hydrometric head, are sufficiently low. It again requires ‘burst’ swimming for ascent with the added difficulty of restricted access if only partially open, and difficulty of location if too deep in the water column.

[5] a Denil fish pass with plane baffles. A design for trout (600mm wide) would require a Denil pass of length not greater than 8 m at a slope of about 20%. The average velocity is quoted at 1.05 m/s to 1.40 m/s. However, these passes are very turbulent and the average water velocity is usually calculated by dividing flow by wetted cross section area: maximum water velocities will be at least 1.5 times average velocities, probably well over 2 m/s.

[6] the Alaskan Steeppass was developed during the 1960s for Pacific salmon and has many baffle variations. The standard form is narrow (560 mm wide, 700 mm high, and a clear interior width of 350 mm), which allows steep slopes (25%) to be used. Its highly effective baffles limit its flow such that a slope of 30% would take a flow of only 0.185 m^3/s and an average velocity of about 1.2 m/s. The disadvantage of this fish pass for salmon is its very low flow capacity, and an auxiliary flow at its entrance may be necessary to enable salmon to locate it.

[7] the Larinier ‘Superactive’ fish pass is another baffled fish pass but with the low height baffles arranged in a herringbone pattern across the bottom of the channel. Advantages are the very low impediment to debris and the ability to juxtapose baffle units to increase flow to improve the attraction to fish. The disadvantage is its low tolerance of fluctuations in upstream water levels since as the water level above the baffles rises, the range of its energy reduction reduces. The recommended baffle height for trout is 100mm, maximum slope 15%, and maximum length 12 m. A maximum upstream water level of 250 mm would result in average water velocities up to 1.15 m/s.

[8] a Baulk fish pass is merely a trough, often wooden, arranged diagonally across the downstream face of a weir to ease fish passage. Maximum water velocity is dependent on the hydrometric head above it and the natural energy reduction on the face of the weir. Water cascades sideways down into the trough, and its lower end if the weir face is relatively smooth, will impact at high velocity. A head of only 300 mm could produce impact velocities at the lower end of the Baulk pass of 2.43 m/s. However, these flows are very turbulent since they are turned through 90º by the Baulk pass trough and add to flows already in the trough. These passes are not baffled and have very little swimming depth.

This is well above the burst speed for a 300 mm eel at 20°C given by the Swimit model (Section 4.7) of 1.12 m/sec, but large numbers of such eels were seen to ascend the pass. Presumably the eels were able to exploit boundary layers to some extent.

An interesting development for pool-and-traverse and vertical slot fish passes is the incorporation of bed substrates to aid the migration of small and slower swimming fish. This approach has been widely adopted for in Germany (FAO/DVWK, 2002), probably because cyprinids and other non-salmonids are often the target species. Typically large cobbles or rocks (300 mm diameter) are embedded into the bed of the pass during construction, and smaller cobbles (60 mm or more in diameter) added loose, which are held in place by the anchored rocks. In submerged orifice or vertical slot passes the substrate can be continuous throughout the pass, greatly reducing the bed-velocity through the orifices or slots. This approach is strongly recommended for elvers, eels and other small or weak swimming species such as bullhead, loach and lamprey.

Experiments in Finland have shown that bristle substrates fixed to the bed of vertical slot fish passes have aided lamprey passage (Laine *et al*, 1998). It is possible that such an approach may help passage of eels and elvers too.

5.11 Attraction Flow

Substrate ramps operate most effectively with very low flows of water within the channel itself; volumes used in successful facilities are as low as 12 l/min or less (see Table 5.4). However, as such low flows may be inadequate to attract eels to the base of the ramp, it is common practice to provide an additional supply of water which is discharged in the general area of the foot of the pass; volumes vary, but are of the order of 300-1200 l/min at a number of sites. There is a perception that attraction water is most effective if it is discharged above the water surface so that it splashes onto the surface around the pass. In practice eel passes are often sited adjacent to passes for other species which carry a much higher flow; the discharge from such facilities then also acts as an attraction flow for the eel pass.

The importance of attraction water is difficult to establish, as no comparative studies appear to have been conducted with and without it at any site. One successful type of installation, the Maine "portable passage" (Section 6.6.4), does not employ any attraction water, and the flow down the ramp is only about 12 l/min. The effective operation of these portable passes may instead be dependent upon their precise location where the elvers gather naturally, and the facility to move the installation to find the optimal location. It is therefore suggested that attraction water may be unnecessary if the pass entrance is optimally located, at least in smaller waterways.

Even with attraction water, many successful passes have associated flows that are minuscule relative to the overall river flow. The effective pass at Beauharnois Dam on the St Lawrence uses total flow of 0.0141 m^3/sec including attraction water; the mean summer flow through and over the dam is around 8,000 m^3/sec, of the order of half a million times more than that associated with the pass. Again, its success is likely to be largely dependent upon appropriate positioning of the downstream entrance.

5.12 Maintenance

Installations will vary in the amount of maintenance required. Those involving pumps and/or traps are likely to need frequent visits, possibly daily at times when many fish are migrating. Others may need only occasional maintenance, and experience will indicate the frequency of visits required. In our site visits we saw several passes where maintenance had been inadequate, with debris blocking parts of the passes and extensive plant growth in and on the substrate. Some plant growth may do no harm, and may even enhance pass operation by diversifying the wetted routes through the pass, but if left it can quickly choke the pass blocking the carefully-designed interstices within the climbing substrate. It is suggested that annual inspection, before the commencement of the migration season, is the absolute minimum requirement.

Technological development has made remote surveillance realistic for some situations. This could include an overall view by camera, monitoring of water flow at one or more points in the system, and counts of numbers of fish.

5.13 Health and Safety Considerations

During this study a number of sites were visited where operation or maintenance of the facilities involved activities or actions that were potentially dangerous. This generally arose where facilities had been installed retrospectively, with ramps and traps attached to vertical walls at weirs. This is clearly an unacceptable situation and some facilities are now effectively inoperable because of this. It is essential that human health and safety be considered at all stages of planning, construction and operation of facilities.

5.14 Protecting Downstream Migrants

Although detailed consideration of systems for the protection of downstream migrants from water abstraction and HEP intakes is beyond the scope of this study, discussion of some general principles is appropriate.

Where the abstraction is small relative to the flow of the river, physical screens are likely to be the most realistic option. Any screen that is effective for excluding salmon smolts, involving gaps of 12.5 mm or less, would be effective at excluding all silver eels (Section 4.9). Similarly, the approach velocities appropriate for salmonids (300 mm/sec) should allow silver eels to avoid impingement on the screen.

The real problems arise at hydro electric intakes, where the take may be large relative to the volume of flow in the river, approach velocities may be high, and often the only screens fitted are wide-gap trash racks. Turbine mortality can be high for adult eels, largely because of their elongated form. Monten (1985) presents observations from a number of HEP stations in Sweden, showing death and injury rates for adult eels varying from 40 to 100% passing through Kaplan turbines and 9 to 100% for Francis turbines, depending on the characteristics of the installation. Although HEP installations are not a dominant feature of rivers in England and Wales, interest in the potential for run-of-river schemes is increasing. A study for ETSU by Salford University recorded 58 existing schemes in England and Wales, and shortlisted a further 318 potentially economically viable sites (Salford Civil Engineering Limited 1989).

Rickhus (2001) undertook a thorough review of the available technologies for protection of eels at hydro plants; the conclusions are also presented by Rickhus and Dixon (2003). The conclusions are summarised below.

1. Light barriers appear to be effective under some conditions. Effectiveness is decreased by turbidity, and increased with increasing distance from the intake and with decreased angle of the array to the direction of current.
2. Limited data on sound (especially low frequency, less than 100 Hz) suggests that it could be exploited to divert migrants.
3. Water jets and air bubbles appear to be ineffective at diverting eels.
4. Although eels are sensitive to electric fields there appears to be little scope for practical application mainly because of the small margin between eliciting the desired response and totally disabling the eel, which varies with size, and the limited effective range.
5. Mechanical barriers have potential, mainly in smaller rivers and at smaller projects, where construction of barriers across the entire water column might be feasible.
6. Experimental louver screens show promise, especially set at a shallow angle (15^o) to the flow. A solid bottom overlay, covering the lower 30 cm of the 2.1 m deep array, and a full-depth bypass, improves efficiency.
7. In the absence of any barrier to turbine passage, attraction of migrating eels to alternative routes would require a substantial proportion of the river flow (5-50%) to be diverted through the bypass.
8. The approach of shutting down generation during peaks of migration (discussed in Section 4.9) is likely to be non-viable in many situations because of the difficulty in predicting the times reliably and the high economic cost. However, it may be viable on small river systems where peaks of activity may be shorter and more predictable.

With respect to conclusion 8, it is likely that most UK rivers would be classified as “small” compared to, say, the St Lawrence where many eel studies have been conducted.

Clearly, further investigation of promising candidates for diversion systems is required.

6 SOME INSTALLATIONS ANALYSED

6.1 General

Preparation of the Technical Report (Solomon and Beach, 2004) involved visits to numerous eel and elver passage installations in the UK, France and the USA, with considerable volumes of information gathered regarding sites in Ireland, Canada and elsewhere. About forty of these sites are described in some detail in the Technical Report. Here we select a smaller number of these sites to present information on both successful and unsuccessful aspects of design, with observations on relevant aspects of the site and the constraints that these put on passage facilities.

Figure 6.1. Eel pass at Moulin a Pigné

6.2 Standard Substrate Passes

6.2.1 Moulin a Pigné, River Villaine, near Rennes, France

This is a 1.62 metre-high navigation and mill weir. There are two concrete channels through one of the weir bays, each about 400 mm wide (Figure 6.1). The left channel has been adapted as an eel pass by including a bristle substrate with a lateral slope of about 45º, as shown in Figure 6.2. The second channel is considerably deeper and its function not known – possibly for a future second fish pass, or to provide an attraction flow for the eel pass. At the top of the pass there is a section of the concrete channel with deeper water. This provides a refuge for eels at the top of the pass and affords some protection against the cross-currents at the flow intake to the pass. Both channels are protected from debris by an upstream bar screen. The location of the eel pass in one of the centre weir bays is interesting; one adjacent to the bank would have been more appropriate, as eels may have difficulty locating the pass when the bay between it and the bank is flowing.

Figure 6.2. Detail of eel pass at Moulin a Pigné

Factors that aided design and installation

Concrete channels provided at the time of construction of the weir (good foresight).
Regulated headwater level – navigable river.

Good features of design and installation

Deep water refuge at the top of the ramp.
Vertical concrete wall separates the upstream exit from adjacent fast flows.
Good attraction flow.
Potential for trap to be added at top of pass for monitoring.

Limiting features of design and installation.

Location away from bank.
Limited operating head range – but regulated river so no problem?

6.2.2 Pont-es-Omnès, River Frémur, near St Malo, France

This dam is about 7 km above the tidal limit on this small coastal stream and has been a major site for monitoring both upstream and downstream migration of eels since 1997. The site was inspected in September 2003 at very low flows; the head difference across the dam was about 3.6 m. An arrangement of a combined pass and trap-pass has been installed adjacent to the left bank (Figure 6.3). The pass consists of two 30^{o} slope ramps with bristle substrates (9 mm between tufts) that turn through 180^{o} at a small resting pool. The substrate is fitted with a 28^{o} lateral slope, with a narrow section with a lesser slope in the opposite direction to optimise migration over a range of headwater levels. In this photograph the deeper channel immediately upstream of the upper ramp substrate can be seen; this gives small eels emerging from the substrate at the top of the ramp a refuge to reduce the risk of being swept back downstream. The growth of moss and other plants within the substrate can also be seen – within limits this is considered to be a good thing, increasing the diversity of conditions available to migrating eels. Above the upper ramp, where the pass crosses the dam crest, there is a 1m-long horizontal stretch of channel with a rough pebble substrate, and a sluice gate to control flow down the pass. At the resting pool at the top of the first ramp, the eels can be diverted using a third ramp into a trap, or allowed to continue up to the crest of the dam. For the duration of the research investigation (and thus at the time of the site visit) the trap facility is being used and the upper pass ramp is dry. The trap is operated either by releasing the eels directly to a holding

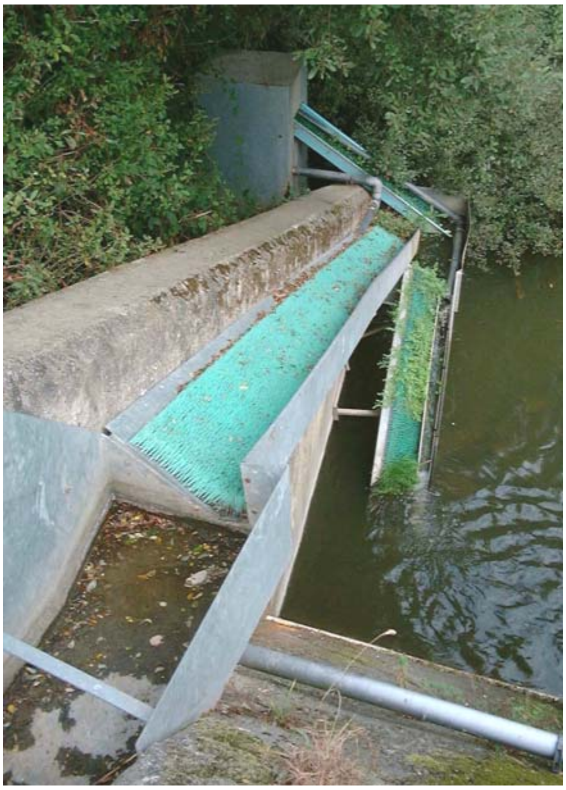

Figure 6.3. Upstream pass and pass-trap at Pont-es-Omnès

tank or, when catches are low, by using a sock-net attached to the outlet pipe. Up to 1000 eels per day are caught in June, average length 10-13 cm.

Factors that aided design and installation

Regulated headwater level – reservoir.
Extremes of streamflow reduced by upstream impoundment.
Limited flow.

Good features of design and installation

Deep water refuge at the top of the ramp.
Trapping facilities incorporated.
Lateral slope to allow operation over a range of head levels.
Downstream entrance close to weir face.

Limiting features of design and installation.

Lack of cover against light and predators.

6.2.3 Chadbury Weir, River Avon, England

This pass is installed in a navigation and mill weir on the Warwickshire Avon about 36 km upstream of the tidal limit. The 700 mm wide substrate is installed with a lateral slope of 17^o, and a longitudinal slope of 9^o giving an overall length of 9.4 m to overcome the 1.4 m head difference.

Figure 6.4. Eel pass at Chadbury

There appears to be considerable scope for eels using this pass to be re-entrained with the flow and carried back downstream. First, the fast flow from the baffle pass impinges on the eel pass so that any eel deviating from the optimal route is likely to be carried back. Second, the accelerating flow into the baffle pass cuts across the top of the eel pass, such that emerging eels are very likely to be washed back downstream. Both these limitations could be addressed by a vertical wall or septum separating the eel pass from the baffle pass; this would need to extend a metre or so upstream of the top of the eel pass, and extend to the river bed upstream of the eel pass.

Figure 6.5. Flow to the baffle pass cutting across the top of the eel pass, Chadbury. The flow down the pass is from left to right.

Factors that aided design and installation

Long-crested weir with headwater level regulated for navigation.

Good features of design and installation

Shallow longitudinal slope.
Lateral slope of substrate to cover range of headwater levels.

Limiting features of design and installation.

Eel pass integral with pass for other species – scope for re-entrainment.
Flow cuts across top of eel pass.

6.3 Pumped-Supply Passes

6.3.1 Fort Halifax Dam, Maine, USA

Following evaluation using temporary ramps (Section 6.6.4), a permanent eel pass was installed in 2000 at this site on the Sebasticook River, a tributary of the Kennebec River in Maine (Wippelhauser 2001, 2002, 2003). It is of wooden construction, 600 mm wide and 100 mm deep (Figure 6.6). The entrance ramp is parallel with the dam face and is 2.6m long with a slope of 30°. A right angle bend with a 600 mm resting area leads to a 4.8 m ramp with a 43° slope. Finally, a 2.4 m long ramp with a slope of 10° leads over the crest of the dam to a collection chute and box. The climbing substrate is Enkamat 7220 stapled to the bed of the ramps. Water is supplied by a hydro-ram pump at a rate of 8 litres per minute. The vertical head at this site is about 4.9 m.

This installation has been successful in passing more than 350,000 elvers and small eels in its first three years of operation. The largest fish recorded using this facility was 236 mm.

Factors that aided design and installation

Regulated headwater level – reservoir.

Good features of design and installation

Trapping facilities incorporated.
Downstream entrance close to weir.
Facility removable for storage and maintenance during winter.

Limiting features of design and installation

Substrate – better alternatives available (see Section 5.3.4).

Figure 6.6. Pumped-supply pass at Fort Halifax Dam. A "portable passage" ramp (see Section 6.6.4) is being deployed alongside. Photograph G Wippelhauser.

6.3.2 Chambly Dam, River Richelieu, Quebec, Canada

Chambly Dam lies on the Richelieu River about 100 kmfrom its confluence with the lower St Lawrence River. It was constructed in 1965, and has a crest length of 270 m and a hydraulic head of about 5 m. It appears that no fish passage facilities were incorporated until an eel pass was installed in 1997 (Desrochers and Fleury 1999, Desrochers 1999, 2001, 2002 and Bernard and Desrochers 2002). A series of removable concrete blocks ("breakwaters") were installed along a 12.6 m length of the dam crest against one bank so that no water spilled here, creating a quiet area for eels to gather below the dam and the site for the eel pass. The pass comprises a sectional channel that leads up the downstream face, over the concrete blocks, and down into the impoundment (Figure 6.7). The channel is 550 mm wide overall, and contains "Eel ladder" modular plastic substrate (see Section 5.4.3). The main run of the pass is 9.3 m in length and has a slope of 52^{o}. A 1.1 m section with a shallower slope (7^{o}) then leads over the blocks on the dam (Figure 6.8). A downward-sloping chute feeds the eels into a pipe fitted with a photoelectric counter and a PIT tag reader. The fish are then returned directly to the head pond or into a net for monitoring purposes. The lower 0.85 m of the steep channel widens to 1.1 m towards the bottom end. The pass is supplied with a pumped water flow of 36 l/min, and the final chute with 6.6 l/min. Attraction water (about 860 l/min) is discharged from two pipes, one each side of the pass, about 2.5 m above the tailwater level.

Figure 6.7. Eel pass at Chambly Dam. Note the breakwater blocks on the dam crest, and the gravity-fed attraction water being discharged from the two pipes part way down the dam face. Photo D. Desrochers.

Figure 6.8. View of Chambly Dam eel pass from above. Note covers over the channel containing the substrate, and the electronic counting device on the pipe carrying the eels from the top of the pass to the keep net. Photo D. Desrochers.

Large numbers of eels had accumulated downstream of the dam in the absence of passage facilities, and in the first year of operation more than 10,800 ascended the new pass. Marking experiments indicated that this represented 57.4% of the eels downstream of the dam; the 9,875 eels ascending in 1998 similarly represented about 55% of eels present. Since then, annual counts have fallen to a few hundred fish per year as the accumulation of fish was depleted; clearly, recruitment has been weak in recent years.

The eels migrating at this site are several years post-elver, with a length range (9875 eels in 1998) of 196 to 741 mm (mean 386.2 mm). This large size and relatively small number made a photoelectric counter effective; trials indicate that the count obtained is within 2% of the true number.

Factors that aided design and installation

Breakwater blocks available.

Good features of design and installation

Excellent modular design with substrate appropriate for the size range of fish present.
Trapping and counting facilities incorporated.
Downstream entrance close to dam face.
Facility removable for storage and maintenance during winter.

Limiting features of design and installation.

Substrate unsuitable for elvers – but none present at this site.
Counting requirement dictates ungainly structure – neater design could be arranged if this requirement was removed.

6.4 Pass-Traps

6.4.1 Rophemel Dam, River Rance, near St Malo, France

The River Rance enters the sea at St Malo. Rophemel dam was constructed to supply drinking water, and generate electricity using two hydroelectric turbines. The reservoir appeared empty when inspected (September 2003).

The eel trap pass at Rophemel (Figure 6.9) is a standard "Fish Pass" model. It consists of a trap and two ramps with an intermediate resting pool. The ramps are 350 mm wide at gradients of 35º, and contain bristle substrates with tuft spacings of 14 mm. The installation is operating effectively; the maximum one-day catch was 11 kg, which overloaded the trap. Originally water for the eel pass was supplied from below the thermocline (<12ºC) and failed to attract eels – but an immediate attraction was achieved when surface water from the reservoir was used. This explains why an eel pass is installed in only one of the two channels that the dam discharges into – the other is supplied with colder water from a deeper level and proved unattractive to eels. Trapped eels are recorded on a daily basis and trucked to above the dam for release. When catches are low daily catches are still recorded but the eels are held in a nearby tank for several days before release.

Factors that aided design and installation

Protected site – no risk of flood or vandal damage.

Good features of design and installation

Trapping facilities incorporated.
Downstream entrance close to weir.
Well constructed and safe operator access.
Well tried and tested design.

Limiting features of design and installation.

Trap can become overloaded – solution; more frequent checking or larger trap box.

Figure 6.9. Rophemel Dam eel pass-trap.

6.4.2 Greeneville Dam, Shetucket River, Connecticut

An eel pass was originally constructed at this site on a tributary of the Connecticut River in 1999, but it was rebuilt to address shortcomings a year later. The original pass was constructed of fibreglass and PVC sheeting and employed "Fish Pass" type S4 bristle substrate. The main limitation was that site restrictions made the pass too steep – about 60^{o} – though more than 800 small eels (mostly less than 150 mm in length) were passed in the first year. In 2000 a more permanent pass was installed. This incorporated a right-angle bend around part of the dam structure to allow a shallower angle for the ramps (Figure 6.10). The main lift is provided by a 9.2 metre long ramp at 27^{o}. This was constructed of 4.8 mm thick sheet aluminium bent to form a 430 mm wide channel. This contains "Fish-Pass" bristle substrate. The pass then goes through a 90^{o} bend into a 6.7 m channel with minimal slope (3^{o}), which leads the eels to a catch box. This section if fitted with "Akwadrain" substrate (see section 5.3.4) which extends beyond the upstream end of the ramp down into the catch box (Figure 6.11). The top of the ramp is supplied with a flow of 3.5 to 7 l/min, and an attraction flow of 75 l/min is provided at the entrance of the pass. The whole pass has removable aluminium covers. The cost of materials for the improved pass was about US $7125 in 2000. About 800 eels were passed in 2000, but a higher proportion were over 150 mm than in the previous year. The total for 2001 was 5739 eels.

Based on the experience at this site Alex Haro suggested the following possible modifications might be incorporated into a similar design elsewhere:-

- Different substrate; brushes may be working well, but may be discouraging larger eels at this site. Suggests Milieu "Eel-Ladder" or different "Fish-Pass" substrates.
- New exit ramp. Eels hesitate on the reverse-slope substrate and try to re-climb. A smooth downward face should prevent this.
- More attraction flow. A flow of 200 to 400 l/min is likely to be more effective than the current 75 l/min.

Figure 6.10. Eel pass-trap at Greenville Dam. Photograph Alex Haro

Factors that aided design and installation

Experience on site – this is the second installation here.

Good features of design and installation

Trapping facilities incorporated.
Downstream entrance close to weir face.
Well constructed and safe operator access.

Figure 6.11. Akwadrain substrate extending beyond the top of the ramp at Greenville Dam eel pass. Photograph Alex Haro.

Limiting features of design and installation.

See Dr Haro's comments above.

6.5 Eel Lifts

6.5.1 Ville Hatte Dam, River Arguenon, France

The Ville Hatte dam is located on the River Arguenon about 20 km upstream of the tidal limit. It is 14 m high with a crest length of 194 m. A section of the dam is shown in Figure 6.12 that also shows the eel passage facilities, which are adjacent to the compensation water spillway. The eel passage facilities comprise two flights of bristle-substrate ramps, which convey the eels to the base of a lift. The ramps are 40 cm wide with a 1.3 m-long intermediate resting pool. The bristle tufts are arranged with a central 130 mm-wide section at 14 mm spacings, and two outer 130 mm-wide sections with tufts at 21 mm centres. Both flights are at a gradient of about 35º; the lower one is 3.3 m long and the upper one 1.7 m long. The downstream section of the eel pass, and the supply pipes for flow augmentation and attraction, are visible in Figure 6.12. These pipes penetrate through the dam wall and take surface water from above the dam.

The trap and lift arrangement is similar to an earlier installation on another local river, with improvements: the hopper has a seamless construction so that eels cannot escape through small cracks. A plug in the base of the hopper (Figure 6.13) is held closed by a spring-loaded plunger. When the trap is hauled to the crest of the dam by an electrically operated winch, a lever mechanism opens the plug and releases the eels into the reservoir. The operation is monitored using CCTV from a control centre on the dam; the usual operation frequency is one complete cycle per day. The contents of the trap hopper are recorded each day on video tape just before release, but the tapes are not routinely examined; the organisation responsible does not consider monitoring to be sufficiently important, and the tapes are recycled.

Figure 6.12. The Ville Hatte Dam eel lift. The substrate ramps can be seen below the platform.

The lift was constructed in 1995 at a cost of about £60,000. Before it was installed, a trap-pass was operated manually to establish that the number of eels arriving at the dam justified a permanent installation.

Factors that aided design and installation

Experience of earlier installation on nearby site.

Figure 6.13. Lift hopper at Ville Hatte Dam eel lift in lower position.

Good features of design and installation

Incorporates improvements on earlier design.
Monitoring facilities incorporated (but not used!).
Downstream entrance close to face of dam.

Limiting features of design and installation.

High construction costs.
Significant operation and maintenance costs.

6.6 Low Cost and Temporary Installations

6.6.1 Explanation

In many situations it is useful to be able to deploy a low-cost or temporary installation for eel and elver passage. Reasons may include one or more of the following:-

- Need for temporary facilities until a more permanent installation can be arranged
- Temporary facilities required while the obstruction or permanent pass are being repaired
- Deployment required to demonstrate the justification for more costly permanent facilities
- Identification of the optimal location for permanent facilities
- Permanent deployment where greater cost cannot be justified or funding is limited
- Experimental study

A number of such installations have been successfully deployed in a range of situations; these are described below.

6.6.2 Temporary installations; Thames, Darent, Severn and Avon

Naismith and Knights (1988) and White and Knights (1994) used temporary installations at sites on a range of rivers as part of stock assessment investigations.

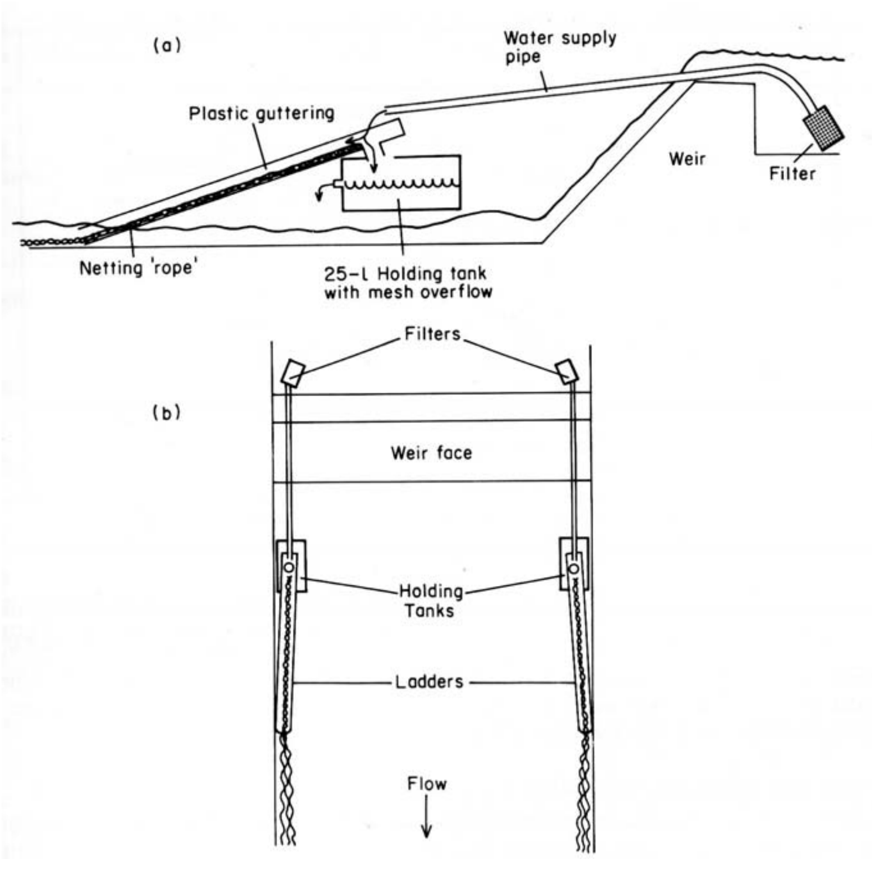

Figure 6.14. Pass-trap design from White and Knights (1994).

The sites were typically at weirs with hydraulic heads of the order of 1 to 3 m. One approach explored was to fix a geotextile "ladder" to the sloping face of the weir, leading to a floating catch box in the headpond. However, problems were experienced with anchoring the devices in appropriate locations, and this design was not appropriate for one or two sites with vertical faces. A common design of pass-trap was therefore developed which was used at all sites (Figure 6.14). The ramp consists of a 1.5-2 m length of plastic roof guttering, 100 mm in width. The substrate is rolled horticultural netting, and extends as a rope below the bottom of the ramp. Eels ascending the ramp fall into a 25 l holding tank. Water is supplied to the ramp through a siphon comprising a 30 mm diameter pipe from the headpond. No additional attraction flow is supplied. The devices were typically installed only during the migration season from May to September. Catches of elvers and small eels ranging from a few individuals to around 30,000 per trap per year were recorded for each installation.

6.6.3 "Fish-Pass" prefabricated passes

These devices are designed to be placed over the crest of sluice gates, and require only minor on-site engineering. They are intended for limited head drops (less than 0.8 m) and where flows are weak – for example at the outfalls from marshes.

There are two models, for different types of gate. The one shown in Figure 6.15 is 1.6 m long and 300 mm wide, and is designed for gates with a stable setting with 50-100 mm of hydraulic head over the crest; in the picture the gate is raised and the pass is dry. The second type is designed for gates that are frequently adjusted, and the device travels up and down with the sluice gate as it operates. Both types use a bristle substrate with a lateral slope, and are gravity-fed.

Figure 6.15. "Fish-Pass" prefabricated sluice-gate pass.

6.6.4 "Portable passages", Maine

Wippelhauser and Gallagher (2000) describe portable ramp-type traps which they term "portable passages". These are used at obstructions where a permanent installation cannot be justified or where a permanent installation is being considered. As they are readily moved they can be very useful in identifying the optimal location for a permanent installation.

The devices comprise a wooden trough 1.8 m in length, 300 m wide and 100 mm deep mounted on a frame at an angle of 35^o (Figure 6.16). The Enkamat substrate is stapled to the bed of the trough. Water is supplied to the top of the ramp at a rate of 10.2 l/min. At the top of the ramp a slide angles downwards into the catch box; this ramp is also supplied with a flow of about 10.2 l/min. The pass is protected by a removable aluminium cover to exclude light and predators.

Figure 6.16. A "portable passage" being operated at Benton Falls Dam in Maine. The cover is lifted to show the Enkamat substrate. Photograph G. Wippelhauser.

Wippelhauser and Gallagher (2000) and Wippelhauser (2001, 2002, 2003) record catches of thousands or tens of thousands per season using portable passages at various sites. Two portable passages installed at Fort Halifax on the Sebasticook River were overwhelmed by the number of elvers in 1999, and many were scoop-netted from the river at the foot of the pass and released above the dam. A total of more than 550,000 elvers were passed over the dam that year by netting and trapping. A larger permanent pass was installed for the following year (see section 6.3.1).

6.6.5 Garrison Lake, Delaware

This is an example of a successful low-cost passage facility at a low-head dam at the tidal limit on a small stream system. The head at this site is about 1.2 m at high tide, and about twice that at low tide. Information and pictures of this site have been provided by Shawn Shotzberger of the PSEG Estuary Enhancement program.

Left: Figure 6.17. Elver pipe-pass at Garrison Lake, Delaware, soon after installation. Photograph S Shotzberger.

Above: Figure 6.18. Garrison Lake elver pass two years after installation. Photograph S Shotzberger

The pass comprises a short length of 100 mm diameter pipe passing through stop-boards on the weir crest, discharging onto the sloping back of the weir (Figure 6.17). A substrate of discarded trawl netting was installed within the pipe, and continues down the sloping back of the weir to simulate a mat of vegetation. Elvers had previously been observed to be able to ascend the weir back in the vegetative mat, but could not negotiate the stop-boards. The effectiveness of the installation has been monitored by placing a sock-shaped catch net over the upper end of the pipe, and anchoring it to the bed of the impoundment. A total of 744 elvers was recorded in the first year of operation (Shotzberger and Strait, 2002).

After two years, a mat of natural vegetation had developed on the trawl mesh on the back of the weir (Figure 6.18), enhancing elver passage. The trickle flow through the pipe was undiminished. This is an interesting observation, as blockage of substrates installed in pipes has been reported elsewhere. Even if periodic cleaning is required this is a viable option for small watersheds, requiring no pumped water supply.

6.6.6 West Harbor Pond, Maine

Three ramp passes installed at this site were partially successful but large numbers of elvers were observed to gather at the dam face beneath the ramps, i.e. between the ramp entrance and the dam (Wippelhauser 2003). One of the ramps was therefore replaced with a vertical board, 550 mm long and 300 mm wide, with Enkamat 7220 substrate stapled to it (Figure 6.19). This was mounted vertically at the top of the dam face, to operate near high tide; a float switch turned on a pump to provide water to the pass when the base of the board was inundated. At the top of the vertical board the pass extended at a shallow angle over the crest, and terminated in a reverse ramp and tube that led to a catch box. This system proved so immediately effective, with significant numbers of elvers using it, that a second ramp was replaced with a vertical board within a week. This collected fish from a lower level and was 1.5 m in height; it too proved effective. A single battery-operated pump with a capacity of 31 l/min supplied all three ramps with water.

Figure 6.19. Vertical substrate board on the west ramp at West Harbor Pond. Photograph G. Wippelhauser.

These are important observations for two reasons. First, they highlight how critical the location of the downstream end of a pass is. Second, they show that vertically mounted substrates can be effective for elvers as long as there are suitable arrangements for passing over the crest of the dam. However, this approach is unlikely to be effective for eels over about 100 mm (see Section 4.7).

7 SUGGESTED DESIGNS FOR SPECIFIC APPLICATIONS

7.1 General

In this section we consider the conditions that occur at specific types of obstruction and the design constraints that this imposes on potential passage facilities. Because each site represents a unique set of circumstances it is not possible to be prescriptive with respect to designs but in most cases one or more types of facility offers clear advantages. The general design considerations discussed in Sections 3, 4 and 5 should be borne in mind throughout the planning and installation process.

Operation of a temporary low-cost passage facility is recommended in any situation where there is uncertainty regarding the number and size of eels requiring passage, variation in head and tailwater level, or optimal location for the downstream entrance. A few months of such operation, coupled with observations made by the personnel tending the temporary facility, should provide the required information and allow design and installation of an optimised permanent facility.

In all situations the first option that should be considered is removal of the obstruction. Many head-retaining structures are now obsolete and their removal may represent an overall improvement in environmental terms (Section 3.7). If this is not feasible then a natural-style by-pass channel should be considered, as it is likely to represent good passage facilities for a wide range of species and an overall environmental gain (Section 5.4). Only if it is concluded that this is not the way ahead should more specific facilities, as discussed below, be considered.

7.2 Low-Head Structures with Relatively Stable Headwater Levels

There are numerous obstructions, especially in lowland rivers, with a hydraulic head of the order of 0.5 to 3 m and with a headwater level that remains within a narrow range (less than about 250 mm) for considerable periods during the eel and elver migration season of April to September. The headwater level may remain within this narrow range due to stable dry-weather discharge, a long crest to the weir, or regulation of level for navigation or amenity purpose by a flow control structure. Such obstructions are most simply addressed by installation of a standard pass with a brush substrate ramp with a lateral slope.

The suggested design range of headwater heights to be covered is that which occurs for the drier 50% of the time between April and September (i.e. height associated with April–September Q100 to Q50 - see Section 5.3.10). This will dictate how realistic a standard pass is in the particular situation, and the ramp width and lateral slope that will be required (see Section 5.3.7). In general, a pass of width of 400 to 700 mm, with a shallow lateral slope of the order of 10 to 20^o, should be the ideal starting point, with wider ramps, steeper lateral slope or multiple ramps at different levels being considered where the head range is large enough to require them. The longitudinal slope should not exceed 35^o (Section 5.3.5). This requires that the horizontal length of the pass is at least 1.7 times the maximum hydraulic head under which the pass is to operate. Ideally the pass should be separated from any adjacent fast flow, down the weir back or in a baffle-type pass for other species, by a vertical wall or septum. This will prevent eels from being entrained in the fast flow and being carried back downstream. For the same reason, the wall or septum should extend at least a metre upstream of the top end of the eel pass, and should extend to the riverbed upstream of the eel pass. The bristle-tuft spacing should be selected to match the size-range of eels and elvers present at the site (Sections 4.4 and 5.3.3).

Other factors to bear in mind in specifying the pass include siting of entrance and exit (Section 5.2), changes in tailwater level (Section 5.3.9), cover against light and predation (Section 5.3.11), upstream outlet arrangements (Section 5.7), monitoring arrangements (Section 5.8) and Health and Safety considerations (Section 5.15). In most situations no attraction water will be required for a standard pass, especially if the downstream entrance is situated close to the main flow.

Development of standard modules is recommended for such installations. This could reduce design and construction costs significantly.

The main advantage of standard passes in this situation is that they require minimal maintenance and have no requirement for a source of power for a pump. However, pumped-supply passes and trap-passes are also potentially viable options for low-head sites with stable headwater levels, and their advantages may outweigh their limitations – see Table 5.1. These alternatives are dealt-with below.

7.3 Low-Head Structures with Variable Headwater Levels

In many situations the headwater level over a weir will be too variable for a standard pass to address adequately. While there would of course be a range of water heights over which such an installation would operate effectively, the proportion of the time during which this occurs may be considered too limited. The two obvious alternatives are a pumped-supply pass and a pass-trap (Section 5.3.1). The latter, which is also suitable for installation at high-head obstructions, is dealt with in a later section.

The channel width for a pumped-supply pass does not need to be as great as that for a standard pass, as there is no requirement for a lateral slope and thus the whole width of the pass is available to the fish at all times. A width of 400mm is likely to be adequate for brush substrates, and in many situations a narrower channel would suffice. For situations where larger eels of 150-750 mm predominate (upstream sites), the Milieu "Eel-ladder" substrate is recommended (Section 5.3.4), which requires a 550 mm wide channel. At the other extreme, the Milieu experimental elver pass substrate requires a channel width of just 140mm (Section 5.3.4). The maximum recommended slope is 35^{o} for brush substrates, while the Milieu substrates can be installed in steeper channels of up to 55^{o}. Flow down the pass can be surprisingly small; the optimal depth over the bed of the ramp for brush substrates is 2 to 12 mm, which probably equates to about 5 - 50 l/min. For the Milieu "Eel-ladder" substrate in a 550 mm channel a flow of about 30 l/min is specified. In most situations this supply will require a pump, though it could be supplied by gravity if a higher level carrier exists at the site. The water is of course supplied to the highest point in the pass, which in turn needs to be a little above the highest headwater level at which the pass is required to operate.

Provision of an attraction flow is likely to be required around the downstream entrance of the pass, as the flow down the pass itself is low. The volume required will be site-specific and will depend upon how close the downstream entrance is to the main flow over the weir. Further, there may be no requirement for an attraction flow if the downstream entrance of the pass can be optimally sited where the fish gather naturally – operation of a mobile temporary installation could help to establish this (Section 6.6).

As the upstream exit is likely to be close to the structure care will be needed to ensure that the eels and elvers are not immediately carried back downstream by the flow. If a trap is incorporated into the design the fish can be released a safe distance upstream. Otherwise a steeply sloping pipe can be used to ensure that the fish emerge close to the river bed at a location where the risk of entrainment with the downstream flow is minimised (Section 5.7).

If the pass can be situated within its own channel it may be robust enough to withstand winter floods and thus can be left installed throughout the year. In most situations where the pass is added an existing structure it will be vulnerable to flood damage and should ideally be decommissioned between October and March.

Other factors to bear in mind in specifying the pass include siting of the downstream entrance (Section 5.2), changes in tailwater level (Section 5.3.9), cover against light and predation (Section 5.3.11), and Health and Safety considerations (Section 5.13).

7.4 High-Head Structures

Although standard passes and pumped-supply passes can be constructed to operate at high head structures (examples of each operating at heads over 25 m are described in Section 5.3.6), the cost and engineering constraints potentially escalate and a pass-trap is likely to be the most realistic option. In addition to being economical it also gives the opportunity for distribution of the fish throughout the catchment, optimising dispersion and possibly avoiding the need for further passage facilities upstream.

The pass need only take the fish high enough to be above the highest tailwater level at which it is required to operate, though in practice it is useful to construct it so that the trap box is easily accessible as it will require daily processing. The ramp characteristics and flow requirements are the same as for the pumped supply pass specified in Section 7.3 above.

7.5 Constraints at Gauging Structures

Many hydrometric gauging structures such as Crump-section weirs are generally readily passed by powerful swimmers like salmon and sea trout. However, they may represent an impediment to the upstream migration of smaller fish and weaker swimmers including elvers and small eels, by virtue of high water velocities and smooth surfaces. Provision of passage facilities at such sites can be problematic as there is likely to be resistance to any interference with the precision of flow gauging, for example through construction of by-pass routes, or installation of any structure which disturbs smooth flow over the weir. The general issue of fish passage past hydrometric structures has been the subject of a number of Agency investigations in recent years, as summarised by White and Woods-Ballard (2003). It is recommended that appropriate facilities for eels and elvers be incorporated in any engineering solution being considered for passage of other species.

Where passage of eels and elvers is the only issue, dedicated facilities may be justified. The generally accepted precision for measurement of low flows at gauging structures is ± 5% (White and Woods-Ballard, 2003), which suggests that the small volume required for a pass-trap or pumped-supply pass should not compromise the flow record, and could in any event be allowed for. By-pass channels which take a larger and variable flow, such as a substrate channel pass a natural-style channel (Section 5.5), may be more problematic. Of particular interest for eels and elvers is the potential for placing a narrow substrate ramp (similar to the "Fish-Pass" prefabricated pass described in Section 6.6.3) along each flanking wall of Crump-section weirs to allow passage at low flows. Such installations could be cheap and pre-fabricated, and tethered so that they are recoverable when washed-out by high flows. Investigation of the feasibility of such a design, including its acceptability in hydrometric terms, is recommended. If this approach proved effective and acceptable in hydrometric terms, more permanent installations could be considered.

Shallow "V" and thin plate gauging weirs are likely to prove more problematic; some sort of bypass arrangement may be the only feasible option.

7.6 Tidal Barriers

Many waterways have some form of barrier at or close to the tidal limit, to retain upstream water level at low tide and in some cases prevent tidal flooding. These barriers take many forms which vary considerably in the degree of obstruction they represent to free movement of eels and elvers.

Where the structure is overtopped at all or many high tides, significant interference to free movement is unlikely; even where the barrier is overtopped only at spring high tides, most eels wishing to move upstream are likely to be able to do so. Where the barrier is a fixed structure over which the freshwater discharge spills, it represents a similar situation to that of any other weir; it may or may not be readily passable depending upon its design and condition, and should be amenable to any eel passage installation that can cope with the tidal variation in tailwater level. Examples of such installations are described in the Technical report (Beach and Solomon, 2004)

Problems for eel passage can occur where the structure is used to prevent tidal inundation, with freshwater discharge being limited to times when the seaward tide level is below the retained freshwater level or being pumped through or over the barrier. Landward migration of eels and elvers may still be feasible at times when seaward discharge occurs, depending upon the design and operation of the control structure. Common devices for such control are flaps and doors that open by water pressure when the tide level falls below the retained level. Firth (2001) investigated fish passage issues at 59 outfalls to the tidal Humber/Trent/Ouse estuary which included 10 pumping stations, 9 flap doors (vertically-hung flaps of rectangular section), 10 flap valves (vertically hung flaps of circular section) and 25 tidal pointing doors (side-hung doors of rectangular section). Generally the tidal pointing doors appeared to present little obstruction to the landward migration of eels and elvers. Some of the flap doors and flap valves represented a significant obstruction, particularly where they were "perched" (discharging well up a vertical wall) and were new or maintained in good condition. Heavy doors are likely to close sooner as equalisation of levels approaches, making landward passage difficult; use of cantilever counter-weights can delay closing.

Armstrong et al (2004) suggest the possibility of re-hanging vertically-hinged tidal flaps and doors to be side-hung or with the hinges between top and side hung, and use of light-weight doors, to delay closure as level equalisation approaches. There may also be scope for addressing perched doors using ramp systems or seaward head-retaining structures to raise tailwater level. It is recommended that a field investigation be commissioned to explore innovative and practical options for addressing the problems of tidal flaps and doors.

Pumping stations generally represent a complete barrier to movement, though a pumped flow could of course be used for a pump-supply pass (Section 3.2).

7.7 Culverts

Culverted sections of stream, where the flow is piped under roads, railways or other structures, may represent an impediment to upstream migration of eels and elvers in two ways. First, the downstream end of the culvert may be "perched" above the stream level so that access to the culvert itself may be impossible. Second, the flow through the culvert may be too fast for the fish to swim against, especially if the pipe is inclined and smooth-bored.

Unless the culvert is to be replaced with a more eel-friendly installation these two problems must be dealt-with separately. Allowing access to a perched culvert can be done in a number of ways:-

- using a substrate ramp
- creating a low-head barrier downstream to raise the tailwater level above the bed of the culvert - though care must be taken to ensure that the new barrier is not an obstruction to migration
- piling rock and rubble at the exit of the culvert to break the fall of water and to provide a substrate for the eels to climb

The problem of excessive water velocity in smooth-bore culverts can be addressed by "roughening" the bore. This can be done in a number of ways, including fitting of baffles, cementing rocks to the bed of the bore, or use of a metal framework to collect and retain shifting bedload material (Scottish Executive 2000; Clay 1995; Baker and Votapka 1990).

7.8 Facilities for Installation of Passes in the Future

At several points we have stressed the importance of considering installation of passage facilities for eels and elvers, and indeed other fish, whenever an obstruction is constructed, rebuilt, modified or repaired. It is likely to be possible to incorporate effective facilities at such times for a fraction of the cost of doing so at a later date. However, in some cases it may not be appropriate to install full passage facilities at such times, on the basis of uncertain need, uncertainty of the best design, or cost. What is possible in such cases is to incorporate scope for later installation at virtually no cost up front.

An effective eel and elver pass can be installed into a channel of about 500 to 700 mm width, and it should be long enough for installation of a ramp pass to overcome the hydraulic head drop at an angle of 35^o or less; this requires the length of the channel to be at least 1.7 times the hydraulic head. Ideally the channel should be longer than this to reduce the risk of the eels being carried back downstream by the adjacent flow and to facilitate incorporation of monitoring facilities (see section 7.2). In many structures such a channel can readily be incorporated, to be kept shut-off with stop logs or a semi-permanent wall until and unless passage facilities are actually required. It is likely that a similar provision for a baffle type pass for other species would be prudent and cost-effective; this is likely to require a channel of greater width. Expert advice should be sought at the design stage to ensure that future opportunities are maximised. In view of the potential problems presented by integrating eel and baffle passes in a single channel (see Sections 6.2.3 and 7.2), it is recommended that two separate channels are provided with a wall between, and that the wall extends upstream beyond the likely upstream end of the eel pass. The layout apparent at the site described in Section 6.2.1 is commended.

7.9 Requirements for Further Investigation

At a number of points in this manual the need for further R&D or evaluation has been highlighted. These include:-

1. There is a need for a semi-quantitative tool to assess the potential productivity of eels in particular catchments and parts of catchments, based upon environmental conditions. This would be a great aid in justifying and establishing priorities for installation of passage facilities (Section 2.1).

2. More investigation is needed on the downstream migration behaviour of eels, including the depth at which they travel and their willingness to rise in the water column to use surface spillways (Section 4.9).

3. Natural-type by-pass channels are a major development in some European countries, but few have been developed in the UK. There is a need for evaluation of the potential for such structures in the UK, and for provision of design guidelines for providing adequate conditions for a range of species including eels (Section 5.4).

4. Little attention appears to have been paid to the design of holding facilities for trapped eels in monitoring facilities in passes. An experimental investigation to establish optimal designs is recommended (Section 5.8).

5. Although beyond the detailed remit of this investigation, there is a need for further exploration of systems for the safe diversion of downstream migrant eels from intakes. (Section 5.14).

6. Development of standard modules for installation of standard bristle substrate passes is recommended, to reduce design and construction costs (Section 7.2).

7. Provision of passage facilities at flow gauging structures is problematic because of resistance to installation of any structure that compromises the accuracy of the gauging record. Investigation of options for provision of passage facilities should be explored with hydrometric interests (Section 7.5).

8. There may be scope for a series of innovative approaches to providing eel and elver passage at tidal barriers such as control flaps and doors. An experimental programme is suggested to establish which of these may be practicable (Section 7.6).

8 SUPPLIERS

8.1 Introduction

There are few suppliers of equipment for passes for eels and elvers, but a number have been mentioned throughout this manual. Their range of products and services, and contact details, are provided below.

8.2 "Fish-Pass", France

"Fish-Pass" is a small company that undertakes research and consultancy on freshwater fisheries, and manufactures and supplies and complete systems for eel and elver passage facilities. Their products include:-

- bristle substrate mats (Section 5.3.3).
- plastic moulding substrates (Section 5.3.4)
- pass-traps (Sections 3.3.1, 5.3.1, 6.4.1)
- prefabricated passes (Section 6.6.3)
- design and fabrication of eel-lifts (Sections 5.6, 6.5.1)
- design of standard passes for eels (Sections 3.3.1, 5.3.1, 6.2.1, 6.2.2)

Contact:- Dr Antoine Legault, "Fish-Pass", 8 Allée de Guelédan, ZA Parc Rocade Sud, 35135 Chantepie, France. Tel +33 (0)2 99 77 32 11. email fishpass@fish-pass.fr Website www.fish-pass.fr

8.3 Milieu Inc, Canada

Milieu Inc is an environmental consultancy and supplier of the "Eel-ladder" substrate ramps. Their products and services include:-

- "Eel-ladder" plastic substrate ramps (Sections 5.3.4, 6.3.2)
- "Eel-ladder" elver substrate (Section 5.3.4)
- design, fabrication and evaluation of eel passes

Contact:- Denis Desrochers, Milieu Inc., 188 Henrysburg, Saint-Bernard-de-Lacolle, Quebec, Canada J0J 1V0. Tel. +1 514 247 2878. Email milieu@gig.net Website www.cam.org/~aceq/angl/membres/amilieu.html

8.4 Bristle substrate suppliers.

In 1994 the National Rivers Authority contacted a number of brush manufacturers to supply quotes for bristle substrate mats to a particular specification (see Section 5.3.3). Below are the current contact details of those that responded.

Cottam Brothers Ltd, Sheepfolds Industrial Estate, Sunderland, SR5 1BB. Tel 0191 567 1091. Email ineo@cottambros.com Website www.cottambros.com

Dawson and Son Ltd, Eldon Brush Works, Clayton Wood Rise, West Park Ring Road, Leeds, LS6 6RH. Tel 0113 275 9321. Website www.dawsonbrush.co.uk

Cooks of Norwich, 9 Concorde Road, Norwich NR6 6BH. Tel 01603 484444. Website www.cooks-brushes.co.uk

W S Read and Sons Ltd, 554 Green Street, London E13 9DA. Tel 020 8472 0825.

8.5 "Pelcar" and "Evergreen" concrete blocks (Section 5.3.4)

Sotubema, Brie Comte Robert, BP 95, 77253 Coubert Cedex, France. Tel +33 1 64 06 76 05.

8.6 Enkamat geotextile

MMG Civil Engineering Systems Ltd, Vermuyden House, Wiggenhall St Germans, Kings Lynn, Norfolk PE34 3ES. Tel 01553 85791. Website www.mmgces.co.uk

8.7 Akwadrain substrate

American Wick Drain Corporation, 1209 Airport Road, Monro, NC 28110, USA. Tel +1 704 238 9200. Website www.americanwick.com

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Carole Fleury, Milieu Inc, Canada.
Merry Gallagher, Department of Inland Fisheries and Wildlife, Maine, USA.
Dr Alex Haro, S. O. Conte Anadromous Fish research Center, Turners Falls, Ma, USA.
Dr Brian Knights, University of Westminster, UK.
Dr Reinar Knösche, Institut für Binnenfischerei, Germany.
Dr Antoine Legault, Fish-Pass, France.
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Guy Verrault, Faune et Parcs Quebec, Canada.
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