Fish Pass design for Eel and Elver (*Anguilla anguilla*)

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Statement of Use

This report describes the migratory behaviour of eels and elvers in relation to provision of passage facilities at obstructions. It reviews current passage facilities in the UK and elsewhere and provides fundamental design criteria for passes for the species. It is intended for use by Agency staff and other fisheries managers with an interest in the design of passes for eels and elvers. It should be read in association with the R&D Publication "Manual of eel and elver pass design".

Keywords

eel, elver, fish pass, fishway.

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EXECUTIVE SUMMARY

1. In 2001 the Environment Agency produced its "National Eel Management Strategy" against a backdrop of a decline in European eel recruitment which has been apparent for the past twenty years or more. Restricted access to potential rearing areas is considered to be a factor in this decline, and there is no doubt that man-made obstructions to migration and dispersion are limiting eel stocks in many parts of the UK and Europe. The strategy states that the Agency will seek to both encourage and fund the construction of eel passes to restore access to areas where it has been denied or restricted by artificial barriers.

2. The overall aim of this study is to produce design criteria and best practice designs for eel and elver passes. This Technical Report uses a review of eel biology and existing installations to develop design criteria for passage facilities for eels and elvers. It should be read in association with the Manual which sets out specific design criteria for eel and elver passes.

3. 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.

4. As passes can also be utilised as traps for monitoring purposes this potential is also explored in the study.

5. This report presents a detailed review of those aspects of the biology and life-history of the eel that influence migratory behaviour. 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. From this a series of biological and non-biological design criteria are developed for upstream passage facilities for eels and elvers. A similar approach is used to develop design criteria for the protection of downstream migrants.

6. The report briefly explores 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.

7. Existing installations at about 35 sites in England, France and North America are described and assessed. Details of their approach to providing benign conditions for passage, construction and operation are presented, with an assessment of their strengths and weaknesses.

8. Basic design guidelines are produced from a synthesis of the review of eel migratory behaviour and the analysis of existing eel passes. These include fundamental design considerations, 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, constraints at gauging structures, tidal barriers, maintenance and health and safety considerations, and protection of downstream migrants.

9. Particular attention is paid to facilities based on substrates as this is the most usual approach. Considerations include types of substrate, slope, length of passes and resting places, width and depth, flow down the pass, changes in tailwater and headwater levels, and cover against light and predation.

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1 INTRODUCTION

1.1 Background and terms of reference

In 2001 the Environment Agency produced its "National Eel Management Strategy" against a backdrop of a decline in European eel recruitment which has been apparent for the past twenty years or more (Environment Agency 2001). Restricted access to potential rearing areas is thought to be a significant factor in this decline, and there is no doubt that man-made obstructions to migration and dispersion are limiting eel stocks in many parts of the UK and throughout Europe. The strategy states that the Agency will seek to both encourage and fund the construction of eel passes to restore access to areas where it has been denied or restricted by artificial barriers. The overall aim of this study is to produce design criteria and best practice designs for eel and elver passes. As passes can also be utilised as traps for monitoring purposes this potential is also explored in the study.

The specific objectives defined by the Agency are:-

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.

In discussion with the project board it was agreed that the study should be extended to include design criteria for facilities for downstream passage of adult eels, though it was recognised that in this case specific designs were probably not appropriate as the situation is likely to be highly site-specific. It was also agreed that the literature review should include all aspects of eel and elver migratory behaviour which were likely to affect design and operational criteria, and not just swimming speed.

Many of the principles and much of the practice of design and construction of passes for eels and elvers are of application throughout the freshwater range of anguillid eels. It is therefore proposed that the Manual which is being developed from this work will be international in its coverage.

While some recommendations are made in this Technical Report, others will arise from the manual. The overall recommendations from this study will therfore form a short third output, to be submitted at the end of the project.

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

The extent to which any particular structure represents an obstruction is highly site-dependent, and will vary with 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.

Addressing problems for passage of eels and elvers is a whole-catchment process. For example, there will be very much 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 obstructions according to the level of problem they represented from 1 (no obstruction) to 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. Again he used a five-point scale to assess the level of obstruction represented by over a thousand structures in this large catchment.

Reference was made above to the ineffectiveness of installing passage facilities at upstream sites before downstream problem sites had been addressed. However, it may be cost effective to consider future requirements for eel passage if an obstruction upstream is being 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 if opening up the catchment downstream is a realistic possibility thought 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. 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.

2 ASPECTS OF EEL BIOLOGY

2.1 Life cycle

The following is brief description of the life cycle of the European eel, concentrating on aspects of relevance to the issue of migration in fresh waters. Fuller descriptions of eel life history and biology are given by Tesch (1977) and Moriarty (1978). The great majority of information presented in this report refers to the European eel, *Anguilla anguilla*. Any information gathered from other species is specifically identified as such. A number of references are made to the American eel, *A. rostrata*, which appears to have a very similar life cycle and biology to *A. anguilla*. A few references are made to observations on, and installations for, Australasian species; again these are specifically and individually identified in the discussion.

European eels spawn in the Sargasso Sea, though the spawning act has never been witnessed; the centre of the area where larvae of less than 10 mm are recorded is 26^{o}N, 56^{o}W. Spawning takes place early in the year, and the larval fish use the Gulf Stream to assist their journey across the Atlantic. For most of this time the young eel is in the larval leptocephalus form, laterally flattened and somewhat resembling a willow leaf in shape. However, as they pass the 1000 metre depth contour of the European continental shelf they start to metamorphose into the more familiar eel shape of the glass eel stage; this is typically around September. The glass eels approach the coast and enter estuaries from around October/November in western Ireland and the SW Peninsular of Britain, and spread around the coast of the British Isles over the next few months. However, they do not start to actively migrate into rivers until the spring. Many elvers pass the tidal limit of rivers from April through the summer, and as the season progresses they develop from the transparent glass eel into pigmented elvers. Some elvers remain in tidal waters and enter the river in subsequent years, while others may spend the whole of their lives in tidal water without entering fresh water at all. Eels may continue to migrate up river for many years, on a discontinuous basis during the warmer months of the year, so that the lower reaches are dominated by younger age-classes while the upper reaches of large rivers may only contain large old individuals, predominantly female. Growth rates vary between locations but typically maturing females are 45 to 85 cm in length, and of the order of 10 to 12 years post metamorphosis, and males are 30 to 45 cm and 6 to 10 years post metamorphosis. In slower-growing populations individuals may achieve a considerable age before maturing; Poole and Reynolds (1996) record females as old as 57 years in Western Ireland. Maturing eels undergo physical changes and their coloration changes from yellowy-green (yellow eels) to silvery and black (silver eels). They migrate seawards typically in late summer and autumn and return to the Sargasso to spawn.

Growing "yellow" eels therefore occur throughout UK waters from inshore seas and estuaries right through to the uppermost accessible reaches. They occur in all types of fresh waters of all sizes including lakes, marshes, ditches, slow flowing lowland rivers and fast flowing streams. It is clear that maximising production of eels involves ensuring that they have access to the maximum area of inland water.

It is customary to refer to the age of eels in fresh water in terms of years post-metamorphosis; thus an elver is age 0. In this report we will use the term 0 group (or elver) for fish between January 1 and December 31 of their elver year, 1 group for fish in their next year, and so on.

The term glass eel is often used to describe elvers which have yet to develop pigment. As this transition appears to have little significance in terms of migration the term is for the most part not used in this report; such fish will be referred to as elvers or 0 group along with pigmented elvers.

2.2 Patterns of upstream migration

2.2.1 Seasonal timing and extent of migration

Elvers start to enter rivers in the spring, though many will have been present in inshore waters and estuaries for several months. They arrive off the south west of England and Ireland from October onwards; Matthews *et al* (2001) report that glass eels have been recorded in Irish estuaries as early as November; but they do not arrive in the Southern North Sea until February (Tesch 1977). Matthews *et al* (2001) report that the peak of catches of glass eels in the estuary of the Erne, taken by trawling and other netting methods, is in February and March, whereas the main catches in traps at the tidal limit is between April and June. Moriarty (1978) reports a similar seasonal pattern in the Shannon estuary.

The period of migration of elvers close to the tidal limited is of limited duration, not apparently because it is terminated by the onset of unfavourable conditions, but because all fish that wish to migrate have done so (Moriarty, 1986). At the tidal limit on the Bann between 1936 and 1943 the range of dates for the start of the run was March 6 to April 15, and for the end of the run June 13 to July 7 (Lowe 1951). On the Erne most elvers are observed at the tidal limit during May, but significant numbers are still migrating, on a discontinuous basis, until late July (Matthews *et al*, 2001). On the Darent in 1985 to 1987 the main migration took place each year within about 50 days, between mid May and early July (Naismith and Knights 1988).

As described in Section 2.1, eels may continue their upstream migration throughout much of their freshwater lives. In terms of providing appropriate facilities to facilitate this dispersion it is important to consider the requirements separately from those of elvers. Not only is the size of the fish, and thus its swimming and climbing abilities quite different, but it also appears that the seasonal timing of migration is different and thus may take place under different conditions.

Monitoring facilities at tidal limits have usually recorded large numbers of 1-group eels migrating upstream as well as 0 group elvers. Naismith and Knights (1988) found that 1 group fish outnumbered elvers by about 1.6 to 1 at a trap located about 0.5 km above the tidal limit on the River Darent. Traps close to the tidal limits on the Severn and Warwickshire Avon also caught slightly larger numbers of 1 group fish than elvers (White and Knights 1997). Matthews *et al* (2001) reported young 1-6 group eels becoming "increasingly prevalent" among catches of elvers late in the season at the tidal limit on the Erne.

While differences between the seasonal timing of the migration of elvers and older eels are reported, these do not at first sight appear consistent. Naismith and Knights (1988) noted that the curves for cumulative frequency of total catch for elvers were a month or so behind those for older eels at a trap 0.5 km from the tidal limit on the Darent, and Moriarty (1986) observed that eels over 15 cm migrated earlier in the season than those of less than 10 cm. However, Matthews *et al* (2001), observed that 1-6 group eels were consistently later-running than elvers at the tidal limit on the Erne; indeed, the authors state that the appearance of these "bootlace" eels is a reliable indicator that the year's elver run is drawing to a close. Small numbers of these older fish continue to make their way upstream via the salmon pass through to late summer.

These apparent contradictions with regard to timing of migration may be a result of local factors and conditions, and the location of the monitoring site with respect to where each group of fish starts their migration. Naismith and Knights (1988) noted numbers of elvers being present at the tidal limit on the Darent on May 5 1987, 26 days before any were recorded at the monitoring site at Acacia Weir 0.5 km upstream. More extreme is the situation reported at Tange, 35 km from the tidal limit on the river Gudenå in Denmark (Dahl, 1983); here young eels of 1 to 8 age group start migrating as soon as the water temperature reaches about 15^{o}C, but 0 group elvers (representing about 7% of the total run numerically) do not arrive at this site until "late summer" reflecting the time taken to migrate from the tidal limit.

Migration of eels (*A. rostrata*) at the Chambly Dam on the Richelieu River (a tributary of the St Lawrence in Quebec) takes place between June and October, with half or more during June (Desrochers and Fleury, 1999; Desrochers, 2000). The onset of migration occurs following a major rise in water temperature, and most movement takes place at temperatures above 20^{o}C. This site is of the order of 100 km from the tidal limit – though this is difficult to define on the St Lawrence, as there is a long tidal freshwater reach, without flow reversal, and the location of the exact tidal limit varies considerably with river discharge. The mean length of the 9875 eels trapped at the dam in 1998 was 38.62 cm (range 19.6 to 74.1). No age determination was carried out; however, a PIT tagging study indicated an average growth increment of only 7.7 mm in a year, so most fish at this site would appear to be several years post elver.

Migration of *A. rostrata* has also been studied at and between two dams on the St Lawrence river itself; Beauharnois, in Quebec, about 150 km from the tidal limit (but see note above about the problem of defining the tidal limit on the St Lawrence); and the Moses-Saunders Dam at Cornwall, Ontario, a further 80 km upstream (Desrochers 2000, 2001, 2002; Bernard and Desrochers, 2002; Verdon and Desrochers 2003). In 2002, 10,503 eels were trapped in the pass at Beauharnois with a mean length of 42.62 cm (range 24.0 to 74.2). Between 1994 and 2002 the annual mean length has ranged from 42.06 (2001) to 47.17 cm (1998). Interestingly, a second trap intercepting upstream migrants on the opposite shore of the river below the dam in 2002 indicated a lower average length of 38.85 cm. Most eels are captured at this dam between the beginning of July and the end of August, when the water temperature is over 20^{o}C throughout. In 1998, 3980 eels were PIT tagged at Beauharnois and released either upstream or downstream of the dam. Of the 1197 released upstream of the dam, 22 (1.4%) were recorded in the same year arriving at the Moses-Saunders Dam about 80 km upstream. The mean journey time was 72.8 days, representing a ground speed of 1.1 km/day; the fastest journey was 35 days (2.3 km per day). Although similar numbers of PIT tagged eels were released upstream and downstream of the dam at Beauharnois, recaptures of upstream releases outnumber downstream releases at Moses-

Saunders Dam, indicating that the former structure represents a major impediment and delay to movement. The average growth rate of 53 PIT tagged eels recaptured after up to four years was only 12 mm per year, suggesting that the fish at these sites, although still migrating upstream, may be of considerable age.

Jessop (1987) noted a distinct upstream migration of *A. rostrata* individuals of 30 cm plus in the autumn from the estuary into a stream in Nova Scotia, and mentioned that a similar phenomenon had been noted by other authors. As this has not been reported for *A. anguilla* it may be a rare example of a definite specific difference between the migratory behaviours of the two species.

2.2.2 Effects of water temperature

Temperature appears to be the most important factor determining the migration of elvers out of the estuary and into fresh water, though discharge and other variables also affect the timing and dynamics of movement. Swimming activity has been observed in tank studies at temperatures as low as 4-7^{o}C (Linton and Jónason, undated), and Tesch (1977) records that orientation towards, and apparent interest in, fresh water starts at 6-8^{o}C. However, activity at or close to the tidal limit in field studies starts at a somewhat higher temperature, though this does appear to vary between sites. Tesch (1977) records activity at the freshwater interface on the Ems (Germany) starting at 9-11^{o}C; Matthews *et al* (2001) 9-10^{o}C on the River Erne; Naismith and Knights (1988) 10-14^{o}C on the River Darent; White and Knights (1997) 14-16^{o}C on the Severn and Warwickshire Avon; and Hvidsten (1985) 11^{o}C on the River Imsa, Norway. Activity increases with rising temperature above these thresholds, at least as long as elvers are available to migrate; White and Knights (1988) noted that the daily catch increased rapidly at the tidal limit on the Severn and Warwickshire Avon at water temperatures above 18-20^{o}C. Conversely, cold conditions such as the onset of a northerly wind or a frosty night have been observed to stop elvers migrating; "no matter how great the run may be, if the wind moves to the North they immediately disappear and the run stops" (Menzies, 1936). So strong is the link between water temperature and activity that cool summers may have a direct effect on the level of recruitment of elvers to fresh waters, at least in the northern part of the distribution; Hvidsten (1985) observed a strong correlation between annual total degree-days above 11^{o}C and total years recruitment to the River Imsa, with the variation in recruitment being more than twenty-fold.

Several studies suggest that older eels are less temperature-sensitive than are elvers (Sorenson 1951, Nyman 1972, Alm 1932). Naismith and Knights (1988) noted that this appeared to be the case on the River Darent in some years but not in others; they suggested that perhaps river flow was in fact more important, with the larger eels able to make upstream progress at higher flows (and thus higher current speeds) than smaller fish, thus appearing sooner in trap catches.

The issue of migratory behaviour and water temperature is discussed further in Section 2.3 below.

2.2.3 Effects of river discharge

River discharge does not appear to have any direct major influence on migration of elvers except in larger rivers where high flows are associated with reduced movements.

Lowe (1951) noted that high flows delayed the start of run of elvers on the Bann (N. Ireland) by up to several weeks e.g. from March 6 (in 1943, low flows) to April 15 (1940 and 1941, high flows). Matthews *et al* (2001) observed that movement at the tidal limit on the regulated River Erne was greatest at low flows; if electricity generation commenced (increasing discharge) while elvers were running the effect was immediate, with the fish dropping out of the water column or moving to the shore. Jessop (2003) noted a negative correlation between discharge and numbers of elvers of *A. rostrata* in a Nova Scotia stream.

Similarly, river discharge appears to have little or no effect upon the upstream migratory behaviour of 1-group and older eels. White and Knights (1997) analysed trap catches on the Severn and Warwickshire Avon and attributed variation in catch per trap per day to a range of variables. Most of the variation was explained by temperature and year effect (i.e. total run for that year); virtually none of the variation could be attributed to river flow. Indeed, it would seem logical that a fish that migrated upstream by exploiting areas of low current speed, and ascended obstacles using edge effects and crevices, would choose to move at times of low flow. The preference for migrating at high water temperatures is also likely to result in movement at times of settled, anti-cyclonic weather which are generally associated with low flows.

Upstream migrant eels and elvers are attracted to flowing water as a lead for suitable migration routes. They therefore tend to gather at the most upstream point beneath obstructions, close to the main flow. This tendency has important implications for siting of the downstream entrance of passes, and for the provision of attraction flows in addition to the small flow through the pass itself.

2.2.4 Effects of tide and lunar cycle

Observations regarding the effect of tides on elver migration are varied. While there is no doubt that elvers use tidal flow to effect landwards movement in the estuary (Deelder 1952, Creutzberg 1958, McCleave and Kleckner 1982), and thus catches in estuaries are modulated by the spring/neap cycle, the extent to which a tidal signal persists at the tidal limit varies. White and Knights (1997) observed that the tidal signal was weak in trap catches at the tidal limit on the Severn and Warwickshire Avon, while Myers (1941) observed elvers entering the rivers Wyre and Lune for three or four days around spring tides; between these times practically no elvers migrated from the estuary. Menzies (1936), making observations based on trap catches of more than 45 million elvers at the tidal limit on the Bann, noted that activity peaked around spring tides and that there were usually blank periods of around 4 to 5 days around neap tides. Sorenson and Biachini (1986), trapping elvers of *A. rostrata* 200 m upstream of the tidal limit in a small stream in Rhode Island, noted a 14.8 day periodicity in catches lagging behind spring tides. Reports of several studies of elver migration (e.g. Naismith and Knights 1988; Lowe 1951; Matthews *et al* 2001) make no reference to either the presence or absence of a lunar related cycle, so the assumption is that none was obvious.

2.2.5 Effect of time of day

Observations on time of day and state of light during migration are also equivocal. Tesch (1977) noted that migration to the tidal limit on the river Ems was mainly in darkness. He cited experimental studies where elver activity increased as the light level was reduced from 120 down to 9 lux, but ceased again when it was increased to 18 lux. Myers (1941) observed elver migration close to the tidal limits on the Lune and Wyre at all times of day, and noted that at night elvers were attracted by light. Sörenson (1951) concluded that while light had a marked obstructive effect on the migration of larger eels the "smaller elvers do, to a certain extent, make their way upstream in light". Menzies (1936) recorded that elvers arrived at the tidal limit on the Bann "by day and by night indifferently".

In contrast to elvers, migratory activity of 1-group and older eels appears to be almost entirely nocturnal. Sorenson (1951) noted that light had a marked obstructive effect on the movement of larger eels. Desrochers (2000) observed American eels (*A. rostrata*) using a pass at a dam on the Richelieu River, a tributary of the St Lawrence, with the great majority of activity being between 21:00 and 0500 hours, with the peak around 01:00 hours.

2.2.6 Climbing activity

At times, elvers and small eels will climb sloping or even vertical wetted surfaces, especially if they are covered in moss or algae. The conditions for such activity appear to be a little different to more conventional upstream passage. First, only fish below about 10 cm demonstrate this behaviour (Legault, 1988). Second, the temperature thresholds appear to be higher than for upstream swimming activity. In laboratory experiments the threshold for swimming was 4-7^{o}C, with maximum activity at 12-17^{o}C; whereas for climbing the threshold was 12-14.5^{o}C, and the peak was observed at the highest temperature tested, 22 and 25^{o}C (Linton and Jónason, undated).

2.2.7 Dispersion and rate of upstream migration

The distance travelled upstream by elvers in their first summer in the river is restricted by their limited swimming ability and the short length of the season in which they move. In their studies on the Severn and Warwickshire Avon, White and Knights (1997) noted very few elvers in their trap at Diglis weir, 26.5 km above the tidal limit on the Severn, and none at Bevere (30.5 km) or further upstream. Similar results were obtained on the Avon; few elvers were noted at Strensham (9.5 km) and Nafford (15 km), and none at Wyre Mill (25 km) or upstream. Trap catches on lower Thames tributaries at Lullingstone on the Darent (15 km from the tidal limit) and at Zenith Weir on the Mole (7 km from the tidal limit) contained no elvers and were predominantly of 1-group fish. Although large numbers of elvers enter the Shannon at Ardnacrusha, few if any reach Parteen, 15 km upstream, in their first year; trap catches there are made up of about 50% fish in their second year, with the remainder being up to ten years old (Moriarty 1978). In steep rivers the distances travelled in the first season may be even less than the above figures indicate; in a small river system flowing into the Gulf of St Lawrence, no elvers of *A. rostrata* reached a monitoring site 4 km upstream of the tidal limit, though some 1-group eels did (Dutil *et al*, 1989). Equally, in lowland catchments with few obstructions, elvers may penetrate rather further in their first year; trap catches in eel passes at Tange, 35 km from the tidal limit on the River Gudenå in Denmark, contain 7.3% of fish in their first year in fresh water; most (40%) were in their second year (Dahl 1983). Legault (2000) reports that about 0.8% and 3.9% of the trap catch in two years at Maison Rouge Dam, 202 km from the tidal limit on the Vienne River, a tributary of the Loire, were 0 group. This represents extraordinary progress upstream; even if these fish did not arrive until the end of the main run in August they have still covered this distance in about four months, representing a ground speed of around 1.7 km per day or 1.8 cm/sec, night and day, since they passed the tidal limit. Perhaps the higher water temperatures and lack of obstructions encouraged faster migration than is observed further north in the UK. The higher temperatures may also account for the large size large size of these assumed 0-group fish (mean lengths in the two years 118.9 mm and 122.2 mm).

Some estimates of speed of migration of elvers can be obtained from the timing of first arrivals or peaks of migration at two points on a river, or from mark and recapture studies. In a steep stream in Rhode Island (mean gradient 2.2%) elvers (*A. rostrata*) took about 4 weeks to travel 180 m, i.e. about 6 metres per day (Haro and Krueger, 1988). On the River Darent, migrants took 17 to 46 days to migrate upstream through a reach of 2 km containing one weir, representing migration rates of 43 to 118 metres per day (Naismith and Knights, 1988).

As already mentioned, eels may take many years to penetrate the upper reaches of large river systems, so that the populations of the upper reaches, though maybe low in density, consist entirely of older and larger individuals. The youngest eels in the Vyrnwy and Camlad, two upper tributaries of the River Severn about 160 and 190 km from the tidal limit and about 50 m and 70 m above sea level respectively, were 8-group; and the youngest in two upper tributaries of the Welsh Dee were 10-group (River Lliw, about 100 km from the tidal limit and at an altitude of about 160 m above sea level) and 13-group (Hirnant, about 90 km and 150 metres) (Aprahamian, 1988). The overall maximum rates of upstream dispersion were calculated at 20-30 km per year on the Severn, and 10 to 20 km per year on the Dee, the latter slower rate presumably being influenced by the steeper gradient. Higher and lower maximum rates of dispersion have been recorded in the British Isles; eg 46 km per year on the Tweed (Aprahamian 1988) and 8 km per year on the Frome (Mann and Blackburn 1991).

Male eels mature at a significantly lower age than females (see section 2.6.2). Thus the population of fish in the upper reaches of large rivers may comprise almost entirely females. Verreault (2002) observed *A. rostrata* up to 10-group (mode at 4-group) migrating upstream at a trap 4 km from the estuary of the Sud-Ouest River in Quebec, though lakes further upstream contained eels up to 29-group. Ibbotson *et al* (2002) examined the pattern of distribution of eels of different ages in 18 UK rivers and hypothesised that it is achieved by a two-phase process; phase 1 is an initial rapid migration into fresh water driven by density. Phase 2, involving older eels, is fundamentally a random dispersion which gives rise to the observed demographic pattern. They argued that a wave-form migration (ie a directed upstream migration year by year) would lead to an obvious population density peak upstream; this is not apparent, with population densities steadily falling with distance upstream from the tidal limit.

2.2.8 Other relevant aspects of behaviour

The way in which elvers migrate is of course important in considering the provision of appropriate passage facilities. In the estuary they appear to exploit selective tidal transport, that is they move with the body of the flood flow landwards, and shelter on, in or near the bed or banks on the ebb tide (Deelder 1952; Creutzberg 1961; McCleave and

Kleckner 1982). Clearly this mechanism cannot be used to actually reach the tidal limit as it depends upon a landwards flow at some stage of the tidal cycle; in most situations the tidal rise in the uppermost reaches of the estuary is caused by a reduced seawards flow rather than a flow reversal. However, the pattern of arrival at the top of the zone of selective tidal transport may explain why the timing of arrival at the tidal limit still displays a tidal cycle signal in many cases. In some situations where a man-made barrier represents the tidal limit the obstruction may only be overcome by elvers at the higher spring tides; in such situations a tidal signal in elver activity could persist for some distance upstream.

In the upper estuary and around the tidal limit elvers appear to move close to the surface along the banks, often in a dense band within about a metre of the shore (Moriarty 1978). Tesch (1977) reports observations on such "bands" of elvers being up to 4 m wide and 5 m deep in some of the Atlantic rivers in France (where presumably elver number are large), whereas in some German rivers the "band is seldom more than a few centimetres or decimetres wide, and only measures about 5 cm in depth". Deelder (1984) reports surface migration in tidal waters as far as 140 km from the coast, while Tesch (1977) records it up to 150 km landwards of the Elbe estuary; however, there is doubt in this latter case regarding whether the observation is still in tidal water as the author goes on to say that "however, daytime ascent is limited to the uppermost 30 to 40 km, ie to the area above the influence of the flood tide". Moriarty (1978) suggests that this form of active migration ceases "within a few kilometres of the highest point of the tide, and increasing numbers of elvers drop away from the school to begin to feed and adopt the individualistic habits which they will keep for the next few years". Where further upstream migration of 0-group elvers does occur this appears to be mainly nocturnal, on an individual fish basis rather than in a school, and demersal rather than pelagic in nature.

An important issue with respect to passage of elvers and eels past obstructions, and in designing passage facilities, is the tendency to make progress under difficult flow conditions by crawling along and through the substrate rather than by swimming in the water column. Eels are extremely adept at exploiting boundary layers as well as actually using projections in the substrate to gain a purchase for their sinuous mode of movement. As already described, elvers and small eels can climb wetted vertical surfaces, especially if they are covered in algae, moss or other growth, and eels of all sizes may migrate over wet ground close to the edge of the stream. Thus open-water swimming ability may be of limited relevance to assessing obstructions and in the design of passage facilities – though of course it is still important for approach to and leaving substrate passes, and in considering the ability of eels to use passes designed for other species.

Another important aspect of elver migratory behaviour is their reaction to the "smell" (or at least chemical emanations) of other eels. Creutzberg (1959, 1961) appears to have been the first to observe that the attractiveness of fresh water to elvers is at least partly dependent on some organic constituent of natural streams, the attractive ingredient being removed by passing the water through a carbon filter. Miles (1968) observed that filtered water became more attractive to migrating elvers of *A. rostrata* when others eels were kept in the flow, but that this attractiveness was in turn reduced when large concentrations of elvers were added. Sorenson (1986) also working with *A. rostrata* found that conditioning filtered water with elvers and maturing eels rendered it more attractive, but not as attractive as stream water; presumably the latter contained eels but also some other attractive ingredients. He concluded that the main source of the freshwater attractant was the micro-organisms responsible for the decay of leaf detritus. However, renewed support for the importance of pheromones comes from observations made at the Arzal Dam on the River Vilaine in France (Briand *et al*, 2002). Trap catches of both elvers and young eels were on average 1.4 times higher when the outflow from the trap bin already containing elvers and young eels was piped into the attraction flow. Theoretical calculations suggested that the attractive effect would operate up to about 5 metres from the trap entrance.

These observations on the importance of chemical clues have implications for the design and operation of eel passes and traps. First, it would be prudent to provide the flow down the pass or from the trap from the river itself and not from an alternative source such as treated water. Second, it may be very useful to hold numbers of elvers and young eels within a trap incorporated into a pass to provide an attraction for other migrating individuals. This may be particularly effective in large rivers where the entrance to the pass or trap may not otherwise be easy for the fish to locate.

Predation is a significant issue for elvers. Matthews et al (2001), quoting Norwegian work, suggest that elvers may suffer 50 to 84 % predation by birds and fish during their stay in and passage through the estuary. Particular depredation may occur while the elvers are migrating to and past the tidal limit, when the fish are concentrated in a “band” on the water surface near the bank. Even more extreme danger may arise when the whole of the run of a river is concentrated around and within an elver pass. Menzies (1936) describes the situation at an elver pass on the River Bann:-

> “At the time of a big run the whole pass may be a moving, writhing black mass of elvers which are preyed on by every imaginable creature; adult eels and trout, various gulls and other birds, even rats, take their toll”.

Prevention or minimisation of predation is therefore a significant issue in the design and deployment of passes.

2.3 Temperature, activity and swimming ability

Swimming ability and behaviour of various life history stages are clearly important in considering certain design criteria for eel and elver passes. We must take account not just of maximum swimming speed, but also of ability to maintain certain swimming speeds for long enough to ascend a pass that may be many metres in length.

As with all cold-blooded animals, both inclination to swim and swimming ability are influenced by water temperature. This obvious fact is, rather surprisingly, overlooked in many studies which have been conducted at a single temperature, often rather cooler than that associated with maximal migratory activity. Some studies even fail to report the temperature at which the measurements were made.

A useful overview of the effect of temperature on eel swimming activity is provided by Nyman (1972). His observations are summarised in Table 2.1.

Table 2.1 Effect of water temperature on the activity of European eels in an aquarium. Based on Nyman (1972).

Temp. °C	Observation
5-8	Eels inactive, completely hidden in mud substrate
8+	gradual movement within sediment – from mud to rocks "the size of a fist"
9	10-20% of eels poke their heads from between the rocks
11	a few individuals emerge as much as half a body length
13	60 % of eels have heads protruded from rocks
14	Remarkable shift in habitat and activity; several free-swimming individuals, especially at night
16	All free-swimming or resting on bottom.

These observations are well-supported by field observations, with few eels migrating upstream at temperatures below about 12°C, with peaks of activity associated with temperatures of 20°C+.

Turning to observations on swimming ability, this is an area fraught with difficulty. For most fish species, which spend most of their lives within the water column at least matching the speed of the current in which they live, testing swimming speeds in a flume is fairly straightforward. Eels on the other hand spend much of their time within the substrate or on the river bed where they are not having to swim to maintain position. They only need enter the water column when they wish to migrate, and even then much of their movement is likely to be close to the bed, within a boundary layer, and with frequent rests. The behaviour of elvers when confronted with a sudden increase in river flow has already been described in section 2.2, viz they immediately drop out of the water column or swim to the banks to avoid the main flow. This does not necessarily indicate that the faster flow is beyond their swimming capacity, merely that they choose not to fight it but instead to seek easier routes or wait until conditions revert.

One of the earliest studies of eel and elvers swimming ability (Sörenson 1951) is also one of the most useful in practical terms of pass design criteria, as the work was done in an experimental pass. The apparatus comprised four chambers 45 cm long, 30 cm wide and 30 cm deep, joined by sloping channels 120 cm long. The vertical location of each chamber could be adjusted to alter the slope of the connecting channels and thus the velocity of the water flowing through them. Eels (n = 65-88, length range 70 to 300 mm) were introduced to the lower chamber and left, typically overnight, to migrate up the apparatus at will. At the end of the experiment the distribution of the eels throughout the apparatus was recorded along with their lengths in each chamber. The results are summarised in Table 2.2.

A number of features are apparent. First, at the lower temperature of 12°C few eels migrated and then not the smallest ones. Second, at the higher temperature in dark conditions virtually all the eels migrated against flows of 0.4 m/sec, with successively fewer at higher water velocities, with the smaller fish represented less and less. Many fewer fish migrated in shady conditions than in the dark, with smaller fish less affected by the presence of light than larger fish. These results highlight how both underlying swimming ability and the desire to actually migrate at the time play an important part in the observed activity. They do not of course provide direct information on how long various swimming speeds can be maintained, though clearly it was long enough in each case to ascend a 1.2 m length of trough. Other observations from this work are that an 80 mm elver could overhaul a 0.3 m/sec current for "several minutes" but is swept back by a 0.4 m/sec current "after a minute or so", and could withstand a current of 0.5 m/sec for 10 to 20 seconds only. A 13 cm eel could withstand a current of 0.5 m/sec "for a few minutes", and a 16 cm eel showed a "burst speed" in excess of 1.5 m/sec. All these observations were made at 19.8°C.

Table 2.2. The smallest eels that succeeded in passing between chambers connected by troughs flowing at a range of water velocities at two water temperatures, in darkness and shade. The figures in brackets are the percentages of the whole group (n = 65 to 88, length range 70 to 300 mm) that made the ascent. Data from Sörenson (1951).

Water velocity m/sec	**12°C (dark)**	**19.8°C (dark)**	**19.8°C (shade)**
0.4	100 mm (13.8%)	70 mm (96.0%)	70 mm (17.0%)
0.6		70 mm (85.9%)	70 mm (10.2%)
0.7	200 mm (9.7%)		
0.9		100 mm (50.8%)	
1.2	200 mm (4.2%)		
1.3		120 mm (20.0%)	
1.5		150 mm (11.8%)	160 mm (1.1%)

McCleave (1980) studied the swimming activity of elvers in a darkened flume. He tested a range of swimming speeds from 0.25 to 0.5 m/sec, equivalent to 3.6 to 7.2 body-lengths per second (BL/s), and observed the time to fatigue; these ranged from 16 seconds at 0.5 m/sec to 2.44 minutes at 0.25 m/sec. The distance travelled through the water (not ground covered) represented by these extremes are 8 metres (0.5 m/sec for 16 seconds), and 36.6 metres (2.44 minutes at 0.25 m/sec). Similar results were obtained for fish acclimatised to, and tested in, fresh and salt water. This approach allows consideration of the ability of the fish to overcome any particular structure or pass where the velocity and length of channel are known. The main limitation of these results is that the experiments were undertaken at water temperatures of 11.1–13.3 °C, at the lower end of the range associated with migration past tidal limits and upstream.

Barbin and Krueger (1994) examined the swimming performance of elvers of *A. rostrata* (mean length 59 mm) in two flumes, one with a pebbly substrate and the other without. In the substrate chamber many elvers spent the whole of the experimental period within the substrate, while others made upstream progress in short bursts separated by periods within the substrate. The migrators made use of the boundary layer close to the substrate. In the non-substrate chamber the fastest current speed successfully overcome was 0.35 m/sec, with 51% of fish tested at 0.1 to 0.35 m/sec successfully traversing the 1.5 metre test zone. An interesting observation was that the ground speed tended to be relatively constant; that is, the elvers chose to swim at a relatively constant speed over and above that of the water flow. This is likely to be a behavioural trait that has evolved to optimise swimming performance – this is discussed further below.

Langdon and Collins (2000) undertook experiments to establish the maximal swimming performance of the elvers of two Australasian species. The results were similar to those obtained for Atlantic species; perhaps of greatest interest here is a comparative table the authors presented of sustained, prolonged and burst swimming speeds of elvers and small eels of several species based on the literature. These different swimming speeds correspond to points of inflection on the graphs of swimming speed against time sustainable, and correspond to sustained swimming times of the order of 10 minutes or more, one to ten minutes, and less than one minute respectively. The results reviewed by Langdon and Collins (loc cit) for *A. anguilla* and *A. rostrata* are presented in Table 2.3, to which are added other results for *A. anguilla*.

Table 2.3. Experimentally observed (references 1-4) and modelled (reference 5 and 6) swimming duration times for elvers and small eels. References:- 1 = McCleave 1980; 2 = Tsukamoto *et al* (1975); 3 = Sörenson 1951; 4 = Barbin and Krueger (1994); 5 = Clough and Turnpenny (2001); 6 = Clough et al (2002). (a) time not known, indicates successful passage of 1.2 m.

	Sustained		**Prolonged**		**Burst**			
Length mm	**Vel. m/sec**	**Time min**	**Vel. m/sec**	**Time min**	**Vel. m/sec**	**Time sec**	**Temp ^{o}C**	**Reference**
A. anguilla and A. rostrata								
50	0.19	46	0.21	5	0.36	20	11.1	5
60	0.23	39	0.25	6	0.41	20	11.1	5
70	0.27	35	0.29	7	0.46	20	11.1	5
72			0.36	1	0.54	20	11-13	1
72			0.25	3			11-13	1
80	0.3	?	0.4	1	0.5	10-20	19.8	3
80	0.31	32	0.33	8	0.50	20	11.1	5
80	0.3	60	0.33	several			?	5
90	0.15	60			0.8	30	25	2
70					0.6	(a)	19.8	3
100					0.4	(a)	12	3
100	0.13	30	0.15	11	1.02	20	15	6
100					0.9	(a)	19.8	3
120					1.3	(a)	19.8	3
150	0.2	25	0.23	9	1.1	20	15	6
150					1.5	(a)	19.8	3
200	0.26	30	0.3	11	1.16	20	15	6
200					1.2	(a)	12	3
130			0.5	several			19.8	3
A. rostrata								
56	0.15	10+	0.25	10?	0.4	?	17-23	4

Elvers (Clough and Turnpenny 2001) and eels (Clough *et al* 2002) were included in a recent Agency R&D programme examining swimming speeds in a range of freshwater fish species. The results of flume swimming tests were used to generate a model (Swimit) to give burst swimming speeds (speeds that could be maintained for 20 seconds), and endurance time of swimming that could be maintained against slower water velocities. Sample outputs from the models for elvers and small eels are included in Table 2.3.

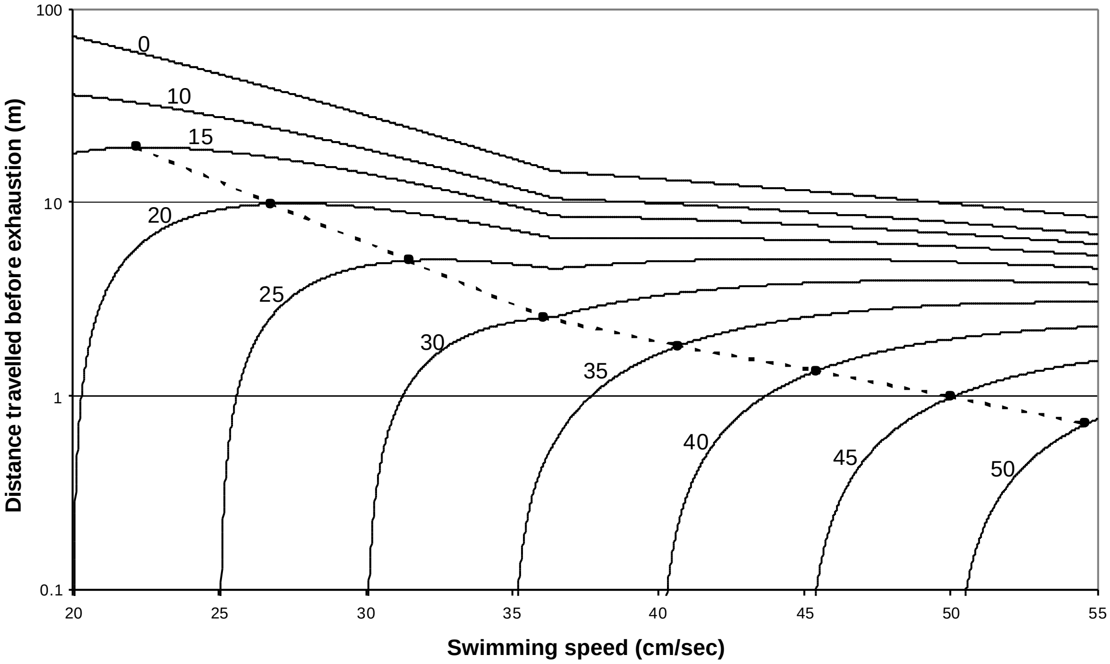


Figure 2.1 Distance travelled before exhaustion by a 72 mm elver at different swimming speeds and current speeds, based on the results of McCleave (1980). Each curve represents a particular current speed as indicated by the numbers (cm/sec). Also shown (dots and dotted line) are selected swimming speeds according to the findings of Barbin and Krueger (1994).

Combining results from two of the above studies allows a consideration of the optimal swimming speed for an elver or eel to overcome an area of rapid flow. The solid line curves in Figure 2.1 are derived from formulae for sustained swimming times before exhaustion for various swimming speeds for a 72 mm elver derived by McCleave (1980). They show the distance travelled before exhaustion according to the swimming speed selected, for a range of current speeds. An elver will be able to travel furthest before exhaustion if it selects the swimming speed that corresponds to the highest point on the curve for the particular current speed; for example, in a current speed of 20 cm/sec the optimal swimming speed is about 27-28 cm/sec, which would result in a distance of 10 metres over the ground being travelled before exhaustion. Swimming at a lower or higher speed would result in a lesser distance being achieved. The dots and dotted line in Figure 2.1 represent the swimming speed selected by a nominal 72 mm elver according to the formula for observed ground speed of swimming elvers reported by Barbin and Krueger (1994). The apparent selection of the optimal swimming speed to move upstream against currents over the range 10 to 25 cm per second is remarkable. The apparently less good correspondence at higher current speeds may be a reflection of the less reliable nature of McCleave's results in this area; his swimming speed/endurance line is a noticeably less close fit to the actual observations for swimming speeds in excess of 35 cm/sec. These models show too a reasonable fit with the results obtained by Sörenson (1951), already discussed, which showed that a 100mm eel was able to ascend a 1.2 m distance against a current speed of 40 cm/sec at 12°C, close to the temperatures prevailing during McCleave's experiments.

With respect to larger eels, there are some data available from Sörenson (1951) for fish up to 20 cm, as detailed in Table 2.3. The Clough *et al* (2002) study discussed above included adult eels in generating the "Swimit" model. Predicted burst speeds (speeds that can be maintained for 20 seconds) for various sizes of eel and temperature are shown in Figure 2.2. These are in broad agreement with the other experimental results for small eels given in Table 2.3. Blaxter and Dixon (1959) give a figure for a "maximum" swimming speed of a 60 cm eel at 10-15°C of 1.14 m/sec, a little lower than the "Swimit" burst-speed predictions of 135-137 cm/sec over this temperature range.

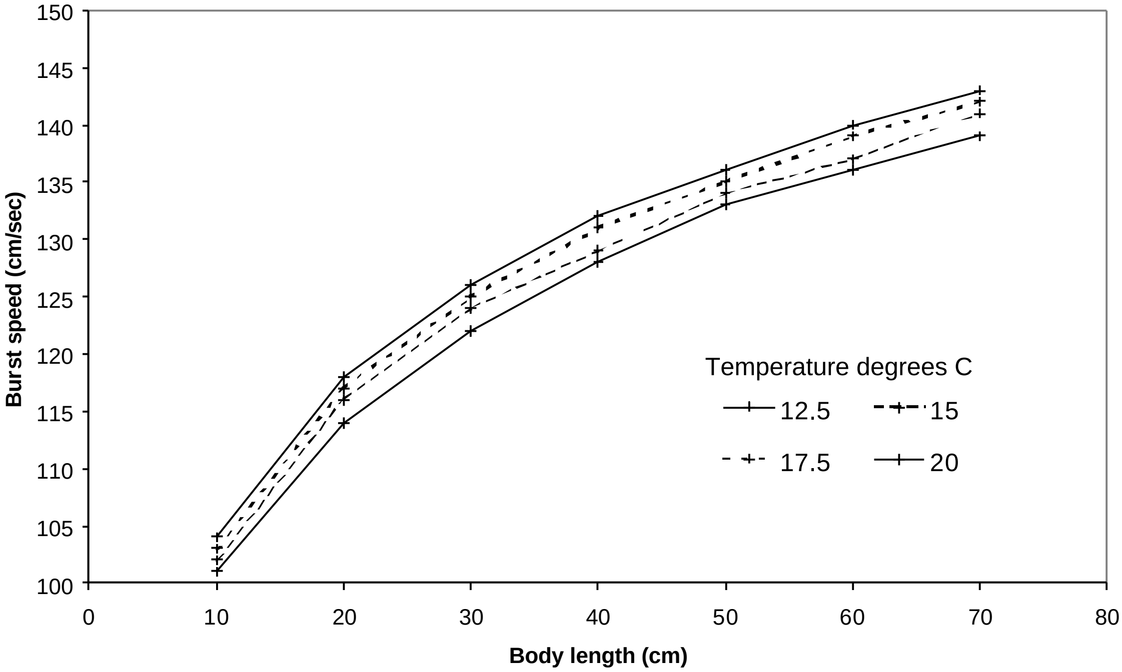


Figure 2.2. Predicted burst speed for eels of different sizes at four water temperatures produced by the Swimit model.

2.4 Biological criteria for design of upstream facilities

2.4.1 Introduction

From the observations described in sections 2.1 to 2.3 we can now draw a number of conclusions regarding design criteria for facilities for facilitating upstream progress eels and elvers. This section summarises these observations and develops such criteria.

2.4.2 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.

2.4.3 River flow

Many (most?) 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 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.

2.4.4 Size of fish to be catered for

At or close to the tidal limit the upstream migration will be dominated by elvers (60 to 90 mm in length) and 1-group fish (90 to 130 mm). However, numbers of fish up to 30 cm may also pass upstream at times, and facilities should cater for fish throughout the 60 to 300 mm 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.

As one moves 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, 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.

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.

2.4.5 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.

2.4.6 State of light

As discussed in section 2.2.5, 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 bright 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 5.16.

2.4.7 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 of elvers and small eels are described in Section 2.3. 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 0.35 to 0.6 m/sec, depending on body length. Burst-speeds for larger eels are of the order of 1.15 m/sec for 20 cm fish, 1.25 m/sec for 40 cm fish, and 1.35m/sec for 60 cm 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.

2.4.8 Predation

Predation is a major risk for elvers and small eels and they are likely to be particularly vulnerable in passes, and as they leave the upstream exit. All 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 emerging from the upstream exit.

2.4.9 Non-biological design criteria.

The fact that fish passes often cause all or most of the run of fish to pass through a confined space containing only a small part of the flow of the whole river means that they represent an ideal opportunity to trap fish for monitoring of recruitment and gathering of biological data. Such facilities also of course provide a means to investigate the effectiveness and selectivity of the pass itself. Design criteria for incorporation of trapping facilities are discussed later in this report.

Human operator health and safety are fundamental concerns for all facilities requiring maintenance, seasonal installation and removal, and especially monitoring. These issues are dealt-with in later sections of this report. Vandalism may be an unwelcome feature at some sites, making robust construction necessary.

2.5 Downstream migration

2.5.1 General description

After a number of years feeding and growing in fresh water, estuaries or coastal waters the yellow eels start to mature, metamorphose to the silver eel stage and commence their migration to the Sargasso Sea to spawn. Downstream migration in fresh water generally takes place in late Summer or Autumn, with large numbers of eels migrating together under favourable conditions. Downstream migrants are vulnerable to being entrained at water intakes and hydro-electric plants. There are a number of approaches to protection of downstream migrants at such facilities. Features of the migration that are relevant to establishing design criteria for such protection facilities are the size of the animals involved, the seasonal and diurnal timing of the migration, the environmental conditions under which movement takes place, and the behaviour of the migrating fish. These are reviewed in the following sections.

2.5.2 Size of eels involved.

In this section only observations from the British Isles are included as growth rates at different latitudes may mean that the size ranges also vary.

Male eels generally mature at a younger age and a smaller size than females. This is relevant here as eels in the uppermost reaches of large rivers may be almost exclusively female, with the result that the size range of downstream migrants will represent only the upper part of that apparent further downstream.

Statistics for the silver eels in a number of river systems in the British Isles are presented in Table 2.4.

The overall observed length range of male silver eels within these river systems is 28.7 to 46 cm, and for females 35 to 102 cm. Some care is needed in interpreting these figures as a true representation of the situation in any particular river as some of the observations are based upon observations from a limited time period within one or a few years. However, it is suggested that this is a fair representation of the length distribution of silver eels throughout the British Isles.

Table 2.4 Means and ranges of length and age of male and female silver eels. References: 1= Moriarty (1991); 2 = Moriarty (1989); 3 = Poole and Reynolds (1996); 4 = Matthews *et al* (2001); 5 = Aprahamian (1988); 6 = Frost (1950); 7 = Knights *et al* (2001).

	Males mean (range)		**Females mean (range)**	
River system	**Length cm**	**Age years**	**Length cm**	**Age years**
Corrib (1)	36 (30-42)	(7-17)	47 (38-87)	(12-19)
Shannon (2)	38 (30-43)	(12-19)	60 (43-90)	(9-21)
Burishoole (3)	42 (29-46)	(10-33)	43 (41-97)	(8-57)
Erne (4)	37 (30-42)	(5-16)	66 (36-102)	(5-38)
Severn (5)	36.4(28.7-43.9)	11.9 (4-20)	64.3 (35-84.1)	17.8 (9-27)
Bann (6)	38.5 (33.5-44)		54.2 (44.5-86)	
Leven (6)	40.6	9	58.2 (47-95)	12.3 (9-19)
Piddle (7)	(30-c.45)	(3-17)	(c.45-76)	(5-25)
Frome (7)	(30-c.45)	(10-22)	(c.45-84)	(12-22)

2.5.3 Seasonal timing of migration

Care is needed in establishing the seasonal timing of silver eel migration as much of the information comes from catches rather than of runs themselves. Some fisheries are likely to operate only over the peak of the run, so that the "tails" of the distribution are unrecorded. Again, only observations from the British Isles are considered here.

Frost (1950) trapped throughout the year on the river Bann and recorded the following monthly distribution of silver eel movement; June 0.4%, July 1.5%, August 9.9%, September 32.4%, October 45.2%, November 8.6%, December 0.4% and January 1.6%. While the total length of the season was considerable, more than 96% of migration took place in August to November, and over 77% in September and October. On the Erne system silver eel fishing takes place from late August to early January, but the main runs occur in October-November (Matthews *et al* 2001). A wide range of casual observations from other river systems suggests that the above seasonal distribution is broadly applicable throughout the British Isles.

There is evidence from rivers draining to the Baltic that the seasonal timing of migration of the two sexes may be different. Deelder (1970) reported that silver eel catches at Rugen comprised only 39% females in early September, but 90% during December. Deelder also reported that the presence of deep water (of the order of 10 m) in the system appeared to delay migration by up to two months in the Netherlands.

2.5.4 Environmental conditions during migration

Migration generally takes place on elevated flows on dark nights. Vollestad *et al* (1986) found that they could account for over 90% of the variation in the date of commencement of the silver eel run on the River Ims in Norway from variation in water temperature and river discharge; low temperatures in July-August and high flows in August-October meant an early start to the run. Most eels migrated at water temperatures between 9 and 11^{o}C, with strong inhibition of movement at temperatures above 18^{o}C and below 4^{o}C. Further evidence of the importance of water temperature comes from observations by Lobón-Cerviá and Carrascal (1992) on the seasonal timing of occurrence of silver eels in a stream in Northern Spain where water temperatures are relatively high (eg 10^{o}C in January). Silver eels were observed from September to March, around three months later than in the British Isles and Scandinavia.

Many other authors have also noted the correlation between elevated discharge, with its associated increased turbidity, and major movements of silver eels (eg Frost 1950, Tesch 1977, Moriarty 1978, Matthews *et al* 2001).

State of light also has a major influence. Very little migration takes place during daytime (Frost, 1950) and movement is greatest on dark nights. This apparent avoidance of bright conditions suggests that the use of light may be a useful diversion mechanism. Lunar cycle has a significant effect, with most movement being recorded in the first (Haraldstad and Vøllestad 1985) and last (Tesch 1977) quarter of the moon. While this is probably because the time around new moon is associated with little moonlight and thus dark nights there is some evidence of an endogenous lunar rhythm apparent in the activity cycles of silver eels kept in laboratory conditions unaffected by moonlight (Tesch 1977). Deelder (1970) reported a study in which most silver eel activity occurred between sunset and midnight, with the main migration frequently taking place in a period of less than an hour.

There is some evidence that increases in silver eel activity may precede arrival of obvious weather conditions associated with migration (Tesch 1977). Deelder (1954) suggested that silver eels could detect an area of low atmospheric pressure at some distance from the associated micro-seismic oscillations that are generated. These oscillations have an average period of about three seconds and are equivalent to pressure fluctuations of the order of 0.002 millibars.

2.5.5 Other aspects of migratory behaviour

In contrast to yellow eels, which generally move close to the substrate, silver eels migrate downstream distributed throughout the water column. Moriarty (1978) describes experiments at the Ardnacrusha dam on the Shannon in which nets were set at various levels in the water column to sample silver eels. When the runs were minor most fish were close to the bed, but when a major run was occurring the fish were distributed throughout the water column. However, Durif *et al* (2003) tentatively concluded that a hydro-electric dam bypass with its entrance in the lower half of the water column was more effective at attracting silver eels than one with its entrance in the upper half. Haro *et al* (1999) and Rickhus (2001) report telemetry tagged eels making extensive vertical migrations during downstream migration in deep rivers. Rickhus (2001) and Dixon and Rickhus (2003) conclude that downstream migrating eels do not use visual clues but physically bump into barriers; and on encountering such obstructions show a startle response and dash a short distance back upstream, rather than seeking a way round the object.

Durif *et al* (2003) made some useful observations radio tracking eels around a small hydro-electricity plant with a bar rack across the turbine intakes. The space between the bars was 30 mm, and this appeared to prevent the passage of large eels, though one with a head-width of 35 mm did manage to pass through; this eel was 57 cm in length. Another eel with a head width of 35 mm (length 61 cm) and several fish with head-widths of 40 to 60 mm (length 65-90 cm) approached but did not pass through the rack. These figures provide a useful staring point for consideration of design criteria for bar screens.

Silver eels may either be attracted to sound (Patrick *et al* 2000) or repelled by it (Deelder 1970). The latter observation was based on reduced catches in fyke nets in the IJsselmeer when trawlers were operating nearby.

2.5.6 Conclusions for downstream migrants

From the foregoing 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 affected 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 size of eels involved in the downstream migration of maturing fish range from about 28 cm to more than a metre. Based on rather few data for larger eels (Durif *et al* 2003), a fish of 28 cm 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.

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 for limited periods of time. However, several attempts to develop the predictive model required for such an approach, with mixed success; they are 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.

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

3 FUNDAMENTAL APPROACHES TO PROVIDING FACILITIES FOR EEL PASSAGE

3.1 Approaches.

The fundamental aim for upstream eel pass design 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 (Sections 2.2.6, 2.2.8 and 2.3).

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 is the most widespread of the six approaches and commonly involves the use of ramps with a crawling or substrate.
2. Trap the fish at the base of, or part the way up the face of, the obstruction and release them above.
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 barrier.

Basic features of these approaches are now described. A wide range of sites employing these approaches is then presented in Section 4, and a detailed analysis of design features forms Section 5.

3.2 Facilities based on ramps with substrate

3.2.1 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. Two types of artificial substrate in widespread use, as described in Section 3, are bristle mats manufactured by "Fish-Pass" in France, and "Eel-ladder" rigid plastic matrix manufactured by Milieu Inc. of Canada. These an other types of substrate used are described in detail in Section 5.4.

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

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

- 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.

- 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 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 fall 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.

3.3 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 though 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.

3.4 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 at 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.

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.

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.

3.5 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.

3.6 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 a stream habitat. The possibility should at least be considered before other major works are planned.

3.7 Downstream passage facilities

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 supply or to drive machinery such as HEP turbines, and where any eels going with that part of the flow are likely to be killed or injured. The requirement is to prevent or discourage passage from the intake, and to guide the migrants to a safe bypass route. Approaches to this are discussed further in Section 5.16. The alternative of shutting down generation at times of peak eel migration has been discussed in Section 2.5.6.

4 SOME INSTALLATIONS ANALYSED

4.1 Introduction

In this section, installations in several countries are described and analysed with respect to design features and performance. The coverage is far from complete, rather examples are selected where they show some particular feature of interest. Some of the facilities have been highly successful while others have experienced problems and limitations – the latter are considered as important as the former in the context of this study! Some of the facilities represent massive engineering installations on very large rivers, while others are low-cost solutions for small watercourses and specific situations. Most of the facilities described were visited during this study.

4.2 British Isles

4.2.1 Upper Lode Weir, Tewkesbury, River Severn

Figure 4.2.1. Location of fish passage facilities at Upper Lode Weir

Upper Lode Weir forms the tidal limit on the River Severn, about 250 m below the confluence with the River Avon. The 1.2 m-high weir is about 40 m in length, with separate salmon, shad and elvers passes on the right bank (Figure 4.2.1).

The elver pass comprises a concrete channel about 0.5 m wide with a slope of about 10^{o} and a V shaped bed (Figure 4.2.2). The lateral slope of the two sides of the bed is about 45^{o}. Bristle mats are fitted to one of the bed faces, while the other is roughened with coarse gravel embedded in resin. When inspected the depth of water over the bottom apex was 0.15 m and the flow relatively turbulent. No monitoring of the performance has been undertaken but local fisheries staff suggest that the pass functions effectively at low river flows but at higher flows the upstream invert level is too low with the result that the bristle substrate drowns and the pass ceases to be effective.

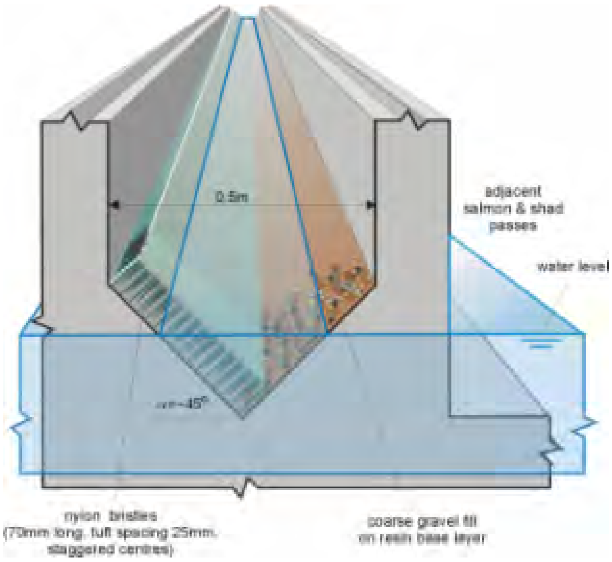


Figure 4.2.2. Upper Lode weir elver pass - configuration

4.2.2 Stanchard Pit, Tewkesbury, River Avon

The weir at Stanchard Pit is situated a few hundred metres upstream of the confluence of the River Avon with the River Severn. Thus fish arriving here have already passed the weir at Upper Lode (Section 4.2.1). The weir is 1.5 m high and about 40 m long. Bristle ramp trap-passes are located at each end of the weir (Figure 4.2.3). The pass alongside the left bank is a standard "Fish-Pass" pumped-supply design comprising two 0.42 m wide ramps each at a gradient of 45° with nylon bristles, and with a trap at the upper end (figure 4.2.4). Irrigation and attraction water flow are supplied by a submersible pump. The pass was not operational when inspected; the lower section was missing, having been damaged in a flood some time earlier. A similar installation on the right bank had been completely destroyed and replaced with a temporary pass. The elver pass alongside the right bank is pump-fed and consists of 0.15 m-wide ramps each at a gradient of about 16° with bristles substrate, and a trap at the upper end (Figure 4.2.5). Both the elver passes at Stanchard Pit are considered to have been effective and both are monitored by virtue of their in-built traps. The peak catch of elvers during the season was said to be of the order 10 kg per week. As their operation is independent of upstream water levels they can operate in all flows. However, as can be seen in Figure 4.2.5, gantry arrangements and ladders are required to access the passes for maintenance and to operate the traps, with potential risks for operators. Additionally, the location of these structures and their relatively fragile construction renders them prone to damage at flood flows: upstream water levels can increase by as much as 3 m.

Figure 4.2.3 Elver passes at Stanchard Pit Weir

Figure 4.2.4 Left-bank elver pass at Stanchard Pit, with lower ramp missing due to flood damage.

Figure 4.2.5. Right-bank elver pass at Stanchard Pit Weir

4.2.3 Strensham Weir, River Avon

Strensham Weir is situated about 7.5 km upstream of Stanchard Pit Weir. "Fish-Pass" pumped-supply passes have been installed at each end of the 60 m-long weir. Each comprises two 0.33 m-wide ramps 2 m long with a 40^o slope. The top of the pass is above the normal upstream water level, and fish successfully ascending pass down a 0.1 m diameter pipe from the top chamber, which discharges into a shrouded release port extending to just above the bed of the river just upstream of the weir. This reduces the risk of eels being washed downstream again (Figure 4.2.6). Water for the operation of the pass and for attraction is provided by a submersible pump. Monitoring of performance has been undertaken by securing a sacking trap to the end of the release pipe, but this was discontinued for reasons of operator safety.

Figure 4.2.6 Water supply and release ports for Strensham right-bank eel pass

Figure 4.2.7 Right-bank eel pass at Strensham Weir. It has been severely damaged during a flood by a log that is still jammed beneath the resting pool.

At the time of a site visit in June 2003 neither pass was operational. The one on the right bank had been severely damaged by a flood (Figure 4.2.7), and the submersible pump for the pass on the left bank was faulty. These passes are said to have worked effectively for a few years.

4.2.4 Bristle substrate passes on the River Avon

Several passes of similar design have been installed on the Warwickshire Avon. Three were visited and examined in June 2003 and as the designs and observations are so similar they are dealt-with together. All are installed in concrete channels on the gently-sloping downstream faces of weirs with long crests (Figure 4.2.8). Headwater level varies little because of the long weir crest and the regulation of level for navigation. The eel passes occupy about half of the 1.2 to 1.5 m width of the channel, the

Figure 4.2.8. General view of Chadbury Weir showing left-bank eel pass

remainder being occupied by a Larinier bottom-baffle fishway for other species; there is no septum between the two components of the pass. The eel pass comprises bristle substrate mats with a lateral slope of 17-30°, with the downward slope towards the baffle pass element (Figure 4.2.9). Some dimensions of the three passes are given in Table 4.2.1.

Table 4.2.1. Details of three eel passes on the River Avon. The dimensions and slopes were determined by site survey and are approximate. TL = tidal limit.

Site	Distance from TL	Head	Length of pass	Slope	Pass width	Eel mat width	Lateral slope
Fladbury	24 km	2.14 m	15.3 m	8°	1.24 m	0.7 m	30°
Chadbury	36 km	1.41 m	9.4 m	9°	1.56 m	0.7 m	17°
Evesham	40 km	2.0 m	22.9 m	5°	1.54 m	0.7 m	23°

While the flow on the day of the site visits was within the effective operating ranges of all three passes, limitations of the installations were apparent.

At all three passes the situation at the top end of the pass appeared to be less than ideal. Because of the large volume of flow being drawn into the baffle part of the pass the current "cuts across" the top of the elver pass – the situation at one of the Evesham passes is shown in Figure 4.2.10. It seems that small eels, having successfully negotiated the main body of the pass, are likely to be entrained with the flow across the top and be carried back down the baffle pass. This could perhaps have been largely overcome with the use of a septum to separate the two parts of the pass, at least at the top. In this respect the pass at Abingdon on the Thames (Section 4.2.7) may represent a better design, in that the two parts were separated by a wall, and the eel substrate was sloped away from the baffle part of the pass.

Figure 4.2.9 Bristle substrate and baffle fish pass at Chadbury Weir

Figure 4.2.10 The top end of the bristle substrate mat pass on the left bank at Evesham Weir. Note how the flow entering the baffle part of the pass cut across the upstream end of the substrate mat

4.2.5 Sunbury Lock, River Thames

Sunbury Lock is situated about 13 km upstream of the tidal limit. In addition to passage facilities at the associated weir (Section 4.2.6) facilities for passage of elvers and small eels have been provided within a sloping concrete channel designed as a canoe ramp, alongside the lock. The ramp is 20 m in length, 0.92 m in width and has a gradient of 5.2°. The head difference is of the order of 1.8 m. About 0.4 m of the width of the channel bed is fitted with an Enkamat substrate (Figure 4.2.11).

Figure 4.2.11 Canoe ramp at Sunbury lock showing Enkamat elver substrate on right-hand side.

No monitoring of the effectiveness of this facility has been undertaken. At the time of a site visit in June 2003 the Enkamat substrate was rather matted with algal growth which may reduce its effectiveness for elver passage. Further, the channel is highly susceptible to fluctuations in upstream water level due to lock operation; when the lock was filling, the upstream level dropped and no flow passed down the canoe ramp. At other times in the lock operating cycle there was a very fast flow of water about 8 cm deep over the substrate, and any elver emerging from within the substrate is likely to have been swept downstream. This latter situation is likely to prevail at night, when the lock is not being operated and most migration will be taking place. Finally, predation by rats may be a problem as the dual use of the channel precludes the fitting of covers.

4.2.6 Sunbury Weir, River Thames

Figure 4.2.12. Sunbury Weir elver pass

Sunbury Weir is situated about 1 km upstream of Sunbury Lock. It has a very long crest (in excess of 100m) and has an eel and elver pass built into the downstream face. This comprises a concrete channel 1 m in width and with a total length of 11.7 m to overcome the head drop of about 1.9 m. The gradient of the lower 8 m length is 13°, reducing to 6.3° for the upper 3.7 m length. There is a lateral slope on the bed of the channel of 10°. The bed is fitted with bristle substrate mats in 1 m^2

sections. The base of the mats is 10 mm thick polypropylene and the nylon bristles project 70 mm, and are arranged in rows of tufts (about 30 bristles to the tuft) in 5 mm holes at 20 mm staggered centres. The Thames is a navigable river with well-regulated, closely controlled levels; it is likely that the upstream level is within the effective operating range of the pass for the great majority of the time during the migration season. Possible limitations of this installation are its location (part-way along a long weir – will most elvers find it?) and the heavy growth of emergent vegetation on the substrate, largely blocking the interstices. The missing or displaced covers apparent in the photograph would allow access by predators. We understand that when originally built the downstream end of the ramp was perched above the tailwater level in a similar manner to that at Abingdon (see below), and that the tail was extended by about 1 metre with a steeper slope to overcome this miscalculation. No monitoring has been undertaken at this site.

4.2.7 Abingdon Weir, River Thames

Figure 4.2.13 Abingdon Weir eel and baffle passes, covers removed, Feb 2003

Abingdon Weir is well up the catchment, 142 km from the tidal limit. This pass has an interesting arrangement in that the fishway is a composite eel pass, 2-pool deep-notch fish pass and Larinier baffled fish pass (Figure 4.2.13). The lower of the two deep-notch pools are common to both passes. The eel pass commences at the end of the second pool notch and runs alongside the Larinier pass. The total length of the fish pass is 18.1 m and the head across it 1.8 m. The length of the elver pass is about 10 m and its width 0.7 m. The bed of the eel pass has a lateral slope of 9° away from the Larinier pass and is fitted with bristle substrate mats.

Figure 4.2.14 Downstream end of Abingdon eel pass in June 2003, showing tail-water level well below the bottom of the pass

While the Thames is a navigable river with water levels fairly closely regulated there is clearly a major problem with respect to downstream water level at this site. In Figure 4.2.13, taken in February 2003, the downstream level is within the effective operating range of the pass. However, at the time of a site visit in June 2003 the downstream water level was considerably lower, so that the lower end of the eel pass was perched some 17 cm above it (Figure

4.2.14). Under such conditions the pass is likely to be totally ineffective. This tailwater level is maintained throughout much of the drier part of the year. Remedy by raising the cill levels in the lower part of then pass is apparently planned. Another design anomaly is the use of bristle substrate for a site so far upstream; they are generally designed for the passage of elvers and small eels, whereas only larger eels are likely to occur here.

4.2.8 Cobham Mill, River Mole

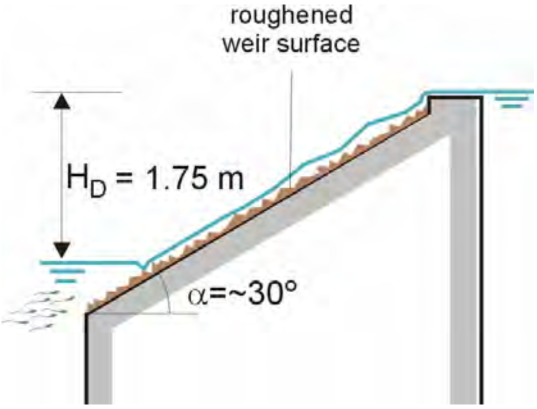


Figure 4.2.15. Features of Cobham Mill Weir

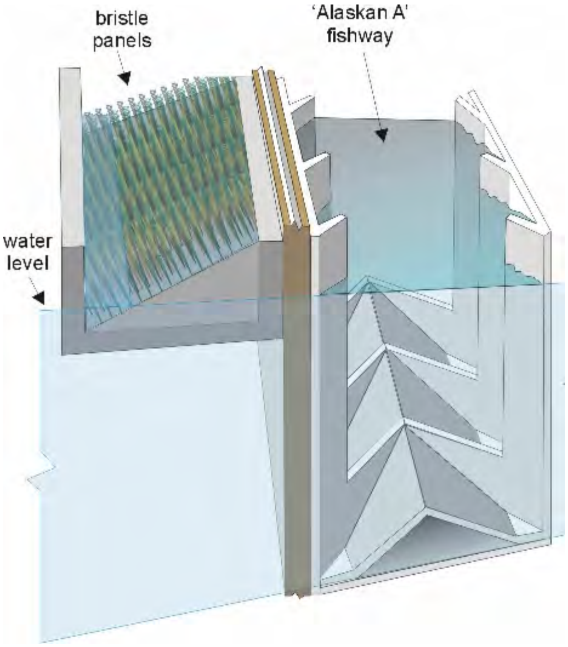
Figure 4.2.16. Cobham Mill Weir. Note vertical lip at weir crest, and broken water due to roughened surface.

Cobham Weir is on The River Mole, a tributary of the River Thames, about 28 km above the tidal limit. A roughened texture has been applied to the downstream face of the weir during major reconstruction. Figure 4.2.15 shows the approximate dimensions of the weir. No information is available about the effectiveness of the roughened surface for the ascent of eels. At the time of a site visit in June 2003 the conditions looked impossible for eel passage due to the gradient, water velocity, and the vertical lip at the crest of the weir.

4.2.9 Stoke Mill, Guildford, River Wey

Stoke Mill Weir elver pass is located on the River Wey, a Thames tributary, about 36 km above the tidal limit. The fish pass structure is a composite of two modular units, an 'Alaskan A' fishway and an eel pass with a concrete dividing wall between the two (Figure 4.2.17). The 9 metre-long fish pass complex was constructed in 1994 at a cost of about £45k.

The eel pass is within a concrete channel and employs bristle substrate. It has a level section part way up and the two sections, 5 m and 4 m in length, have a longitudinal slope of about 14°. The bed of the eel pass also has a lateral slope of about 30° (Figure 4.2.17); the bed slopes away from the adjacent fishway so that the lower entrance for elvers is not too close to the turbulent water outlet from the fishway and the exit route at the top is not too close to the accelerating flow down the fish pass. The downstream end of the elver pass was designed to be 8 cm below river tail-water level. When inspected in June 2003 the water level was 15 cm over the lower edge of the bristle panel, and the upstream water level was also well within the effective operating range of the pass. However, there was considerable clogging of the upper part of the eel pass with waterborne debris, and of the substrate itself with emergent vegetation (Figure 4.2.18). The site was clearly in need of maintenance.



Left: Figure 4.2.17. Diagrammatic representation of a cross section of the eels and fish pass at Stoke Mill Weir.

Above: Figure 4.2.18. Stoke Mill Weir eel pass showing excessive growth of vegetation – too much of a good thing?

4.2.10 Staines Lino Mill Weir, River Colne

Staines Lino Mill Weir is on the River Colne, a short distance upstream of its confluence with the River Thames, and is 31 km upstream of the tidal limit. The fish passage facilities are another example of a dual fish pass constructed within concrete channels; an eel pass and a Larinier baffled fishway. The weir has a head across it of 1.4 m. The eel pass comprises bristle substrate fixed to the bed of a sloping concrete channel. Figure 4.2.19 shows the weir and the fish pass channels; the elver pass is adjacent to the right bank. The bristles panel slopes away from the baffled fishway to enable elvers to exploit the lower velocities at the bank edges, and be afforded some protection from the outflow from and inflow to the fishway. The gradient of the elver

Figure 4.2.19. Staines Lino Mill eel and baffle passes.

Figure 4.2.20. Staines Lino Mill Weir – top of bristle ramp. Note fast flow and erosion of bristles.

pass is about 7° and the width of its concrete channel 0.7 m. The cross gradient is about 30° and although the flow through the elver pass appeared relatively turbulent, only half the bristle panel was submerged. The usual arrangement of bristle tufts was apparent: approximately 30 nylon bristles to the tuft with 2.5 cm between tufts and tufts ranged in staggered lines. Figure 4.2.20 shows detail of the upstream entrance to the bristle substrate; it can be seen that a section of the bristle matting has been eroded and a further area of bristles is flattened by the fast flow, with a resultant increase in turbulence, and a more difficult exit for elvers from the pass.

4.2.11 Barking Barrage, River Roding.

The Barking Barrage regulates the upstream level in the tidal part of the River Roding, 4 km from the confluence with the Thames. It comprises two 5 m-wide gates and an adjoining 14 m-wide weir. The weir is overtopped, and the gates are opened to allow passage of pleasure craft, for about 2-3 hours around high tide. The fish pass and elver pass are located alongside the weir at its right bank. The elver pass consists of a 0.2 m diameter pipe, 15 m long (Figure 4.2.21). The lower 11 m section slopes at 13°, and the upper 4 m section is horizontal; the hydraulic lift is about 2.45 m at low tide. The pipe is loosely packed with a climbing substrate made from rolled horticultural mesh with a 20 mm hole down the centre to help maintain a flow. The downstream entrance comprises a perforated vertical pipe from which the sloping pipe takes off. A similar perforated vertical pipe comprises the upstream outlet.

Figure 4.2.21. View down the fish pass at Barking Barrage at low tide. The elver pipe pass is on the left, and passes through the wall of the fish pass. The top of the perforated vertical stand pipe that represents the entrance of the pipe pass is just visible at the far end.

This is a strange design of pass with a number of limitations apparent. First, as the weir is overtopped on all high tides there would appear to be little justification for a pass at all; elvers are very adept at gaining access through and past barriers at high tide. Second, the choice of a pipe rather than an open channel substrate pass is surprising and has distinct drawbacks. Pipe passes, especially those with a long run, are highly susceptible to blockage with debris such as leaves and algae. This may not be a major factor in high-head dams where the reservoir acts as a settling tank and the water drawn into the pipe is clear of debris, but in this situation the problems are likely to be tremendous. There appears to be no provision for easy access for clearing any blockage. The fixed nature of the effective entrance is another limitation in a tidal situation. While elvers can gain access at surface level to an open channel as it is inundated by the tide, and should be able to do so at the furthest upstream point they can reach at any time, the entrance to the pipe pass is well seawards of the most upstream attainable point at any state of tide other than dead low.

The pass has provision for operation of a trap in a square-section stand-pipe located near the highest point. However, this is apparently difficult and potentially dangerous to operate and little attempt has been made to do so. There are therefore no observations on the effectiveness of the pass; the presence of eels upstream is to be expected as the barrage is overtopped at high tide.

4.2.12 Cathaleen's Fall Dam, River Erne

This hydro-electric dam at the tidal limit on the River Erne in Ireland has a height of 27 m. An elver pass was incorporated into the design when it was constructed in 1946 Matthews *et al* 2001; McGrath 1957). The original pass comprised a 75 cm wide channel affixed to the downstream face of the dam (Figure 4.2.22). There were several entrances to the pass to collect elvers from points where they were likely to gather, including within the salmon pass. The channel contained a layer of gravel, which was prevented from washing downstream by wooden battens fitted across the width of the channel at 1.8 m intervals. While elvers were observed to use this pass it was concluded that the arduous climb resulted in significant losses. Therefore in the 1960's the ladder was decommissioned and replaced with two ramp traps; the elvers captured in these are distributed throughout the catchment upstream of the dam. A third trap was added in 1994, following an exceptional run of over 4000 kg in the spring of that year.

Figure 4.2.22. The original elver pass at Cathaleen's Fall Dam.

The two traps comprise ramps of 70 cm width, about 1.5 m in length. Initially the ramps contained a climbing substrate of stones and straw ropes. Clumps of heather were laid over the substrate to prevent predation. Subsequently an artificial substrate (Tensar) has been used, though problems have been encountered with larger "bootlace" eels sometimes becoming trapped within the mesh; replacement with bristle mats is being considered.

A flow of water is provided down the ramps. The system is considered to work well, with an annual total of 647 to 1536 kg of elvers being recorded between 1996 and 2001. At the height of the run the traps may catch in excess of 100 kg per day.

4.2.13 Temporary installations; Thames, Darent, Severn and Avon

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

Their experience is most valuable for other situations where temporary or low-cost installations are required, for example for investigations of the requirement for a pass (how many eels are presently wishing to ascend any particular obstacle), to explore the optimal location for the downstream entrance for a more permanent installation, or where installation of more permanent works is delayed for some reason.

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 4.2.23). 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.

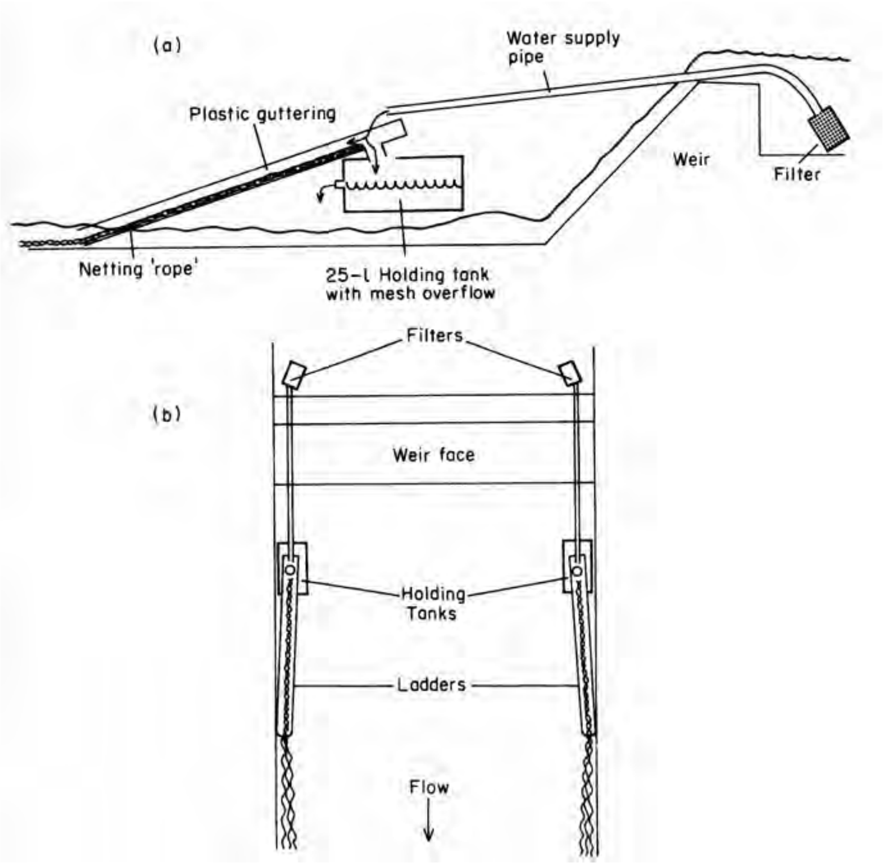


Figure 4.2.23. Pass-trap design from White and Knights (1994).

4.3 France

4.3.1 River Frémur – general description

The Frémur is a small river in Brittany about 20 km long and with a catchment area of about 40 km^2. The mean flow at Bois Joli, about 8 km from the tidal limit, is of the order of 400 litres per second. A major research programme is underway looking at the biology of the eel throughout the catchment. This is being undertaken by Antoine Legault and his 'Fish-Pass' colleagues on behalf of the Fédération Départment des Associations de Pêche et de protection du Milieu Aquatique d'Ille et Villaine and comprises the following elements:-

- annual electric fishing samples at more than 30 stations within the principal waterways;
- analysis of the migrations of juvenile eels at two upstream traps and adult eels at two downstream traps;
- marking experiments using PIT tags and dye marking;
- the measurement of specific characteristics of all captured eels.

The data collected from the Frémur has enabled a diagnosis of the status of its eel population, and the identification of improvements required to increase stocks. In particular, it has been possible to specify appropriate recruitment densities of juveniles throughout the catchment to optimise the number of descending mature adults.

The river has three dams where eel passes and traps have been installed; these are described in the following sections, and their location is indicated in Figure 4.3.1.

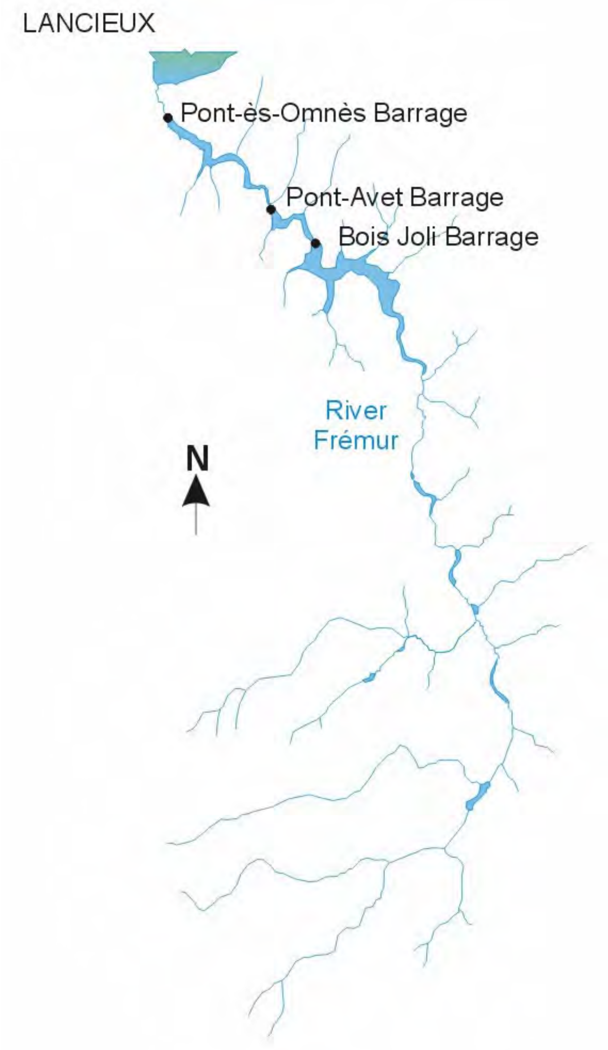


Figure 4.3.1. The Frémur catchment.

Figure 4.3.2. Pont Avet elver pass.

Figure 4.3.3. Upstream pass and trap pass at Pont-es-Omnès.

Figure 4.3.4. Elver trap at Pont-es-Omnès.

Figure 4.3.5. Small eels in trap at Pont-es-Omnès.

4.3.2 Pont-Avet, River Frémur

Pont Avet is a 2 m-high dam built during the Second World War for water supply purposes. It is about 5 km above the tidal limit. Electric fishing indicated a considerable concentration of elvers/small eels downstream from the dam when not spilling, but when spilling, eels are able to ascend the structure. A bristle substrate ramp has been installed below the dam at its upstream corner (Figure 4.3.2) to allow eel passage at low flows. The bristle substrate slopes at 30° both laterally and longitudinally and comprises a combination of tufts spaced at 9 and 14 mm. Below the bristle section is a resting pool, and below that a ramp with rough pebbles. No monitoring has been conducted at this site but numerous eels have been observed at sites further upstream.

4.3.3 Pont-es-Omnès, River Frémur – upstream facilities

This dam is about 2 km above Pont-Avet 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 4.3.3). A metal bar has been attached to the downstream face of the dam to prevent eels from using this route and bypassing the trap. The pass consists of two 30° slope ramps with bristle substrates (9 mm between tufts) that turn through 180° at a small resting pool. The substrate is fitted with a lateral slope, with a narrow section with a lesser slope in the opposite direction (Figure 4.3.3) 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 1 m-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 tank or, when catches are low, by using a sock-net attached to the outlet pipe. The cumulative catch for about 2 days in September 2003, comprising about 30 small eels, is shown in Figure 4.3.5. Many eels are trapped earlier in the year with up to 1000 per day being caught in June, average length 10-13 cm. Upstream migrants are marked by immersion in tetracycline, which fluoresces when exposed to ultraviolet light. The tetracycline can be detected subsequently in mucus and in the skin of juveniles for some time after marking, and in the otoliths of adults. This marking system has been in use on upstream migrants for six years and this year (2003) the first marked mature adults were observed as emigrating males at this site.

4.3.4 Pont-es-Omnès, River Frémur – downstream facilities

The downstream eel trap, which can operate at river flows up to 3 m^3/s, is shown in the Figure 4.3.6. It comprises Wolf grids with narrow gaps with a collecting trough at their downstream edge from which adult eels are conveyed by pipe down to a mesh holding-box. The catch is about 600-800 eels per year; mark/recapture suggests a total downstream run of 800-1200. During electric fish surveys upstream, all eels longer than 20 cm are PIT-tagged, and all downstream migrants are checked for tags at Pont-es-Omnès and the next upstream dam at Bois Joli (see below), at a distance of 1 km above Pont-es-Omnès. Some fish take a full year to pass down between the two dams.

Figure 4.3.6. Downstream eel trap at Pont-es-Omnès.

4.3.5 Bois Joli, River Frémur

This dam is about 1 km above the dam at Pont-es-Omnès, and the retained water level at the lower dam backs up to the foot of the higher one. The hydraulic head across the dam is about 13 m, which is a total obstruction to the upstream migration of eels and elvers. A fish lift was installed at this site in 1992, but is no longer used as such. The lower part

Figure 4.3.7. Eel lift at Bois Joli Dam.

of the old installation is used instead as an eel pass-trap (Figure 4.3.7). This consists of four, short 40 cm-wide ramps, with intermediate resting pools, and incorporates a 90º bend. The slope of each section is about 35º with bristle substrate mats. A box trap is installed at the top of the last ramp Figure 4.3.8). Figure 4.3.9 shows detail of the water sprinkler system at the top of the elver pass.

Figure 4.3.8. Top of elver pass and fish lift

Figure 4.3.9 Sprinkler water inlet at top of elver pass , Bois Joli

The now-disused lift operated by use of a tank in place of the present trap box, which was periodically hauled to the top of the dam to release the eels. When the motorised lift commenced its ascent a valve in its base closed to prevent the escape of eels and elvers. At the crest of the dam the lift engaged with a port in a release pipe to discharge the eels. The lift system is no longer used for two reasons. First, since the instigation of the whole-catchment research programme an accurate count of upstream migrants using a trap is now required. As eels can only pass this point via the pass-trap this operation gives a precise measure of the recruitment to the catchment upstream. Second, there were various design limitations (which have been overcome at a later similar installation at Ville Hatte Dam – see below). The main problem was that the design of the lift tank was too complex, with small apertures that allowed elvers to escape and perish on the face of the dam during the ascent operation.

Compensation flow through the dam is 10% of the mean flow of about 0.4 m^3/s. At this discharge, 20-30% of downstream migrants pass down through a discharge pipe and regulating flap valve. Heavy mortalities resulted since the valve only needed to be open about 1 cm to achieve the required compensation flow. The shape of the discharge orifice has now been changed to be more ‘eel friendly’, yet provide the same discharge. Mortalities are now less than 10%.

4.3.6 Plancoet Dam, River Arguenon

The River Arguenon flows northerly into Bancieux Bay with its estuary adjacent and to the west of the River Frèmur. Figure 4.3.10 shows the Arguenon catchment and the location of the two sites inspected, Plancoet Dam and Ville Hatte Dam. Not all the tributaries are shown and some have been truncated for brevity.

This dam normally forms the tidal limit of the River Arguenon and is used both to protect the town from inundation, and to maintain the upstream level for amenity purposes. However, when inspected, the hydraulically-operated sluice gate was fully open, allowing the channel upstream to drain at low tide (Figure 4.3.11).

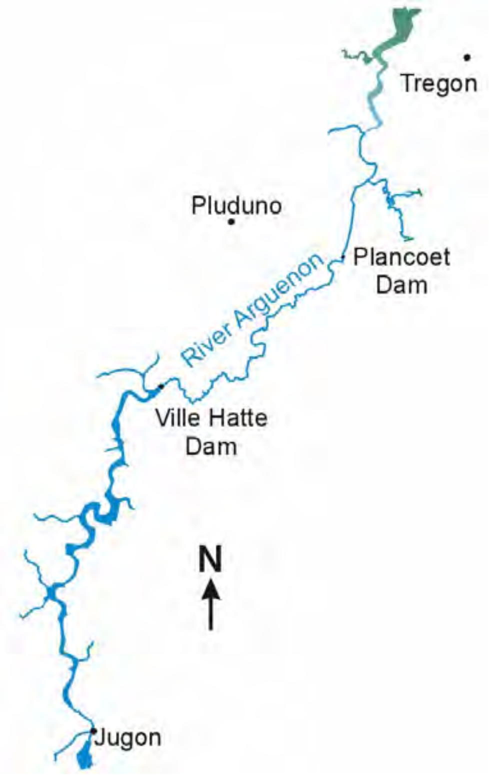


Figure 4.3.10. The River Arguenon.

Figure 4.3.11. Plancoet Dam from upstream. The sluice is open so the water surface is well below the usual retained level.

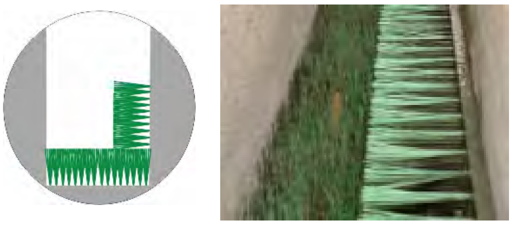


Figure 4.3.12. Detail of the substrate in the Plancoet Dam pass

An elver pass about 10 m long and with a gradient of 18 % is located within a 20.5 cm-wide concrete slot in the right hand sluice pier. As this is not wide enough to allow the more usual lateral slope to be incorporated, the bristle climbing substrate is folded through 90º to give a 20.5 cm-wide horizontal section and 20 cm-high vertical section (Figure 3.4.12). The lower section of the vertical array of bristles has been removed before the substrate panel was folded to retain the usual inter-tuft spacings. At the exceptionally low water conditions viewed the elver pass was not of course operating and the upper end can be seen to be well above the upstream water level (Figure 4.3.11).

4.3.7 Ville Hatte Dam, River Arguenon

The Ville Hatte dam is located about 20 km upstream from Plancoet. It is 14 m high with a crest length of 194 m. A section of the dam is shown in Figure 4.3.13 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 13 cm-wide section at 14 mm spacings, and two outer 13 cm-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 1.7m long. The downstream section of the eel pass, and the supply pipes for flow augmentation and attraction, are visible in Figure 4.3.13. These pipes penetrate through the dam wall and take surface water from above the dam.

Figure 4.3.13. The Ville Hatte Dam eel lift. The substrate ramps can be seen below the platform.

Figure 4.3.14. Lift hopper at Ville Hatte Dam eel pass in lower level position.

The trap and lift arrangement is similar to that at Bois Joli (see above) but 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 4.3.14) 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.

The lift was constructed in 1995 at a cost of 600,000 French Francs. 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.

4.3.8 Rophemel Dam, River Rance

The River Rance is the next river east of the Frèmur, and 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 4.3.15) is a standard early "Fish Pass" model and was deployed at Ville Hatte prior to 1995. It consists of a trap, and two ramps with an intermediate resting pool. The ramps are 35 cm wide at gradients of 35°, and contain bristle substrates with tuft spacings of 14 mm. The trap collection box (Figure 4.3.16) 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.


Figure 4.3.15. Rophemel Dam eel trap pass


Figure 4.3.16. Eel trap box at Rophemel


Figure 4.3.17. Pont Réan Weir eel pass

4.3.9 Pont Réan Weir, River Villaine

The River Villaine is a large watercourse, which flows west to Rennes and then south and west to its estuary at Pénestin. It is navigable for small boats from upstream of Rennes to the sea, and the level is regulated by a series of weirs with navigation locks. Pont Rean weir is about 20 km downstream from Rennes and is about 1.8 metre-high. The eel pass (Figure 4.3.17) also functions as a 15 metre-long canoe ramp but has bristle substrates at the sides of the 2.35 m-wide channel with a lateral slope of about 30º (no precise measure was taken). Chevron baffles


Figure 4.3.18. Eel pass at Moulin a Pigné

had been installed across the base of the channel, to allow passage of other species. The gradient of the channel is about 7º. The downstream turbulence would be difficult for migrating eels but the upstream level is being retained about 30 cm higher than usual due to the drought conditions. The pass is said to be effective at allowing the ascent of eels, but no monitoring is undertaken.

Figure 4.3.19. Detail of eel pass at Moulin a Pigné

Figure 4.3.20. Eel pass at Rennes Weir

Figure 4.3.21. Eel pass and adjacent channel at Rennes Weir

4.3.10 Moulin a Pigné, River Villaine

This is a 1.62 metre-high navigation and mill weir on the River Villaine downstream from Rennes. There are two concrete channels through one of the weir bays, each about 40 cm wide (Figure 4.3.18). 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 4.3.19. 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 channels is a horizontal section 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.

4.3.11 Rennes Weir, River Villaine

This 2.1 m-high weir is on the River Villaine in the centre of Rennes. An eel pass with a bristle substrate is located through the right bank (Figure 4.3.20). It consists of two 3.4 m-long sloping channels, each about 40 cm wide. One contains a bristle substrate but the function of the other channel was not clear: either for additional attraction flow, or for a second fish pass at a later date (Figure 4.3.21). The slope of the eel pass was 25º with a lateral slope of about 45º. The flow through the eel pass was low with virtually none of the bristle substrate immersed; this appeared to be due to partial blockage of the trash screen at the upstream entrance to the pass. The upper section of the pass comprised two horizontal channels concealed beneath access covers in the riverbank. The channels turned through two 90º bends before re-entering the river above the weir through trash screens. Each screen consisted of seven vertical, steel square-section bars Figure 4.3.22). The orientation of the bars, angle outwards instead of flat face, encouraged blocking by debris. It is suggested that a louver type of construction would be more effective at guiding debris away from the eel pass inlet and over the weir.

Figure 4.3.22. Trash screen at the upstream end of eel pass at Rennes Weir

Figure 4.3.23. Eel pass at Iffendic Weir

4.3.12 Iffendic Dam, River Meu

This is a small dam about 1.5 m high located on the River Meu about 40 km from the confluence with the River Villaine downstream of Rennes. The 4.3 metre-long elver pass (Figure 4.3.23) has a bristle substrate in a 70 cm-wide channel with tuft spacings of 11 mm. The slope of the pass is 22º with a lateral slope of about 10º to cope with 10 cm variations in upstream water levels. However, in the recent past the weir crest has been lowered by about 20 cm, leaving the top of the eel pass above the upstream water level and totally dry.

4.3.13 "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 4.3.24 is designed for gates with a stable setting with 5-10 cm 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 4.3.24. "Fish-Pass" prefabricated sluice gate pass

4.4 North America

4.4.1 Moses-Saunders Dam, St Lawrence River, Quebec

Figure 4.4.1. Two ramps of the new double-channel Moses-Saunders eel ladder. Photo D. Desrochers.

Figure 4.4.2. Details of the double channel pass at Moses-Saunders Dam. Photo D. Desrochers

The 25 m high, 1 km long Moses Saunders Dam was constructed on the St Lawrence River in 1959. No provision was made for fish passage until an experimental prototype eel pass was installed in 1974. This pass, and its successors, have been described by Whitfield and Kolenowsky (1978), Reid (1981), Eckersley (1982), Liew (1982) and McGrath *et al* (2003b).

The first pass was a sloping channel which zigzagged up the steep face (70^o) of a spare ice chute The channel was constructed from wooden boards and was 0.3 m wide and 0.25 m deep (outside dimensions). The pass ascended a total of 29.3 m, and at a slope of 12^o crossed and re-crossed the face of the ice chute 8.5 times, with a resting chamber at each change of direction. The total length of the pass was 156.4 m. The base of the channel was fitted with wooden baffles, 5 cm square in cross-section, set in a herringbone pattern. On top of the baffles was laid a substrate of green willow cuttings, but these were subsequently replaced by an artificial vegetation substrate ("Cassonia"). Water was pumped to the top of the ladder at a rate of 2.3 l/sec, and depth within the trough was typically 4.5 cm. The pass proved very effective, and more than 3 million eels passed up it in the first four years of operation. As this site is well up river the eels were several years old; the size range over the first four years was 13 to 84 cm, with 85% being 20 to 45 cm.

Although the pass worked well, the wood used for its construction rotted rapidly and it was replaced by an aluminium pass of essentially similar design after 5 years. However, the capacity was doubled by installing two parallel troughs of similar cross-section to the original, each carrying 2.3 litres/sec (Figures 4.4.1 and 4.4.2). In addition, there is an attraction flow of 7.5-11 l/sec. The new pass also worked well, with an average of 890,000 eels per year through to 1985. However, numbers have fallen markedly since then with an average of less than 4,000 per year by end of the 1990's; this is thought to be due to recruitment failure rather than to any feature of the pass.

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 following the initial ascent. A study was therefore undertaken to establish the optimal release location for planning future installations (McGrath *et al*, 2003c). 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%

4.4.2 Chambly Dam, River Richelieu, Quebec

Chambly Dam lies on the Richelieu River about 100 km from 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 eel passage facilities were incorporated until a pass was installed in 1997 (Desrochers and Fleury 1999, Desrochers 2000, 2001, 2002 and

Figure 4.4.3. Eel pass at Chambly Dam. Note the breakwater blocks on the dam crest, and the gravity-fed attraction water being discharged from two pipes part way down the dam face. Photo D. Desrochers

Figure 4.4.4. View of Chambly Dam eel pass from above. Note breakwater blocks on dam crest, covers over the channel containing "Eel – ladder" substrate, and electronic counting device on the pipe carrying the eels from the top of the pass to the keep net with its flotation collar. Photo D. Desrochers

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 4.4.3). The channel is 0.55 m wide overall, and contains "Eel ladder" modular plastic substrate (see Section 5.4.4). The main run of the pass is 9.3 m in length and has a slope of 52°. A 1.1 m section with a shallower slope (7°) then leads over the blocks on the dam (Figure 4.4.4). 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 0.6 l/sec, and the final chute with 0.1 l/sec. Attraction water (about 14.4 l/sec) is discharged from two pipes, one each side of the pass, about 2.5 m above the tailwater level.

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 19.6 to 74.1 cm (mean 38.62 cm). 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.

4.4.3 Beauharnois Dam, St Lawrence River, Quebec

The Beauharnois complex on the St Lawrence River comprises several dams on separate channels. Eel passage facilities have been installed at the central Dam (Desrochers and Fleury, 1999; Desrochers, 2000; 2001; 2002; Bernard and Desrochers 2002). The central Dam was constructed around 1932 and has a crest length of 850 m and a hydraulic head of about 24 m. For many years the only upstream migration route for eels was via the navigation locks; for the period 1975 to 1999 the number of eels observed migrating each year at the Moses-Saunders Dam, 80 km upstream, were correlated with the number of lock

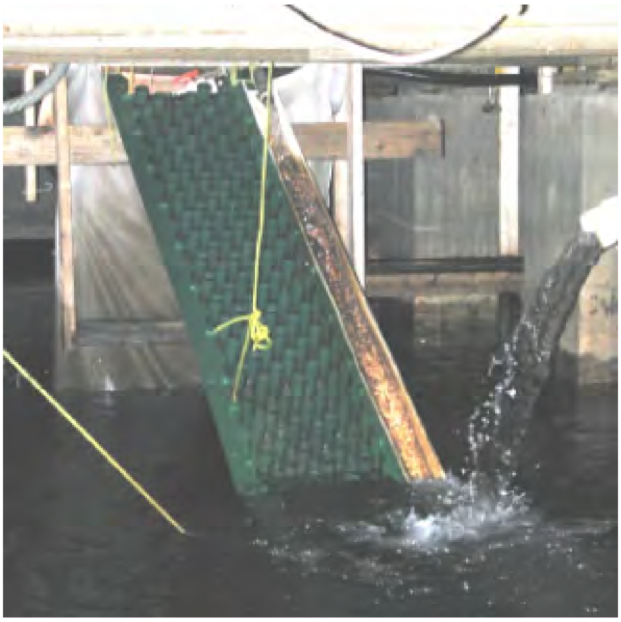


Figure 4.4.5. Earlier eel pass-trap at Beauharnois, using "Eel-ladder" substrate. Note attraction flow. Photo D. Desrochers

operations at Beauharnois the previous summer.

Between 1994 and 2001 a pass-trap was operated in a debris chute at the western end of the central Dam (Figure 4.4.5). This comprised a 1.52 m long "Eel-ladder" ramp (see section 5.4.4) with a slope of 45°. The ramp was supplied with a flow of water of 0.5 l/sec, and a further 3.5 l/sec of attraction water was released near the foot of the ramp. On reaching the top of the ramp the eels slid down a chute into a large keep net (1.5 x 1.5 x 2.0 m) made of 2 mm mesh. Between 6,800 and 24,700 eels were caught each year, with a mean length of around 42 cm.

A permanent pass was installed in the same location in 2002. This comprised "Eel-ladder" substrate ramps leading up the full 24 m head of the dam. The design was complex due to the constraints of the site, with several changes of direction. The pass comprises five main sections with small level areas at each turn (Table 4.4.1).

Table 4.4.1 Details of the five sections of the pass at Beauharnois Dam.

Section	Length	Slope
1	6.3 m	22°
2	9.4 m	22°
3	2.7 m	15°
4	31 m	40°
5	2.4 m	45°

The total length of the pass is 52 m. The lowermost quarter of the first section is submerged at normal tailwater levels. At the top of the fifth section, a chute 1.2 m in length and with a downward slope of 22° takes the eels into a keep tank or head pond.

The "Eel-ladder" moulded sections are supported in an aluminium angle frame, and are covered with aluminium sheets during normal operation (Figure 4.4.6). A flow of about 0.4 l/sec is pumped to the top of the pass, with a further 14 l/sec of attraction water being discharged near the entrance to the pass.

The new pass has clearly been a success, with more than 13,000 eels ascending it in its first year of operation. In the same year (2002) a trap pass was operated on the eastern side of the central Dam; this caught more than 32,000 eels.

Optimal release location has been studied at this site in the same way as described for Moses Saunders Dam (Section 4.4.1). The rate of return to downstream of the dam for release locations at

Figure 4.4.6. The bend between Sections 3 and 4 of the new eel pass at Beauharnois. The aluminium lids are lifted to show the "Eel-ladder" substrate and the resting chamber. Many small eels are visible in the resting chamber. Photo D. Desrochers

different distances upstream on each bank of the river are shown in Table 4.4.2.

Table 4.4.2 Rate of recovery of eels downstream of Beauharnois Dam, according to upstream release location.

Distance above dam (m)	West side	East side
0	4.5%	12.0%
90	5.0%	4.2%
1600	3.2%	1.1%

4.4.4 "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.

Figure 4.4.7. A "portable passage" being operated at Benton Fall Dam in Maine. The cover is lifted to show the Enkamat substrate ramp. Photo G. Wippelhauser

The devices comprise a wooden trough 1.8 m in length, 0.3 m wide and 0.1 m deep mounted on a frame at an angle of 35^{o} (Figure 4.4.7) . The Enkamat substrate is stapled to the bed of the trough. Water is supplied to the top of the ramp at a rate of 0.17 l/sec. At the top of the ramp a slide angles downwards into the catch box; this ramp is also supplied with a flow of about 0.17 litres per second. The pass is protected by a removable aluminium cover to exclude light and predators.

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 4.4.5).

4.4.5 Sebasticook River Dams, Maine

Following evaluation using "portable passages" (Section 4.4.4) permanent eel passes were installed at two sites on the Sebasticook River, a tributary of the Kennebec River in Maine (Wippelhauser 2001, 2002, 2003).

The pass at Fort Halifax (Figure 4.4.8) was installed in 2000. It is of wooden construction, 0.6 m wide and 0.1 m deep. The entrance ramp is parallel with the dam face and is 2.6 m long with a slope of 30^o. A right angle bend with a 0.6 m resting area leads to a 4.8 m ramp with a 43^o slope. Finally, a 2.4 m wide ramp with a slope of 10^o 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.

Figure 4.4.8 Pass at Fort Halifax Dam. A "portable passage" ramp is being deployed alongside. Note layout to ensure that entrance to pass is close to the face of the dam. Photo G Wippelhauser

The pass at Benton Falls (Figure 4.4.9) was installed in 2001. This comprises twin entrance ramps of wooden construction, each 1.7 m in length at a slope of 47^o. There is then a level transition platform followed by a 10.8 m ramp at 39^o, followed by a 3.6 m ramp at 4^o leading over the dam crest into a holding pen. These two main ramps are made from aluminium cable tray 0.45 m wide with plywood attached to the bed. The climbing substrate of Enkamat 7220 is stapled to the plywood. The vertical head at this site is about 7.3 m.

Figure 4.4.9. Pass at Benton Fall Dam. Note layout to ensure entrances to pass are close to the dam face. Photo G Wippelhauser

These two installations have been successful in passing considerable numbers of elvers and small eels

(Table 4.4.3). The largest fish recorded using these facilities was 23.6 cm.

Table 4.4.3 Numbers of elvers and small eels recorded at passes on the Sebasticook River. Some of the total for 2001 at Benton Falls was recorded using portable passages before the permanent pass was installed.

Year	Fort Halifax	Benton Falls
2000	81,628	
2001	224,373	231,859
2002	56,292	22,502

4.4.6 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 (“west”) was therefore replaced with a vertical board, 0.55 m long and 0.3 m wide, with Enkamat 7220 substrate stapled to it (Figure 4.4.10). 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 (“east”) 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 4.4.10. Vertical substrate board on the west ramp at West Harbor Pond. Photo 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 100mm (see Section 2.2.6).

4.4.7 Garrison Lake, Delaware

This is another 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 4.4.11. Elver pipe-pass at Garrison Lake, Delaware, soon after installation. Photo S Shotzberger

Above: Figure 4.4.12 Garrison Lake elver pass two years after installation. Photo 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 4.4.11). 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.

After two years, a mat of natural vegetation had developed on the trawl mesh on the back of the weir (Figure 4.4.12), 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.

4.4.8 Greeneville Dam, Shetucket River, Connecticut

Information and photographs of this site have been supplied by Alex Haro of the USGS Anadromous Fish research Center. 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° – 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 4.4.13). The main lift is provided by a 9.2 metre long ramp at 27°. This was constructed of 4.8 mm thick sheet aluminium bent to form a 43 cm wide channel. This contains "Fish-Pass" bristle substrate. The pass then goes through a 90° bend into a 6.7 m channel with minimal slope (3°) which leads the eels to a catch box. This section if fitted with "Akwadrain" substrate (see section 5.4.4) which extends beyond the upstream end of the ramp down into the catch box (Figure 4.4.14). The top of the ramp is supplied with a flow of 3.5 to 7 l/minute, 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 1990. About 800 eels were passed in 1990, but a higher proportion were over 150 mm than in the previous year. The total for 2001 was 5739 eels.

Figure 4.4.13. Eel pass at Greeneville Dam. Photo A. Haro

Figure 4.4.14. Akwadrain substrate extending beyond top of ramp at Greeneville Dam eel pass. Photo A Haro

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 "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/minute is likely to be more effective than the current 75 l/minute.

4.4.9 Westfield Dam, Westfield River, Connecticut

Figure 4.4.15. Eel pass-trap at Westfield Dam viewed from above. The eel pass is the pale grey installation on top of the Denil fish pass. The eel pass has two ramps, one collecting fish from within the fish pass, the other from between the fish pass and the dam wall.

A visit was made to this site, on a tributary of the Connecticut River, in October 2003. A pass-trap is installed at one end of this long low-head hydro power dam. It comprises two parallel ramps, one to collect eels from the lowermost section of a Denil fish pass, and the other to collect fish from the base of the dam behind the fish pass (Figure 4.4.15). The head of the trap pass is of the order of 3 m and the ramps are mounted at an angle of about 40^o. The ramps are of aluminium sheet construction, about 50 cm in width, and are fitted with "Akwadrain" plastic substrate. The ramps are covered with sheet aluminium lids. Eels which use the two ramps are kept separately within the trap tank to establish which route was used. Each ramp is supplied with a flow of the order of 20 l/min (Figure 4.4.16), and an attraction flow of about 75 litres/sec is supplied to the lower part of each ramp.

Figure 4.4.16 Top of one of the ramps at the Westfield pass-trap showing the Akwadrain substrate and the jets of water irrigating the ramp.

Most eels use the fish-pass ramp when the fish pass is operating, otherwise most use the ramp which collects fish from close to the dam face, behind the fish pass. Between 50 and 5000 eels have used the pass each year since its installation a few years ago. No elvers are caught this far up river, most eels caught being 100-120 mm in length.

The pass-trap was designed by Dr Alex Haro of the USGS Anadromous Fish Research Centre at Turner's Falls. Based on operating experience he suggests that he would make the he following modifications to the design for any new installation:

- Use of a different substrate such as the Milieu "Eel-ladder". While the Akwadrain material is cheap and fairly effective it is not very robust. At the time of the site visit the lower few metres of substrate was missing from one of the ramps because of flood damage.

- Make ramps easier to remove in the winter Floods and ice cause significant damage.

- Make the fish-pass ramp less steep; constraints of the site required a steeper slope.

- Supply a greater attraction water flow.

5 TOWARDS BASIC DESIGN GUIDELINES

5.1 Introduction

In this section design criteria 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 Section 4.

5.2 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.

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 attractive 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 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 being immediately washed downstream can be avoided.
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, for those that prevail for most 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 have already been considered in Section 2.

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, and removal of facilities during the winter. This latter option may 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 do not have access.

5.3 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 5.8.

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 (such as the pass-traps described in Sections 4.2.13 and 4.4.4) 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; in Section 4.4.6 a situation is described 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.

5.4 Facilities based on substrates

5.4.1 Advantages and limitations of different types of installation

The advantages and limitations of the three types of substrate facilities (as defined in Section 3.2) 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.

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.	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. 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). May be vulnerable to flood damage and vandalism.

5.4.2 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 (Tesch 1977; Rigaud *et al* 1988; Dahl 1991). The ramps for elver traps at Cathaleen's Falls on the Erne (Section 4.2.13) included three of these materials; a layer of stones and straw ropes, covered with clumps of heather to prevent bird predation! (Matthews *et al*, 2001). While some of these materials have suitable properties for this purpose they appear to be inferior to the range of modern artificial materials and their use is fast disappearing.

Limitations include rapid deterioration causing conditions repellent to eels in the pass (Dahl 1991) and necessitating frequent replacement; for example, green willow cuttings stapled to the wooden trough throughout a 156 metre-long pass at the Moses-Saunders Dam on the St Lawrence River (see Section 4.4.1) required replacing every week of the operating season; after four years of operation they were replaced with artificial plastic vegetation. Some natural materials have also proved selective in the size range of eels that could use them. Moriarty (1986) compared two ramps side by side at Parteen on the River Shannon, one with a substrate of ropes made from hay, the other with artificial bristles. The largest eel observed having ascended the hay ramp was 13.9 cm long, whereas eels as large as 50 cm were observed to use the bristle ramp. Tesch (1977) reported a situation where the number of elvers using a pass increased fourfold when the brushwood substrate was replaced with bristle brushes.

It is therefore suggested 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 5.5).

5.4.3 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. Typical are the range of bristle mats marketed by the company "Fish Pass" in France. These are typically 1 m by 0.4 m polypropylene mats with clumps of bristles about 7 cm 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 spacings 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 1 m x 0.4 m panel for all bristle spacings. For many sites in England mats have been fabricated to a particular specification in the UK. A number of installations using these substrates are described in Section 4.

Legault (1992) investigated number and size selectivity of pass ramps according to the spacing of the tufts of bristles (7, 14 and 21 mm) and the slope (15^o, 30^o and 45^o). 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^o**	**30^o**	**45^o**
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 (7mm) was less used than the larger 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. 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.

5.4.4 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; see section 4.4.7), nylon garden netting and Astroturf (Knights and White 1998), artificial vegetation, trade name "Cassonia" (Eckersley 1980; see section 4.4.1) 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".

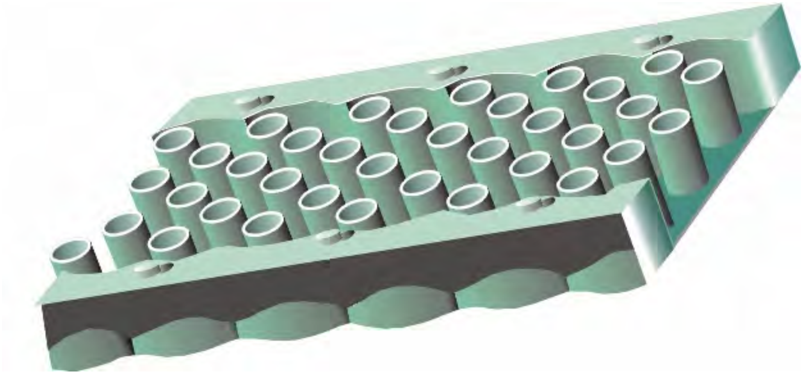


Figure 5.1 Milieu "Eel-ladder" substrate for eels over 15 cm in length

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 mucous. They also found it to be size selective, only allowing passage of eels of less than 26 cm. The main use of these substrates would thus appear to be at lower river sites where elvers and small eels predominate.

Figure 5.2. "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. One used extensively in North America is called "Eel-ladder" and has been developed by Milieu Inc of Quebec (Figure 5.1). 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 layout and spacing are indicated in

Figure 5.1. The material is provided in moulded modular channel form so only needs a frame to support it. This substrate is designed for eels of 15 to 75 cm, so is best suited to passes some distance up river. This design has been used with great success in passes at Chambly Dam (see section 4.4.2) and Beauharnois (see section 4.4.3) both in Quebec, and a number of other sites in Canada. 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 of 140 mm in width.

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 5.2. The substrate is designed to be laid in an aluminium channel. Exploration of the need for, and options for, coating of the machined material are continuing.

Another solid plastic substrate, developed by "Fish-Pass" in France, is illustrated in Figure 5.3. 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°. This substrate is under evaluation at sites in France.

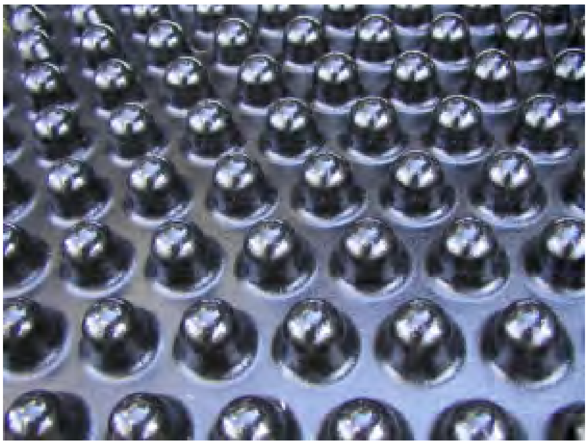


Figure 5.3 Plastic eel pass substrate developed by "Fish-Pass" in France, currently under evaluation.

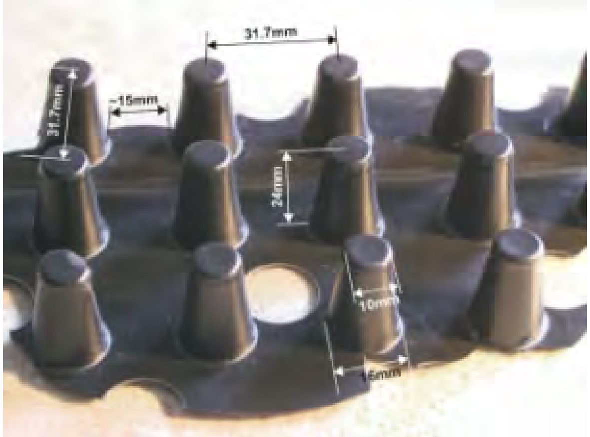


Figure 5.4 "Akwadrain" plastic substrate

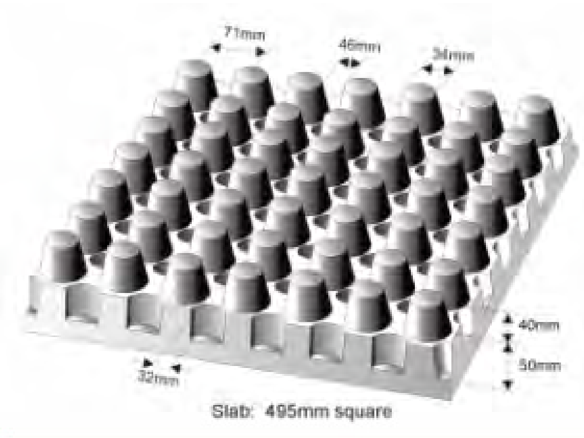


Figure 5.5 "Pelcar" concrete substrate

Several eel passes in North America (eg Sections 4.4.8 and 4.4.9) 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 5.4. The main advantages of this material is 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.

Experiments have been conducted in France using concrete block substrates. Voegtle and Larinier (2000) examined the effectiveness of several such substrates including some made specially but also one manufactured for car parks and walkways called "Evergreen" (similar to the "Pelcar" slab, Figure 5.5), 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). 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 (15 cm) 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.

5.4.5 Slope

The vertical slope of ramps represents a compromise between ensuring restricted water velocities and making climbing 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 (see section 4.4.1) 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 slopes for brush substrates should be not more than 35°.

The Milieu "Eel-ladder" substrate described in Section 5.4.4 is designed to be installed at slopes of up to 55°. Chambly Dam (Section 4.4.2), 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 (Section 4.4.3), 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° at Fort Halifax and 47° at Benton Falls; each of the these installations passed over 200,000 elvers and small eels in 2001 (Wippelhauser 2002). These passes are described in

Section 4.4.5. Enkamat has also been used successfully attached to vertical surfaces for passage of limited numbers of elver (Section 4.4.6).

5.4.6 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 °	Length (m) for 1 m of head
10	5.8
15	3.9
20	2.9
30	2.0
35	1.7
45	1.4

Thus for the 35° 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; this 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 5.4.9).

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. However, no investigations could be identified where the requirement for, and effectiveness of, such provisions had been examined.

The greatest hydraulic heads overcome by ramp passes that could be identified were 27 m at Cathaleen's Fall on the Erne (Section 4.2.13) and 25 m at Moses-Saunders Dam on the St Lawrence (Section 4.4.1). 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° the pass is 156.4 m in length, the longest eel pass identified in this study. It incorporates eight resting boxes, 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 Falls 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.

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.

5.4.7 Width and depth

Most of the substrate ramp passes reviewed in this study (Section 4) have channels between 0.3 and 0.7 m in width. One design (temporary pass-traps used on a number of rivers, described in Section 4.2.13) is only 0.1 m wide, and the pass at Sunbury Weir on the Thames Section 4.2.8) is 1.0 m 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 (Section 4.4.1), which was only 0.3 m wide, handled over a million sizeable eels per year apparently without undue congestion. However, two "portable passages" at a site in Maine (Section 4.4.4), each 0.3 m wide, were apparently overwhelmed by a run of elvers in excess of 550,000. 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 horizontally. 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 10-15 cm being typical. Most of the wider ramps are in passes where the substrate is laterally-sloped to allow for changes in headwater level (see Section 5.4.10), and thus only a fraction of the substrate is usable at any time. Such channels are inevitably deeper, typically of the order of 0.3 to 0.5 m.

It is therefore suggested that a ramp width of 0.3 to 0.45 m and depth of 0.1 m 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 0.15 m wide elver substrate units produced by Milieu Inc (Section 5.4.4). Where the substrate is installed with a lateral slope, a width of 0.4 to 1.0 m 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 bed.

5.4.8 Flow down the pass

Most substrate passes operate most effectively with a surprisingly small flow down the ramps. 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 5.12.

The flow supplied to a range of effective passes is shown in Table 5.4.

Table 5.4. Flow down a selection of substrate passes.

Site	See section	Substrate	Width	Flow l/min
Moses-Saunders	4.4.1	Cassonia	60 cm	138
Chambly	4.4.2	"Eel Pass"	55 cm	36
Beauharnois (pass-trap)	4.4.3	"Eel Pass"	55 cm	30
Beauharnois (new pass)	4.4.3	"Eel Pass"	55 cm	24
Maine "portable passage"	4.4.4	Enkamat	30 cm	10.2
Fort Halifax	4.4.5	Enkamat	60 cm	8
Greenville	4.4.8	Bristle	43 cm	3.5-7
Westfield	4.4.9	Akwadrain	50 cm	20

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 5.4.4), 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°, less than 10 mm at 30°, and less than 5 mm at 45°. Bristle substrates manufactured by "Fish-Pass" give best results with 2 – 12 mm depth over the bed (A. Legault, pers. comm.).

5.4.9 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.

Installations at some sites have failed to address the full range of variation, for example at Sunbury on the Thames (Section 4.2.6), requiring corrective engineering.

5.4.10 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 (see Section 3.1), 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 70 cm 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 well illustrated by some of the bristle ramp passes on the Avon (Section 4.2.4).

Table 5.5 Effective head-range and effective corridor-width of a 70 cm 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 70 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	cm	cm
0	7.0	70.0
10	19.2	39.8
20	30.9	19.2
30	42.0	12.2
40	52.0	8.4
45	56.5	7.0
50	60.6	5.9
60	67.6	4.1
70	72.8	2.5

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 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.).

Some long-term statistics for the period April 1 to September 30 (the main period for upstream migration of elvers and eels) are shown in table 5.6.

Although the Agency uses a design criterion of allowing effective passage for 90% of the time for salmonids, as discussed in Section 2.4.3 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 3.8 cm for the Asker, 24.5 cm for the Stour, and 48.3 cm 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 excedence figures for the period April to September for gauging stations on three rivers in Southern England.

	Stage height or range of stage heights (cm)		
Flow or flow range	**Asker**	**Stour**	**Avon**
Q100	13.2	19.4	2.6
Q95	14.3	35.7	33.3
Q50	17.0	43.9	50.9
Q10	23.3	59.8	72.0
Q100 toQ10	10.1	40.4	69.4
Q100 to Q50	3.8	24.5	48.3

5.4.11 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. Most ramp passes are therefore fitted with covers to exclude or discourage such predators. 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.

5.5 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 (Section 4.2.8) by roughening the weir back but has probably been unsuccessful due to the steepness of the weir back and other hydraulic features. Knights and White (1998) suggest optimal hole/crevice sizes of about 2 mm for "glass eels", 4 mm for fish of 15 cm, and 7-15 mm for 20-40 cm 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 most of Europe in this important development and it is strongly recommended that this approach is explored as an option wherever passage facilities for eels and other species is required.

5.6 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 4.4.7) to more than 65 m (Patea Dam, New Zealand; Clay 1995, Mitchell 1995). Typically pipes of the order of 0.1 to 0.2 m diameter are used (for examples see Sections 4.2.12 and 4.4.7). Substrates deployed have included netting (Sections 4.2.12, 4.4.7), 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 4.4.7) 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. Limitations of the pipe pass on the river Roding have already been discussed in Section 4.2.12.

The long pipe pass at Patea Dam, New Zealand (Clay 1995; Mitchell 1995) is not a pipe pass in the same sense as those already considered 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. Problems have arisen with high temperatures due to solar heating killing elvers within the pipe; with a bottle-brush substrate 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 bottle brush substrate has now been replaced with aggregate which is bonded to the base of the pipe with epoxy adhesive.

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.

5.7 Lifts and locks

Only two eel lifts were identified in the site survey, both in France (Sections 4.3.5 and 4.3.7). They were of similar design, and the later one took into account the operating problems experienced at the first. 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 to fall into the hopper; 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 retuned 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 FF600,000. 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.

5.8 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 looked likely.

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 the Beauharnois Dam on the St Lawrence – details are given in Section 4.4.3. 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.

For pumped-supply passes and lifts, the discharge pipe from the top of the facility can be routed to an appropriate release point; a good arrangement, with a shrouded discharge port extending deep into the water, is described in Section 4.2.3.

For straightforward 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 river bed to above the surface to allow the emerging fish to return safely to deeper water.

5.9 Monitoring arrangements

Monitoring arrangements are of considerable importance for several reasons. First, they provide an 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 an 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 5.10).

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 tunnel pass is a little more complex but by no means impossible.

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

- 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.

- The trap should provide safe refuges for the animals collecting there. Sacking bags and brightly lit boxes without refuges, from which the animals are constantly trying to escape, are not satisfactory.

- 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).

- The trap should be protected from excessive temperatures that might be caused by direct solar radiation.

Another approach to monitoring is automatic counting. Both resistivity and photo cell 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. 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.

5.10 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 may be a productive feeding ground.

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 (Section 4.2.13) and Cliff. The elvers are released at 30 to 50 sites throughout the catchment, and the target stocking rate is 1 kg per hectare per year.

5.11 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 (rocky/vegetation-filled channel) installations 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 is 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 (2000) reports visual evidence of eels passing through fish passes fitted with observation windows. Travade *et al* (1998) report large numbers of 20-30 cm eels using a vertical slot fish pass at Bergerac on the Dordogne River, with a head-loss of 30 cm 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 (30 cm) the pools were more turbulent (200 W/m^3 compared to 150 at Bergerac) and this was thought to be a factor.

The maximum flows 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. The predicted velocities may be compared with the information in Section 2.3, which suggests that a 60 cm eel should be able to maintain a burst speed of around 1.4 m/sec for 20 seconds. 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.

Table 5.7. Typical velocities in fish passes

Pass type	Conditions	Velocity (m/sec)[1]	Note
Pool and traverse	30 cm head between pools	2.43	2
Vertical slot	30 cm head between pools	2.43	3
Undershot sluice	60 cm 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, 0.35 m headwater depth	1.3	7
Baulk		? 2.5	8

Notes on Table 5.6:

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

[2] is fish pass with a notched traverse with a maximum velocity dictated by the hydrometric head over the traverses. It can accommodate significant variations in upstream water variations provided the downstream variations are similar. 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. As for [2] above, this fish pass can accommodate significant variations in upstream water variations provided the downstream variations are similar. 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 pass is designed mainly for higher flows and is more suitable for salmon (minimum flow ~0.15m^3/s, and minimum notch width 0.2 m).

[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 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 1960's for Pacific salmon and has many baffle variations. The standard form is narrow (0.56 m wide, 0.70 m high, and a clear interior width of 0.35 m), which allows steep slopes (25%) to be used. Its highly effective baffles limit its flow such that a slope of 30% for a 3 m section 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 is 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 10 cm, maximum slope 15%, and maximum length 12 m. A maximum upstream water level of 0.25 m would result in average water velocities up to 1.4m/s; again maximum water velocities may exceed 2 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 30 cm 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.

For example, in the situation described above for a 30 cm head loss through a vertical slot at a pass at Bergerac, the mean velocity through the slot is predicted at 2.43 m/sec. This is well above the burst speed for a 30 cm eel at 20°C given by the Swimit model (Section 2.3) of 1.12 m/sec, but large numbers of such eels were seen to ascend the pass.

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 (30 cm dia) 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 (Anne Laine, pers.comm.). It is possible that such an approach may help passage of eels and elvers too.

5.12 Attraction flow

Substrate ramps operate most effectively with very low flows of water within the channel itself; volumes used in successful facilities reviewed in Section 4 are as low as 0.2 litres/sec 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 5 – 20 litres/sec 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", does not employ any attraction water, and the flow down the ramp is only about 0.17 l/sec. 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 them to find the optimal location.

Even with attraction water, many successful passes have associated flows which are miniscule relative to the overall river flow. The effective pass at Beauharnois Dam on the St Lawrence (Section 4.4.3) 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 may well be largely dependent upon appropriate positioning of the downstream entrance.

5.13 Constraints at gauging structures

Hydrometric gauging structures such as Crump-section weirs are generally readily passed by powerful swimmers such as 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 are 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 along each flanking wall of Crump-section weirs to allow passage at low flows. Such installations could be very 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.

5.14 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 most 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 a re 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 sections 4.2.1, 4.3.6 and 4.4.6.

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 seawards 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 (undated) 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. 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).

5.15 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.

5.16 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 are considered at all stages of planning, construction and operation of facilities.

5.17 Protecting downstream migrants

Although detailed consideration of systems for the protection of downstream migrants 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 2.5.6). Similarly, the approach velocities appropriate for salmonids 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% for 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.

- 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.

- Limited data on sound (especially low frequency, less than 100Hz) suggests that it could be exploited to divert migrants.
- Water jets and air bubbles appear to be ineffective at diverting eels.

- 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.

- Mechanical barriers have potential, mainly in smaller rivers and at smaller projects, where construction of barriers across the entire water column might be feasible.

- 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, improved efficiency.

- 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.

- The approach of shutting down generation during peaks of migration (discussed in Section 2.5.6) is likely to be non-viable because of the difficulty in predicting the times reliably and the high economic cost. It may be viable on small river systems where peaks of activity may be shorter and more predictable.

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

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