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Eel passes

Improving design and performance

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Foreword

Scientific research and analysis underpin everything the Environment Agency does. It helps us to understand and manage the environment effectively. Our own experts work with leading scientific organisations, universities and other parts of the Defra group to bring the best knowledge to bear on the environmental problems that we face now and in the future. Our scientific work is published as summaries and reports, freely available to all.

This report is the result of research commissioned and funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme. Our vision is that the nation is recognised as a world leader in researching and managing flooding and coastal change.

The Joint Programme is overseen by Defra, the Environment Agency, Natural Resources Wales and the Welsh Government on behalf of all risk management authorities in England and Wales.

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If you have any comments or questions about this report or the Environment Agency's other flood and coastal erosion risk management work, please contact fcerm.evidence@environment-agency.gov.uk.

Dr Robert Bradburne
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Director of Flood Strategy and Adaptation

Contents

List of abbreviations

ACE	Aquatic Control Engineering
AIMS	Asset information management system
CCTV	Closed-circuit television
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
EMPs	Eel management plans
GRP	Glass reinforced plastic
HDPE	High density polyethylene (HDPE)
ICES	International Council for the Exploration of the Sea
IUCN	International Union for Conservation of Nature
LEDs	Light emitting diode
MEICA	Mechanical Electrical Instrumentation Control and Automation (MEICA)
PIT	Passive Integrated Transponder

Executive summary

There has been a severe decline in the numbers of European eel (*Anguilla anguilla*) in England and Wales since the 1980s. Under the Eels Regulations (England and Wales) 2009, regulators can legally require measures to be implemented to restore eel numbers in both fresh and estuarine waters. One of these measures is to install eel passes at man-made obstructions, such as weirs and tide gates, to help different life stages of eels to migrate freely upstream.

A detailed review of eel passes in the UK and other countries was carried out by Solomon and Beach (2004) to provide criteria for eel pass design, and since then over 500 eel passes have now been installed by the Environment Agency. Drawing together research and case studies on how eel passes have worked, this document can be used as a resource to:

- make sure current eel passes work as efficiently as possible
- identify any issues with passes that may have been installed for several years

A summary of the characteristics of upstream eel migration that are important when designing and operating passage facilities is included. Migration patterns are strongly seasonal and affected by temperature, river flow, moon phase and tidal cycle. Migration mainly occurs at night. It is important to consider differences in the physical capabilities of eels at their various migratory life stages to ensure passes are designed to accommodate the full size range of eels potentially migrating upstream.

The report includes detailed case studies of 2 facilities that have been operating and monitored for more than 10 years. These are Judas Gap Weir (Essex) and Greylake Sluice (Somerset).

We used information from the literature together with lessons learned from existing facilities to produce recommendations for optimising the design and operation of passes. Aspects covered include the type of pass and positioning, climbing substrates, pump operation, conveyance flow, attraction flow, slope, transit time, construction materials, monitoring methods and maintenance.

Finally, the report identifies areas of future research – including gathering data and knowledge to improve the future design and performance of eel passes.

Disclaimer

This report signposts potentially relevant considerations for practitioners when managing eel passes. It is not intended to be, and should not be read as, prescriptive, exhaustive, or a statement of best practice.

The research findings presented in this report were commissioned by the Environment Agency for this project.

The outputs from this project are being used by the Environment Agency to review and improve our internal management processes. We apply a risk-based approach to all our activities, ensuring public money is targeted in a way to achieve the most benefit. This means that we may conclude that some of the techniques set out in this document are not appropriate for the Environment Agency to use.

This research report seeks to reflect best practice at the time of issue. When applying any conclusions or outputs from the report (as part of a wider-risk based approach), you will always need to consider the impact of any more recent research or developments.

None of the recommendations, conclusions or outputs in this report are prescriptive. Each site and situation will be unique and you will need to apply considerable judgement to assess and identify an appropriate, risk-based approach for each project.

The research proposals and programme identified is meant as an aid to support future research and is not prescriptive in its application. It is expected that ongoing developments and opportunities may present themselves in helping to adapt and take forward research in this field.

Acknowledgements

The authors of this report would like to thank to all those who have contributed to developing this report, in particular:

- the area teams who undertook surveys of eel passes
- Geoff Way for providing the data for the Greylake case study
- Dan Hayter and Ben Norrington for providing the data for the Judas Gap case study

1 Introduction

The status of the European eel (*Anguilla anguilla*) is of significant concern, with continuing advice from the International Council for the Exploration of the Sea (ICES) to reduce human impacts to as close to zero as possible. The species has also been listed as 'critically endangered' on the International Union for Conservation of Nature (IUCN) Red List and in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES).

Under the EU Eel Regulation (EC 1100/2007), EU member states must implement eel management plans (EMPs) to allow at least 40% of the silver eel biomass to escape to sea. The target biomass is estimated from population levels that should be present without human impact. Many member states' EMPs have identified the need to address barriers and improve passage along watercourses to help achieve escapement targets.

Section 14(1) of the Eels (England and Wales) Regulations 2009 states that where a dam or obstruction impedes, or is likely to impede, the passage of eels, the responsible person can be required to take remedial action, for example by removing an obstruction or construction of a bypass channel or eel pass. The Eel Manual, published by the Environment Agency (Environment Agency, 2011a), provides best practice guidance on protecting and enhancing eel populations, one of which is providing eel passes. The Eel Pass Manual was updated in 2020 and further updates are in progress.

In 2011, there were an estimated 16,000 artificial obstructions in England and Wales that could potentially prevent eels from migrating upstream (Environment Agency, 2011a). These were assessed to measure how much of a barrier they presented and were then prioritised in terms of mitigation measures. Following this assessment, passage facilities have been installed at approximately 500 of these structures that the Environment Agency owns, with further passes installed by other organisations or privately. There are a wide variety of designs in use, ranging from the simple addition of artificial climbing substrate such as bristle boards, to the barrier face, to technical up-and-over passes, which provide a migration route that completely avoids the structure.

With so many passes installed, many of which have been operating for several years, there is an opportunity to learn lessons from experiences at current facilities which will help improve the design and operation of both current and future eel passes. A detailed review of eel passes in the UK and other countries was last carried out in 2004 (Solomon and Beach, 2004). Criteria for designing passes were also produced.

By reviewing relevant research and presenting 2 case studies which reviewed how passes worked after they were installed, this report aims to provide a resource to make sure current facilities work as well as they can and to help develop future ones.

This report highlights lessons learned and the need to improve sustainability and performance of eel passes for all life stages. The 'Eel Recovery Group', which was set up in 2018, is implementing the improvements highlighted in this report. There is also further research being undertaken to improve current guidance.

This report is set out in 5 chapters:

1. Introduction
2. Factors affecting eel passage
3. Case studies
4. Design considerations
5. Conclusions and further research

2 Factors affecting eel passage

This chapter sets out what is known about characteristics of upstream eel migration that are important when designing and operating passage facilities.

2.1 Introduction

European eels spawn in an area of the Sargasso Sea, south of Bermuda, although the precise location remains unknown (Schmidt, 1923). Larvae called leptocephali are carried for between 10 months and 2 years on oceanic currents to Europe (Bonhommeau et al., 2009). Leptocephali metamorphose into transparent glass eels (~60 to 80 mm length) on the continental shelf and these migrate into estuaries using tidal currents (Tesch, 2003). Migration into freshwater occurs predominantly in the spring and summer, although some individuals remain in estuarine/coastal waters (Daverat et al., 2006; Marohn et al., 2013). Once glass eels become pigmented and reach a length greater than 80mm, they are known as elvers. Eels smaller than 100 to 120 mm can climb vertically on damp surfaces (Jellyman, 1977; Legault, 1988), but larger individuals require shallower gradients to ascend, which is an important consideration in eel pass design. When elvers reach a length of 120mm they are classed as yellow eels and they continue to feed and grow for several years. They may remain in freshwater or make multiple migrations between freshwater and estuarine/coastal waters (Daverat et al., 2006; Marohn et al., 2013). At the end of this growth phase, yellow eels metamorphose into silver eels and migrate downstream to begin their long migration to the Sargasso Sea to spawn and die (Tesch, 2003).

2.2 Seasonal migration patterns

The migration of glass eels and elvers from estuaries into freshwater is strongly seasonal, occurring predominantly in the spring and summer months in the UK, and is largely driven by temperature (Tesch, 2003). In a 10-year study on the River Shannon (Ireland) upstream migration began between 17 May and 24 June, but generally at the end of May, and typically continued through to the second week of September. There was substantial yearly variation, with the end of the migration season ranging from 29 July to 6 October. It was also noted that while larger eels (more than 150 mm) migrated throughout the season, smaller eels (smaller than 100 mm) mainly moved upstream from mid-June to mid-August (Moriarty, 1986). Ten years' of trapping data from the River Thames revealed a similar pattern, with the season extending from April to October, but the majority of migrants moved in May and June (Naismith and Knights, 1988).

Data from the up-and-over pumped pass at Greylake Sluice indicate that eels ascended from mid-March until mid-November, with activity starting when water temperatures reached 12°C. Very few (less than 20) individuals moved outside of this period (Don, 2009). Comparison with the catch data from Judas Gap Weir, reveals that although the extent of the migration season is broadly similar in the 2 locations, there is a temporal shift in the peak migration which occurs 2 months later, during June, at Judas Gap. At Brownshill Sluice (Cambridgeshire), which is further inland than both Greylake and Judas Gap Weir, the peak in migration occurs later during July (see Figure 1). Both geographical location and interannual variation should therefore be considered when formulating the operating schedule of upstream eel passes.

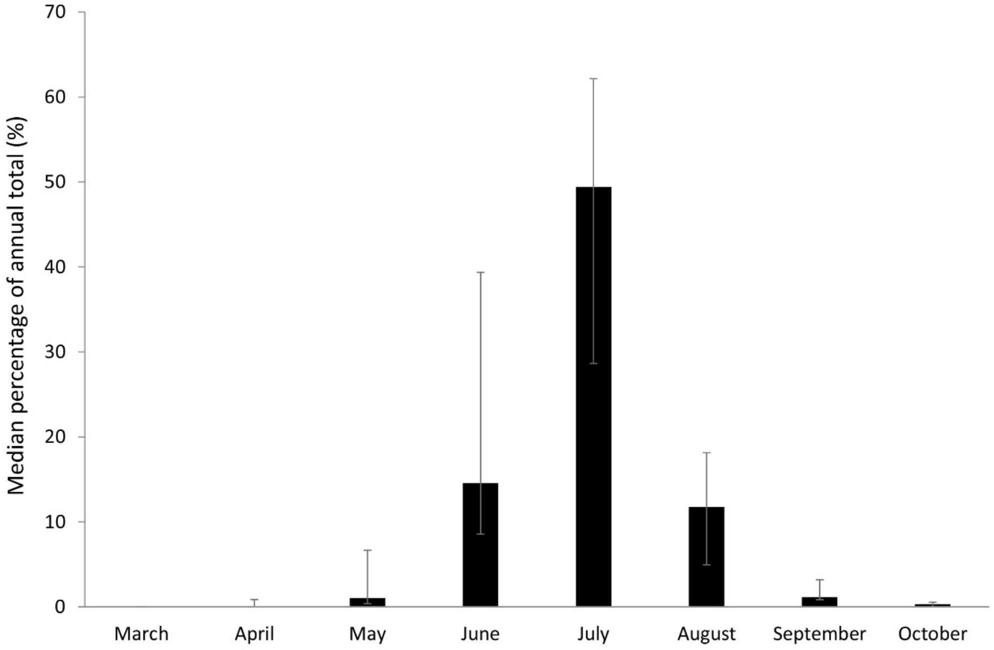

Figure 1: Median percentage of total number of eels that ascended the pass at Brownshill Sluice on Great Ouse in Cambridgeshire, recorded each month from 2008 to 2018 (error bars represent the interquartile range)

Figure 1 shows a bar chart of the median percentage of total number of eels that ascended the pass at Brownshill Sluice, River Great Ouse, Cambridgeshire, recorded each month from 2008 to 2018. The error bars represent the interquartile range. The chart shows that the highest bar occurs in July, followed by June, August, September, May, October, and the lowest in April. Brownshill Sluice (Cambridgeshire) is further inland than both Greylake and Judas Gap Weir.

2.3 River flow

For eels advancing through estuaries, the salinity gradients, currents and olfactory cues provided by freshwater discharging from rivers inform both orientation and navigation of migrating eels (Crivelli et al., 2008; Feunteun et al., 2003; Tosi et al., 1990). Many studies demonstrate that the influence of river flow on eel migration behaviour extends far upstream of the tidal limit, into the freshwater catchment. The upstream movements of radio-tracked yellow phase American eels (larger than 500 mm) at the Millville Dam and within the Shenandoah River during spring were associated with higher flows and increasing temperatures (Hammond and Welsh, 2009). In a study of passage at an eel ladder installed at the same dam, the catches of eels (190 to 750 mm length) increased with higher river flow and low levels of lunar illumination (Hildebrand, 2005).

White and Knights (1997) found that river flow was positively related to eel catches at one of 5 sites monitored on the River Avon, and one of 5 sites on the River Severn. In a mark-recapture study of an up-and-over pass with bristle substrate (45° angle; 6 m length) at a small weir located 4 km from the tidal limit, Bassin d'arcachon (France), water level (a proxy for river flow) was the most important environmental determinant of attraction and passage rates. There was a positive relationship between water level and both metrics, which the authors suggest may be a consequence of higher migratory activity in the river, greater attraction to the pass, or reduced predation pressure downstream of the pass under high flows (Drouineau et al., 2015). The concept that heightened river flow stimulates eel activity is supported by data from the River Stiffkey, Norfolk, where increases in activity levels of Passive Integrated Transponder (PIT) tagged eel frequently coincided with peaks in river flow (see Figure 2) (Piper & Wright, unpublished data).

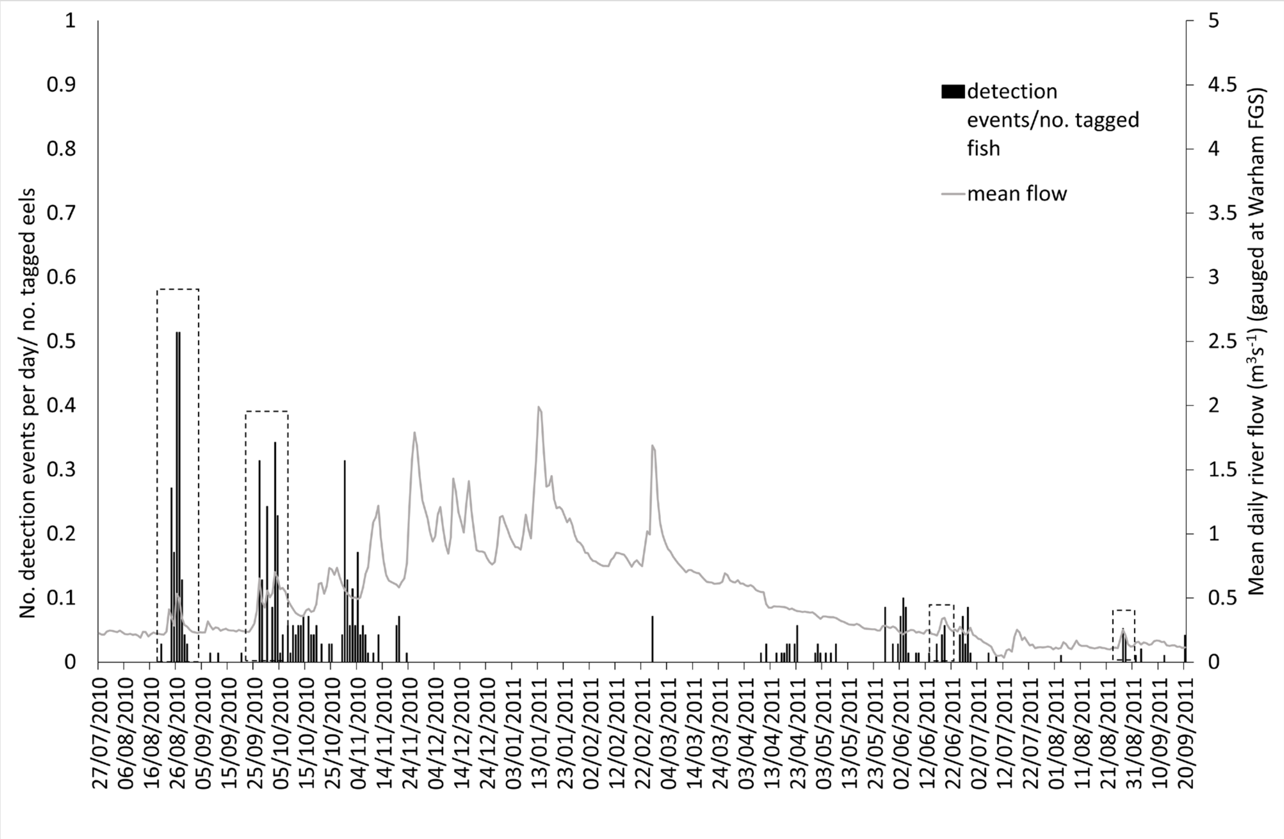

Figure 2: Graph showing activity of Passive Integrated Transponder (PIT) tagged European eels (155 to 475mm) at Little Walsingham on River Stiffkey in Norfolk from 27 July 2010 to 20 September 2011 in relation to river flow (continuous grey line). The rectangular outlines show peaks in activity coinciding with heightened flow

Figure 2 shows the number of detection events per day/number of tagged eels on the left vertical axis and the mean daily river flow in cubic metres per second on the right vertical axis, gauged at Warham flow gauging station. Each data point represents a day across the horizontal axis and spans from the 27 July 2010 to the 20 September 2011. The graph illustrates that high numbers of detection events are seen corresponding to small peaks in river flow within the migration period.

The positive response of juvenile eel to flow is well documented (Feunteun et al., 2003; Knights and White, 1998). An increase in river flow would provide a cue for upstream migration, up to the point at which it becomes too difficult to swim upstream or the water velocity exceeds swimming capabilities. In pumped passes, the optimum flow rate through the pass therefore represents a balance between sufficient flow to attract eels to the pass and stimulate them to ascend, while maintaining velocities comfortably within the swimming capabilities of the target life stages. Solomon and Beach (2004) provide a detailed review of eel swimming capabilities to help produce design criteria for passage facilities.

2.4 Diel periodicity

Evidence from both trapping and telemetry studies indicates that upstream eel movement into and within freshwater occurs mainly during the hours of darkness. Video monitoring of eel behaviour during ascent of a pass at Greylake Sluice (Somerset), showed that around 98% of activity occurred in darkness, mainly between 11pm and 3am (Don, 2009). In a study of eel catches at a ladder on the Millville Dam, Lower Shenandoah (West Virginia, USA), most movement occurred overnight (Aldinger and Welsh, 2017). A telemetry study in a chalk stream, Hampshire, revealed that yellow eel movements similarly increased at night, with greatest mean movement occurring 3 to 4 hours after sunset (Riley et al., 2011). This diel periodicity has implications for both the operating schedule of passes and their siting with regard to artificial light sources. White strobe light has shown some effectiveness as an eel deterrent, particularly among the larger life stages (Patrick et al., 1982), although this is not considered a reliable alternative to screening. To reduce the potential deterrent effect of light, passes should ideally be placed in locations to reduce exposure to artificial light and, in affected sites, light-excluding covers should be incorporated into pass designs.

2.5 Water temperature

As ectotherms, temperature exerts an important influence on both the swimming and climbing activity of eels, and many studies deduce a temperature threshold associated with upstream migration. For example, White and Knights (1997) report that upstream migration in the rivers Severn and Avon began once temperature exceeded 10 to 11°C, but substantial numbers of migrating eels were not observed until temperatures exceeded 14 to 16°C. Maximum catches occurred at 18 to 20°C (White and Knights, 1997a). In a study of tagged yellow eel in a chalk stream, no eel movements were detected when temperature fell below 10°C (Riley et al., 2011). In a study of glass eels (mean length 68 mm ± 3 mm Standard Deviation), the threshold for active swimming was 4 to 7°C, while the threshold for climbing an artificial waterfall at 35° was higher at 12 to 14.5°C (Linton et al., 2007). Within the most commonly installed up-and-over (trough type) eel passes migrating eels must actively climb and/or swim to ascend the pass. Water temperature is therefore a major constraint on these passes being able to operate, restricting their use to the warmer spring/summer months.

2.6 Moon phase and tide height

The influence of the lunar cycle on eel migration is through its effect on tide height and ambient light level. Heightened commercial glass eel catches within the estuary have been associated with the new moon, reflecting increased tide height without the light associated with a full moon (Harrison et al., 2014). Once eels progress upstream, the influence of moon phase declines. For example, Piper et al. (2012) found no influence of the lunar cycle on eel catches in 4 up-and-over passes installed experimentally at Judas Gap Weir on the tidal limit of the River Stour, Essex. Riley et al. (2011) similarly found no significant effect of moon phase on yellow eel movements in a chalk stream. Where an effect is reported upstream of the tidal limit, it results from changes in light level. Upstream migration of PIT-tagged eels (80% of which were yellow eel life stage) at Lixhe Dam, 323 km upstream of the North Sea on the River Meuse, was correlated with the waxing and waning phases, that is, not at full moon. At an eel pass installed at the Millville Dam, Shenandoah River (USA), the catch of American eels *Anguilla rostrata* (190 to 750 mm length) increased with low levels of lunar illumination (Hildebrand, 2005). Passage of tagged American eels (74 to 510 mm) at an eel ladder on a tributary of the Hudson River was highest on the darker phases of the moon (new moon) and with high river flows (freshets) (Schmidt et al., 2009). In essence, while considering the moon phase is important in operating passage facilities that target glass eels, its influence declines upstream of the tidal limit.

2.7 Life stage

In estuarine waters, glass eels move by selective tidal stream transport, that is, successive passive upstream movements on flood tides interspersed with shelter-seeking behaviour during the ebbs, thereby maximising distance travelled for energy expended (McCleave and Kleckner, 1982). In unobstructed systems, eels can advance far inland by this method (Tesch, 2003). The widespread foreshortening of estuaries by building sluices and tide gates prevents tidal stream transport, causing the eels to accumulate downstream of the barrier (Briand et al., 2003). The up-and-over (trough type) eel passes that are commonly installed to help migration at these structures rely on active climbing/swimming. There is concern that while these facilities enable elvers and larger life stages to migrate past the barrier, they do not restore connectivity for glass eels (Bult and Dekker, 2007). For example, within 4 pumped up-and-over passes (34° slope, 4.6 m length, 12 mm nylon netting as climbing substrate) used at Judas Gap Weir, the tidal limit of the River Stour (Essex), just 20% of eels that successfully ascended were glass eels (less than 80 mm); the majority of the catch (66%) comprised eels from 81 to 90 mm (Piper et al., 2012). In trials of a simple siphon pass (110 mm diameter PVC pipe with hand-operated vacuum pump) at 2 navigation locks on the tidal limit in the Netherlands, glass eel catches were 6 times higher than in a trap which required active swimming (Bult and Dekker, 2007).

Passage solutions that do not rely on active swimming such as siphon passes, light weight tide gates and timed opening of ship locks should therefore be considered for intertidal structures, potentially in addition to conventional up-and-over passes that are shown to be effective for larger life stages.

The size of upstream migrating eels increases with distance from the estuary, and this should be considered when selecting a passage solution (Naismith and Knights, 1988; White and Knights, 1997b). However, the size range found at the same point in the catchment can be large. For example, at the tidal limit where small eels dominate, migrants of larger than 200 mm were recorded (White and Knights, 1994). This was also the case at Judas Gap where eels up to 321 mm used the passes (Piper et al., 2012). Therefore, even though a passage facility may target a certain life stage dependent on its position in the catchment, it should be able to accommodate the full range of size classes available to ascend.

2.8 Summary

This chapter has summarised the factors which affect eel passage and migration. The lifecycle of an eel is complex – eels have different physical capabilities depending upon where they are at in their lifecycle. Designing passes which adequately accommodates all life stages and the different factors described here is challenging.

3 Case studies

To understand more about how passes work after they have been installed, case studies of 2 facilities that have been in operation and monitored for more than 10 years are presented in this chapter. The passes are located on or close to the tidal limits of rivers, one on the east and one on the west side of England. This also highlights the differences in migration timing between these locations.

3.1 Case study 1. Judas Gap Weir, River Stour, Essex

At Judas Gap, a broad-crest weir (20.98 m width) built of concrete forms the tidal limit of the south channel of the River Stour, Essex (51.954898° N, 1.0256580° E), which is shown in Figure 3. Due to abstraction demands combined with low spring/summer flows, and as shown in the main photo, the weir does not spill for extended periods, particularly during the upstream eel migration period (Piper et al. 2012). There is a negotiated agreement between the Environment Agency and the water company that abstracts from the lower Stour catchment that, at our request, abstraction is reduced or halted to temporarily allow spill over Judas Gap. This occurs for short periods during exceptionally low flow periods in the spring/summer upstream eel migration season and is shown in the smaller photo inset in Figure 3.

Figure 3: Judas gap weir on the River Stour in Essex when not spilling - and inset image shows during high winter flows (source: Adam Piper)

3.1.1 Eel passage measures installed

A simple trough-type eel pass in the pool and weir fish pass at the southern end of the weir was installed in 2002 and is shown in Figure 4.

Figure 4: Simple trough-type elver pass with conveyance flow supplied by a bilge pump, powered by 12V leisure battery housed in wooden box fixed to the wall above the pass (source: Dan Hayter)

Figure 4 shows that the pass comprised a section of standard household guttering lined with netting, supplied with conveyance flow by siphon. Due to breaks in the conveyance flow - caused by the pipe inlet being blocked with weeds and by fluctuating water levels causing the siphon to fail - a bilge pump powered by a 12V leisure battery was later fitted, which can be seen attached to the wall. Eels that ascended the pass collected in a plastic catch pot, which was emptied upstream regularly. The pass was operated from April/May to September. Between 2002 and 2009, annual catches ranged from a minimum of 625 in 2005 to a maximum of 33,771 in 2007.

This initial pass design meant staff spent a great deal of time emptying the trap and replacing the battery. Despite fitting the bilge pump, the conveyance flow occasionally failed, with the potential for killing some of the captured eels. There were also health and safety concerns regarding the manual handling needed to replace the battery and raise the catch pot to the top of the weir to be emptied.

In 2013, the monitoring station was replaced by a full trough pass of HDPE construction installed by an external contractor. This included a tower within which the catch pot was raised to the walkway above the weir using a gearing system with hand-wind wheel. The tower enabled the catch pot to continue to be located close to the downstream water level, therefore retaining an acceptable angle (approximately 30°) for the climbing section of the pass, which was lined with green nylon bristles. Conveyance flow was intended to be supplied from upstream using a ram pump. The ram pump was not able to lift enough water and was replaced by a battery-operated pump.

Several design issues with the pass became apparent during the first few years of operation:

- the configuration of the gearing system meant that hand winding took longer (over 5 mins) to raise the catch pot
- the catch pot was designed to empty most of the water before it was raised - this didn't work well and eels were able to escape and could also become trapped in seams and remain in the pot after they were emptied
- warping of the HDPE created gaps and seams where small eels could become trapped
- the bristle boards had become detached in places, creating crevices underneath the boards in which eels could also be trapped.

Modifications carried out to solve these issues included:

- re-designing the catch pot to include a sloping base to make sure all eels are removed when the pot is emptied, and a non-return baffle at the rim to reduce the likelihood of eels escaping
- replacing the battery operated pump with an electric impellor pump powered by a bank of batteries charged by solar panels

Figure 5: Eel pass at Judas Gap after modification by adding a flow splitter to provide attraction flow at the base of the pass (red circle) (source: Adam Piper)

As shown in Figure 5, a flow splitter and an additional pipe were installed to provide overhead sprinkling flow at the base of the pass after Piper et al. (2012) reported that this type of flow doubled eel catches at a trough pass.

Analysis of the long-term catch data raised concerns that the smallest size class encountered (glass eel, less than 80 mm length) were less able to ascend the bristle substrate than the netting used historically (Dan Hayter, Pers. Comm.). So, in 2017, all the bristle substrate was replaced with netting (knotless nylon 12 mm diamond mesh). To investigate this further, the pass was modified in 2018 to allow trials to be carried out to compare the efficiency of 2 different substrates. The ascent section of the pass was divided in half along its entire length and one side was covered with capillary matting and the other with netting. Catches were monitored from May to September and the substrates were switched over once during this period to limit the effect of any side bias. Netting allowed significantly more glass eels (smaller than 80 mm) (2.7 times more throughout whole season) and elvers (81 to 120 mm) (1.9 times more) to pass through than the capillary matting. There was no difference for the yellow eel life stage (larger than 120 mm) (Hayter & Wright, unpublished data).

3.1.2 Monitoring results

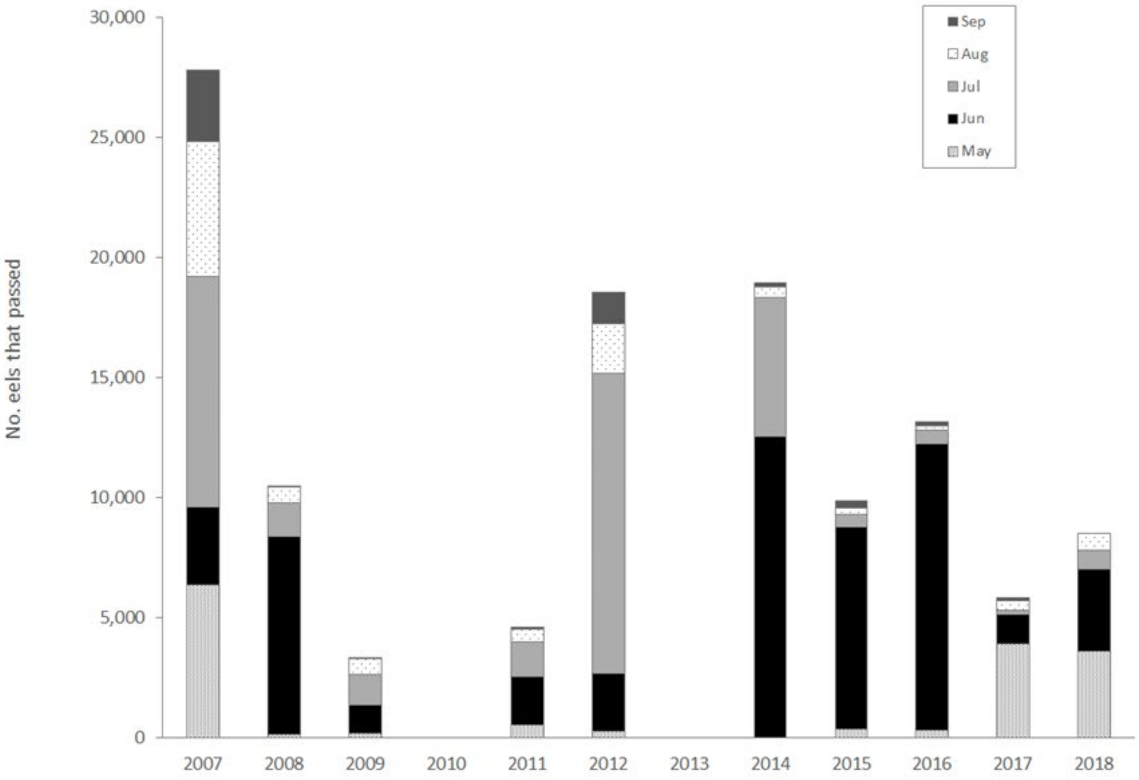

Figure 6: Total number of eels that ascended Judas Gap in Essex from 2007 to 2018 displayed by month

Figure 6 shows that over 120,000 eels were captured and released upstream during 10 years of monitoring at the Judas Gap eel pass. The data was recorded between May to September between 2007 and 2018. The highest annual catch was reported in 2007 when the pass was still a simple trough (gutter) design, fed by a leisure battery-powered submersible pump. High catches were also recorded in 2012 and again in 2014 when the box section HDPE pass came into operation. Catches have generally declined year on year since 2014.

Although a useful indication of the magnitude of the annual eel run, the validity of comparing catches between years at Judas Gap is limited by the numerous design modifications that the pass underwent over the study period. To allow for this inter-annual variation, the median of the percentage of the total eel catch recorded each month was calculated for all years.

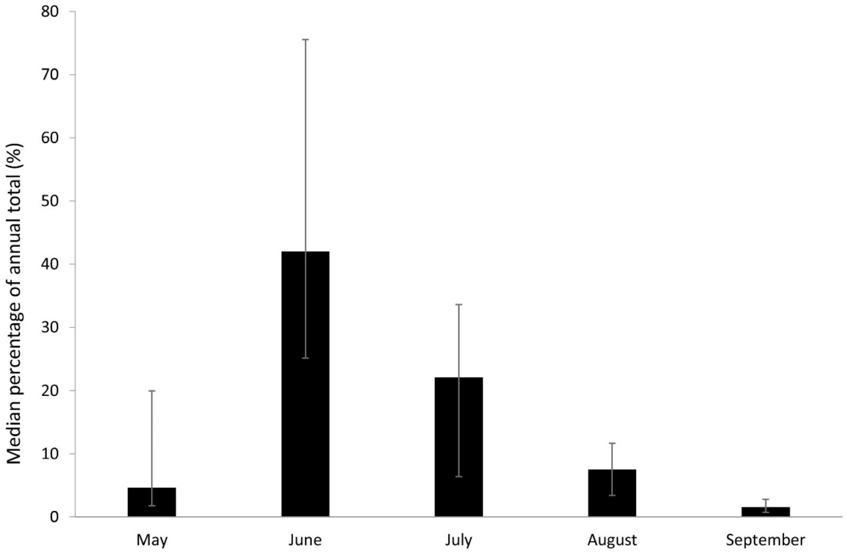

Figure 7: Median percentage of total number of eels that ascended the pass at Judas Gap in Essex. Recorded each month between 2007 and 2018 (excluding 2010 and 2013)

Figure 7 illustrates that the highest median percentage occurred in June (42%) followed by July (22%) (), then August, May, and the least occurred in September.

3.2 Case study 2. Greylake Sluice, King’s Sedgemoor Main Drain, Somerset

Greylake Sluice (51.106235° N, 2.8624031° W) is located on King’s Sedgemoor Main Drain in Somerset, 11.70 km from the confluence with the tidal River Parrett.

Figure 8: Greylake sluice on King's Sedgemoor Main Drain in Somerset which comprises 2 bottom-hinged tilting weirs (source: Andy Don)

Figure 8 shows that Greylake Sluice comprises of 2 bottom-hinged tilting weirs that are typically set to retain water within the canal upstream during spring and summer (April to October) to allow little or no spill. Under this operating system, eels were unable to pass through the sluice during the main period of upstream migration, and in 2008, 2 up-and-over pumped passes were installed, one close to each bank.

3.2.1 Eel passage measures installed

Figure 9: Pumped up-an-over eel pass at Greylake Sluice in Somerset (source: Andy Don)

As the 2 photos in Figure 9 show, the passes were constructed of stainless-steel box section (200 mm width) lined with nylon bristle boards, with a mixture of spacing between the bristle clusters (20 mm and 30 mm). Due to difficulties caused by the site configuration, the gradient of the climbing sections ranged from 45° to 55°, which is steeper than the recommended 30° (Solomon and Beach, 2004). At the crest of the pass, the box section was joined to a pipe (110 mm diameter) containing no substrate and through which eels were carried to the upstream side of the structure by pumped flow split from the main conveyance flow.

To monitor eels moving through the passes, a CCTV camera was mounted to each pass above the bristle substrate. Each camera had in-built infrared LEDs; infrared is outside the spectral sensitivity of European eel (Archer et al., 1995), and so filming could take place under darkness without affecting the eels' behaviour. Bristles that could be seen in the field of view were trimmed in length slightly so that the eels could be seen more clearly and flaring under the infrared lights could be reduced. Footage was recorded onto the internal hard drive of an onsite video recorder that was offloaded every 6 to 8 weeks.

3.2.2 Monitoring results

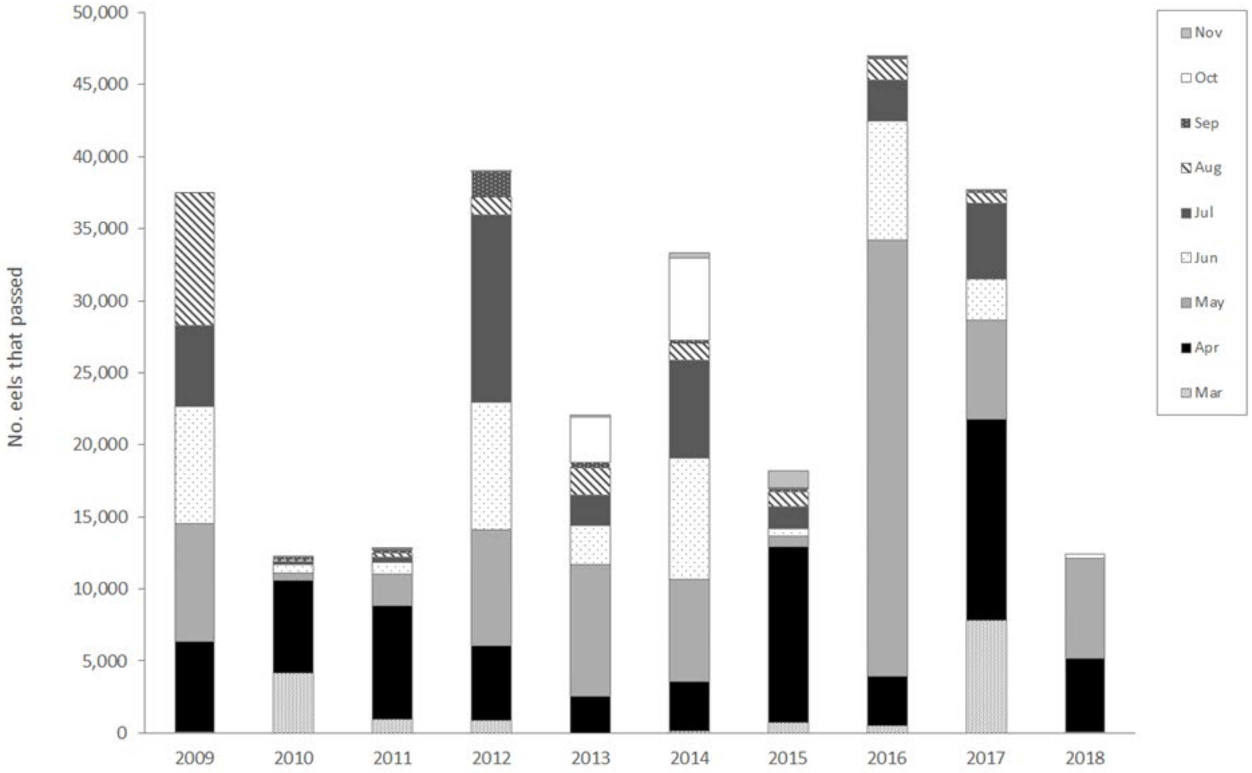

Figure 10: Total number of eels that ascended the 2 passes at Greylake Sluice in Somerset from 2009 to 2018 displayed by month

Figure 10 shows that in excess of 270,000 eels were observed ascending the 2 passes during the monitoring periods from March to November, between the years 2009 to 2018. The graphs illustrates that there was substantial yearly variation, with the highest eel numbers observed in 2016 and the lowest in 2010. Individuals ranging from pigmented glass eel to yellow eel life stages (up to 670 mm) were observed using the passes (Don, 2009).

The main migration period extended from April to July, although in the few years when monitoring continued beyond this period, eels were recorded in the pass during all months, albeit in low numbers during the winter.

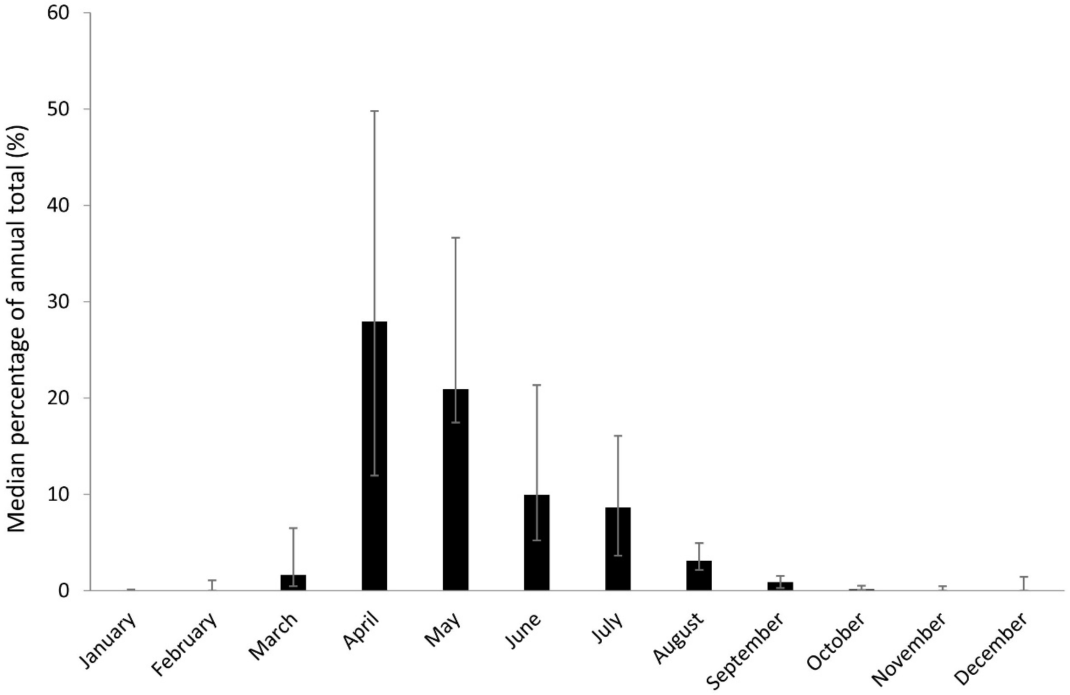

Figure 11: Median percentage of total number of eels that ascended the 2 passes at Greylake Sluice in Somerset, recorded each month from 2009 to 2018 (error bars represent the interquartile range)

Figure 11 shows that the highest percentages of the annual eel count between 2009 and 2018 were observed in April and May. The next highest percentages follow in June, July, August, March, September and then negligible amounts were counted in February, January, October. November, and December.

3.3 Summary

In the 10 years they have been operating and monitoring carried out, the 3 passes have allowed a substantial number of juvenile eels (more than 390,000) to ascend further into the freshwater catchments than would have previously been possible. Both water control structures were previously considered impassable or near impassable during the migration season. The monitoring results suggest that eel recruitment to the study rivers is likely to have improved markedly as a consequence of installing passes.

Data from the 2 sites also indicate a clear temporal difference in the peak upstream eel migration that occurred during April at Greylake Sluice and in June at Judas Gap. This is consistent with the later arrival times of glass eels to the east coast of the UK after their arrival and metamorphosis from leptocephali on the western edge of the continental shelf and passage eastwards through the English Channel (Tesch, 2003). There are also yearly variations in recruitment to the west and east coasts.

Both sites presented challenges with regards to installing and maintaining passage facilities. The configuration of the infrastructure at Greylake Sluice meant several changes of direction had to be incorporated into the passes. This resulted in steeper than desirable climbing gradients. At Judas Gap, the 3 main difficulties were the absence of a mains power supply, fluctuating water levels upstream, and the relatively high head drop over which eels had to be conveyed (up to 4 m depending on the tide).

Different monitoring approaches were used at the 2 sites. The catch pot at Judas Gap needed emptying daily and therefore more staff time and resources were needed. Daily checks, however, also meant that problems with the functioning of the pass were identified and, when possible, solved quickly. The CCTV system at Greylake proved effective and reliable and far fewer staff visits to the site were needed than at Judas Gap. However, a significant amount of time was needed to watch back and analyse the footage. But, using an analogue rather than a digital system enabled fast playback speeds (up to 128X). In more recent years, the cameras have been connected to the internet so that staff can view the condition of the pass remotely. This has been useful for informing when maintenance is needed. Importantly, using CCTV monitoring also allowed eel behaviour in the pass to be observed, thereby providing greater understanding of exactly how and when eels ascended.

4 Design considerations

4.1 Introduction

The following chapter describes a wide range of design considerations for designing and operating eel passes. These considerations will help steer the design of a pass that is suitable for the structure in question and ensure its long-term efficacy, including monitoring and maintenance requirements.

4.2 Site access

Selecting structures where eel passes can be installed is directed by both need (how much of a barrier the structure presents) and feasibility. Once installed, the pass will have to be accessed regularly for inspection and maintenance, and twice a year for decommissioning/removal and recommissioning /re-installation at the start and end of the upstream eel migration season, respectively. Therefore, after the structure has been selected to install a pass, an integral part of the design process should be considering how easily and safely the facility can be accessed.

4.3 Choosing the right pass

Removing an obstruction is the preferred option for provision of passage. If this is not feasible the type of pass will largely be determined by the type of obstruction to be overcome. When developing the specific design, it is necessary to consider a wide range of other factors such as: the need for gauging; flood risk management; eel life stages; other species targeted; flow characteristics; access for maintenance; availability of a power supply and risk of vandalism.

The main types of pass, their suitable applications, advantages and known issues are outlined in this chapter. The need to overcome site-specific challenges has, in some cases, led to developing highly technical passes (e.g. Judas Gap case study). Bespoke designs and increasing complexity, however, also carry the risk of other issues that are difficult to predict because of the lack of thorough testing. Given the current lack of quantitative testing of the efficiency and functioning of passes generally, it is recommended that it is kept simple, avoiding any unnecessary complexity.

Seven different types of eel pass are described below, setting out their most suitable application, and describing their main advantages and disadvantages.

4.3.1 On-weir box section, gravity-fed

This eel pass is:

- a substrate or box section containing substrate fixed horizontally onto weir/obstruction, flow rate determined by upstream water level
- suitable for non-gauging weirs and other obstructions
- beneficial because it:
    - is a simple design
    - is easy to maintain
    - does not require a power supply
    - is low cost
    - has no risk of pump failure
- known to have the following issues:
    - inappropriate design levels
    - damage to the pass in high flows
    - blocking by debris
    - detaching substrate

4.3.2 Hook-over, gravity-fed

This eel pass is:

- designed to hook over weirs and other sluice gates
- suitable for a wide range of sluices, including tilting weirs and penstocks, the self-adjusting designs allow for changes in sluice position and upstream water level
- advantageous because:
    - fairly simple design
    - no power supply required
    - no risk of pump failure
- has these potential identified issues:
    - inappropriate design levels
    - damage to substrate in high flows
    - vulnerable to being washed away in high flows

4.3.3 Vertically-oriented bristles/tiles

This eel pass:

- is made of bristle boards or eel tiles fixed vertically against wingwall of structure
- is suitable for gauging weirs >2 m wide and other obstructions
- is advantageous because:
    - effects on gauging are quantified
    - relatively low cost
    - simple design
    - no power supply required
    - no risk of pump failure
- has these potential identified issues:
    - clogging of bristles due to build-up of sediment or algae

    - macrophyte growth
    - detachment from fixings

4.3.4 Up-and-over, pumped

This eel pass is:

- a sloping box section pass lined with climbing substrate and fed with pumped river water
- suitable for gauging weirs; all weir types, especially useful at large structures with high head drop
- advantageous because:
    - can be used to completely circumvent the structure
    - little/no impact on gauging
    - can convey eels over long distances
    - can be easily fitted with catch box or camera for monitoring
- has these potential identified issues:
    - pump failure (and/or power failure)
    - clogging of substrate
    - substrate detachment/gaps
    - overheating (when covered and during pump failure)
    - inefficient passage due to confused flow patterns at the crest and in splitter boxes

4.3.5 Nature-like passes

This eel pass:

- is a portion of main flow diverted through a nature-like channel to circumvent the obstruction
- is suitable for wide range of sites but needs space and resource available for significant engineering works
- is advantageous because :
    - can be used by a range of species and under wide range of flows
    - self-maintaining if designed correctly
- has the potential identified issue that maintenance may be required if water availability is a limiting factor in the design

4.3.6 Pet-flaps

This eel pass:

- is made of a small flap inset in tide gates that opens for longer periods than the tide gate
- is suitable for tide gates and tidal sluices
- is advantageous because :

    - no power supply required
    - self-maintaining if designed correctly
    - can be retrofit at relatively low cost
- has these potential identified issues:
    - incorrect weighting of float mechanisms resulting in opening for only short periods – limited opportunity for passage
    - can cause salinity and silt build-up upstream

4.3.7 Dampeners/retarders

This eel pass:

- is a fitting that delays closure of tide gates
- is suitable for tide gates
- is advantageous because
    - no power supply is required
    - self-maintaining; can be retrofit at relatively low cost

4.4 Climbing substrate

A range of materials has been developed specifically to facilitate eel climbing within passage facilities, while others are adapted from use in other industries (e.g. construction, horticulture). This section presents an overview of bristle boards, eel tiles, peg boards, geotextiles and nets, and granular substrates. Results from the survey of current facilities in England indicate that the most commonly used substrates are bristle boards and eel tiles (studs).

4.4.1 Bristle boards

Bristle boards that comprise tufts of stiff synthetic fibres on a backing board are used both horizontally, usually lining the box section of up-and-over type passes, and vertically, mounted parallel to the wingwall of a weir with the bristles protruding towards the wall.

Figure 12: Left image - bristle substrates on a rigid backboard (source: Aquatic Control Engineering). Right image – bristle substrate on a flexible rubber backing (source: Cottam Brushware Supplies)

Figure 12 shows 2 photos of bristle boards - one demonstrating bristles on a rigid backboard, and the other one with bristles on a flexible backboard. Both types of installation have been shown to be effective at passing pigmented glass eel through to yellow eel life stages (Briand et al., 2005; Kerr et al., 2015; Watz et al., 2019).

The efficiency of the substrate for different size classes is affected by the spacing of the bristle clusters, with smaller spacings deemed more suited to small eels and vice versa (Environment Agency, 2011a). This was clearly observed in video footage of eels ascending Greylake Sluice, Somerset, where a mixture of bristle spacings were present in the same pass. Small eels (smaller than 200 mm length) favoured the denser substrate (20 mm spacing), while larger eels (bigger than 200 mm length) made greater use of the wider (30 mm) spaced bristles (Don, 2009). Eels sampled in the Canal Des Etangs that had successfully ascended a bristle-lined pumped pass (45° slope, 15 mm bristle spacing) were smaller (mean 86 mm) than those (mean 109 mm) that had successfully ascended 2 subsequent passes lined with concrete studs (similar to Evergreen, Pelcar and Rugofish, 30° slope, 30 mm diameter studs, 30 mm spacing). This indicates the suitability of closely spaced bristles for smaller life stages (Podgorniak et al., 2017). However, providing a mixture of bristle spacings is now more currently widespread in UK facilities.

The main problems of bristle substrate are loosening of the boards in box section passes and clogging by silt, weed and other debris. Discontinuity of the substrate, that is gaps between the edges of bristles boards and the box section and at joins between box sections has also been reported.

4.4.2 Studs

Eel tiles, rigid sheets of high-density co-polymer with studs of variable spacings, tend to be used in locations such as weirs where high flow rates would distort or damage bristle boards.

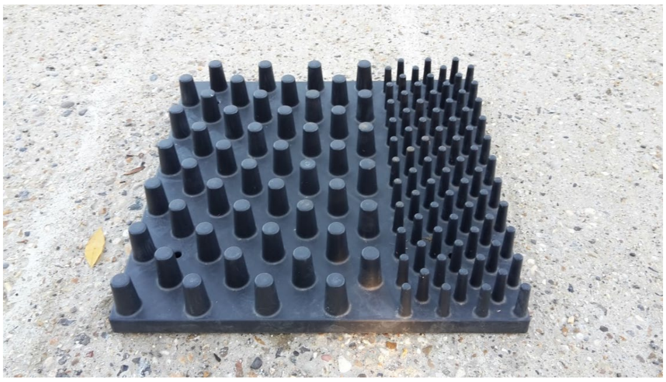

Figure 13: Eel climbing substrate with 2 sizes of studs and spacings, manufactured by Berry and Escott Engineering (source: Paula Rosewarne)

Figure 13 shows an example of a climbing substrate with 2 different spacings for 2 different size studs. The tiles can either be attached horizontally onto the weir face or oriented vertically along the wingwall with the studs facing the wall. When tiles (500 mm length and width; large and small studs of 50 mm height and 30 mm and 55 mm spacings, respectively) were trialled in both orientations on a model crump weir (11.3° slope) in a flume, the tiles increased upstream passage efficiency of yellow eel 424 ± 76 mm (mean ± S.D.) by 20% when vertical and by 46% when horizontal (Vowles et al., 2017).

In field trials at a Flat-V weir, eel tiles were either fixed onto the surface of the weir or recessed so that the top of the studs was level with the surface of the weir. Passage results were similar for the 2 configurations, with 91% and 100% success rates among PIT-tagged eels that attempted to ascend via the recessed and raised tiles, respectively (Coe et al., 2015). A size bias was observed whereby eels that successfully ascended the recessed tiles were larger (310 to 430 mm) than those that passed the raised tiles (270 to 400 mm). However, these results should be treated with caution because sample sizes were low and small eels were less visible in the recessed section. Further tests are required to inform whether it is preferable to recess the tiles. Video observations of individuals of a wider range of size classes than those tagged suggested that small eels (smaller than 150 mm) struggled to ascend the tiles in either configuration. 63% of attempts among eels 101 to 150 mm ended in wash down and no attempts were made among eels smaller than 100 mm (Coe et al., 2015).

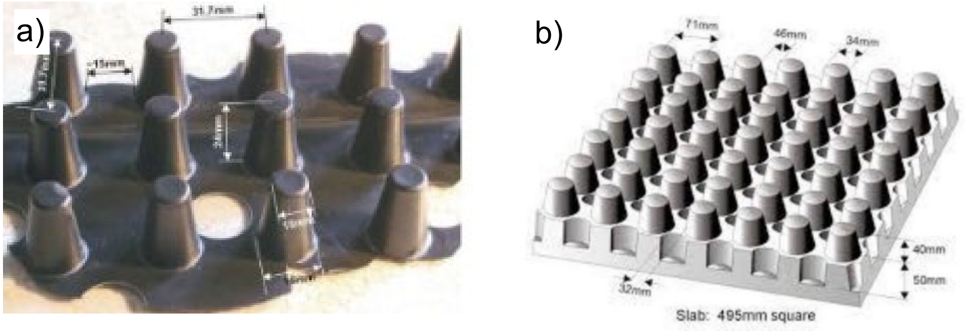

Figure 14: Two examples of stud substrates with non-staggered studs (source: a) Akwadrain, b) Pelcar)

Other stud-type substrates include Evergreen, Pelcar, Rugofish, Akwadrain/Miradrain and EF16. Unlike on the eel tiles where the studs are arranged in staggered rows, the rows of studs on these products (which are designed for the construction industry) are not staggered. Figure 14 shows 2 examples of these. In a study that compared European eel ascent of concrete studded substrates with various stud arrangements, Voegtle and Larinier (2000) found the layout created by staggered rows was the most effective.

4.4.3 Peg boards

Several eel-specific substrates that use shapes such as cylinders fixed onto a solid back board have been developed and used in pumped passes, mostly in North America. These can be referred to as peg-boards and 2 examples are shown in Figure 15. The first on the left shows Milville eel ladder - the substrate of the ladder is recommended for eels 150 mm to 750 mm and when used on the Shenandoah River, USA, successfully passed eels ranging from 190 mm to 750 mm (Hildebrand, 2005). The second example on the right shows a similar substrate also manufactured by Milieu Inc. with narrower spacings (12.7 mm) that has been designed to accommodate eels smaller than 150 mm. Although the passage efficiency of this substrate is yet to be independently tested, trap and transport collection facilities at Roanoke Rapids dam, North Carolina, use eel traps lined with it and collectively pass more than 35,000 eels annually (Sturke et al., 2018).

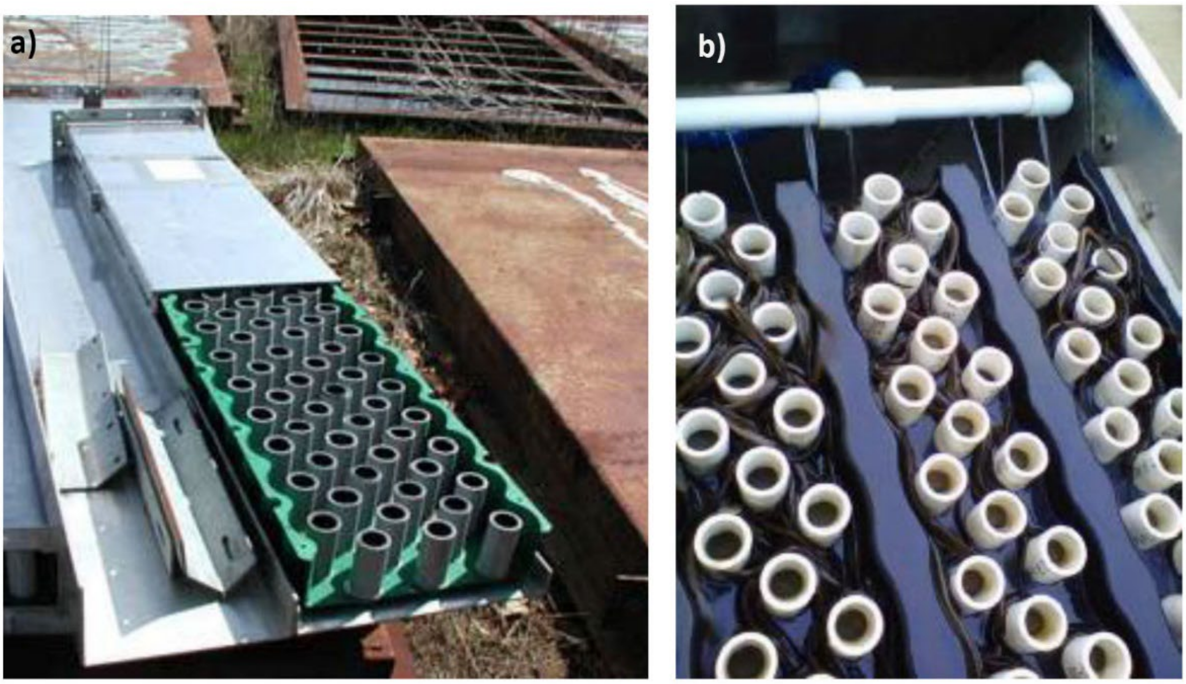

Figure 15: Image a) Section of Milville eel ladder Shenandoah River USA. Image b) Milieu substrate designed for smaller eels (smaller than 150mm) (source: Hildebrand and Sturke, 2005)

4.4.4 Geotextiles and nets

Geotextiles and nets, generally developed for the horticulture industry, have been widely applied in eel passes, particularly in the early designs (Dahl, 1991). For example, the Danish Eel Management Plan from 2008 stipulates that the open weave geotextile substratum Enkamat should be preferentially used in upstream passes. In recent tests alongside bristle and stud substrates using eels ranging from 60 to 110 mm, the Enkamat performed least well. However, differences were mainly related to variation in attraction efficiency between the substrate types rather than likelihood of successful ascent (Watz et al., 2019). Other authors have noted that Enkamat is only suitable for eels less than 260 mm and can cause individuals to lose considerable amounts of mucus (Voegtle and Larinier, 2000).

Fruit/bean cage netting (for example, Netlon) with a square mesh size of 20 mm folded or rolled into a loose mat has been shown passable for all upstream-migrating size classes (Naismith and Knights, 1988; White and Knights, 1994). Nylon netting (usually material recycled from damaged fyke or seine nets) was widely used in the early trough-type passes configured from gutter/drainpipe sections and is still present in some installations. It has been shown passable by eels ranging from glass and pigmented glass eels (smaller than 80 mm) to yellow eels (larger than 120 mm) (Dan Hayter, pers. comm.), but does carry the risk of entanglement because the author (Ros Wright) has observed larger individuals ‘gilled’ within dense sections of netting.

Small eels (smaller than 120 mm) are able to climb vertical surfaces so long as they are damp (Jellyman, 1977) and ambient temperature is sufficiently high (Linton et al., 2007). Wicking material or capillary matting laid over otherwise smooth and dry surfaces may facilitate eel ascent by maintaining a damp roughened surface.

Polypropylene mussel spat rope (‘Super Xmas Tree’, Donaghys Industries, NZ) has been shown to be effective in enhancing passage through culverts for juvenile rainbow trout (*Oncorhynchus mykiss*), adult *Galaxias maculatus* and *G. fasciatus*, and the shrimp *Paratya curvirostris* (David et al., 2014, 2009). This material is increasingly used in New Zealand to facilitate passage at culverts where installing baffles is not appropriate, and at perched culverts. Although quantitative studies of eel climbing ability of this substrate are lacking, juvenile eel *A. dieffenbachii* and/or *A. australis* have been recorded ascending a vertical length of mussel rope installed at a perched culvert. Trials with different types of spat rope are underway.

4.4.5 Granular substrates

The addition of sand/gravel to a previously smooth surface increases the likelihood of successful ascent, particularly for smaller size classes (Jellyman et al., 2017). In a test of different grain sizes, 1 to 4 mm was more effective than less than 1 mm for both glass eels (50 to 69 mm) and elvers (90 to 147 mm) (Anwar and Haro, 2017). In both of these studies, the substrate was fabricated by sticking the granules to the eel ramp using a general purpose adhesive. The robustness of this setup over time and within variable flow rates is questionable, and the authors are unaware of a commercially produced example of this type of substrate. Further work is being undertaken on pebble resin substrates and different sizes of pebbles are being trialled.

4.4.6 Results from climbing substrate tests

The results of tests of the main climbing substrate types extracted from the literature (peer-reviewed and grey) are summarised in Appendix 1. Few studies conducted tests under different flow scenarios and/or conducted flow velocity measurements (but see Kerr et al., 2015; Voegtle and Larinier, 2000; Vowles et al., 2017), yet flow is likely to be an important determinant of the observed attraction and passage efficiencies. Watz et al. (2019) note that in the bristle passes water flowed evenly over the bottom, whereas the studs, which proved more attractive to eel, created turbulence, but no measurement of flow patterns were made. Not considering the flow characteristics created by the different substrates enough currently makes it difficult to transfer the findings to passes with different design specifications (e.g. slope, conveyance flow rate). Understanding the effect of stage/discharge on water velocity within the substrate is particularly important at sites such as flow gauging weirs where the flow permissible to divert to the pass will be minimal.

4.4.7 Considerations for climbing substrates

Target life stage

Considering the eel life stages likely to be present at the pass location is fundamental to selecting the appropriate climbing substrate. Where passage is required for a wide range of size classes, multiple types of substrate within the same facility should be considered.

Based on current evidence, the most appropriate substrates for small eels (smaller than 110 mm) are closely spaced studs or pegs (12 to 14 mm spacing) in quincunx arrangement and granular substrate (1 to 4 mm grain size). Closely spaced bristles and nylon netting can also be ascended by this size class but data on passage efficiency are lacking. For larger eels (larger than 150 mm), the most effective tested substrates are wider spaced stud and peg substrate (≥ 16 mm spacing) (for example, eel tiles, Miradrain/Akwadrain, Milieu substrate, Pelcar) and bristle substrate (≥ 14 to 18 mm spacing).

A general rule apparent throughout the literature is that smaller eels require substantial support during climbing (Anwar and Haro, 2017; Jellyman et al., 2017), therefore narrowly spaced studs, pegs or continuous substrate (for example, netting) are most appropriate. Conversely, larger size classes may be impeded by narrow spacings (for example, Legault, 1992) and become entangled in continuous substrate such as netting and geotextiles.

Prevention and remediation of debris build-up

All climbing substrates are vulnerable to the build-up of debris and/or algae and macrophyte growth. There is some indication that in horizontal deployments eel tiles are less susceptible to debris build-up than bristles, but this may simply reflect variation between sites. Site characteristics will be important determinants of the rapidity and type of build-up that occurs. For example, up-and-over passes at estuaries, may be subject to major siltation problems because water pumped from an estuary is highly turbid and silt accumulates on the bristle boards during periods of no flow.

Regularly checking and, if necessary, cleaning the climbing substrate within a pass should be an integral part of the maintenance programme. Where the pass design incorporates a cover, it should be removable to allow the climbing substrate to be easily inspected and cleaned.

Various approaches are also available to reduce debris build-up in the first instance; their applicability will vary from site to site. Two examples are considered here. Figure 16 shows an upstream debris boom, which can be installed for passes that receive flow directly from the river (non-pumped) and which may effectively divert debris from entering the pass. Figure 17 shows a photo of a hook-over gravity fed eel pass with debris deflector at the upstream end.

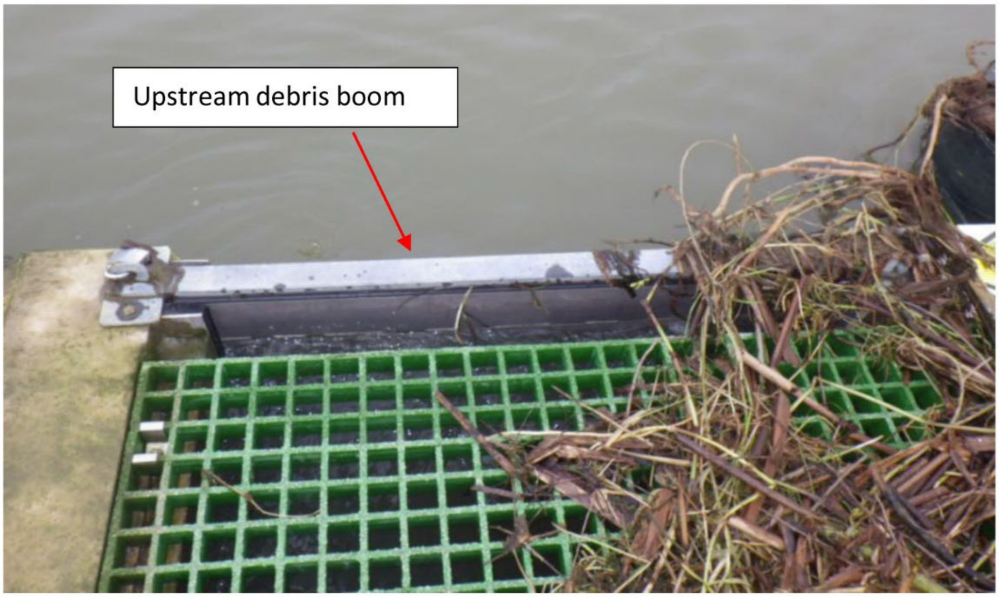

Figure 16: A boom to reduce the entry of debris at the upsteam end of a multispecies fish and eel pass at Tallington gauging station in Lincolnshire (source: Hugh Bunker/James Hooker)

Figure 17. Hook-over gravity fed eel pass with debris deflector at the upstream end, deployed on Bargate sluice in Lincolnshire (source: Hugh Bunker/James Hooker)

Robustness

Detachment of the bristle boards within box section passes can pose a major problem with this substrate. Boards are generally fixed onto the box section using screws, bolts or brackets. Joints between neighbouring boards and where boards interface with the box section may also be sealed with aquatic sealant. Where boards are bedded onto a pass with no sealant, or aquatic sealant alone, gradual loosening of the boards over time can allow water flowing down the pass to enter under the boards and loosen them further by mechanical action. This can trap eels in the silt that accumulates underneath loosened boards (Dan Hayter, pers. comm.). Using point fixings (marine grade stainless steel screws or bolts) as well as an appropriate specialist aquatic non-toxic underwater sealant is the most secure and eel-friendly attachment method.

Quality of construction

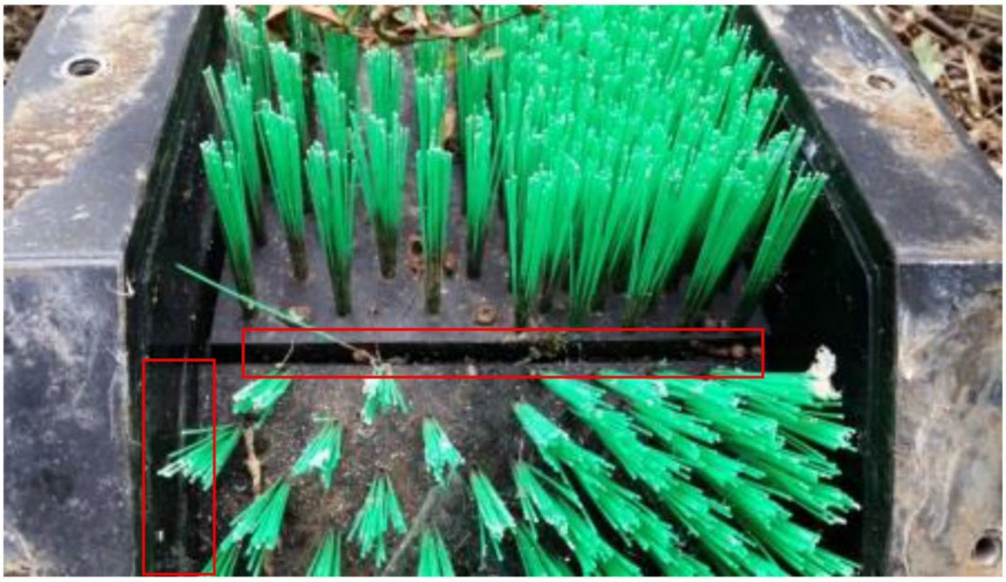

Figure 18: Gaps at the side of bristle boards and between boards at the change in slope (source: Laura Bullock)

Deficiencies can originate from the construction process rather than develop over time. For example, Figure 18 shows gaps between the edges of bristles boards and the box section and discontinuity of the bristle substrate at a change in slope. These gaps may affect the effectiveness of the pass.

To avoid these problems, new installations should be inspected by fisheries experts as soon as possible after they are built. This will mean any deficiencies in the construction or design can be identified and rectified as soon as possible. Regular inspections as part of an ongoing maintenance programme will highlight the need for remedial works.

4.5 Pumps

Pumped up-and-over passes are the most commonly installed type of pass, yet they are prone to failure due to problems linked to inadequate or non-continuous water flow. The 2 main causes of this are power failure and pump failure.

4.5.1 Power failure

Many sites do not have mains power which presents a challenge in powering the pumps for up-and-over passes. Solar arrays can be used but several panels and a large battery bank may be needed to store enough power. Also, depending on the amount of public access to the site, solar arrays at ground level can be vulnerable to vandalism; it is difficult to make them vandal proof. Large solar arrays may also require specific planning permission in sensitive areas.

The advantage of fuel cells is that they can run continuously regardless of weather conditions. Additional telemetry can also be added so that the operator can monitor the power supply remotely and be alerted to problems immediately. If contained within a strong metal box, fuel cells can be made relatively safe from vandalism. However, they are expensive to buy and the fuel cartridges need replacing regularly.

Ram pumps are an environmentally friendly, low-cost option that don’t need an external power source. However, they won’t be suitable for many situations. For example, at Judas Gap the ram pump installed was not able to lift water to the required head. They can also become blocked and so are only appropriate for sites that are checked regularly.

4.5.2 Pump failure

All pumps operating in the riverine or estuarine environment are subject to biofouling which, if not regularly removed, can cause the pump to fail either because the inlet and/or outlet become blocked or the moving parts seize. Pumps may also become clogged by organisms, algal mats/macrophytes or pieces of debris that are drawn into the inlet. Impellor pumps are particularly vulnerable to damage if run dry for extended periods. So, if a blocked inlet is not cleared quickly the pump may overheat and fail. Piston pumps are less susceptible to this problem and can run dry for several weeks without sustaining damage. The fluctuation of water levels at the pump inlet location, for example due to the tidal cycle or abstraction demands, can also cause pumps to run dry and eventually fail. Even within an ideal operating environment, pumps, in common with all mechanical equipment, are subject to the general wear and tear caused by use.

It may be appealing to assume that because eel movements are predominantly nocturnal, there is little, if any, passage during daylight hours (Feunteun et al., 2003), so pumps could be operated on a 12 hours on/12 hours off schedule and be switched off during the day. However, stopping the water supply to an up-and-over pass, even if only temporarily, can have serious consequences for eels that have already begun their ascent. For this reason, pumps should operate continuously during the period of eel migration.

By definition, up-and-over passes provide a migration route that circumvents the structure and therefore extends above and/or alongside the river channel. Passes can be long (for example, 45 m pass at Wiffholme Pumping Station, Yorkshire), producing substantial transit times, therefore conditions within the pass must be maintained within the eels’ physiological comfort range. Eels that are still within the pass when the pumps switch off lose the flow cue that induces ascent and may remain in situ rather than advancing or descending back to the river. Among teleost fishes, eels are comparatively tolerant of high temperatures and hypoxia. The upper lethal temperature of European eel ranges from 32 to 35°C (Tongiorgi et al., 1986) and they can survive an oxygen concentration as low as

5% saturation for at least 1 hour (Peyraud-Waitzenegger and Soulier, 1989), partly by increasing oxygen uptake through the skin (Le Moigne et al., 1986).

Aerial breathing enables eels to survive emersion for extended periods (20 hours at 15°C for adult female *A. anguilla*) before visibly weakening, but few test subjects survived 60 hours of emersion (Berg and Steen, 1965). The challenge of emersion is compounded by elevated temperature and drying out of the substrate. Direct sunlight on a pass with no conveyance flow causes temperatures to rise quickly. This is made worse in facilities constructed from HDPE, which tends to be black and so absorbs more heat, and where the cover is solid as opposed to perforated and so traps heat more effectively. Rectifying this issue in current and future facilities should be a significant priority going forward.

4.5.3 Alternatives to impellor pumps

Air lift pumps that use the injection of compressed air to convey liquid against a small head may offer an alternative to impellor pumps. Due to the absence of mechanical parts immersed in the water, air lift pumps are less vulnerable to the problems of clogging and biofouling. The simple design also makes them more reliable than other types of pumps. Another alternative is 3-spindle miniature screw pumps that use a development of the Archimedean screw. These are of a simple design and are self-priming as well as intrinsically smooth, quiet and robust.

4.5.4 Considerations for pumps

All Environment Agency pump installations should be approved by MEICA (Mechanical Electrical Instrumentation Control and Automation), or a qualified electrician for other organisations.

Small submersible pumps need checking and maintaining regularly to make sure that they have not become blocked or have failed due to drawing in debris. If regular checks (for example, weekly) are not possible or telemetry systems are not installed, it may be prudent to install a larger non-submersible centrifugal pump, which due to larger fin spacing and more robust components (for example, typically bronze impellor) is less likely to become blocked. Another option is ‘dirty water’ or sludge pumps, which are specially designed to be resilient to debris blockage. However, these are relatively expensive and use more energy.

To reduce the chance of clogging, the inlet of the pump should be adequately screened to prevent larger organisms and debris getting in. There are a range of screening options available, including self-cleaning intake screens that operate an automatic backwash to regularly clear the filter. Note: Screening is required for compliance with Part 4 Section 17 Eels (England and Wales) Regulations 2009 on pumps abstracting >20 cubic meters/day unless exempted by the Environment Agency.

Pumps should be self-priming so that if there is an interruption to the power supply or a temporary blockage, flow will be restored once the power is restored or the blockage passes.

One option to extend pump life is to only operate eel-specific passes during the main eel migration period. At the end of each season they could be switched off and, if feasible, removed for maintenance and storage. Each year, a staff member should return to the site a few weeks before the start of the migration season to reinstate the pump and make sure that the pass is otherwise in good condition and ready to use. If there are unforeseen difficulties, the few weeks grace period will allow time for these to be rectified before the main migration period begins. Permission is needed from the Environment Agency to run passes seasonally.

Before a pass is installed, it is crucial to understand fully how water levels at the site fluctuate. This information should be used to site the pump inlet so as to minimise the likelihood of drying out.

Pumped passes should never be operated on a 12 hours on: 12 hours off schedule. The installed pump must therefore be capable of running continuously.

4.6 Flow through the pass (conveyance flow)

The optimum rate of conveyance flow through the pass represents a balance between sufficient flow to induce ascent by upstream migrants, while not generating velocities that exceed the swimming capabilities of the smallest target size classes, which will result in ‘wash down’. Low flow rates may also be associated with the settling out of suspended solids causing clogging of the substrate, drying out of the substrate, and elevated temperatures in the pass because flowing water dissipates heat from the pass walls. Beyond this, site-specific factors may influence the degree to which the optimum flow rate can be applied. For example, on gauging structures, Environment Agency guidelines state that pumped passes should abstract no more than 0.5 L s-1 (Environment Agency, 2011a).

4.6.1 Gravity-fed passes

In gravity-fed passes, water flow through the pass depends on the relative elevations of the upstream end of the pass (or the pipe inlet to the pass) and upstream water level. 2 causes are: 1) blockage due to debris accumulating at the upstream end preventing water flowing through the pass, and 2) insufficient head due to the position of sluice gates.

Main considerations when calculating an appropriate upstream level for the pass are:

- only use the predicted/measured flow rates at the site during the main period of upstream eel migration - within this, there should be a bias towards achieving optimum flow rates under the higher flow levels expected during this period because there is evidence that elevated flow stimulates eel movement - upstream elevation calculations should not be based on the annual hydrograph (Q95)

- seek stage/discharge velocity relationships for the type of pass being used to make sure that the likely range of velocities are within the swim capabilities of the target life stages - if these relationships are unknown, carry out empirical velocity measurements within the pass under a range of flows post-installation and adjust as necessary

The main function of many of the structures that pose obstructions to eel migration is flood risk management. Facilitating eel passage at adjustable structures such as sluice gates and at sites where up and downstream levels fluctuate is particularly challenging. However, designs are evolving and self-adjusting passes that move in relation to upstream water level to maintain greater flow consistency down the pass under a wider range of scenarios are increasingly being used.

Figure 19: Two images of self-adjusting passes at sluice gates (source: a) Paula Rosewarne and b) Environment Agency, 2011a)

Figure 19 shows 2 examples of self-adjusting passes at sluice gates, where the passes have been designed to accommodate different water levels and sluice flows..

4.6.2 Pumped passes

In up-and-over pumped passes, water is pumped to the crest of the pass where it splits. Most flows to the downstream length of the pass as conveyance flow and the remainder flows to the upstream section to transport eels to the upstream side of the structure or into a catch pot.

Unlike gravity-fed passes, pumped passes offer the advantage of greater consistency in conveyance flow rate because pumping rate will be only slightly affected by changes in ambient water level. However, there remains insufficient evidence within the literature to formulate guidelines on optimum flow rates. Most documented passes and test facilities operate at flow levels equivalent to 8 to 66 L minute-1 per m width of pass (Solomon and Beach, 2004), but these rates are derived from facilities with various longitudinal slopes and substrates, both of which have a strong influence on resultant velocities in the pass. Knights and White (1998) suggest that a velocity of 0.5 m s-1 is adequate to stimulate climbing, although passes successfully operate below this, for example 0.25 m s-1 in the Moses-Saunders pass, St Lawrence River, Canada. In the absence of guidelines, empirical velocity measurements and trials at the pass facility should be used to optimise flow rate. For example, trials of different flow rates conducted at Greylake Sluice, Somerset, identified 0.5 l s-1 as optimum to feed both the downstream bristle channel and the upstream delivery pipe (Don, 2009).

Using a flow splitter arrangement with easily adjustable valves enables fine control of the delivery rate to the up – and downstream pass sections. The splitter arrangement should be as simple as possible with ample, linear flow in both directions to make sure that once eels reach the crest, they are quickly conveyed down to the pass exit without opportunity to turn around and return down the ascent section. The difficulties associated with the propensity for eels to turn into the flow (positive rheotaxis) and swim upstream, back towards the pass exit, was neatly illustrated during design of the St Lawrence-FDR eel passage facility, USA. To prevent washdown after exiting the 55 m long eel ladder, the release point for migrants was sited 300 m upstream of the main dam. Trials with a pipe (0.15 m diameter) to convey eels to the release point showed that even with a substantial flushing flow, eels were able to turn and swim against velocities of 1.8 ms^{-1}. It was therefore decided to reverse the flow direction and rely on the eels to swim upstream against the flow to reach the end of the pipe. A study of passage efficiency and transit times showed that all the eels that successfully ascended the ladder also passed through the 300 m long pipe, generally taking ~30 minutes to do so (McGrath and Tatham, 2007).

Figure 20: Effective flow splitter arrangement in use in Somerset (source: Andy Don)

Some problems with splitter boxes include confused flow patterns (vortices), and fouling and debris accumulating underneath the splitter tap. This latter problem can be caused both by high debris loading in the input water and the splitter tap outlet being located too close to the bristle substrate underneath. The build-up of debris within the bristles quickly reach the splitter tap and can cause unbalanced delivery to the pass sections.

4.7 Attraction flow

Generating adequate attraction to up-and-over passes is a challenge at the many sites where the pass is situated beside a weir or other structure passing substantial flow. The conveyance flow delivered to an up-and-over pass will constitute only a small fraction of the total flow passing the main structure, therefore the latter exerts a strong attraction to migrating eel.

There is enough evidence to recommend the supply of additional flow close to the pass entrance to enhance attraction. At the 156.4 m long ladder at the Moses Saunders Dam on the St Lawrence River, a low pressure hose (50 mm diameter) delivers water to the entrance of the pass (McGrath et al., 2003). It is thought that the turbulence created may be an attractant for eel, as it is for migrating salmonids (Coutant, 2001; Katopodis and Williams, 2012; Piper et al., 2012). Field trials at Judas Gap intertidal weir, Essex, indicated that supplementary freshwater attraction flow was most effective when sprinkled from 1.9 m above the downstream entrance of the pass, and that only a small volume (0.5 l s-1) was necessary. This simple addition doubled the number of eels using the pass (Piper et al., 2012). Wherever feasible, pass design should incorporate a flow outlet to deliver sprinkling overhead flow to the downstream entrance of the pass. This has already been adopted at facilities in the UK and the Netherlands. Figure 21 shows a flow splitter added to deliver attraction flow at the base of the pass in the UK. Figure 22 shows multiple plunging flow outlets to enhance attraction to the downstream end of the pass in the Netherlands.

Figure 21: An eel pass at Judas Gap after modification – flow splitter added to deliver attraction flow to the base of the pass (source: Adam Piper)

Figure 22: Elver pass at Nieuwe Statenzijl, Netherlands with multiple plunging flow outlets to enhance attraction to the downstream end of the pass (source: Peter Paul Schollema)

4.8 Cover

Covers are typically fitted to all box section up-and-over passes to protect eels within the pass from birds and rodents, and to prevent eels climbing out of the channel during ascent. If the location is wooded, providing a cover would also prevent fallen leaves accumulating in the pass. In areas with high levels of artificial light, a cover reduces the deterrent effect of light on the nocturnally migrating eel.

Covers may also be fitted to passes made of vertically-mounted bristle boards or eel tiles to reduce the build-up of silt and other debris, and by excluding light to limit the growth of plants within the substrate (Figure 23 and Figure 24).

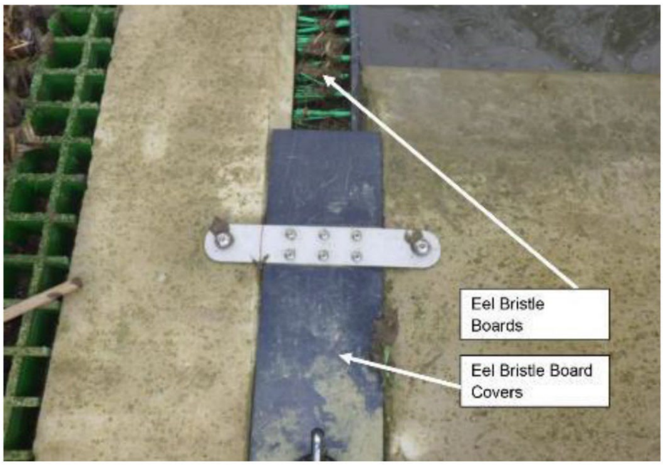

Figure 23. Cover fitted on vertical bristle board eel pass at Tallington gauging station in Lincolnshire (source: Hugh Bunker/James Hooker)

Figure 23 shows plants growing on the exposed bristle board above the covered area.

Figure 24: Debris accumulation and plant growth on the vertical bristle board section of an eel pass at Partney in Lincolnshire (source: Lesley Shuttleworth)

Figure 24 shows accumulate plant growth and debris against the bristle board at the water level.

Issues concerning covers include:

- difficulty accessing the pass for inspection because of the type of fixings used to secure the cover
- concerns about heat retention by solid covers
- damage and warping of the cover either due to being struck by debris or, in the case of HDPE covers, thermal cycling

4.8.1 Considerations for covers

Cover type – selecting an appropriate cover depends on site-specific factors. The main functions of the cover at the site in question should be considered (for example, keeping out predators, light and leaves, as well as for security purposes) and how vulnerable the pass will be to factors such as debris damage and high flows. Solid covers tend to be more robust, but due to reduced air flow they can cause heat to build up inside up-and-over passes. For this reason, a perforated cover is preferable in locations exposed to full sun unless keeping light out is also a vital requirement. Glass reinforced plastic (GRP) grating may be a more robust alternative to the perforated steel or aluminium sheeting that is commonly used. Figure 25 shows a gridded plastic cover in image a) and a damaged cover compromising debris damage and security in image b).

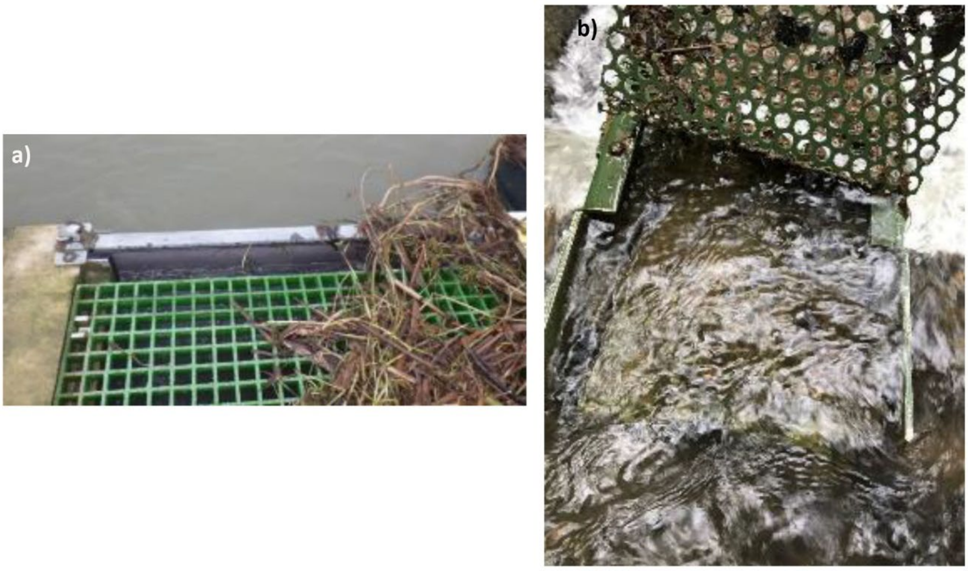

Figure 25: a) Glass reinforced plastic (GRP) cover at Tallington fish pass in Lincolnshire b) Damaged cover on a box section pass at Church Rd in Hampshire (source: a) Hugh Bunker/James Hooker, b) Kerry Sims)

Figure 25 shows a GRP cover keeping debris off the pass and another pass with a damaged cover where debris has accumulated and in the pass.

Ease of access – the cover should be able to be easily opened to inspect and maintain the pass. If a solid cover is to be fitted, it should preferably be hinged rather than screwed down, and secured at one point with a lockable latch (for example, stainless steel hasp and staple type). This would enable easy access to the pass while ensuring that the cover remains secure and robust at other times.

4.9 Slope

4.9.1 Longitudinal slope

The design of a passage facility should aim to minimise the energetic expenditure demanded of the fish to pass it (Castro-Santos et al., 2009). Upstream eel passage facilities frequently rely on ascent by climbing, therefore steeper gradients require a higher energy expenditure per metre of pass. However, there is an obvious trade-off with pass length; a steeper pass will be a shorter pass.

Several studies have compared eel passage efficiency on substrates with various slopes (25 to 70°) and, in general, the shallower slopes were associated with highest passage (Anwar and Haro, 2017; Jellyman et al., 2017; Watz et al., 2019). The exception was for glass eels (50 to 69 mm) ascending gravel surfaces (1 to 4 mm grain size), where passage efficiency was unaffected by slope ranging from 25 to 45° (Anwar and Haro, 2017).

The Environment Agency guideline recommending that up-and-over passes with bristle substrate do not exceed 30° is well supported. Site configuration may nevertheless require the pass to be constructed, either wholly or partly, with a gradient steeper than the recommended maximum. Vertical climbing is associated with juveniles smaller than 100 mm (Legault, 1988; Linton et al., 2007) that are present in the lower sections of the freshwater catchment, especially at intertidal barriers. Steep pass gradients may be acceptable in these locations if site architecture does not allow a longer, shallower facility to be installed. Further upstream in the freshwater catchment where the proportion of larger life stages using the pass increases, compliance with the current recommended gradient of ≤ 30° is more important.

4.9.2 Lateral slope

The majority of constructed passes currently operating in England are rectangular in cross-section and aligned flat on the horizontal plane. Using a V or U-shaped cross-section or tilting a rectangular pass to introduce a lateral slope both reduces the wetted perimeter, thereby reducing the quantity of conveyance flow required to achieve the same velocities, and creates a greater range of velocities within the same channel. Although lateral slope is being incorporated into pass design (for example, Baker and Boubee, 2006; Jellyman et al., 2017), quantitative comparisons of passage efficiencies for different eel size classes and the flow patterns created by different slopes and cross-sectional shapes are lacking. Research on this topic has since been published, see Piper et al. (2023).

4.10 Positioning

Upstream eel migration is bank-oriented (Deelder, 1958), particularly among the smaller life stages once they have transitioned to the active swimming phase (Harrison et al., 2014; Piper et al., 2012; Watz et al., 2019). Passes should therefore ideally be sited near to the bank because this is where most eels are moving upstream, especially the smallest life stages (Piper et al., 2012; Watz et al., 2019). Bankside positioning maximises the likelihood of intercepting eels before they advance onto the weir or other structure seeking an ascent route.

Similarly, given that upstream migrating eels may use the full height of the water column (Tesch, 2003), it is supposed that extending the ascent section of the pass (or at least the climbing substrate) to the channel bed rather than terminating mid-water column will maximise the likelihood of eels intercepting it (Knights & White, 1998).

Knights and White (1998) recommend positioning pass entrances in quiet water, and that providing rocks or rubble will help entry because eels tend to use the boundary layers near obstacles. In a study at a bristle pass (6 m length; 45° slope) located at a weir and gravity fed with water, Drouineau et al. (2015) recorded the highest capture rates when river flow was highest (0.8 m sec-1), but noted that under these conditions the reverse currents observed close to the pass entrance may have attracted or conveyed eels to the entrance.

The general lack of knowledge on eel response to flow characteristics such as turbulence, particularly for juveniles, currently prevents desirable flow characteristics being produced for pass entrances.

With regards to positioning of the pass exit, it should be located where water velocities do not exceed the swim capabilities of the smallest target life stage to minimise the risk of exiting eels being washed back downstream of the structure. The other main factor to consider is predation. The pass should ideally exit in deep water with adequate cover, for example macrophytes, cobble substrate to minimise predation by birds and other fish. If this is not possible, artificial refuges (for example, rip-rap or brushwood faggots) should be provided close to the pass exit.

4.11 Transit time

A passage facility should aim to minimise the transit time, which is the time it takes an ascending eel to travel between the entrance and exit of the pass. This can be achieved by:

- using the minimum length required to circumvent or ascend the structure, taking into consideration recommended gradients
- selecting the most appropriate climbing substrate for the life stages present, considering flow conditions at the site
- optimising attraction flow, flow rate at the crest and down the pass
- simplifying the route and structure of the pass, that is to minimise the occurrence of changes in direction, joins between sections, changes in pass diameter or cross-sectional shape that could cause confusing flow patterns

Up-and-over passes, in particular, can be long. One of the longest passes reported in the literature is on the Moses-Saunders Dam, St Lawrence River, Quebec, where the 156 m long pass results in a minimum transit time of 70 minutes (Solomon and Beach, 2004).

In passes with long sections buried underground, inspection chambers are typically incorporated to allow access at points along the pass for inspection and maintenance. A typical inspection chamber of a box with accessible lid is shown in photo a) of Figure 26. As in the image, the chambers tend to be empty (no climbing substrate), flat-bottomed boxes that are significantly wider than the cross-section of the pass ascent/descent sections. Similar boxes are also incorporated into passes at the crest to accommodate a flow spitting arrangement – this shown in image b) of Figure 26.

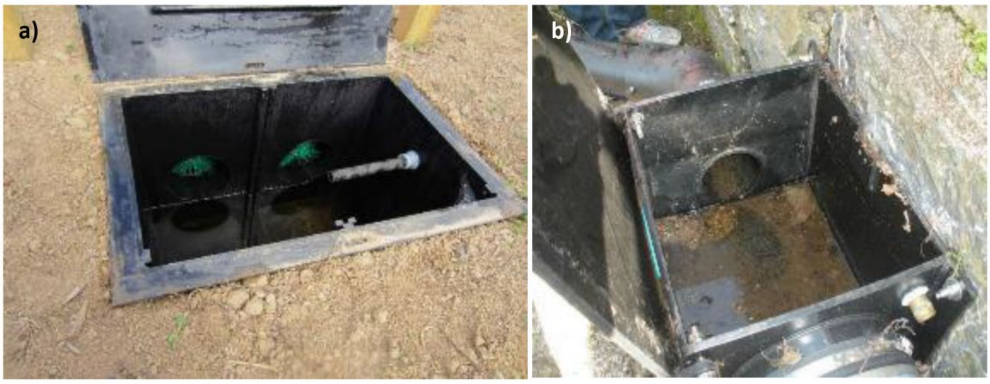

Figure 26: a) Inspection chamber at Stokesby in Norfolk, b) A splitter box at Kilbury weir during decommissioning (source: a) Paula Rosewarne, b) Andy Don)

When water flowing down the pass enters an inspection chamber or water is delivered into a splitter box its velocity is reduced and suspended solids settle out, causing silt to accumulate in the box over time. More detrimental, however, are the multidirectional flow patterns and flow vortices created when water slows down and pools in the base of the box. Flow direction and olfaction form the principal navigational cues for juvenile eel immigration into estuaries and rivers (Deelder, 1954; Crivelli et al., 2008). The pools and counterintuitive flow cues created in inspection chambers have been observed by the author (Paula Rosewarne) to cause disorientation among migrants, with some turning and exiting the box in the wrong direction, thereby increasing transit times. Similar observations have been made by the author (Ros Wright) at the splitter box on a pass crest, where eels that reached the crest dwelled for some minutes, apparently caught in a flow vortex, and were not immediately washed down into the catch pot as intended.

4.11.1 Possible actions to reduce transit time

Inspection chambers and splitter boxes should resemble the main pass in cross-section size and shape as closely as possible. The floor of the chamber should be sloping towards the exit, and left smooth to facilitate rapid transit in the descent section. Corners create areas of low velocity and recurrent flow which may cause disorientation, so baffles that direct flow away from the corners and towards the pass exit should be provided on the slope towards the descent section. A sloping floor and baffles can be easily and inexpensively retrofitted to flat-bottomed chambers after installation.

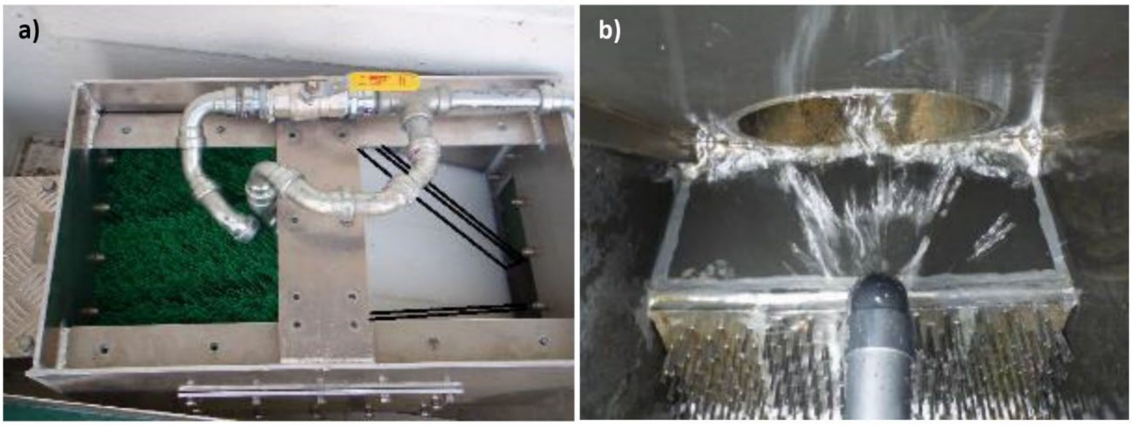

Figure 27: A splitter box and an inspection chamber after addition of a sloping floor (Source: a) Andy Don, b) Paula Rosewarne)

Figure 27 shows a splitter box which consists of a metal box split in 2 with water pipes feeding into it – it also shows the inside of a metal inspection chamber after addition of a sloping floor.

4.12 Operating schedule

Most current facilities are operated all year round rather than seasonally. Although upstream eel migration occurs throughout the year, the strong and broadly predictable relationship between season and upstream movements provides a basis for operating passes during the main migration period only. The potential benefits from adopting a seasonal operating schedule will vary between sites but may include reduction in damage to the pass incurred during high winter flows. Box-section passes fixed directly onto a weir face or hooked over sluice gates are most vulnerable to damage from high flows and the large pieces of debris carried within them. In extreme cases, the pass may be broken from the structure and carried downstream, resulting in loss or damage to the pass, environmental pollution, and a potential flood risk if it obstructs the channel.

The smaller hook-over type passes can be easily removed and transported for storage at the end of the season and reinstalled at the start of the next. The feasibility of removing and storing other types of pass will depend on their size and how they are attached to the structure. Therefore, along with ensuring easy access to the pass for inspection and maintenance, removing the pass annually should be considered during the design and installation stages.

Running pumps continuously induces wear and tear, which may be regarded as unnecessary during the winter months when there is little eel movement. Furthermore, the heightened levels of debris carried by high winter flows pose greater risk of blocking and/or damaging the pump than at other times. Shutting off and drying out the pump for an extended period (winter months) also kills biofouling organisms, allowing them to be easily removed during re-commissioning at the start of the season

The optimum timing of a seasonal operating schedule will vary with pass location. Ideally, several years' monitoring data from the pass itself or other passes within the same area should be used to inform the schedule. If monitoring data are not available, facilities on the west side of the country may be operated from March, while those on the east side may commence slightly later in April/May and run through to the end of September or for longer if there is a local need. Further guidance on seasonal operations will be available as notices are required to remove passes and this may be co-ordinated nationally.

4.13 Construction materials

Current eel pass facilities are constructed from a range of materials, including high-density polyethylene (HDPE), fibreglass, stainless steel and aluminium. Depending on the site-specific requirements, passes may be purchased off-the-shelf (that is, complete and ready-made), in modular sections, or as a fully customised facility designed and constructed specifically for the site. In all instances, choice of construction material is limited by what manufacturers offer, although in the case of custom-built passes there may be scope to trial alternative/novel materials. A summary of the most commonly used construction materials, their advantages, disadvantages and reported issues is presented in Appendix 2.

4.13.1 Considerations for construction materials

Considerations for choice of construction materials:

- all metal fixings should be made of marine grade stainless steel (316) to prevent rusting
- for all materials, design the pass to minimise the number of joins needed
- when using plastics, ideally low-expansion types and/or combine with other materials (for example, composite backing boards) to reduce the likelihood of warping

4.14 Monitoring

Long-term (more than 10 years) monitoring has been carried out at several passes around the UK and these data are supplied annually to the ICES Working Group on Eel who review data on the stock and issue management advice.

Monitoring data are highly valuable for gauging recruitment into a system over time as well as providing site-specific information to inform optimal functioning of the pass (for example, operating schedule, flow rate, climbing substrate). However, there are inherent costs and risks associated with this type of data collection. Guidelines on monitoring can be found in 'Monitoring elver and eel populations' (Environment Agency, 2011b). Appendix 3 presents a summary of the main monitoring methods used at eel passes, their advantages, disadvantages and other considerations.

4.15 Maintenance

Regular maintenance is essential to the optimal functioning of eel passes. Regularly maintained facilities require less remedial actions to return them to optimal functioning than facilities which are less regularly maintained. All passes must be subject to a regular inspection and maintenance programme that is formulated and budgeted for the type of pass during the planning stages. Maintenance and repair of eel passes is a legal requirement under Part 4 Section 15 of the Eels (England and Wales) Regulations 2009 which states:

- a responsible person must, at their own cost, maintain an eel pass in an efficient state
- failure to comply with paragraph (1) is an offence

The required frequency of maintenance will be site specific. Some considerations when formulating the maintenance programme are:

4.15.1 Accessibility

Design – ease of access for inspecting and maintaining the pass should be a core consideration at the planning and design stages. Where applicable (for example, hook over passes), provision should be made to remove the pass at the end of the migration season each year.

Inspection chambers – burying pass sections underground should be avoided if possible. If necessary, regular access points (every 5 m is suggested) should be incorporated, but these should resemble the pass in cross section as much as possible. A ‘trap door’ cut into the box section of the pass is the preferred option; large box-shaped inspection chambers should be avoided.

Top cover – make sure that the pass design includes a cover that can be easily removed.

Health and safety – many passage facilities are located at sites classified as ‘confined spaces’ or with other heightened health and safety risks. In such cases, access may be restricted to specially trained staff and this must be considered in the maintenance programme.

4.15.2 Cleaning

Considerations for cleaning:

- climbing substrate may be effectively cleaned by pressure washing
- often there is no electricity supply at sites, so cleaning equipment that uses alternative power sources may be needed
- small passes and some substrates are easily removable so could be taken and cleaned off-site

4.15.3 Pumped passes

The relevant staff/contractor must have appropriate qualifications and clearance to install, maintain and repair pumps. Installation of pumps must be approved by Mechanical Electrical Instrumentation Control and Automation (MEICA) and regular maintenance under the Environment Agency's assets information management system will alleviate these issues.

4.15.4 Scheduling

The majority of structures with passage facilities are owned by the Environment Agency, so ensuring adequate maintenance at these passes would represent a substantial step towards the ultimate goal of maintaining all passes.

Passes at gauging weirs are checked and maintained regularly. Indeed, many of the fish passes themselves constitute a gauging structure, so it is important for accurate gauging that they are in good repair and kept clear of debris.

There are existing inspection schedules for flood defence structures and other assets owned by the Environment Agency recorded on their inventory of asset information management systems (AIMS). Many of these structures have passes installed so there is an opportunity to incorporate fish and eel pass inspection into the existing programmes, which would be the most cost-effective way of making sure passes are regularly inspected and maintained. Maintenance standards are being developed and there may be site-specific requirements.

4.15.5 Remote monitoring

Some sites have a remote camera installed to monitor the gauging structure. This can also be used to check the pass for obvious blockages or damage. These checks should be carried out particularly after high flow or flood events.

Some pumped passes have alarm systems to indicate pump failure, and this is recommended where possible. There may be an option to incorporate pump operation monitoring into existing telemetry systems at a site. For example, a power usage monitor could be used to indicate if the pump is still running, and conductivity monitoring could indicate if the pump is clogged.

4.16 Summary

This chapter has summarised important design and maintenance considerations when planning an eel pass.

5 Conclusions and further research

Evidence from both published studies and unpublished data sets from facilities that have been in operation for several years indicates that there is substantial scope for improvement in the maintenance schedules, design and functioning of eel passes. Based on the literature review carried out in preparing this document, there was a particular lack of evidence in the following areas of research, which will also provide more information to help improve the design and installation of upstream eel passes.

5.1 Assessments of performance

Few studies provide quantitative estimates of attraction and passage efficiencies of tested facilities, which makes it very difficult to make comparisons between types of passes and design features. Some relatively new types of pass (e.g. pet flaps) are particularly under-evaluated. Laboratory-based investigation offers the opportunity to obtain additional detailed metrics (for example, transit time) and behavioural insights through video observation (for example, Anwar, 2018; Kerr et al., 2015; Vowles et al., 2017), while carefully designed telemetry arrays using the standardised protocol for fish pass assessment can yield robust estimates in field situations (CEN, 2018).

5.2 Optimum climbing substrates

Although several studies have compared climbing substrates under different longitudinal slopes, few have used a wide enough range of eel size classes to draw firm conclusions about their applicability for different life stages. Furthermore, the degree to which the different flow characteristics created by the substrates underpin the observed results remains almost entirely unaddressed and makes it difficult to transfer findings. This is particularly relevant given that a recent study highlighted that the substantial differences observed in the number of eels that passed the different test substrates did not reflect their ability to ascend, but rather that they were attracted to ascend, which may be related to flow characteristics (Watz et al., 2019).

5.3 Optimum shape and slope

Variations in lateral slope created either by tilting a flat-bottomed pass or using a V or U-shaped cross-section can achieve a diversity of flow rates within the same pass channel. A 10° lateral slope is being adopted into standard substrate pass design in New Zealand (Baker and Boubee, 2006; Jellyman et al., 2017). As well as minimising the volume of conveyance flow required by creating a smaller wetted perimeter, it is hypothesised that this variation of flow will provide suitable hydrodynamic conditions for a range of eel size classes within the same facility, and this is currently being tested. Aspects of the research on this topic has now been published (Piper et al., 2023).

5.4 Appropriate hydrodynamic conditions

Optimising flow conditions at pass facilities is crucial to ensure both efficient attraction and passage.

5.4.1 Attraction to the pass entrance

Adding attraction flow at the base of the pass has been shown to be beneficial at some facilities, but we need to understand better the range of scenarios this applies to and how to optimise attraction in situations with substantial competing flows passing the main structure. This may be achieved by modifying the rate and type of attraction flow provided, or the positioning of the pass relative to the main structure.

5.4.2 Conveyance flow rate

There is an absence of stage/velocity relationships for all the ramp-style passes commonly used. Velocities within the pass depend on:

- depth of water at the crest
- cross sectional area and shape
- substrate type
- longitudinal slope

Stage/velocity relationships developed through empirical testing under controlled laboratory conditions for the most common types of passes, substrates and for a typical range of slopes (15 to 50°) would prove a valuable advancement in knowledge. By relating them to the burst and sustained swimming capabilities of different eel size classes, which have been well studied (Solomon and Beach, 2004), these relationships could be used to underpin best practice guidelines and optimise conveyance flow rates for a large number of facilities in the UK, and further afield.

5.4.3 Crest and splitter box design

A critical element of eel pass design are the hydraulic conditions at the crest of gravity-fed passes or within a splitter box which may be present on pumped passes. Optimum pass design should ensure that once eels reach the crest, they are quickly conveyed down to the pass exit without opportunity to turn around and return down the ascent section. Problems such as washback from the crest and confused flow patterns within splitter boxes have been identified in existing facilities.

There is a need to test the effectiveness of pass design modifications including 1) provision of velocity refuges at the crest, 2) configuration of flow splitter taps, and 3) optimising the relationship between slope angle, channel/trough characteristics and hydraulics at the upstream exit section, all under the typical operating range of flow rates and for the full range of upstream migrating eel size classes. The required research will generate empirically-derived recommendations for pass crest designs and flow splitter arrangements for the most commonly encountered pass types under a range of flow scenarios.

The research to improve eel pass design and performance is being undertaken and this will be published as results become available.

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7 Appendix 1. Summary of climbing substrates

This appendix summarises climbing substrates, including specifications and tested efficiencies for different eel life stages.

7.1 Bristle board (solid base) – Watz et al., 2019

Manufactured by Fish-Pass, France

Specifications:

- nylon bristles fixed to polypropylene sheet
- bristles 70 mm long, mixture of spacings: 16 and 28 mm

Size class: 60 to 110 mm

Longitudinal slope: 30°

Eel species: *A. anguilla*

Flow velocity:

- 0.07 L s-1 to each ramp, 2 m long, 0.32 m wide
- some diverted as attraction flow

Attraction efficiency: less attractive than studs but higher attraction than Enkamat

Passage efficiency: ~50% (not different to studs or bristles)

Study: Watz et al., 2019

7.2 Bristle board (solid base) – Piper et al., 2018

Manufactured by ACE

Specifications:

- nylon bristles fixed to polypropylene sheet
- bristles 100 mm long, 18 mm spacing

Size class:

- 157 to 542 mm tagged and released
- 172 to 346 mm successfully passed

Longitudinal slope: 26°

Eel species: *A. Anguilla*

Flow velocity:

- passage occurred 0.2–5.0 L s-1 (ramp 6 m long, 0.2 m wide)
- velocity not measured

Attraction efficiency:

- 47% (31–63, 95% CI) right-hand pass
- 27% (14–46, 95% CI) left-hand pass

Passage efficiency:

- 94% (72–99, 95% CI) right-hand pass
- 86% (49–97, 95% CI) left-hand pass

Study: Piper et al., 2018

7.3 Bristle board (solid base) – Legault, 1992

Manufacturer unknown

Specifications: bristles of 7, 14 and 21 mm spacings

Size class: 223 ± 43 mm (mean ± S.D.)

Longitudinal slope:

- 15°
- 30°
- 45°

Eel species: *A. Anguilla*

Flow velocity: flow not stated (ramp 2.4 m long, 0.3 m wide)

Attraction efficiency: not quantified

Passage efficiency: highest proportion passed 14 mm bristles

Study: Legault, 1992

7.4 Bristle board (solid base) – Kerr et al., 2015

Manufactured by Fish-Pass, France

Specifications:

- nylon bristles fixed to polypropylene sheet
- bristles 70 mm long, 30 mm spacing (15 mm between staggered rows)

Size class:

- 82 to 320 mm
- 322 to 660 mm

Longitudinal slope: vertically-oriented

Eel species: *A. Anguilla*

Flow velocity:

- 3 flow treatments
- maximum velocities 2.43, 1.91, and 0.80 ms−1
- velocity in substrate not measured

Attraction efficiency: >85% for large eel, irrespective of bristles

Passage efficiency: overall weir passage efficiency under high velocity increased due to bristles from 0% to 91.5% (small eels) and from 4.6% to 56.7% (large eels)

Study: Kerr et al., 2015

7.5 Miradrain / Akwadrain – Jellyman et al., 2017

Specifications: raised plastic studs 24 mm height, 16 mm spacing

Size class:

- <155 mm
- most effective for eels >108 mm
- (did not test >155 mm eels)

Longitudinal slope:

- 30°
- 50°
- 70°

Eel species: *A. australis* (n=30/treatment)

Flow velocity:

- L s-1 down ramp (0.1 m wide, 1.5 m long) (=60 l/min/m of pass width)

- velocity not measured

Attraction efficiency: not quantified

Passage efficiency:

- 87% (30° slope) (mean)
- 57% (50° slope) (mean)
- 14% (70° slope) (mean)

Study: Jellyman et al., 2017

7.6 EF-16 Studs – Watz et al., 2019

Manufactured by Elghagen Fiskevard, Astorp, Sweden

Specifications: studs (14 mm height; 28 mm max diameter) and depressions (14 mm depth; 16 mm max. diameter) evenly spaced at 14 mm

size class: 60 to 110 mm

Longitudinal slope: 30°

Eel species: *A. Anguilla*

Flow velocity:

- 0.07 L s-1 to each ramp 2 m long, 0.32 m wide
- some diverted as attraction flow

Attraction efficiency:

- most attractive compared to bristles and geotextile
- once eels attracted, more likely to initiate climb

Passage efficiency: ~50% (not different to studs or bristles), but eels climbed faster than bristles or Enkamat

Study: Watz et al., 2019

7.7 Studded tiles – Vowles et al., 2017

Manufactured by Berry & Escott engineering

Specifications:

- solid co-polymer construction
- studs are tapered

- 30 mm and 17 mm spacing of small studs
- 55 mm and 29 mm spacing of large studs

Size class: 424 ± 76 mm (mean ± S.D.)

Longitudinal slope:

- 11.3° (when secured flat on crump weir)
- tested vertically

Eel species: *A. Anguilla* (n = 90)

Flow velocity:

- 2 flow treatments
- maximum velocities on weir face 1.99 and 2.12 m s-1

Attraction efficiency: horizontal studs reduced attraction efficiency relative to control (because they reduced velocity)

Passage efficiency:

- studs had no effect under low velocity
- under high velocity, horizontal stud tiles increased efficiency to 93.3%

Study: Vowles et al., 2017

7.8 Studded tiles – Coe et al., 2015

Specifications:

- solid co-polymer construction
- studs are tapered
- 30 mm and 17 mm spacing of small studs
- 55 mm and 29 mm spacing of large studs

Size class:

- tagged 270 to 615 mm
- video observations of smaller eels

Longitudinal slope:

- 11.3°
- tested both 1) flat on Flat-V weir, 2) recessed into surface

Eel species: *A. Anguilla* (n = 72)

Flow velocity:

- Q99 of 0.044 m3 s-1
- velocities not mapped

Attraction efficiency: 57.6% (for whole weir inc. control area without substrate)

Passage efficiency

- 100% (raised tiles)
- 90.9% (recessed tiles)
- most effective for larger eels >150 mm

Study: Coe et al., 2015

7.9 Eel-ladder substrate by Milieu – McGrath and Tatham, 2007

Manufactured by Milieu

Specifications:

- open-topped cylinders 50.8 mm diameter, 101.6 mm height
- spacings are 63.5 mm and 30.5 mm
- designed for eels of 150 to 750 mm

Size class:

- passed 190 to 750 mm at Millville, Shenandoah
- 300 to 500 mm (mean 379 mm) on St Lawrence

Longitudinal slope: 35° (St Lawrence)

Eel species: *A. rostrata*

Flow velocity:

- 0.36 L s-1 down ladder 0.37 m wide, 55 m long
- 21 L s-1 attraction flow at pass entrance (St Lawrence)

Attraction efficiency: not quantified

Passage efficiency:

- 85% in ladder (St Lawrence)
- transit time was ~60 minutes

Study:

- Hildebrand, 2005
- McGrath and Tatham, 2007

7.10 Pelcar Evergreen and Rugofish – Voegtle and Larinier, 2000

Manufactured by Terraqua Environmental Solutions

Specifications:

- concrete construction, used for car parks and walkways
- stud dimensions and spacings vary with product (for example, Pelcar: studs 40 mm high, 46 mm diameter at base, 32 mm spacing at base)

Size class - 5 size classes tested:

- <180 mm
- 181 to 220 mm
- 221 to 260 mm
- 261 to 300 mm
- >301 mm

Longitudinal slope:

- 15°
- 30°
- 45°
- trialled 30° lateral slope

Eel species: *A. Anguilla*

Flow velocity:

- conveyance flow ranged from 0.01 to >6.67 L s-1 down each ramp (3 m length x 0.4 m width)
- velocity (m/s) ranged:
    - 15°: 0.08 to 0.91
    - 30°: 0.10 to 1.23
    - 45°: 0.20 to 1.82

Attraction efficiency: observed eels most attracted to ramps with lowest turbulence at base, for example to substrates that dissipated most energy

Passage efficiency:

- trialled Evergreen (and other custom-made concrete substrate)
- >50% for Evergreen

- closely spaced concrete studs most effective for smallest eels
- quincunx most effective layout

Study: Voegtle and Larinier, 2000

7.11 Sand and gravel mix – Jellyman et al., 2017

Specifications: tested grain size 2 to 15 mm

Size class

- <155 mm
- able to pass smaller eels than Miradrain
- (did not test >155 mm eels)

Longitudinal slope:

- 30°
- 50°
- 70°

Eel species: *A. australis* (n=30/treatment)

Flow velocity:

- 0.1 L s-1 down ramp (0.1 m wide, 1.5 m long)
- velocity not measured

Attraction efficiency: not quantified

Passage efficiency:

- 80% (30° slope) (mean)
- 13% (50° slope) (mean)
- 3% (70° slope) (mean)

Study: Jellyman et al., 2017

7.12 Sand and gravel mix – Anwar and Haro, 2017

Specifications – tested grain sizes:

- 0.18-0.25 mm
- 0.25-0.60 mm
- 0.60-1.00 mm
- 1.00-2.00 mm
- 2.00-4.00 mm

Size class:

- 50 to 69 mm
- 90 to 147 mm

Longitudinal slope

- 25°
- 35°
- 45°
- v-shaped cross section

Eel species: *A. rostrata* (n=40/treatment)

Flow velocity:

- 0.01 L s-1 down ramp (0.5 m long)
- (=20 l/min/m of pass width)
- velocity not measured

Attraction efficiency: highest proportion of climbing attempts on rougher substrates and shallow slopes

Passage efficiency:

- glass eels: highest for 2 roughest substrates, irrespective of slope
- elvers: highest for 2 roughest substrates at 25° slope

Study: Anwar and Haro, 2017

7.13 Geotextile – Watz et al., 2019

Enkamat 7020 (Colbond, Geosynthetics, Arnhem, the Netherlands)

Specifications: open weave geotextile

Size class: 60 to 110 mm

Longitudinal slope: 30°

Eel species: *A. Anguilla*

Flow velocity:

- 0.07 L s-1 to each ramp 2 m long, 0.32 m wide
- some diverted for attraction

Attraction efficiency: least attractive compared to studs and bristles

Passage efficiency: ~50% (not different to studs or bristles)

Study: Watz et al., 2019

8 Appendix 2. Summary of construction materials

This appendix summarises of advantages and disadvantages/reported issues of construction materials commonly used in eel passes.

8.1 High density polyethylene (HDPE) (box section)

Advantages:

- HDPE is the most environmentally stable of all plastics; type 2 HDPE is mainly made from post-consumer waste and can itself be fully recycled at end of useful life
- UV resistant

Disadvantages/reported issues:

- vulnerable to warping due to thermal cycling (High thermal expansion coefficient: 120x10-6 mm/°C)
- generally black so absorbs heat readily causing temperature rise in pass
- not self-supporting over long spans without additional structure
- heavy

8.2 HDPE (twin wall pipe)

Advantages:

- environmentally friendly; HDPE is the most environmentally stable of all plastics; type 2 HDPE is mainly made from post-consumer waste and can itself be fully recycled at end of useful life
- UV resistant
- low cost

Disadvantages/reported issues:

- not self-supporting over long spans without additional structure

8.3 GRP (Fibreglass)

Advantages:

- lightweight
- UV resistant

- low risk of warping due to temperature changes (low thermal expansion coefficient: 16 to 22x10-6 mm/°C)

Disadvantages/reported issues:

- not self-supporting over long spans without additional structure

8.4 Stainless steel

Advantages:

- robust and self-supporting over large spans
- UV resistant
- low risk of warping due to temperature changes (low thermal expansion coefficient: 17.8x10-6 mm/°C)

Disadvantages/reported issues:

- vulnerable to theft due to salvage value

8.5 Aluminium

Advantages:

- robust and self-supporting over large spans
- UV resistant
- lightweight
- low risk of warping due to temperature changes (low thermal expansion coefficient: 23.1x10-6 mm/°C)

Disadvantages/reported issues:

- vulnerable to theft due to salvage value

9 Appendix 3. Summary of monitoring methods

This appendix summarises the methods used to monitor migration at passage facilities.

9.1 Catch pot

Eels drop into holding container after successful ascent

Advantages:

- can collect morphometric data
- pass is visited by staff regularly – can quickly address any problems if malfunctioning

Disadvantages

- labour-intensive – must be checked and emptied regularly
- heightened risk of mortality if pump fails and water supply to catch pot stops

9.2 CCTV

Camera(s) with infrared lighting installed in pass

Advantages:

- allows observation of behaviour as well as numbers
- non-intrusive (no handling of eels)
- video images useful for illustrative and educational purposes

Disadvantages:

- analysis of images can be time consuming
- cannot identify individuals; counts less accurate than capture methods

9.3 Automatic counter

Various technologies available to remotely count fish (for example, VAKI use optical beam)

Advantages:

- non-intrusive (no handling of eels)
- automated, so low labour input

Disadvantages:

- may be expensive to install, but low cost novel solutions are being developed (for example, Erten and Özdilek, 2018)

9.4 Mark-recapture

Marks applied by dip-dye or visible implant elastomer

Advantages:

- can determine passage efficiency
- intrusive (requires handling)

Disadvantages:

- labour-intensive over a short period
- does not provide long-term data

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