Environment Agency

Screening at intakes and outfalls: measures to protect eel

The Eel Manual – GEHO0411BTQD-E-E

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Horizon house, Deanery Road
Bristol BS1 5AH
Tel: 0117 934 4000
Email: enquiries@environment-agency.gov.uk
www.environment-agency.gov.uk

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Executive summary

Why eels and elvers are at risk

Eels are a catadromous species: they spawn in oceanic waters and migrate into coastal and inland waters to grow to adulthood. Their need to move through estuaries and rivers to complete their life cycle puts them at risk of being accidentally drawn into water intakes and outfalls:

- Intakes – adult silver eels are particularly vulnerable when they actively follow currents downstream (‘positive rheotaxis’).
- Outfalls – juveniles (glass eels, elvers or smaller yellow eels) are more at risk during active migration upstream (‘negative rheotaxis’).

Outside their migration periods, eels may simply enter intakes randomly.

Unlike salmonids and most other fish, eels respond tactilely to screens (by touch) rather than using a visual sense. Where an alternative route is not immediately discernible, they can squeeze themselves through screen mesh or bar spacings that are smaller than their body diameter. It is particularly important that intake solutions which rely on screening or diversion guide eels effectively towards safe downstream areas.

Design criteria for screening

Where the intake screen is flush with the riverbank, the natural sweeping flow of the river can provide the stimulus for guiding eels to safe downstream areas. In other situations, placing the screen across the channel along a steep diagonal angle (preferably $\Phi \leq 20$ degrees to the channel axis) can generate the necessary sweeping flow. See Figure S1. At the downstream end of the screen, a suitable bywash must then be provided. Sweeping velocity must allow fish to locate a bywash (or the downstream end of the screen for river bank intakes) within a reasonable time, recommended as 60 seconds. This is calculated for the scenario of fish being carried by the flow rather than actively swimming by Time = Length of screen divided by Sweeping Velocity. Under these circumstances, if water velocities in the approach to the screen are within the limits set out in Table S2, it is acceptable to use mesh sizes or bar spacings up to that shown in Table S1.

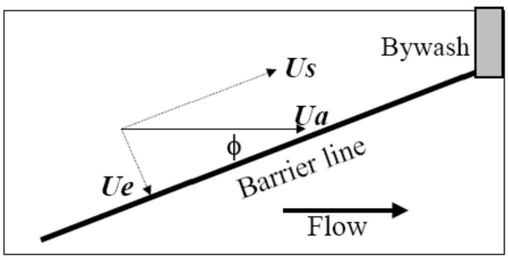

Figure S1: Flow velocity components in front of an angled fish screen or barrier. Ua is the axial channel velocity, Ue (=UsinΦ) is the fish escape velocity, and Us (=UcosΦ) is the sweeping velocity component along the face of the screen.

Screening requirements are more demanding for water intakes whose design would not allow this arrangement or which have a screen angle to flow, Φ, that is between 21 and 90 degrees. In such cases a narrower mesh or bar spacing will be required to physically prevent eels from passing the screen. Table S1 gives suitable values for eels of different sizes and life stages. Also, the escape distance from any point on a 21 to 90 degree angled screen to a bywash should be no more than five metres.

Table S1: Selection of mesh sizes and bar spacings for eel at different sizes and life stages. Measurements are based on the use of rectangular section bars.

Eel life stage (minimum size protected)	**Mesh size/bar spacing for exclusion (mm)**	
	Screen angle Φ >20 deg	Screen angle Φ ≤20 deg
Elver/glass eel	1-2*	1-2*
Yellow (14cm)	3	3
Yellow/silver eel (30 cm)	9	12.5
Silver eel (50cm)	15	20

Table S2 gives the suggested limits for water speeds at the approach to an intake. The velocities are measured 10 centimetres upstream of the screen face and apply to the component which is perpendicular to the screen face.

Table S2: Advisory screen approach velocities for eel

Life stage	**Screen angle Φ 21 to 90 deg**	**Screen angle Φ ≤ 20 deg**
Elver/glass eel	10 cms^{-1}	25 cms^{-1} (screen length<10m)
Yellow >14cm	15 cms^{-1}	30 cms^{-1}
Yellow >30cm/ silver eel	20 cms^{-1}	40 cms^{-1}
Silver eel	40 cms^{-1}	50 cms^{-1}

(Note: If there are salmonid smolts present, the acceptable maximum water speed in the approach to a well-designed screen with a bywash is 60 cms^{-1}. For juvenile to adult coarse fish and shad this falls to 25 cms^{-1}, and for lamprey the acceptable maximum is 30 cms^{-1} (Environment Agency, 2009). Both the screen openings and the velocities must be suitable for all species at all relevant times of the year.

Bywash entrances for adult eels should open at bed depth, preferably via a full-depth opening. However, a submerged pipe or an adjustable sluice gate may suffice if the arrangement is only for adult eels. The bywash entrance should be of a 'bellmouth' design as this creates a smooth acceleration flow into the bywash channel. The water velocity at the entrance to the bywash should be 1 to 1.5 times higher than that at the approach to the screen and should increase smoothly.

* See Section 4.2.2.5

For hydropower schemes, or other intakes set in channels, the bywash flow is usually set at between 2 – 5% of turbine or channel flow. However, a higher percentage may be necessary.

Where screens are installed at a steep angle to the flow ($\Phi \leq 20$ deg) and the bywash entrance is located immediately downstream of the screen, a discharge of at least 2% of the intake flow to the bywash may be satisfactory. Where the screen is installed at larger angles to the flow, the discharge to the bywash must be at least 5%.

Screening and guidance techniques

The design, installation and operation of fish screens and barriers can add significantly to the capital and operating costs of facilities. It is important for owners to be aware of the range of available screening and guidance techniques.

This manual reviews the wide range of techniques that are in common use for fish screening. Some rely on physical devices, others use behavioural approaches.

For yellow and silver eels, there are five main types of physical screening techniques that are suitable:

1. traditional passive mesh screens – these screens are commonly used to exclude fish, but usually require manual cleaning;
2. self-cleaning vertical or horizontal bar screens;
3. self-cleaning Coanda screens – these wedge-wire spillway screens are mainly used with upland hydropower schemes;
4. the 'Smolt-Safe™' screen – another type of spillway screen;
5. band- or drum-screens that have been modified for fish recovery and return (FRR).

For juvenile and smaller fish, there are four main physical screen choices:

1. passive wedge wire cylinder (PWWC) screens – this is the most widely used method for juvenile and larval fish protection;
2. small-aperture, wedge-wire panel screens;
3. sub-gravel intakes and wells – these use the riverbed as a filter;
4. self-cleaning belt screens such as Hydrolox™

Many of the existing water supply intakes that are currently fitted with band or cup-screens could comply with the new eel-screening requirements if they were modified to incorporate FRR facilities.

While the presumption is for physical screening as specified above, behavioural technologies can be used where this is not possible. When designed correctly and operated in suitable environmental conditions, the best techniques can be 75-95% effective against fish, including eels. There are five main types that have been used within the UK:

1. louvre screens – this semi-physical barrier may have some potential for silver eels;

2. bubble curtains – this most basic behavioural barrier provides relatively poor protection but is sometimes useful as a temporary measure;

3. electrical barriers, such as the 'Graduated Field Fish Barrier (GFFB™)', are suitable for outfalls (provided that they contain no descending fish) but not for intakes;

4. acoustic fish deterrents – as yet there are no forms suitable for eel;

5. artificial lighting – such as strobe lights – either illuminate physical structures or act as an attractive or repellent stimulus.

Of these behavioural deterrents, strobe lights are the most promising. The new low-voltage LED-based strobes offer a potentially simple retrofit solution that may be suitable for many existing intakes. However, further work is needed on the best design and operating criteria.

Behavioural techniques may be most effective when used in combination or as a supplement to traditional fish screening.

Screening is not always the best solution. It may be more effective, in terms of costs and protection, to minimise or avoid abstraction during the seasons, days or even times of day when eels are most at risk. A fish return system may be suitable for larger abstractions.

For non-consumptive water use, the use of fish friendly pumps or turbines (e.g. Archimedean screw technology) should be considered as it may avoid the requirement to screen for fish.

Monitoring for screen effectiveness

There are well-established guidance methods and screening techniques (physical and behavioural) for a wide range of species. However, not enough is known about the effectiveness of these techniques for eels. Monitoring will help to improve current designs and perhaps lead to better approaches in the future. Monitoring is particularly important where behavioural methods are used, or where physical methods do not comply with our recommendations for mesh-size, bar spacing, deployment angle or approach velocity.

Suitable monitoring techniques for adult eels include:

- high-resolution acoustic telemetry – by tracking eels in 2-D or 3-D in front of a screen, it is possible to estimate the screen's effectiveness;
- Didson™ acoustic camera – surveys areas in front of the screen and bywash;
- combining the batch-marking and release of eels upstream of the screen with some form of monitoring / trapping behind the screens and in the bywash – the results can be used to estimate screen efficiency.

The choice of technique will depend on the site's characteristics and on costs.

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1 Introduction

1.1 Background

European eel stocks are at an all-time low and continue to decline. The European Commission has therefore put in place a recovery plan, which the UK and other member states must implement.

The European Commission’s Eel Recovery Plan (Council Regulation No. 1100/2007) aims to return the eel stock to sustainable levels, both in terms of glass eel recruitment and the abundance of adult eels. The Eel Management Plans (EMPs) for England and Wales describe impacts of entrainment on eel and measures to reduce these impacts via appropriate screening.

Risks from abstractions

When water is abstracted from surface water bodies, there is a risk that fish and other organisms will be drawn in. This may prevent fish from migrating naturally, transfer them to harmful environments and cause death or injury to fish at screens, turbines and pump mechanisms.

The Environment Agency has a statutory duty to maintain, improve and develop fisheries of salmon, trout, freshwater fish and eels. We also have regulatory powers to require, where necessary, the installation and maintenance of fish screens or equivalent fish-protection measures.

Purpose of this manual

This manual sets out our detailed advice and updated guidance on screening both adult and juvenile European eel at water intakes and outfalls.

The guidance in this manual has been produced primarily to support the implementation of EMP measures to reduce the impacts of entrapment to ensure free passage for eel.

In addition the manual supports compliance with The Eels (England and Wales) Regulations 2009 Statutory Instrument, which requires the owners of water undertakings and other abstractions to fit suitable screens or equivalent eel exclusion measures. This is on top of any existing legal requirement to fit fish screens (see Appendix A).

This manual was produced following a two-day workshop held in October 2009 with input from Dave Bamford, Ben Bayliss, Steve Coates, Ian Dolben, Paul Frear, Emma Hazard, Steve Sheridan, Ida Tavner, Neil Trudgill and Ros Wright.

Andy Turnpenny and Richard Horsefield were then commissioned to ensure information on contemporary screening and guidance technologies were included and to build on the 2005 Screening for Intakes and Outfalls: a Best Practice Guide with particular focus on eels.

Subsequent expert review and input came from Greg Armstrong, Miran Aprahamian, Steve Axford, Darryl Clifton-Dey, Steve Colclough, Andy Don, Steve Sheridan, David Solomon, Graeme Storey and Huw Williams.

General guidance on fish screening

Operators of abstractions may be required to screen for other fish species or may wish to minimise fish ingress irrespective of legal requirements. We have therefore produced guidance notes to help owners, operators, developers and consultants:

- assess requirements for fish screening;
- select appropriate techniques.

For general guidance on fish screening, please read our Science Report No SC030231, Screening for Intake and Outfalls: a best practice guide (Turnpenny and O'Keeffe, 2005). The report provides some information about screening against eel.

We have also recently published updated guidance specific to nuclear and other large thermal power stations: Science Report No SC070015/SR, Cooling Water Options for the New Generation of Nuclear Power Stations in the UK (Turnpenny *et al.*, 2010).

1.2 Entrapment risk for eels

Eels are catadromous, that is they migrate between marine and freshwater environments. Spawning is thought to occur in the Sargasso Sea, from where juveniles migrate into European coastal, estuarine and freshwater habitats over a period of one to three years. Sub-adults may remain in freshwater or estuaries for between 6 to 20 years before migrating back downstream and out to the Sargasso Sea to spawn (Van Den Thillart, 2005).

Potentially, eels can get caught up in intake flows and screens at any stage of their life. However they are most at risk during their upstream and downstream migrations within freshwater. How they behave in near-shore marine, transitional and fresh waters will determine how vulnerable they are to entrainment during this period.

Eels have a distinctive elongate body. They have a high 'fineness ratio': body length divided by maximum body diameter. This body shape makes it easier for eels to get through a mesh that would successfully exclude other fish of a similar size. Eels passing through a pump or turbine can be injured by, among other things, mechanical (blade) strike, grinding and shear pressure. However their body shape makes them particularly susceptible to blade strike (Turnpenny, 1999).

There are many places where eel can get trapped. The most significant are considered to be power stations, hydropower sites, pumping stations and abstractions for drinking water. Unless these places are adequately screened, eel may not be able to reach the sea to spawn. This will mean that the targets for eel escapement will not be met. Table 1.1 lists some of the potential entrapment hazards in England and Wales.

Power stations' cooling water systems
Hydro-electric power installations
Pumping stations
Desalination plant
Drinking water abstractions
Water transfer schemes
Industrial abstractions
Industrial discharges
Sewage treatment works
Agricultural abstractions
Flood alleviation schemes
Water level management
Fish farms
Temporary abstractions

Table 1.1 Summary of potential sources of entrapment

The risk to eel stocks depends on the location of the installation within the catchment. Eel density declines as you move upstream, away from tidal influence. However, although stock densities are noticeably lower within the upper reaches of river basins, they are made up of markedly larger, more fecund, female fish (Aprahamian and Jones, 1989). These fish may contribute significantly to the spawning population.

1.3 Regulatory Drivers

Several pieces of legislation require screening to prevent injury to, or loss of eel, through entrapment. These are detailed in Appendix A.

When considering the screening requirements for eels, please be aware that other legislation may require different measures for other species. These measures may possibly be more stringent. Such legislation may arise for example from the Water Framework Directive or Habitats Directive.

1.4 Aims and scope of this manual

This manual provides technical guidance on screening methods for eel. We have taken much of the information in this manual directly from Science Report No. SC030231, Screening for intake and outfalls: a best practice guide (2005). However we have updated it where necessary to focus on requirements for eels.

The regulatory requirements for screening to protect eel are relatively new. We therefore have only limited information at present. However interest in, and research into, this subject is growing, especially within the European Union.

Of necessity, some of the information in this manual is new and does not come from peer-reviewed sources. We plan to update and expand the manual as evidence and research become available.

Current available information suggests that eels react to screens quite differently from fish such as salmonids or cyprinids that taper towards each end (fusiform). Hence it is important to understand eel behaviour. Information on the behaviour of eel is included in Appendix B.

1.5 Who is this manual for?

Within the Environment Agency, this manual is for:

- Fisheries Technical Staff – Sampling & Collection, Analysis & Reporting, Fisheries, Recreation & Biodiversity, Fisheries Technical teams, Regional Technical and Strategic Specialists, Environment & Business, Evidence;
- Water Resources;
- Flood & Coastal Risk Management;
- Assets System Management;
- Operations Delivery;
- Environmental Planning;
- National Permitting Centre;
- National Environmental Assessment Service;
- National Capital Programme Management Service.

This manual may also be useful for outside groups such as:

- developers;
- consultants;
- conservation bodies;
- fisheries trusts and angling bodies;
- screen manufacturers and suppliers;
- energy companies;
- organisations and individuals working in aquaculture;
- organisations and individuals working in agriculture;
- waterways organisations;
- water industry;
- highways departments;
- Internal Drainage Boards;
- construction companies.

2 Eels and screens

2.1 Eel behaviour in relation to screens

Eels are a catadromous species: they spawn in oceanic waters and migrate into coastal and inland waters to grow to adulthood. To complete their life cycle (see Appendix B) via fresh waters, they must have unimpeded passage through river networks in order to migrate between spawning grounds and freshwater habitats.

The provision of screening specifically for eels is a relatively new requirement, not just in England and Wales but also in Europe and North America. Consequently, research and development in this field is not well advanced.

The positive-exclusion methods already used for other fish species are normally suitable for eel, but they do need to meet the criteria for mesh sizes and approach velocities discussed in Section 5. For example, where smolt screens are already used seasonally for salmonids, it may be sufficient to extend the season to include the autumn/early winter period. This will often allow the operator to meet the requirements to protect silver eels. However, screens of a slightly larger mesh spacing than used for smolts could be acceptable during this period in some circumstances.

Silver eels do not respond in the same way to screens as salmonids and most freshwater fish. There are two key aspects to this. Firstly, unlike smolts and coarse fish fry, silver eels tend to swim near the bed; although research shows that when they approach a screen, they search the whole water column (Dixon, 2006). Nonetheless, silver eels spend more time near to the bed. A number of studies have shown that bywash entrances for eels work better when the openings are at bed level (see for example Gosset *et al.*, 2005). Work from the United States also indicates that entrainment can be reduced by fixing a solid plate along the sill of the screen. This plate allows eels to work their way along to the bywash. See link

A second difference between eels and many other species is that eels appear not to react before making physical contact with the screen. Knights (1982) reported that eels show a marked ability to force themselves through small apertures, aided by copious mucous secretion; large ones can exert enough force to bruise themselves and distort grading meshes and bars. Similarly, when their passage is blocked by a screen, eels have been observed to compress their bodies to squeeze through the bars or meshes (Adam, B: see link). As a result, the bar spacing may need to be less than the body diameter of the eel. Salmonid smolts and most freshwater species do not behave in this way. When there is sufficient light, they react and turn to head upstream before making physical contact with the screen (Turnpenny, 1988).

This is not to say that eels do not exhibit behavioural avoidance responses to screens. Eels do exhibit searching behaviour after they have made initial contact with the screen. This behaviour has been observed in various studies for example using acoustic tags to track eels at intake sites (Behrmann-Godel & Eckmann, 2003); under experimental conditions at bar racks (Russon *et al.*, 2010) and in footage from Didson™ acoustic cameras
See link

You can make screens more effective by placing them diagonally to the flow. This reduces the risk of entrainment, even when the screen's bar spacings are large enough to let silver eels pass. For details, see Section 5. In general, the narrower the angle relative to the incident flow, the higher the deflection rate is likely to be[1]. The sweeping velocity parallel to the screen face carries the fish towards its downstream end, where there should be a bywash to carry the silver eels to safety. This applies to mesh panels, bar racks and louvre screens. In all these cases there is probably initial physical contact followed by behavioural avoidance of entrainment. There is therefore an argument that we should refer to this use of screens as 'semi-physical', rather than as either 'positive exclusion' or 'behavioural'.

Purely behavioural methods, such as strobe lights or acoustic infrasound, appear to offer possibilities for eel. For more information, see Section 4.3. However, without the initial tactile component, strong stimulus levels are likely to be required. Alternatively, such approaches may be used to reinforce semi-physical methods.

The screening of elvers and glass eels is likely to require use of fine positive-exclusion screens with low approach velocities. Appropriate options include passive wedge-wire cylinder screens (PWWC) or fine-meshed belt screens (such as Hydrolox polymer screens), with suitably small openings (see Section 4.10).

2.2 How effective should a fish screen be?

There is a common misconception that all positive-exclusion fish screens are completely effective, if they have the optimum mesh size and water velocities are appropriate. In practice, this success rate is seldom achieved. Inspection surveys frequently reveal faults in the operation or maintenance of even the best designed screening systems. Common faults with mesh panel screens include:

- damaged mesh panels;
- damaged screen seals;
- screens that are not fully seated;
- screens that have been removed to avoid clogging problems;
- screens that are heavily clogged, which leads to velocity hot-spots where fish are at risk of becoming impinged on the screens.

These problems can all be overcome with appropriate design and by good maintenance that is backed up by monitoring and enforcement.

Certain types of positive-exclusion screen are much less prone to maintenance failures. Passive wedge-wire cylinder (PWWC) screens can be very effective at preventing the entry of fish, unless they become seriously damaged by flood debris or the fish are in very early life stages. Coanda screens also offer a high degree of protection, provided that there is sufficient surplus flow to allow fish to pass. Use these methods, where feasible, if the sensitive status of the fishery demands near perfect screening.

The viability of these methods can be affected by a number of factors: physical constraints; costs; the operational requirements of a particular site, environment or application.

[1] As for louvre screens, an angle of ≤20 degrees works best (Turnpenny and O'Keeffe, 2005).

A variety of behavioural methods have been developed to provide alternative solutions. These primarily deal with sites where high loads of waterborne detritus make screen clogging more likely.

Screen blinding is particularly important for thermal power generation and for other industries where the loss of the water supply might be critical to operations or safety. It is also important to hydroelectric generation, where flow and operating head equate directly to revenue.

For large coastal power stations, no solution has yet been found that will exclude nearly all the fish. The problems include: very high biofouling rates of submerged screens, inundation by weed, jellyfish and other biota and very high rates of water abstraction (60 m^3s^{-1} for a 2,000 MWe fossil fuel plant: Turnpenny and Coughlan, 2003).

2.3 Site-based pilot and commissioning trials

In some cases the Environment Agency may require site trials on operating water intakes in order to assess their screening efficiency, typically where this deviates from agreed good practice for the life stage of eel to be protected. This may be a condition of a new or revised abstraction licence. Site trials may also be carried where pilot or experimental studies need to be scaled up to better reflect the actual size and nature of the intake.

Suitable monitoring techniques for adult eels include:

- High-resolution acoustic telemetry. Tracking eels in 2-D or 3-D in front of a screen makes it possible to estimate the screen's effectiveness.
- Didson™ acoustic camera. This surveys areas in front of the screen and bywash.
- Combining batch-marking and the release of eels upstream of the screen, with some form of monitoring / trapping behind the screens and in the bywash. The results can be used to estimate the scheme passage rate. Automated monitoring using PIT[2] tags may offer a cost-effective solution.

The choice of technique will depend on the site's characteristics and on costs.

In some cases, it may be possible to assess the likely impact on early life stages using data from existing or past entrainment studies. These studies would need to have been based on the same part of the waterbody, and be both relevant and of sufficient scientific quality. Otherwise, it will be necessary to carry out pilot entrainment studies. Trials of this type have been carried out at a number of sites on the Thames to assess entrainment of juvenile coarse fish a to test a variety of fine screen types (Turnpenny *et al.*, 2008). These used trailer-mounted pumping facilities or fixed temporary pumps, an approach which could be adapted to monitor juvenile eel entrainment. However, the programme must cover the appropriate season and obtain sufficient samples to assess entrainment risk.

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[2] Passive Integrated Transponder tags

3 Selecting the best screening solution

3.1 The selection process

The developer or operator is often faced with a potentially bewildering array of options. There are many very different ways to screen fish. Which one will work best in a particular site? Which species of fish needs to be protected and when? Will what is right for one species work for another?

To find the most appropriate solution, operators and developers must address the following questions:

- What is the motivation for fish screening – for example, is it a statutory/planning requirement, a desire to improve environmental performance, or a policy of being a 'good-neighbour'?
- What species and life stages are to be protected and at what times of the year?
- What level of protection is required under BAT[3] principles? Establish this through risk assessment and/or consultation.
- What screening techniques will achieve this protection cost-efficiently, within the environmental and engineering constraints of the site, and with due regard for public safety?
- How will the screening system be maintained, taking account of health and safety issues for the operator?
- What provisions should be made to demonstrate that the screens are working effectively and that they are being operated and maintained in a way that consistently achieves the required level of performance?

An important first step is to consult early on how to develop a fish protection solution. Discussing the issues with the relevant parties and regulatory bodies at an early stage avoids misunderstandings. And it can save much time, trouble and cost.

Tables 3.1 to 3.3 provide a summary of techniques that, from current knowledge, are likely to provide suitable screening solutions. These are matched to various applications and environments and to different species of fish at different life stages. Various techniques may be shown for each situation: the options most likely to be suitable are shown in bold text.

When selecting a technique, take into account the required performance, engineering and environmental suitability, public and operator safety and cost-benefit. Any decision will be highly site-specific and will require skilled professional judgement.

---

[3] Best Available Technology

The Environment Agency, as regulator, will not be able to advise on the selection of techniques. It is the responsibility of the operator to consult fully and take any necessary professional advice in this matter.

Table 3.1 is not comprehensive: there inevitably remain gaps in our knowledge and uncertainties about the performance of certain techniques with particular fish species and applications/environments. There are also situations for which there is no established reliable solution and where further research and evaluation will need to be carried out by the relevant industry sectors to meet the timescales required by the eel regulations. Where similar issues affect a number of industry sectors, there may be scope for collaboratively funded R&D programmes.

Table 3.1: Screening options and where they may be appropriate for use with eel at different life stages.

Life stage	Canal / industrial / potable supplies & fish farms	Thermal power plant & desalination	Wetlands eg RSPB	Pumping stations	FAS / flood storage	Managed realignment	Water transfer temporal eg Kielder	Agriculture and temporary abstractions	Canoe courses	Hydroelectric power plant: low head and high head	Outfalls
Glass eels / elver	PWWC, sub-gravel intakes, modular einclined, strobe light, travelling screens (eg Hydrolox), FRR	PWWC, modular inclined, strobe light, travelling screens (eg Hydrolox), FRR	Passive mesh, PWWC, sub-gravel intakes, modular inclined, strobe light,	PWWC, sub-gravel intakes, modular inclined, strobe light, travelling screens (eg Hydrolox), FRR	Passive mesh, PWWC, sub-gravel intakes, modular inclined, strobe light, travelling screens (eg Hydrolox)	Passive mesh, PWWC, modular inclined, strobe light,	PWWC, sub-gravel intakes, modular inclined, strobe light, travelling screens (eg Hydrolox), FRR	PWWC, sub-gravel intakes, modular inclined, strobe light	PWWC, sub-gravel intakes, modular inclined, strobe light	Coanda, strobe light, travelling screens (eg Hydrolox)	Elevated discharge, GFFB electric barrier, screens <2 mm aperture
Adult yellow/ silver eels	Passive mesh, Coanda, PWWC, sub-gravel intakes, modular inclined, strobe light, eel bottom bypass, travelling screens (eg Hydrolox), FRR	Passive mesh, Coanda, PWWC, modular inclined, strobe light, eel bottom bypass, travelling screens (eg Hydrolox), FRR	Passive mesh, PWWC, sub-gravel intakes, modular inclined, strobe light,	Passive mesh, Coanda, PWWC, modular inclined, strobe light, travelling screens (eg Hydrolox), FRR	Passive mesh, PWWC, sub-gravel intakes, modular inclined, strobe light, travelling screens (eg Hydrolox)	Passive mesh, PWWC, modular inclined, strobe light,	Passive mesh, Coanda, PWWC, sub-gravel intakes, modular inclined, strobe light, eel bottom bypass, travelling screens (eg Hydrolox), FRR	Passive mesh, Coanda, PWWC, sub-gravel intakes, modular inclined, Strobe light, eel bottom bypass	Passive mesh, PWWC, sub-gravel intakes, modular inclined, strobe light, eel bottom bypass	Passive mesh, Coanda, modular inclined, strobe light, eel bottom bypass, travelling screens (eg Hydrolox)	

	Type of screen	Relevant section	Glass eel	Elver	Yellow eel	Silver eel	Comments/ problem	Hyperlink
Physical screens	Passive-mesh/wedge-wire panels, angled towards bywash	7.2.3	*****	*****	*****	*****	Traditional inland solution. Cleaning can be difficult.	Follow link
	Vertical or inclined bar racks, angled towards bywash	7.1.2	NS	NS	**	***	Good for manual or self-cleaning. Eels may force their way through, especially if not angled. No good for fry.	Follow link
	Fish recovery & return (FRR) on band, drum or cup screens	7.1.4	NS	**	****?	****?	Depends on mesh size – usually ≥6 mm but can be 2-3 mm. Further R&D needed on fish bucket design to ensure good survival.	
	Smolt-Safe™	7.1.3	NS	NS	?	?	Fish passage may not be safe at all flows.	Follow link
	Coanda screen	7.1.3	NS	NS	***	*****	Excellent, but only suitable for spillways.	Follow link
	PWWC screen	7.2.2	*****	*****	*****	*****	Excellent where space, depth and currents are suitable. 1-2 mm required for juveniles.	Follow link
	Modular inclined screen	Appendix C	NS	NS	****	****	Yet to be used in UK but looks promising.	Follow link
	Travelling Screen -Hydrolox	7.2.4	****	****	****	****	Better than modular due to rotating band – limited testing in UK	Follow link
	Labyrinth screen	Appendix C	NS	**	****	****	Allows for compact screen arrangement at large sites.	Follow link
	Sub-gravel intake	7.2.5	****	****	****	****	Suitable locations limited	

Table 3.2: Screening techniques suitable for eels – physical screens.

Type of screen		Relevant section	Glass eel	Elver	Yellow eel	Silver eel	Comments/ problem	Hyperlink
Behavioural screens	Louvre barrier	7.3.2	NS	NS	****	****	50 mm louvre spacing, barrier angle 15 degrees, 30 cm high solid plate along bottom, bottom opening bywash.	Follow link
	Bubble curtain	7.3.3	NS	NS	NS	NS	Acclimatisation problems; water needs to be <3m deep???. May work with strobe lights/infrasound added but research needed.	Follow link
	Electric screen (GFFB) outfalls	7.3.4	****	****			Safety issues need to be addressed.	Follow link
	Acoustic (SPA/ infrasound)	7.3.5	?	?	*	*	Limited tests show potential; further research needed.	Follow link
	Continuous light	7.3.6	**	**	**	**	Ineffective in turbid water. May attract some fish.	Follow link Follow link
	Strobe light	7.3.6	***	***	***	***	The most promising behavioural method for eels. Further work required on design criteria, optimisation and efficiency.	Follow link Follow link
	Eel bottom bypass	6.6	NS	NS	NS	**	No design criteria. Requires further research.	Follow link Follow link

Table 3.3: Screening techniques suitable for eels – behavioural screens

Key for Table 3.2 & Table 3.3: note that the ratings assume that the systems are designed using the appropriate criteria for the application.
NS=Not suitable; ** Low efficiency; *** partially suitable ; **** Suitable; ***** Excellent; ? Further research needed.

3.2 Multiple solutions and non-screening solutions

It is important to realise that screening is not always the best solution. It may be more effective, in terms of costs and protection, to minimise or avoid abstraction during the seasons, days or even times of day when eels are most at risk. A fish return system may be suitable for larger abstractions. There are also many other promising combinations of technology which should not be overlooked. These include combinations of bubble curtains, acoustic deterrents and strobe lights and screens and eel-bypasses.

From the information in Tables 3.1 to 3.3 you may be able to identify other techniques that could be combined in order to achieve the best results for the species present at a particular site.

3.3 Intake location and eel life stage

The geographical location of an intake can determine the life stage of eel at risk of entrapment within it and thus the screening required to minimize the risk.
See Appendix B.

Screening of intakes should be fit for purpose and designs based on the size of eels (both resident and transient) likely to be present at that location. For example intakes located in the upper reaches of rivers will require coarser screening than those located much further downstream. Glass eel and elver are unlikely to be found more than 30km above the tidal limit.

Table 3.4 offers a guide on eel life stage likely to require protection at different points within a catchment. However decisions on screening requirements at a site should be made at a local level by Area Environment Agency officers, informed by relevant monitoring data and local expertise applied on a site by site basis.

River location (d/s to u/s range)	Life stage/size of eel likely to be present
From estuary to tidal limit	Glass eel
From tidal limit to 30km u/s	Elver & Yellow eel
>30km u/s of tidal limit	Eel >30cm

Table 3.4 Eel life stage at different river locations
Note: For structures located >50km upstream of tidal limit AND only affecting downstream migrants, only eel > 50cm need be protected.

3.4 Costs of different screening solutions

The costs of installing fish screens or barriers are highly site-specific. They will depend on many factors, including:

- whether the application is new-build or retrofit;
- the existing structures;
- the ground conditions;
- the degree of exposure to flood and other damage;
- whether power (if required) is available.

Table 3.5 attempts to provide indicative costs for some of the main techniques described in Section 4. In most cases the costs are for the screening/ barrier hardware only. They exclude the costs associated with planning and design, consultancy, site investigations and preparation, installation, commissioning and testing. These additional costs may considerably inflate the overall project cost. In the case of fish recovery and return (FRR) systems, the costs are for adding FRR capability to standard drum or band screens. The figures include providing fish recovery buckets, a backwash system and fish return launders (data courtesy EIMCO Water Technologies).

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Screen or barrier type	Inland		Estuarine/ marine		
Size of abstraction	≥1 m^3s^{-1}	10 m^3s^{-1}	≥1 m^3s^{-1}	10 m^3s^{-1}	45 m^3s^{-1}
Positive exclusion screens					
Flat mesh panel, 12 mm	24	50	30	-	-
PWWC screen, 3 mm	50	285	70	430	-
Band, drum or cup screen modified for FRR	129		129		228
Under-gravel filter	160	-	-	-	-
Raked bar screen	40	250	40	250	-
Coanda-effect	13-17	-	-	-	-
Smolt-SafeTM screen	17	-	-	-	-
Behavioural screens					
Bubble curtain	5	15	5	15	75
Louvre screen	24	50	-	-	-
Continuous light	5	20	-	-	-
Strobe light	10	40	-	-	-
Electric GFFB	12	18	-	-	-

Table 3.5: Approximate purchase costs (£k) for fish screens and barriers (2009). Costs are for equipment only and exclude installation (except where indicated).

4 Review of screening and deflection techniques

4.1 Positive-exclusion methods for adult eels

4.1.1 Traditional passive, mesh panel screens

4.1.1.1 General description

Static screens constructed of mesh are by far the most common method of fish exclusion. They are suitable for excluding eels, provided that the right mesh size is chosen (see Section 6.6) and that approach velocities are kept sufficiently low (see Section 6.4).

A standard smolt-screening arrangement uses flat panels of mesh, that are fixed to a stiffening frame (see Figures 4.1 and 4.2) This arrangement is found at many hydroelectric stations, as well as at drinking water and industrial water supply intakes (Aitken *et al.*, 1966). One or more panels are inserted into vertical slots in a fixed supporting structure, and the structure may have an overhead walkway and lifting gear to make it easier to remove and replace individual panels for cleaning and maintenance. Alternatively, the panels can be made to pivot, so that the water flow back-washes off the debris. However this is arrangement not ideal: there may be a risk of fish passing through while the screens are being turned.

Suitable systems can be designed for any size of intake and for most configurations. Ideally, the screen should be aligned flush with the riverbank, or at an angle so that the flow helps to guide fish towards a bywash positioned at the downstream end of the screen. The angle is calculated so that the flow vector normal to the screen face is below the required escape velocity for the target fish species and sizes (see Section 6.4). Angling the screen also creates a sweeping velocity along the face of the screen, which helps to clear debris. The size of individual panels is determined by the overall screening area and by practical considerations of handling.

The mesh size (or free gap) required may vary from season to season. For example, during periods of silver eel migration, it may be appropriate to use larger meshes. It would then be necessary to reduce the screen gap at the times when smaller fish, such as smolts, were at risk. Screen gaps can sometimes be reduced by overlaying mesh panels onto a bar rack. Alternatively, eel screens can be temporarily replaced with finer-meshed panels. Note that the mesh size required depends on both the screen arrangement and the sizes of eels likely to be present. Where the screen forms the recommended acute angle to the incident flow ($\Phi \leq 20$ degrees), the sweeping velocity component is higher. Eels will then exhibit behavioural avoidance and larger screen spacings can be used. Suitable mesh sizes are shown in Table 6.4.

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Figure 4.1: Fixed panel screen installed in 2003 on the River Afan, Port Talbot, to prevent salmonid smolts from entering the docks' feeder.

The mesh can be made from one of a number of materials including plastics. However stainless steel is the norm as the ease of cleaning and the extended life-expectancy outweigh the initially higher capital costs Weldmesh is easier to clean and cheaper to produce than a woven mesh would be. Flexible plastic meshes are used on the band- or drum-screens of some continental power stations. However they are probably not sufficiently robust for use in open water. Stainless-steel wedge-wire is very effective, particularly if juvenile fish also need to be excluded.

A coarser trash rack in front of the screen will reduce the amount of debris that reaches the fish screen, without affecting fish passage. In this situation, a bywash entrance is needed upstream of the trash rack as well as by the fish screen. This is so that larger fish can bypass the structure. There is an example of this arrangement at Scottish Hydroelectric's Dunalastair Dam (see Aitken *et al.*, 1966). Alternatively, a larger bar spacing can be used (for example 15 cm) or gaps can be left at intervals to allow larger fish to pass.

Figure 4.2: Fixed panel screen installed in 2003 on the River Plym, Devon. It protects the entrance to an industrial supply offtake.

Best practice for the design of mesh panel screens

The main design requirements are:

1. For a lateral river intake, the screen should preferably be flush with the riverbank and therefore parallel to the main river flow. When placed across a channel, the screen should be angled diagonally (in plan view) relative to the channel. This has the benefit of guiding fish into a bywash or weir notch. An angle-to-flow of Φ ≤20 deg is desirable and should be provided on all new installations. Table 6.4 sets out the suitable bar spacings for this arrangement.

2. In some cases the screen may have to be placed across the channel at an angle that is less than 20 degrees, or not parallel, to the flow axis. Eels will then find it more difficult to locate a bywash or other escape route, and it is even more likely that eels will try to force their way through the screen. The screen design will therefore need to be more conservative. First, the mesh must be small enough to prevent penetration (see Table 6.4). Secondly, the maximum distance from any point on the screen to the bywash or weir-notch should not exceed five metres.

3. Unless the screen is fitted flush with the river bank and is exposed to a natural sweeping flow, provide a suitable bywash or weir-notch either at or close to the end of the screen. This ensures smooth flow acceleration into the bywash or weir-notch.

4. Measure the approach velocity 10 cm upstream of, and perpendicular to, the face of the screen. The velocity is usually equivalent to the flow divided by the

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screen's total area. Make sure the approach velocity is less than the values indicated in Section 6.4.

5. When specifying the required screen area, allow up to 50% extra area for blinding by weed, leaves and other debris.

In shallow water (typically less than one metre), it may be practicable to operate fixed screens that can be cleared by manual raking or brushing. With designs for deeper water, screens will need to be removable. For this reason, they are normally dropped into vertical slots from which they can be hoisted out for cleaning. In this situation, it is best practice to provide:

- two sets of slots, one behind the other – allowing a cleaned screen to be inserted before the soiled screen is removed;
- adequate seals around the screen to prevent fish passage or injury;
- a datum mark on the screen which aligns with a mark on the slot rails – to show when the screen is fully seated and sealed.

For screens that are manually raked, it is common to cant the screens back, on installation, at an angle of around 10 degrees to the vertical.

Applications

Passive mesh panel screens are suitable in a wide range of situations, provided that the above criteria are met. Limiting factors may include:

- the required frequency of cleaning in order to avoid the risk of a blockage;
- the structural strength in relation to flood damage risk;
- hydraulic head loss where small mesh sizes are used.

These factors tend to become more significant with larger abstraction flows. There are two main advantages of this type of screen: there is no need for electrical power and the capital cost is relatively low, especially on small installations.

Eel life stages

Mesh screen panels are suitable for adult (yellow or silver) eel life stages, subject to meeting the design requirements 1 to 4 above. For elver and glass eel, use flat panels of 2 mm-slot-width, wedge-wire or profile-wire screening material rather than a mesh.

Ease of retrofitting

It is possible to retrofit this type of screen, but much depends on the site. In some cases, simple overlay screens can be placed in front of existing trash rack for the appropriate migration season. A common problem with retrofitting fixed fish screens as a replacement for simple trash racks is that water velocities may be too high. It may then be necessary to widen or deepen the intake, or to fit a longer screen diagonally across the intake entrance. This should reduce the approach velocity to the required level.

4.1.2 Bar rack screens

4.1.2.1 General description

In the past, bar rack screens have been used mainly as trash racks for excluding debris. Many are fitted with moveable tines or raking systems that keep the screens clear of rubbish. Both back- and front-raked systems are available, but the back-raked ones lack horizontal braces and are not recommended for closely spaced bars. Conventional trash rack spacings may be anywhere between 38 mm and 150 mm, depending on the application. Inclining the bars by 10 degrees to the vertical helps to maintain the weight of the rake against the bars. Mild steel (with or without galvanization) is commonly used as the construction material. Another common alternative is stainless steel. One north-American manufacturer[4] offers robust plastic trash racks.

Some installations in the US and Germany have used horizontal, rather than vertically aligned bar racks (Ebel, 2008). The sweeping flows along the screen face appear to improve self-cleaning. Horizontal bar racks can be fitted with automated horizontal rakes rather than conventional bottom-to-top raking systems.

In recent years, by a single-tier bar rack has replaced some two-tier systems, made up of trash racks and mesh fish screens. The single-tier bar rack uses a smaller bar spacing which can act as a fish screen. This provides a self-cleaning (raked) alternative to the traditional manually cleaned mesh panel screen described above. Spacings as small as 10 mm have been used. Scottish and Southern Energy plc (SSE) have been investigating and implementing this approach for a number of years.

The design criteria for bar racks are almost the same as those for mesh panel screens (Section 4.1), except that the minimum mesh dimensions are applied to bar spacing. It is generally not feasible to retrofit smaller bar spacings to existing screens without reducing hydraulic performance. On new installations, the intake size would be increased to create the required open area. Again these racks should preferably be aligned flush with the riverbank or placed diagonally across the channel to provide a sweeping flow for fish guidance.

Rectangular section bars or perforated plates are preferable to round-section bars, which are prone to 'gill' fish. In addition, rectangular bar appear to be less permeable to eels (Travade *et al.*, 2009). A 20mm rectangular section bar slot, for example, is considered to have similar eel exclusion performance to a 15mm slot between round section bars (M. Larinier, pers com).

Solomon (1992) referred to the possible 'louvre-screen' effect of trash racks placed at angles to the main channel flow. The implication is that vortices generated by flow hitting the bars will act as a deterrent to fish. However, this view is not supported by the observations of one of the authors of this manual, AWH Turnpenny. When he observed the flow at tangential trash racks, Turnpenny found that the dominant flow at the trash-rack face during periods of abstraction tends to be near-parallel to the bars.

Additional points in bar-rack design are:

- inclining the screen by 10 degrees to the vertical makes raking easier;

[4] (Structure Guard Inc., Maine, USA)

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- the bars need to be sufficiently stiff to maintain the design spacing throughout the screen – this may require horizontal tie-bars to be fixed across the back of the screen;
- the manual raking of bar screens is probably only safe and practicable in water depths of <1.0-1.2 m.

The photograph in Figure 4.3 shows temporary bars being overlaid on vertical trash racks at Backbarrow in Cumbria (River Leven). The bars are fitted in early autumn and are left in place for the duration of the silver eel migration period. During this time, the flow available for hydropower generation is restricted and the automatic raking is suspended. It is a far from ideal solution.

Figure 4.3: Vertical bar racks being overlaid with additional bars to reduce the effective bar spacing. The photograph was taken at the Backbarrow hydropower scheme in Cumbria during the process of adding bars and is incomplete as shown. The overlay screens only remain in place during the autumn eel migration season.

4.1.2.2 Design best practice

As for Section 4.1.1, with the following additional consideration:

Use rectangular section bars or perforated plates in preference to round-section bars

4.1.2.3 Applications

Bar racks are a suitable alternative for most applications that would otherwise use mesh screens.

4.1.2.4 Life stages

Adult yellow and silver eels.

4.1.2.5 Ease of retrofitting

Overlay screens can be retrofitted but may result in a loss of hydraulic performance. The criteria for approach velocity and proximity to bywash must be met. See Section 6 for details.

4.1.3 Spillway screens

4.1.3.1 General description

A spillway screen uses a grid of some sort on part of the downstream face of a weir. Water falling through the grid enters a channel beneath, from which it is conveyed to the turbine or other application. The surplus flow flushes any fish and debris that are larger than the screen openings across the surface of the grid and away to the downstream side of the weir (Turnpenny, 1998).

4.1.3.2 Coanda screen

The Coanda screen is based on the ‘Coanda-effect’, a phenomenon first identified by Henri-Marie Coanda in 1910. Essentially, the screen design exploits how fluids follow a surface. In this case, the surface is a wedge-wire screen with bars running from side to side across the width of the weir (see Figures 4.4 to 4.6). Water follows the surface of the V-profile wires and runs into the collecting chamber (penstock) below. The wedge-wire screen is contoured to form an ogee-shape curved to a 3 m radius. A curved ‘acceleration plate’ at the top stabilises and accelerates the flow. The spacing between the wedge-wire bars is designed to be small enough to exclude all fish including young fry. Depending on the spacing of bars, the screen can also be used to exclude silts, sand and gravel (Turnpenny, 1998).

To date, the Coanda screen has been used mainly for small, upland hydro intakes. However, there is no reason why it should not be used in other applications where the topography is suitable. In the UK, Coanda screens are sold and installed by Dulas Hydro

Limited[5] and are manufactured by Optima International[6], Doncaster. The screen is available in a range of designs for varying installation sizes:

Screen A: A full-height screen with removable screen material – suitable for flows from 210 ls^{-1} upwards, in 70 ls^{-1} steps.

Screen B: A full-height, one piece small screen – suitable for flows of 80, 100, 120, 140 and 160 ls^{-1}.

Screen C: A half-height, full-width, one piece screen – suitable for flows from 100ls^{-1} upwards in steps of 50 ls^{-1}.

Screen D: A half-height, one-piece small screen: suitable for flows of 20, 30, 40, 50 and 60 ls^{-1}.

Full-height screens have a head loss of 1,270 mm and half-height screens have a 705 mm head loss. Ensure that you can afford this head loss before opting for a Coanda screen. The maximum flow of the screens is dependent on the weir width. A full-height screen has a capacity of 140 ls^{-1} per metre width: therefore a 1 m^3 flow would require a weir just over 7 m in length.

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[5] Dulas Hydro Ltd. – Dyfi Eco Parc, Machynlleth, Powys, Wales, SY20 8AX.

[6] Optima International

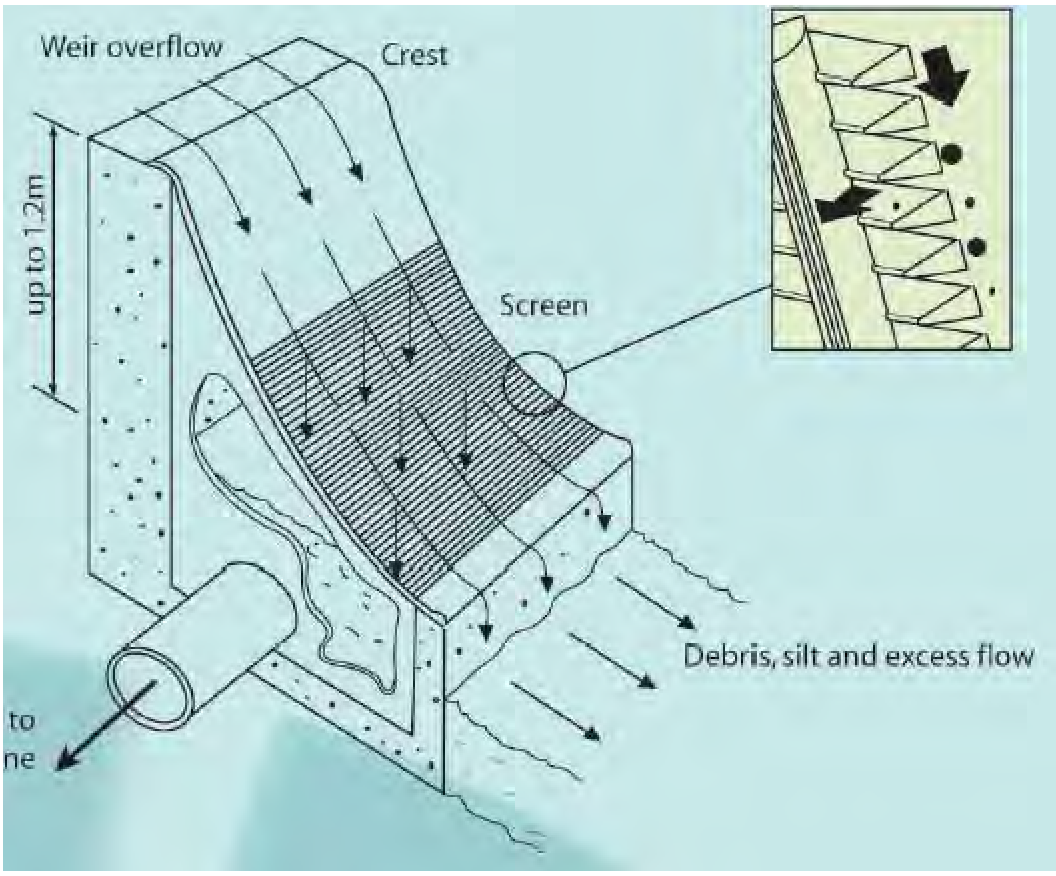

Figure 4.4: Diagram of an Aquashear™ Coanda screen, with a detail of the V-profile of the wedge-wire (Dulas).

Figure 4.5: Example of a Screen A Coanda installation (Dulas Hydro).

The recommended screen materials are 304 grade stainless steel in freshwater, or 316 grade for marine environments. The acceleration plate is a circular arc similar to a parabolic 'ogee' shape. The shape matches the path of an unsupported jet of water. The plate acts to speed up the water, helping the shearing effect. The shearing effect is caused by water striking the triangular edge of the screen wires, forcing some of the flow downwards through the slots. This improves abstraction efficiency.

Figure 4.6: Example of a Screen B Coanda installation (Dulas Hydro).

Coanda screens are designed to be low maintenance. However, during low flows some debris may build up, which will be washed off by subsequent high flows. Brushing with a stiff broom clears most remaining debris. Most screens require periodic visual checks and brushing about four times a year.

By 2005, there were a reported 22 Coanda screen installations within the UK[7]. Most are at small-scale private hydropower installations with capacities ranging from 10 to 1,300 ls^{-1}. One of the larger installations was commissioned by RWE Innogy Hydro to the south west of Fort Augustus in the Scottish Highlands. The screen at this site is a full-height design with a flow capacity of 1,300 ls^{-1}. There were initially some concerns over fouling by algae. However, the screen self-cleans during periods of high flow and the overall verdict on the screen at the site is good (W. Langley, Dulas pers. comm.).

The effectiveness, suitability and cost benefit of this type of screen were evaluated at a small hydropower scheme near Keswick in Cumbria (Howarth, 2001). A screen with 1 mm bar spacings was commissioned in April 1999. It could exclude all debris greater than 1 mm and 90% of particles that were more than 0.5 mm. Its performance was evaluated over a 15-month period. They monitored screen capacity, silt exclusion performance, self-cleaning, slime and algae growth, operation and maintenance requirements, integrity and resistance to damage. They also analysed the cost benefit. After the 15-month period, there were no noticeable signs of wear and, at high flows, up to 94% of suspended silt particles between 0.41 and 1.17mm were screened out. There had been no records of blockages caused by debris, although it was believed that very thin strands of weed might be passing through the wedge-wires. A thin film of algae had developed over the screen,

[7] www.dulas.org.uk

resulting in some loss of capacity. However the algae were readily cleaned off with a stiff brush. Overall the screen was found to be consistently robust and resistant, and it has a high performance rating.

Fish protection performance

The Keswick study did not assess fish-exclusion efficiency or the fishes' condition after passing over the screen. Elsewhere, Bestgen (2000) has reported on tests carried out at the Colorado State University Larval Fish Laboratory on the exclusion and survival rates of fathead minnow passing over a Coanda screen. In 150 trials, fish of different lengths were released and then recaptured downstream. The fish lengths were 5 mm, 7.5 mm, 12.5 mm, 22.5 mm and 45 mm. An exclusion rate of 'nearly 100%' was obtained for fish longer than 12.5 mm.

4.1.3.3 The Smolt-Safe™ Screen

The Smolt-Safe™ screen (Figure 4.7) is manufactured by Rivertec of East Sussex. The principle is broadly similar to that of the Coanda screen. In the configuration shown, the weir is constructed flush with the bank of the river. Water is carried off sideways from below the screen. Water falling through the screen is collected in a take-off channel and a further debris channel carries fish and trash back to the river. There is no reason, however, why the screen should not be constructed as part of a transverse weir, as for the Coanda screen.

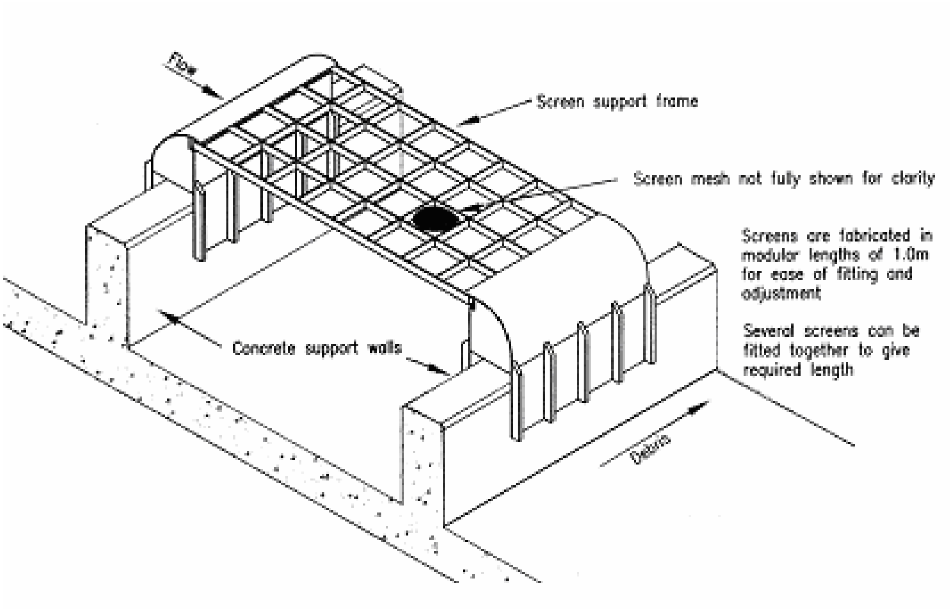

Figure 4.7: The Smolt-Safe™ Screen (Rivertec Ltd).

The example shown in Figure 4.7 was constructed at a distillery where there is a large amount of waterborne debris. The screen mesh size in the example is 10 mm, but this could be varied for other sites, as required. The manufacturer claim the screen is 100% safe for the passage of smolts and other fish. However, this has not been verified by trials.

The Environment Agency found that a similar screen, built at Heltondale in Cumbria, was not suitable for screening pre-smolts (G. Armstrong, Environment Agency, pers. comm.). The problem was that fish became trapped among debris when there was insufficient washover flow. Potentially, this problem can be overcome by blanking off part of the screen at low flows. However the degree of washover is difficult to control when river flows are variable, particularly at remote sites. Also, unlike the Coanda screen, this screen was flat rather than inclined. This does not help debris clearance.

As with the Coanda screen, there are constraints on operation. The manufacturer specifies an operating flow range of 0.5 to 5 m^3s^{-1}. However, there seems no reason in principle why larger flows should not be accommodated, given suitable space and arrangement of the civil works. A second constraint is that at least 25% of flow is required for washover. Thus, for a 5 m^3s^{-1}draw-off, at least 6.25 m^3s^{-1}initial river flow would be required.

4.1.3.4 Design best practice

For spillway screens, the manufacturers' recommendations must at present be regarded as best practice. An important consideration is the relationship between the abstracted flow rate and the surplus washover flow. If the screen is over-sized, then there may be a risk of leaving insufficient ecological flow in the river downstream of the offtake. There may also be insufficient surplus flow to flush fish and debris safely off the screen in the downstream direction. It may be necessary to provide a means of blanking off part of the filtration area during dry weather flows. This problem is likely to be greater on flashy upland streams than, for example, in chalk streams that have a stable flow regime.

Debris should not be allowed to accumulate on the screen, due to the risk of entrapment (Smolt-Safe™) and/or causing fish injuries.

4.1.3.5 Applications

In the UK, Coanda screens have mostly been used at medium to high-head hydropower screens in upland areas. However, there is no obvious reason why either Coanda or Smolt-Safe™ screens should not be used with other types of application where there is a sufficient head of water, for example at fish farms located on upland rivers.

4.1.3.6 Life stages

Screen apertures for these types of screen are:

- less than 3 mm for Coanda screens;
- 12.5 mm or smaller for Smolt-Safe™ screens.

Both types are therefore suitable for yellow and silver eels at some sites.

Elvers are less likely to be present in the upland headwater locations where spillway screens would normally be used. There is therefore no need to take elvers into account when deciding on screen size in these areas.

4.1.3.7 Ease of retrofitting

Coanda or Smolt-Safe™ screens are most likely to be suitable for new-build applications or replacing existing spillway screens.

4.1.4 Band or drum screens modified for fish return

4.1.4.1 General description

Many power stations' intakes and abstractions for potable water are fitted with mobile band screens or drum screens in order to filter out debris. These screens are usually installed somewhere within the pumphouse and not at the intake point. Fish-handling modifications have been developed for both types which can reduce the risk of injury, at least to the more robust species. The modifications relate chiefly to:

- the design of the ledges or 'buckets' used to lift fish and debris out of the water;
- the reduced-pressure backwash sprays used to flush material off the screens and out of the buckets.

Instead of the filtered material being discharged into trash baskets for disposal, a return gully or pipeline puts them back into the waterbody. Such an arrangement is commonly known as a 'fish recovery and return' (FRR) system. More primitive versions simply put fish back to the waterbody without fish handling refinements. These are called 'fish return' systems.

Fish return systems have been used at UK power stations for many years. The earliest ones, were constructed at CEGB estuarine sites in the 1960s for the return of salmon (*Salmo salar*) and sea trout (*S. trutta*) smolts. There are examples at the Uskmouth and Oldbury on Severn power stations. For various reasons, these systems were never fully utilised or evaluated.

A number of other stations, including Dungeness 'B' and Sizewell 'A', have operated simple trash return systems. These periodically discharge to the sea the biological and other debris that has accumulated in trash baskets. There is no attempt to promote the survival of living organisms and, in fact, the system at Sizewell 'A' macerates the debris prior to discharge.

The Sizewell 'B' power station has a facility to direct trash either to baskets or into the cooling water discharge, and has also put in place other engineering measures to reduce stress effects on fish. The Sizewell 'B' system is licensed to operate in fish-return mode, provided that quantities of fish are below a certain level. Otherwise fish must be collected in trash baskets to avoid the possible wash-up of dead fish (notably sprats) on beaches.

The combined cycle gas turbine (CCGT) power station at Barking (Thames Estuary) has a fish recovery system based on modified band screens. This returns fish to the estuary via the cooling water outlet. Two newer CCGT stations have more refined FRR systems with dedicated fish return lines. These stations are at Great Yarmouth (River Yare estuary) and Marchwood (Southampton Water).

4.1.4.2 Operating principles of a fish recovery and return system

The main changes to a standard band or drum screen are to:

- add scoops containing water – also referred to as ‘fish buckets’ – at the bottom of each mesh panel;
- use a low-pressure (≤1 bar) backwash spray to flush fish off into the return launder (trough) without injuring them.

A high-pressure spray (≥3 bar) can be deployed at a later point in the cycle to remove the more persistent debris.

Rotation speed is also an important factor. Where fish are not a concern, band screens are rotated intermittently, either at preset time intervals or when sufficient material has accumulated to cause a head differential across the screen mesh. This saves on bearing wear. With such an arrangement, fish may become impinged on the screens for hours before being lifted out by the screens: they may become asphyxiated or exhausted. During rotation, conventional band screens operate at one of two speeds. The low-speed setting is used for normal levels of trashing. The screen is switched to the faster setting when inundated with trash. To optimise fish survival, the screens are rotated continuously, switching to the higher speed setting if a head loss (usually >100 mm) develops across the screens.

After being washed off the screens by the low-pressure spray jets, the fish and other organisms are flushed into open troughs, and on to a discharge pipeline that returns them to the water. Handling stress is minimised in these stages through the careful design and construction of the launders and pipes. Tight bends are avoided and surfaces are smooth. Swept bends are used throughout and the pipes are made from either stainless steel, fibre-glass or PVC materials. Joints are ground smooth.

The recommended radius for swept bends or change of slope is 3 m when a trough or pipe diameter of ≤0.3 m is used (Turnpenny *et al.*, 1998a). However, space constraints do not always allow this. If the radius of a bend is smaller, fish tend to find shelter and epibenthic species in particular may accumulate. Also, tight bends are susceptible to blockage. There will need to be access for cleaning. Where larger pipe or trough diameters are used (≥0.4 m), there will be less risk of blockage. The bend radius may then be reduced to ≥1.5 times the pipe diameter. The chief requirements are to avoid blockage and hold-up of debris. There must also be access for maintenance in case of blockage. The screen’s wash pumps supply flow for the backwash sprays. This ensures that the fish are kept moving through the system and reduces the risk of blockage.

The use of chlorine or other biocides can, potentially, reduce survival in fish return systems. Biocides are mostly applied from May to September, or when the water temperature is more than 9oC. This is unlikely to clash with the seasonal migration of elvers (spring) and silver eel (late autumn).

Chlorine is the most common biocide used at power stations. Its toxicity depends on the concentration and the exposure time. For biofouling control purposes, chlorine is normally injected in the intake at around 1 mg.L^{-1}, decaying to about 0.2 mg.L^{-1} at the cooling water pumps. The exposure time in the intake forebay and screenwell can be kept to an hour or less in a purpose-built system. The toxic risk is generally low under these conditions. However, unless a detailed analysis of the toxic risk can be undertaken, it is preferable to ensure that chlorine is injected downstream of the screens. The detailed analysis should take into account the local water quality conditions, mixing dynamics and the species and life-stages exposed.

In 2000, Turnpenny reported on the effects of chlorine toxicity on elvers in seawater. Figure 4.8 shows the design dosage/duration box for Shoreham power stations. The results indicate that, with the typical design concentration of 0.2 mg L^{-1} at the condenser inlet and exposure times associated with retention on the plant levels would be well below acutely toxic limits.

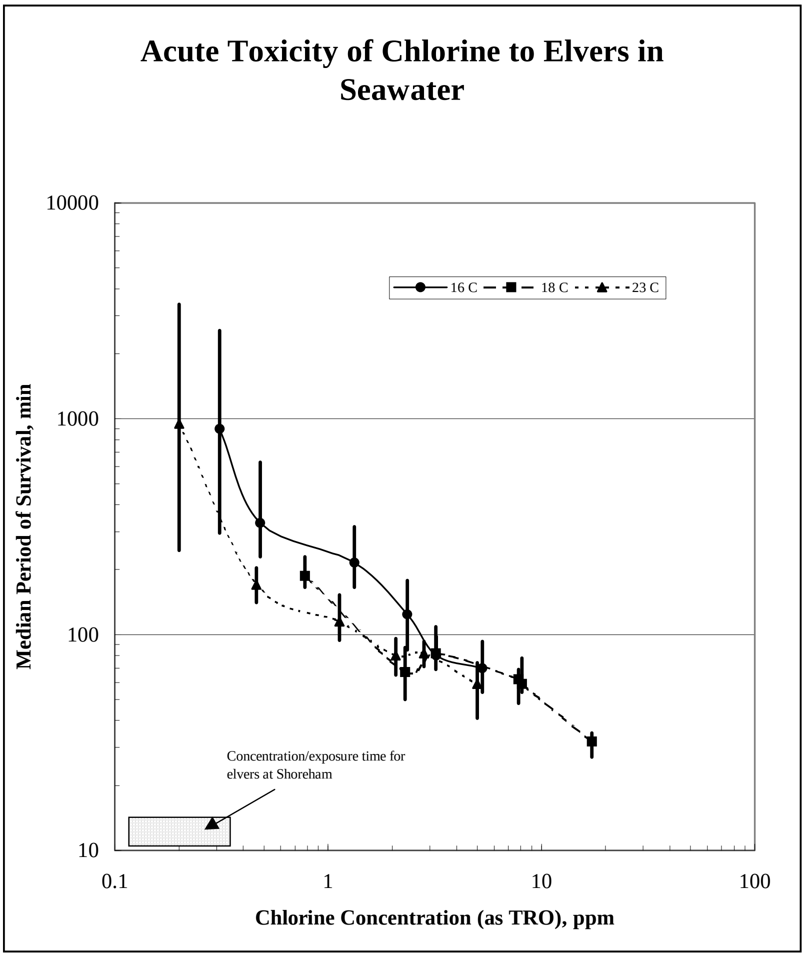

Figure 4.8: Median period of survival of elvers versus chlorine concentration at three water temperatures. The vertical bars are 95% confidence limits. The shaded rectangle in the lower left-hand corner indicates the design exposure time/concentration for Shoreham CCGT power station (Turnpenny, 2000).

4.1.4.3 Fish protection performance

The survival rates of the returned fish can depend on a number of design and operational factors. Design variations revolve mainly around the shape and construction material of the fish buckets and the backwash arrangements. Older designs often had incorrect bucket geometry: fish fell back into the water and were recycled several times or were not washed out from the optimum point of the cycle. Survival rates measured at older fish return systems range from more than 80% for robust epibenthic species to virtually nil for delicate pelagic species. (Turnpenny and O'Keeffe, 2005).

In the US, the requirements to reduce mortalities from fish impingement have led to renewed research into fish return techniques. Recent developments have benefited in particular from the use of computational fluid dynamics (CFD) flow analysis to optimise fish bucket design. Better design can greatly improve fish retention as well as reduce damaging turbulence. Improvements have come from:

- using non-metallic buckets;
- smoother screening materials;
- improved methods of washing off the fish.

One company (Beaudray US) claims to improve fish survival by removing fish before the screen lifts them out of the water.

Recent Environment Agency guidance for large power stations identifies a particular issue for the safety of eels in FRR systems (Turnpenny *et al.*, 2010). The guidance points out that the fish buckets are not designed properly to handle large, sinuous species such as adult eels and lampreys. Survival rates of eels in fish return studies have generally been low (see Clough *et al.*, 2003). The main problem is that eels writhe and fall out of the buckets. This probably happens many times before the eels are removed by the screens. The eels become exhausted and often have multiple wounds and sores by the time they are removed. Directly-cooled power stations could have a potentially significant impact on estuarine eel stocks. The potential for re-designing fish buckets is an important issue and further work is recommended to help resolve this (see Appendix E).

4.1.4.4 Design best practice

Following recent developments in the US, improved designs may soon become more widely available. Some of the innovations are likely to be protected by patents and therefore be available only through certain manufacturers. When you are specifying band or drum screens which are to be used for fish return, it is particularly important to ensure that the design of the fish buckets has been optimised for fish handling. Seek evidence of this from the manufacturer. Other key points to look for in the design of a fish return system are:

- The screens should be capable of long-term continuous operation: intermittent operation is unsuitable for fish return. Look closely at the quality and predicted life of the bearings.
- The screen meshes should be smooth and ‘fish-friendly’. Woven stainless mesh is commonly used.
- The mesh size should be as small as is practical, and with an aperture of no more than 6 mm: it has to protect a wide range of fish species.
- Low-pressure backwash sprays (≤1bar) should be used for fish removal. Higher pressure jets may be used at a later point in the cycle to wash off debris.
- Check that the geometry of the collecting hoppers ensures that the fish which are washed off the screens cannot fall back into the screenwell. This is mainly a problem with drum screens. This is a particularly important issue for eels and lampreys.
- Biocides should be applied downstream of the screens, unless it can be shown that the toxic risk is negligible.
- Fish return launders should be smooth, with any joints properly grouted and finished. They should have a minimum diameter of 0.3 m; for long runs of more than 30 m, a diameter of 0.5 m or larger is preferred.

- It is beneficial to enclose or cover fish return launders to avoid algal growth. Provide suitable access hatches or rodding points to facilitate maintenance.
- Where bends are required, use swept bends with a radius of more than 3 m.
- It is better to use dedicated fish return lines which discharge well below the low water mark. On power plants, only return fish via the heated water discharge where it can be demonstrated that survival rates will be acceptable.
- Provide a continuous washwater supply that will provide water at a depth that keeps fish immersed and moving along the return line.
- At some coastal sites, there may be a risk of occasional inundation by schools of pelagic fish. If this is the case, it may be necessary to provide for diverting the catch to collecting baskets. This is to avoid the risk of discharging large quantities of dead fish onto neighbouring bathing beaches.

When the above guidelines (from the 2005 EA Screening Best Practice Guide) were put into practice at recent new-build stations, it became apparent that there were further details that should be specified. Future projects requirements. The updated Environment Agency guidance for large power stations (Turnpenny *et al.*, 2010) includes the following additional design criteria:

- In order to minimise the fish-handling time, the screens should be rotated at a constant speed of at least 1.5 m per minute.
- Any changes in the slope of launders should use a minimum 3-m swept bend radius for vertical bends. This avoids flow separation from the launder bed.
- The fall on launder sections feeding into horizontal bends should be restricted, as accelerating flow may cause standing waves and overtopping in the bends. One way of achieving this is to restrict the fall on launder sections upstream of a horizontal bend to no more than 1:50.
- Turbulence should be minimised to reduce the risks of fish exhaustion and injury. It is recommended that energy dissipation throughout the system should be kept at or below 100 Wm-3. This is particularly important for any fish sampling or holding facility that may be included for monitoring fish impingement. The method of calculating energy dissipation is described in the Environment Agency Fish Pass Manual (2010).
- High-pressure backwash is primarily intended to remove material sticking to the screen. While most FRR systems allow the backwash to discharge to a trash basket, there should be a facility that allows the discharge of backwashings via the fish return launders. This option can be used, for example, to return significant quantities of shrimps to sea that would otherwise be sent to landfill. However, at times when the high-pressure wash is mostly removing weed and rubbish, the material can be collected for disposal.

4.1.4.5 Applications

Fish return systems are used mainly at estuarine and coastal power stations. However the technique is potentially suitable for fish protection at potable water intakes, where band screens are often used.

4.1.4.6 Life stages

In the past, fish return systems have mainly been suitable for more robust epibenthic species, such as flatfishes and reef/rock-pool species. They have had moderately good results for demersal fishes such as cod and whiting, but offered very poor survival prospects for delicate pelagics such as smelt, herring and sprat.

Yellow and silver eels should be recoverable by well-designed FRR systems. However, with present fish bucket designs, survival rates may be poor. Poor retention of eels in fish buckets can lead to injuries from multiple handling, as well as greatly protracted exposure to biocide at toxic levels. The calculated chlorine exposure times, such as those shown in Figure 4.8, could then greatly underestimate toxic risk. Existing designs should be assessed and, if necessary, remedied (see Appendix E).

Most of the drum and band screens in use have mesh apertures of 6-10 mm. They would not retain the majority of elvers. A study carried out for at Shoreham power station (Turnpenny *et al.*, 2000) showed that it may be relatively safe for elvers to pass through the cooling system. However, this would need to be reviewed for other power station designs.

Some of the new stations currently planned may use mesh sizes as small as 2-3 mm. This mesh would retain most elvers, and it would then be necessary to look at whether they would survive in the FRR system.

4.1.4.7 Ease of retrofitting

In most cases, a system that was designed without fish return facilities will require substantial modification to civil works to accommodate larger buckets, as well as ways of returning fish. However, a specialist in this field may be able to analyse the system carefully and suggest modifications that would substantially improve fish protection.

4.2 Physical screening for elvers and glass eels

4.2.1 Introduction

Of the screening techniques described above, only the Coanda screen is generally suitable for screening elvers. The alternatives described below are also worth considering. They are also, of course, highly effective against larger fish, but would not usually be cost-effective unless it was also necessary to screen out small fish. These methods, with appropriate design, can be used to screen fish as small as larvae or eggs.

4.2.2 Passive wedge-wire cylinder screens

PWWC screens are a tried and tested solution. In the UK they are generally regarded as the best available technology for protecting juvenile and larval fish.

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4.2.2.1 General description

Figure 4.9 illustrates the basic form of a PWWC screen. It is a cylinder, made of wedge-wire material around its circumference. One end is blanked off and flow is drawn off through the opposite end. The blanked end may be closed off either with a flat plate or, where facing into a flow, a conical cap for streamlining.

The wedge-wire material is similar to that used in the Coanda screen (Figure 4.4). The profile of the wire that forms the screen's surface is V-shaped. In manufacture, the longitudinal supporting bars are fixed about a mandrel, around which the vee-wire is wound in a spiral (Figure 4.9). The apex of the 'V' is welded onto the bars at each point of contact. The pitch of the spiral thus determines the slot-width of the screen. Flat panels of the wedge-wire screening material are manufactured by this method, but then flattened out.

One major benefit of using the V-profile wire in PWWC screens is that it offers low hydraulic resistance for a given open area (when compared with conventional screening materials). There is also only a low risk of blocking: particles tend to either wash past the screen or pass through the slots as slot width increases towards the inside of the screen.

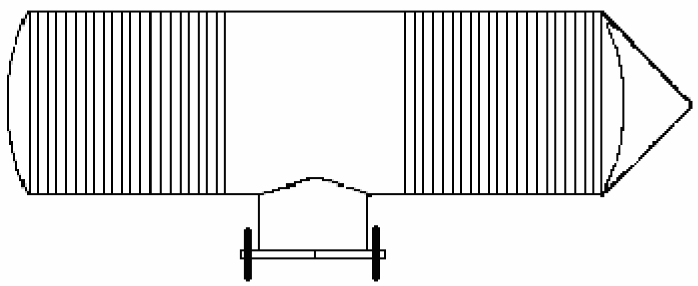

Figure 4.9: The basic form of the passive wedge-wire cylinder (PWWC) Tee-Screen. Drawing courtesy of Johnson Screens.

4.2.2.2 PWWC screen configurations.

Manufacturers offer a range of PWWC configuration options, including single, bulkhead or pipe mounted units, tee-form screens and multiple groupings attached to a manifold. Figure 4.10 illustrates two commonly found arrangements. The option used depends on the water depth, space available and other factors. The configuration is very flexible. For example, where water is shallow, a number of small-diameter units can be used rather than a single large one.

4.2.2.3 Air backwash system

PWWC screens are commonly fitted with an air-blast backwash system, such as the Johnson Hydroburst™ system. In this, a perforated air discharge pipe is welded along the bottom, inside of the screen. This is fed by an air compressor and reservoir, from which explosive bursts of air (up to 10 bar pressure) are released:

- at regular intervals – either daily or more often, depending on debris levels; or
- once a certain pressure differential has been measured across the inside and outside of the screen.

The compressor may be under manual or automatic control. The clearing action is caused by the displacement of water through the slots from inside the screen chamber, as the air volume expands following release. Any debris that has become pinned on the outer surface is lifted off and carried away by local water movement.

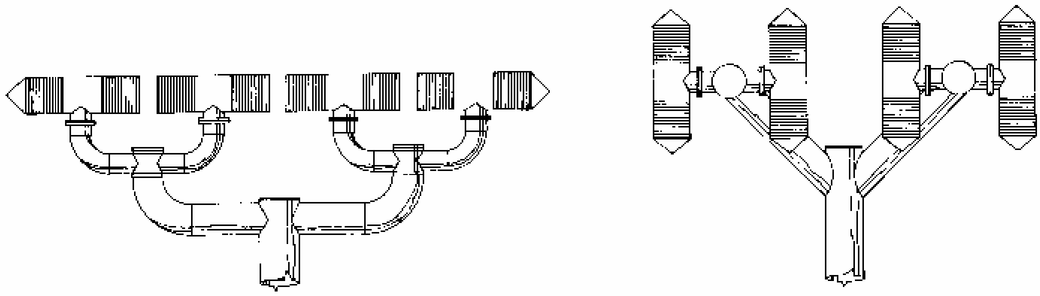

Figure 4.10: Examples of PWWC screen arrangements. These usually involve connection to a manifold. Drawing is courtesy of Johnson Screens.

4.2.2.4 Construction material and biofouling

In freshwater, screens are made from stainless steel, and of a grade suited to the water quality. In marine and estuarine environments, stainless steel screens tend to biofoul rapidly and a copper-nickel alloy is preferred.

Bamber and Turnpenny (1986) tested the efficacy of a small 70%:30% Cu:Ni PWWC screen at Fawley Power Station on Southampton Water, Hampshire. The mean salinity was around 32. The screen showed little sign of biofouling after 15 months of operation, without any cleaning other than the once-daily air backwash cycle. After this time, the measured flow throughput has fallen by only 2% (nominal starting flow rate 10 Ls^{-1}). More recently, an alloy of 90%:10% Cu:Ni composition has been used for estuarine applications. We understand that a large cooling water make-up intake at Connah's Quay Power Station on the Dee Estuary (Cheshire) has PWWC screens constructed of this alloy, and that these screens have operated continuously since 1996 without any need for cleaning (W. Smith, PowerGen plc, pers. comm.).

4.2.2.5 Fish protection performance

PWWC screens have a number of features that make them suitable for preventing fish entrainment. These include:

- the low through-slot velocity, which allows fish to swim away;
- the relatively smooth external presentation of the screen, which reduces the risk of fish abrasion;
- the narrow slot widths available, which makes it possible to prevent the entrainment of fish as small as eggs or larvae.

The last point is the main reason for selecting PWWC screens over lower cost alternatives. This aspect has been investigated in two North American studies (Heuer and Tomljanovich, 1979; Hanson, 1979). The conclusions of the Heuer and Tomljanovich (1979) study were:

- For very small larvae (total length <6.0 mm), a slot width of 0.5 mm and through-slot velocity[8] of ≤7.5 cms^{-1} would be required.
- For larvae of 7-10 mm total length, a slot size of 1.0 mm and through-slot velocity of 7.5 cms^{-1} was ideal. However, a through-slot velocity of 15 cms^{-1} would be low enough for some species.
- For larvae of >10 mm total length, a slot width of ≥2.0 mm is satisfactory, with a through-slot velocity 7.5-15 cms^{-1}.

We have found no reports on the use of PWWC screens specifically for elver and glass eel. Knights (1982) presents data on the mesh sizes/bar spacings required to retain eels. Figure 4.11: Critical grading dimensions (mm) plotted against body weight: (a) shows mean minimum size of eel retained by appropriate mesh apertures and (b) shows the size of eels retained by grid bar spacing.

Knights' data indicates that:

- a slot-width of 1 mm would be required to stop the earliest (0.2 g) glass eels;
- a 2 mm spacing would stop elvers >1 g (~10.7 cm in length);
- a 3 mm spacing would stop anything larger than 3 g (~14.5 cm).

Research on juvenile lamprey provides useful corroboration. For Pacific lamprey transformers, Moursund *et al.* (2003) found that a flat wedge-wire panel screen with 3 mm spacings tended to trap individuals. However, they reported greatly improved results with 1.75 mm spacings.

[8] Note: the term 'through-slot' velocity represents velocity measured between the bars. It is the normal measurement for PWWC screens: use 'approach velocity' for other types of screens.

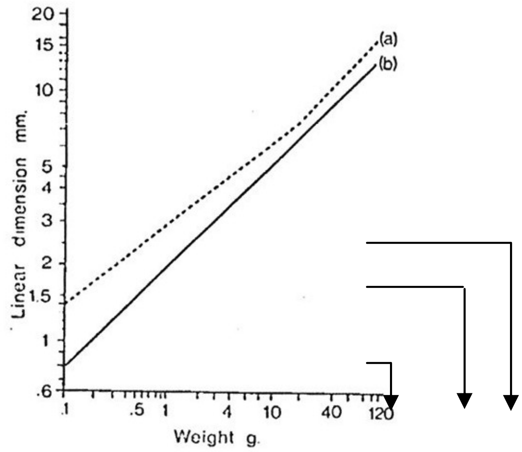

Figure 4.11: Critical grading dimensions (mm) plotted against body weight: (a) shows mean minimum size of eel retained by appropriate mesh apertures and (b) shows the size of eels retained by grid bar spacing.

4.2.2.6 Design best practice

Manufacturers offer design guides that provide the detailed information required for specifying a screening system. We have therefore listed only the main points in this manual. The following information is taken largely from the Johnson Screens' guide.

Through slot velocity

The design velocity is commonly 15 cms^{-1}. This value has been found to offer virtually maintenance-free performance. As screens seldom operate in a fully cleared state, it is important to allow for a degree of occlusion when sizing the screens. An allowance of 25% is normally made.

Slot width

The slot-width required will depend on the sizes of juveniles that are likely to occur at the site in question (see Figure 4.11 above). The smallest life-stages are found in estuaries and the lower parts of river systems. If there has been shown to be a need for juvenile screening at these sites – for example if there is quantitative evidence of entrainment – the slot width would need to be 2 mm or less, or 1-1.5 mm for glass eels.

In some cases there may not be enough information about the risk to juveniles. This information would usually come from historical entrainment data or observations of existing abstractions. In these situations, it will be necessary to carry out appropriately designed pilot entrainment trials over the spring and summer months, the main at-risk seasons. This will enable operators to establish entrainment risk.

Screen diameter and spacing from surfaces

The maximum screen diameter should be half the water depth at the lowest extreme of water level; preferably it should be no more than one-third. Where depth is shallow, consider using tee-configurations or other multiple arrangements of small-diameter screens.

The recommended minimum submergence depth is half the screen diameter, with the screen being spaced an equivalent distance from the bed and any wall. Submergence to this depth avoids the risk of excessive entrainment of surface-carried debris into the abstraction flow. The spacings from the bed and wall are intended to prevent debris that is rolling along the bed from becoming entrained, or larger items from becoming jammed. Placing screens too close to the bed or wall may also compromise the uniformity of the hydraulic field around the screen.

Screen sizing

When selecting the number, types and sizes of screen units for an abstraction, make sure you satisfy the above requirements. Manufacturers' design guides provide tables and formulae from which it is straightforward to calculate what is needed.

Velocity of flow past screen and screen siting

There must be an adequate ambient flow past the screen to clear the debris freed by air backwashing. Otherwise, debris may accumulate. The flow may be river or tidal, or created by wind-driven circulation in lakes and reservoirs.

It is also important that screens are not sited in backwaters where debris naturally accumulates as a result of eddy currents.

4.2.2.7 Applications

PWWC screens are suited to a wide range of flowing water applications in freshwater, estuarine and marine environments. They work best with smaller abstractions of a few m^3s^{-1} or less. Larger arrays may become cumbersome, unless space is unlimited. PWWC screens are used, for example, for potable water abstractions, tower cooled CCGT[9] power stations and supplies to fish farms. However, they are not suitable for low-head hydroelectric generation, for example, where very large flows are involved.

Flood risk may also affect the viability of PWWC screens. The Environment Agency recently refused consent to install PWWC screens at Staythorpe power station on the lowland River Trent. This was due to the potential flood risk associated with installing screens in mid-channel: trees and large branches could have become caught up in the screen arrays.

4.2.2.8 Life stages

Provided the wires are suitable spaced, PWWC screens are probably suitable for excluding eels of all sizes and life stages. The National Rivers Authority carried out a particularly interesting case study at Moor Monkton pumping station on the Yorkshire Ouse (Frear and Axford, 1991, unpublished). They collected impinged fish from the band screens before and after the fitting of PWWC screens to the intake. Between January 1990 and May 1991, 16,022 lampreys (brook and river) were collected. Most were recently metamorphosed pre-adults ('transformers'), but there were also some ammocoetes and adults. In 1995, the intakes were fitted with an array of eight Johnson PWWC screens (model T42 with 3 mm slot-width, total capacity 3.5 m^3s^{-1}). Their subsequent surveys found virtually no lamprey or other fish impingement.

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[9] Combined-cycle gas turbine

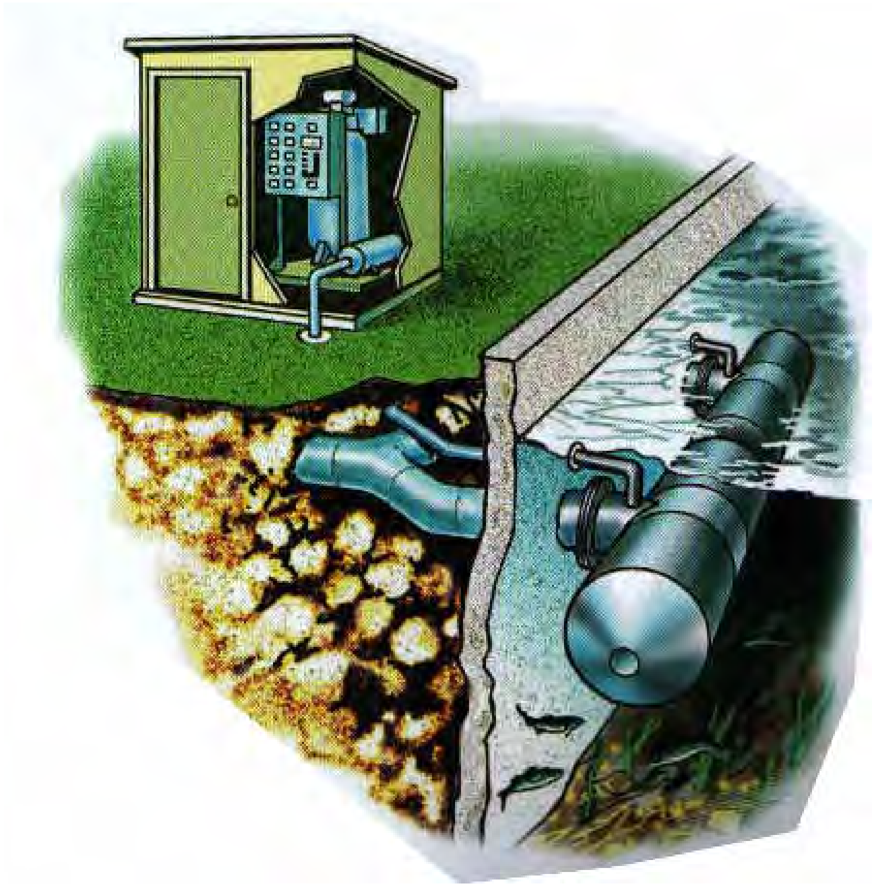

Figure 4.12: Illustration of a bulkhead-mounted PWWC screen array with manifold and air backwash system. The compressor is located in a bankside hut, but it could be located in any neighbouring building. Drawing is courtesy of Johnson Screens.

4.2.2.9 Ease of retrofitting

PWWC screens are not suited to retrofitting on existing intakes, except perhaps for end-of-pipe applications. Sometimes the existing intake is constructed as an open channel or the opening in the riverbank may be protected by a trashrack. It would then be necessary to form a bulkhead onto which a screen manifold could be fixed (Figure 4.12). However, one of the advantages of PWWC screens is that they are available in a wide range of sizes. This means that many different configurations are possible.

4.2.3 Wedge-wire panel screens

Wedge-wire can be used in flat panel screens (see Section 4.1.1) as an alternative to mesh panels. It is more practical for excluding small fish, as it is less prone to clogging than a mesh of equivalent spacings. According to G. Armstrong (Environment Agency), this type of screen was installed at a small hydroelectric plant in the Thames catchment at Huntsmoor on the River Colne.

Another site with this type of screen is the Pontsmill hydropower scheme near Bodmin, Cornwall. This is a high-head (15 m) scheme, with a maximum flow of 550 ls^{-1} and a bywash flow of 55 ls^{-1}. It uses a 3-mm slot-width screen which is aligned almost parallel to the flow in order to give a strong sweeping flow. A timber groyne helps to accelerate flow into the bywash (see Figure 4.13).

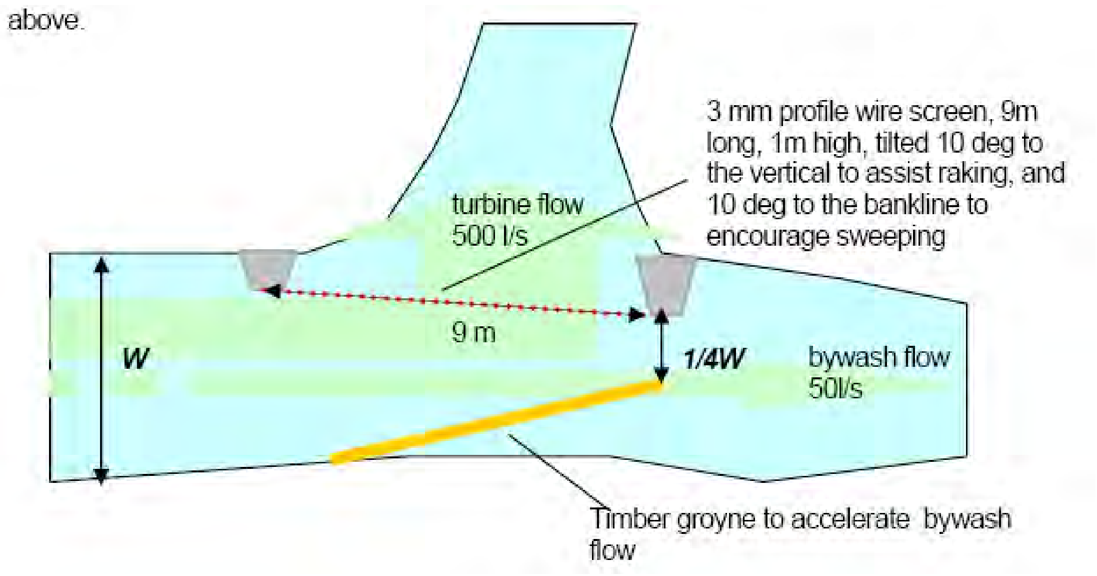

Figure 4.13: Plan view of the Pontsmill fish screen layout.

The experience in the US is that orienting the wires vertically rather than horizontally makes cleaning easier, as vertical raking machines can be adapted for this purpose (S. Rainey, US National Marine Fisheries Service, pers. comm.). However, we advise the use of PWW Cylindrical screen format where possible, as the air-backwash system provides a very effective cleaning mechanism. Air backwashing cannot be used in a vertical flat screen layout, as the air needs to rise through the gaps between the wires.

4.2.4 Self-cleaning belt screens

4.2.4.1 General description

Although Turnpenny and O'Keeffe referred to self-cleaning belt screens in 2005, these screens had not been tried in England and Wales. Since then, they have been tested in water company trials on the River Thames at Egham (Surrey) (Turnpenny *et al.*, 2008). Unlike the steel mesh screen described in our Best Practice Guide, the screen tested at Egham used interlocking polymer mesh panels. These formed a continuous belt. The manufacturer was the US company Hydrolox.

Hydrolox screens are made from individual UV-resistant polymer modules laid in a brick format. They form a screen that typically rotates vertically (Figures 4.14 and 4.15). The modules articulate around engineered polymer hinge rods and high-strength polymer sprockets. The screens can be made to order in virtually any width and length, and there is a range of mesh slot sizes available. The screens' engineered polymer material minimises biofouling and there is the option of having water jet spray bars to facilitate cleaning. Debris is spray-washed back into the river and carried away by the sweeping flow.

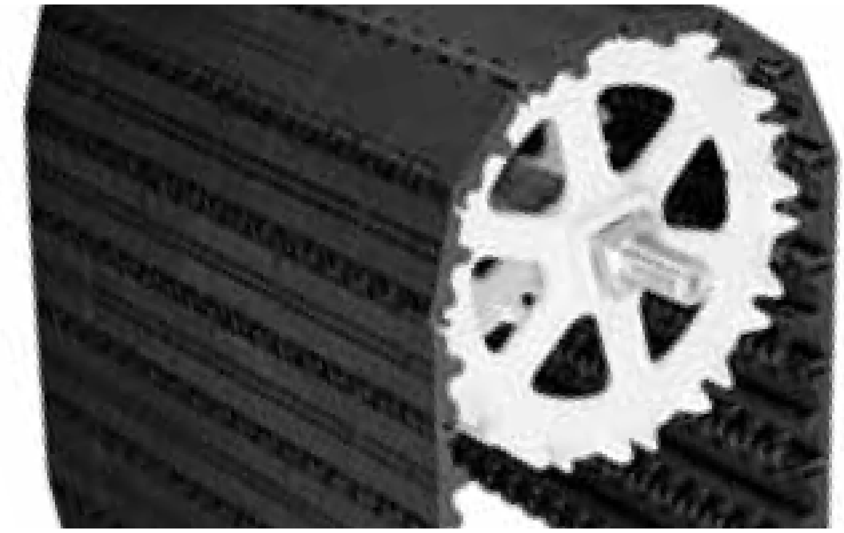

Figure 4.14: Illustration of screen mesh rotating vertically around polymer sprockets (courtesy of Hydrolox).

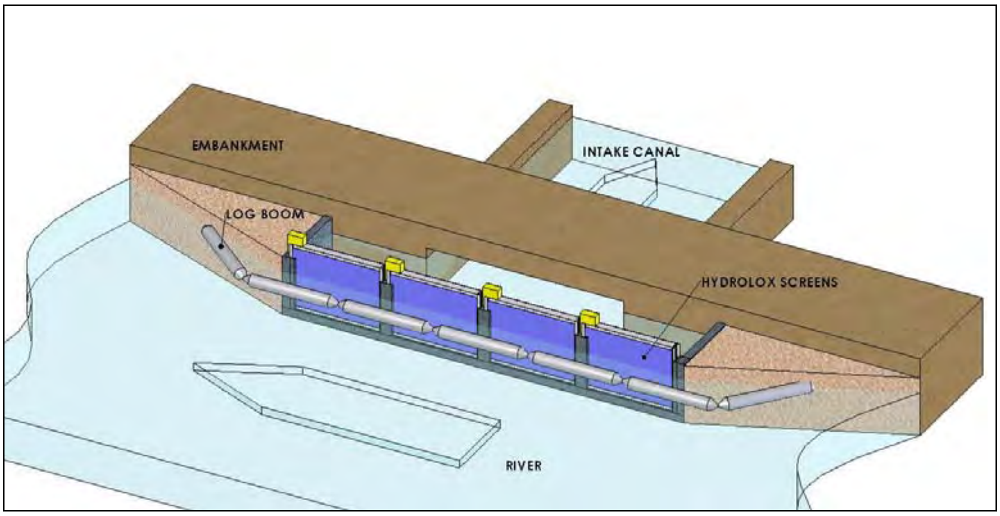

Figure 4.15: Conceptual site layout with travelling screens (courtesy of Hydrolox).

The flow of water passes across the screen, and abstraction occurs through the front of the screen. This through-flow pattern of abstraction means that water is passed through both sides of the screen. This could potentially result in increased head loss across the screen. Studies carried out by the US Department of Interior in 2003 showed that head loss across the screen was about 0.75 inches (20 mm) for the screen on trial.

In the past, screens of this type have been shown to suffer from debris being carried over the top of the screen and into the 'clean' side of the flow. This can be an important consideration in some applications. In the Thames' schemes the carry-over of debris is probably not of great importance;. the intakes either discharge, unscreened, to reservoir storage, or via band-screens/ cup-screens. These (debris) screens can remain in place after any intake (fish) screening upgrades. Debris and fish carry-over can be minimised or eliminated by including a spray backwash system. Tests by the US Department of Interior (2003) found that duckweed (Lemnaceae) was easily removed by the spray bar system. Egeria weed (Egeria densa) did not adhere to the screen in the first place and was swept past the screen.

From a fish protection perspective, the key features of the Hydrolox screen are:

- the large filtration area with low approach velocities, typically designed at 0.15 ms^{-1};
- the sealed edges and smooth mesh surfaces which minimise fish injury and impingement;
- the non-adhering surface which discourages the build up of debris.

The Thames test screen supplied by Hydrolox (Figure 4.16) was a Series 1800 with a slotted mesh 1.75 mm by 19 mm ('1.75 mm mesh'). The screen was 2 m high by 0.8 m wide with a porosity of 32%. The effective screening surface area was 1.2 m^2. The motor to drive the screen was located on top of the screen. Four spray nozzles were placed on a single bar behind the ascending side of the screen, above the water level. However these were only connected up for the autumn tests.

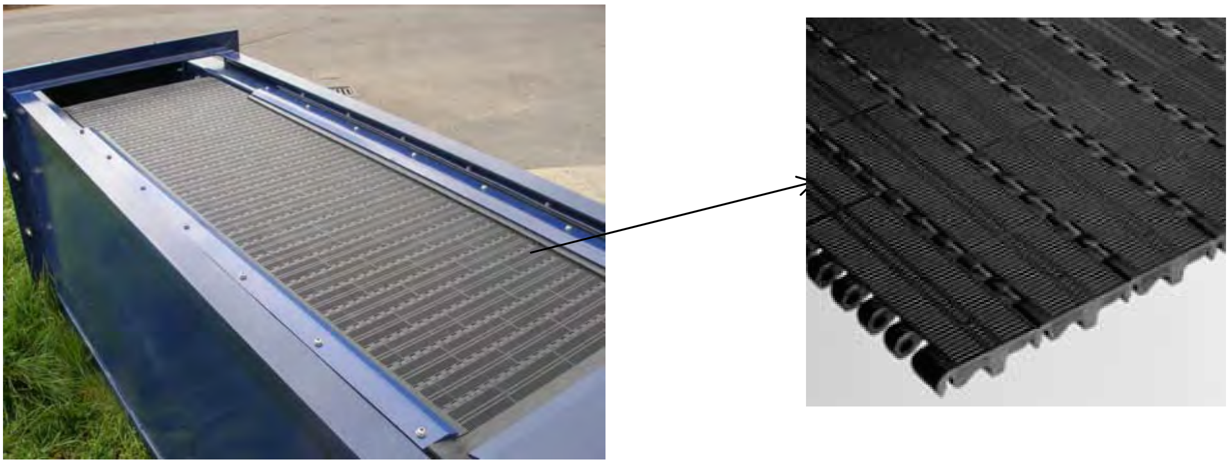

Figure: 4.16: The Hydrolox test screen with close-up view of the screen mesh.

The Thames Hydrolox screen performed well during the autumn, with no screen blockages, reduced flows or increased head loss. During the early part of the autumn tests, some carry-over of leaves was observed on the Hydrolox screen. However, a new and improved spray bar was later fitted, and this stopped any carry-over for the remaining part of the tests.

4.2.4.2 Design best practice

The key requirements for excluding elver and fry exclusion are:

- The screen should be angled or flush to the bank to provide strong sweeping flow.
- Approach velocity should be maintained at ≤0.15 ms^{-1}.
- Mesh size should be ≤3 mm.
- Low-pressure (≤1 bar) spray jets should be used to prevent the carry-over of elvers and other fry.
- The screen should be sealed all round to prevent fish passing through gaps that otherwise might be larger than the screen mesh.

- The height or design of the screen should avoid the risk of overtopping during flood events.

4.2.4.3 Applications

Hydrolox screen can be considered a good alternative to PWWC screens for excluding fish fry. The Thames trials found that the Hydrolox screen was as about as effective. Size and cost may be limiting factors, as a large screening area is required to maintain approach velocity at ≤0.15 ms^{-1}. However, the Hydrolox screen would be suitable for most potable intakes, as well as for thermal power stations that use tower cooling.

The Hydrolox screen is unlikely to be suitable for hydropower installations – except at high-head sites, where hydraulic head-loss is less critical and generating flows are no more than a few cumecs.

4.2.4.4 Life stages

This type of screen would normally be used only where it was necessary to exclude fish in early life stages. It is suitable for elver and glass eel, but will exclude fish of all life stages.

4.2.4.5 Ease of retrofitting

Self-cleaning belt screens are normally aligned parallel to the bank to take advantage of sweeping flow. They can be retrofitted, but this would normally require substantial re-engineering of the intake civil works in order to seal the screen to the bank.

4.2.5 Sub-gravel intakes and wells

4.2.5.1 General description

Solomon (1992) discussed the applications of sub-gravel intakes and wells. Since then there has been no real change in the approach used. We have included a brief summary of these technologies and examples for completeness.

Sub-gravel intakes use the riverbed as a screen by abstracting the water from underneath the bed or from an aquifer. Relying on natural filtration reduces treatment costs, but the number of suitable locations is extremely limited.

There is an example of this form of abstraction at Ibsley on the Hampshire Avon. An abstraction of 0.57 m^3s^{-1} is taken from four streams. A wedge-wire screen with 8 mm slot width is supported over a concrete chamber. Layers of gravel are placed over the screen up to the level of the original bed. A geo-membrane sheet is placed between gravel layers and backwashing maintains gravel cleanliness.

South West Water's Littlehempston abstraction on the River Dart, uses a collector well 4 m in diameter which reaches down to bedrock at 10 m below the riverbed. Twelve lateral perforated pipes extend from the well at two depths. The abstraction licence granted to the well is for 0.28 m^3s^{-1} and the system offers both high fish protection and partial water treatment (Solomon, 1992.

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4.2.5.2 Applications

This technique is feasible only for small abstractions in fast-flowing, eroding-substrate rivers. It is suitable, for example, for potable water supplies or supplies to fish farms.

4.2.5.3 Life stages

The technique should prevent the entrainment of elvers.

4.2.5.4 Ease of retrofitting

There are unlikely to be many situations in which this would be a suitable method for retrofitting.

4.3 Behavioural barriers and guidance methods

4.3.1 Behavioural deterrents background

Deterrent methods are normally used where it is impractical to use positive-exclusion methods for fish screening. This may be due to the risk to navigation or the likelihood of fouling from either attached biofouling or waterborne organisms and debris.

Fish deterrent systems are commonly known as ‘behavioural barriers’ or ‘behavioural screens’. They are a substitute for, or supplement to, more conventional positive-exclusion fish screens. If operated and maintained correctly, some positive-exclusion screens can exclude all fish. Behavioural screens cannot.

Fish have a number of well-developed senses, and. They are able to detect and react to light, sound and vibration, temperature, taste and odour, pressure change, touch, hydraulic shear, acceleration, electrical and possibly magnetic fields. Their sensitivity and capacity to react to any of these stimuli varies from species to species and at different life stages.

Fish deterrent methods use one or more of these stimuli to repel fish from the immediate area of the water intake, and in some cases to guide them past the intake into a bywash or to a point downstream. To be effective, the stimulus must be strong enough to repel fish at a range where they are not at risk of being involuntarily drawn in by the strength of the water current. However, the stimulus must also be weak enough to avoid the risk of injuring the fish or of clearing fish from too large an area. This might cause habitat loss, damage commercial fishing, or block natural patterns of fish migration in rivers.

Environmental variables, such as flow, depth, turbidity and water temperature, may affect the success of behavioural methods.

4.3.2 Louvre screens

4.3.2.1 General description

Louvre screens have been used since the 1950s and can be an effective option for diverting salmonids and some other species. They are a semi-physical barrier which can deflect high percentages of fish (>90%) under optimal conditions (Aitken *et al.*, 1966, Solomon, 1992). In general, the efficiency of louvre devices varies between 80 and 100%, depending on how well the louvre spacings and angles are matched to the requirements of the fish species/lifestages.

The louvre screen relies on the reaction of fish to current vortices created by the action of water flow on the louvre slats (Figure 4.17). Approaching fish sense a shearing flow – different velocities across different points along its body. As a result, they avoid the face of the screen. The fish are guided by the angle of the face of the screen into a bywash channel.

For best efficiency, position slats at a 90 degrees angle to the incident flow. Space the individual slats of the screen at appropriate intervals: the maximum gap used is about 30 cm, and this is suitable for large fish such as adult Atlantic salmon; gaps down to 2.5 cm are used for smaller species such as catfish and smelt (Therrien & Bourgeois, 2000).

The angle of the screen to the axis of the flow can vary from 10 to 30 degrees, but the optimum is usually found to be between 10 and 15 degrees. Efficiency generally decreases as the angle increases. This optimum angle to the flow dictates the length of the screen, which is 3.86 to 5.76 times the channel width (Solomon, 1992). Most fish penetration occurs close to the entrance of the bywash and the design works better if the gap between the slates is reduced to around 5 cm close to the bywash entrance. This also reduces the attraction velocity required within the bypass channel. Provided that the slats run to full depth, water depth appears to have little effect on the efficiency of louvre screens. The screens have been successfully used within a channel depth of up to 4 m (Ducharme, 1972).

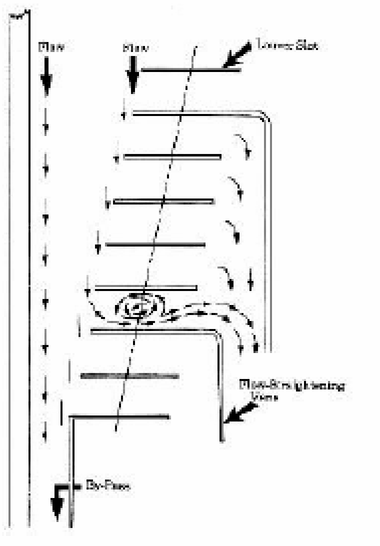

Figure 4.17: Schematic of louvre screen.

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There appears to be little reported on the experience of using louvre screens to protect eel. However, an unpublished conference presentation, of work carried out at Alden Laboratories in the US[10], reports good results with silver-stage American eel (A. rostrata) of ~560 mm in length. Louvre angles of 45 and 15 degrees were tested at channel approach velocities of 0.3, 0.6 and 0.9 ms 1. Louvre slat spacing was 50 mm. A deflection efficiency of 60% was initially recorded. Their research also demonstrated that, while eels explored the screens throughout the water column, they spent most time near the bed. The researchers then fitted a solid plate along the bottom of the screen (height not specified but appears to be about 30 cm). This helped to improve efficiency: deflection efficiencies increased to around 90% (88.6-95.1%). These results did not appear to be much affected by approach velocity.

Although this is a behavioural screen, there is a substantial physical structure involved and debris can become trapped within the channel. This will be less of a problem than it would be with conventional mesh screens, but regular maintenance will be required and there will be running costs. Cleaning is made easier if the slats can be lifted away from the screen. Trashing can be reduced by the addition of a coarse trash rack upstream of the louvre screen. This would allow fish to pass unhindered but prevent the movement of debris.

Several papers have set out the range of suitable current velocities. Louvre screens have been shown to work from 0.3-1.2 ms^{-1} with no loss in efficiency. However, they become ineffective as the approach velocity falls below this level because shear flows are not generated. The water velocity perpendicular to the face of the louvre array (the 'escape velocity') must be less than the fishes' swimming ability. The velocity in the bywash entrance, however, must be greater than that of the channel, in order to provide sufficient attraction. Of velocities tested within the range of 110-300% of the screen approach velocity, a figure of 140% is considered to be the ideal (Solomon, 1992). As the louvre screen itself restricts the water velocity in the main channel, it is generally easy to maintain a bywash velocity of 1.4 times the main channel. The Alden Laboratories tests, cited above, found a bywash velocity factor of 1.5 to be the most effective.

At sites where head loss may be a problem, the louvres can be fitted with deflectors or current rectifiers can be installed along the louvre line at regular intervals. These measures can improve hydraulic efficiency (Therrien & Bourgeois, 2000).

4.3.2.2 Floating or partial depth louvers

Turnpenny and O'Keeffe (2005) refer to the use of floating louvers, which screen just the surface layers. Floating louvers may be suitable when screening for fish such as salmon smolts that only travel in the upper layers of the water column. However, all the evidence indicates that eels prefer swimming near the bed. Floating louvers would not therefore be suitable for eels.

4.3.2.3 Installations in the UK

Turnpenny and O'Keeffe (2005) reported very little take-up of louvre screen technology in the UK. None appear to have been used or tested for eel deflection in the UK. However

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[10] See link

Adams and Schwevers (1997) describe laboratory-based work carried out in the USA, which reported good deflection efficiencies with louvre screens and American eel (*Anguilla rostrata*).

4.3.2.4 Design and operational best practice

For best performance, louvre screens should be designed as follows:

- The screen array should be aligned at an angle of 10-15 degrees to the channel axis; the slats should be orientated at 90 degrees to the flow.
- The required slat spacing for silver eels of 60 cm or less should be no greater than 50 mm.
- Approach velocities should be between 0.3-1.0 ms^{-1} at all times in order to achieve vortex generation.
- Allow for cleaning the louvres, for example by having upstream trash racks to catch most of the debris or by having removable slats. Provide safe access for this purpose, for example via an overhead walkway with safety handrails.
- The screen should run to the full depth of the channel.
- Louvre screens operate best when sited within a headrace canal, or in other situations where uniform approach velocities can be achieved. Hydraulic modelling may help to assess the uniformity of approach flow.
- Design the bywash entrance to maintain velocity at around 140-150% of the channel velocity.
- For a more compact arrangement, louvre screens can be arranged in a V-shape (in plan), with the bywash located in the centre. See also the Labyrinth screen arrangement in Appendix C.

Velocities outside the range 0.3-1.0 ms^{-1} will impair screening efficiency, as will any accumulation of debris on the slats. It is important to recognise that louvre screens will not prevent fish entry when the water is very slow or static. This means that on a hydroelectric plant, for example, fish may get past the screen when the turbines are shut down and subsequently be at risk of injury within the turbine(s).

4.3.2.5 Applications

Louvre screens are best suited to canalized and regulated watercourses where a uniform approach flow can be achieved. Large flows can be accommodated with minimal head loss which may, for example, suit some low-head hydropower applications. They are unlikely to be suitable to locations where they could be inundated by weed and debris, for example on chalk streams where weed is routinely cut.

4.3.2.6 Life stages

Louvre screens may be suitable for larger (>50 cm) yellow and silver eels.

4.3.2.7 Ease of retrofitting

Louvre screens are suitable for retrofitting into engineered channels, such as hydroelectric headraces or water supply aqueducts. A trash rack placed upstream will help clear away debris.

4.3.3 Bubble curtains

Bubble screens are one of the most basic types of behavioural barrier. Turnpenny and O'Keeffe (2005) reported that they work moderately well for some migratory species, but that resident species rapidly habituate to and ignore bubble barriers.

For any screen to work, eels need to come into mechanical contact. Bubble curtains on their own do not provide sufficiently strong sensory cues for eel deflection and are not a suitable barrier for eels. It may be better to combine bubble curtains with stronger sensory cues, for example strobe lights or low-frequency sound (see below).

4.3.4 Electric barriers

Electric intake screens were first developed in the 1950s by MAFF Fisheries Laboratory. Although some were installed in the UK, most were later removed because of fears about their safety. The effectiveness of such screens is uncertain.

A critical issue with electric screens is that the potential difference experienced by a fish depends upon the source voltage and the size of the fish: larger fish are exposed to a proportionately greater voltage than smaller fish. If the electric field is strong enough to repel small fish, it may be too strong for larger fish, stunning them and causing them to be drawn into the intake (Turnpenny, 1998). For this reason Turnpenny and O'Keeffe (2005) advised against the use of electrical barriers for intake screening. This advice is particularly relevant to eels, given their large overall length. However, the method may be considered for outfall screening (Section 5). Note that appropriate permissions would be required and due consideration must be given to potential impacts on other wildlife. Early consultation with your local Biodiversity officer is recommended.

4.3.5 Acoustic guidance

4.3.5.1 General description

The hearing range of most fish falls within the audible range to humans. Maximum sensitivity lies in the sub-3 kHz band down to infrasound frequencies (Hawkins, 1981; Sand and Karlsen, 1986). Many species of fish react to and avoid loud noises and this behaviour has been used to good effect in acoustic fish barriers.

Acoustic barriers and acoustic fish guidance have developed considerably in the last 15 years or so. They have been especially effective for use against pelagic fish at larger intakes, especially in estuaries and marine waters (Turnpenny and O'Keeffe, 2005).

Audiogram measurements have shown that eels are sensitive to sound pressure at frequencies centring on 90 Hz and to vibrations of around 40 Hz (Jerkø *et al.*, 1989). In early experiments, carried out by Fawley Aquatic Research Laboratories (Turnpenny *et* *al.*, 1993), silver eels were exposed a range of pure tones, bursts of noise and chirps. These sounds were produced by a large military sound projector in the range 50-2,000 Hz at levels of up to 180 dB re 1 µPa. The experiments revealed no signs that the eels detected the noise, even when almost touching the sound projectors. Detection of sound pressure in teleost fish is enhanced by the swimbladder organ (Hawkins, 1981). A factor that may influence the sensitivity of eels to sound is infestation with the swimbladder parasite, Anguillicoloides (Anguillicola) crassus, which can cause thickening of the swimbladder walls (Münderle *et al.*, 2004). This aspect does not appear to have been investigated in the Fawley experiments.

Of particular interest is the finding that adult silver eels migrations are successfully influenced by an infrasound source. This finding was made in river trials reported by Sand *et al.* (2000). Whereas widely used acoustic techniques contain frequencies extending down into the infrasound (<20Hz) region, true infrasound devices are designed to emit primarily in this waveband. More information on this appears in a review written by Sand *et al.* (2001). Normally, the sound is generated by a mechanical, motor-driven device that drives pistons to generate high particle velocities in the region of the source. For Atlantic salmon smolts, sound intensities above 10-1ms-2 at 10Hz are an effective deterrent and have been used successfully to block channels. Sand *et al.* (2001) mention that the source devices have had problems with mechanical reliability and metal fatigue problems and that this has limited their practicability in the past. However they suggest that these may be reduced or eliminated with further development.

While the effects of infrasound or low frequency sound as a deterrent may merit further investigation, such methods are not at present ready for use.

Appendix D contains guidelines on the safe and environmentally-friendly use of underwater noise for fish deterrence applications.

4.3.6 Light-based systems

4.3.6.1 General description

Light is used in two ways to reduce entrapment:

6. 1. Illuminating physical or behavioural screens to make them more visible. Fish can then orientate themselves in relation to the flow using the optomotor response.

7. 2. Using the stimulus of light in its own right to either attract or repel.

The use of light as a fish deterrent was first studied in the 1950s. Brett and MacKinnon (1953) used light to restrict the movement of animals in a canal. Although these early tests were not extensive, there were two important findings: firstly, different reactions were displayed by different species; secondly, flashing lights were more effective at eliciting a response than continuous light.

The greatest impingement of fish in physical screens occurs during the hours of darkness. Up to 97% of young fish entrained will be entrained at night (Pavlov, 1989). During hours of darkness in particular artificial lighting will help fish to orientate themselves better and this reduces entrainment. This deterrent may be further enhanced by carefully positioning light sources behind structural elements. This provides maximum visual contrast by throwing the structure into silhouette (Turnpenny, 1998). By adding lights to an intake

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structure, Pavlov reduces the entrainment of young cyprinids and percids by up to 91%. The effectiveness, however, varies with species: up to 100% of perch (Perca fluviatilis) and ruffe (Gymnocephalus cernua) were deterred, but entrapment actually increased with three-spined-sticklebacks (Gasterosteus aculeatus) (Hadderingh, 1982). Light can therefore act as either a repellent or an attractant to different species.

To minimise light pollution and to achieve the highest possible effectiveness, it is necessary to submerge the light source. This significantly increases the capital and maintenance costs, as a mechanical recovery system is then needed for the necessary frequent cleaning of the lamps . Lamps are most commonly positioned in an arc on the bed around the intake entrance. This ensures water velocities at this point are low enough to allow fish to escape (Turnpenny, 1998). The angle of positioning of the lamps is also important: an upwards tilt of $40\text{-}45^0$ is the most effective (Johnson *et al.*, 2001).

4.3.6.2 Constant illumination

Continuous illumination is not the best method for most species, but does work for eels. Its use has been tested extensively in the Netherlands (Hadderingh and Smythe, 1997). Eels show strong phototaxis and positive rheotaxis (orientation into currents). Light can therefore be used to discourage the tendency of eels to follow water flow. The lights can be incandescent lights, mercury vapour lights or fluorescent lights. Trials have mainly used fluorescent lights (specified as 36W, PL-L Philips, spectrum with peaks at 440, 550 and 610nm). Deflection rates of up to 74% have been observed at some thermal and hydroelectric power stations.

The method is also used by the operators of commercial eel racks on the River Test in Hampshire. The intention is to block eel access to side channels, effectively steering eels into the eel racks. In this case, 500 W halogen floodlights are positioned ~1m above the water surface and aimed vertically downwards. The effectiveness of this light configuration has not been formally assessed.

4.3.6.3 Strobe lights

Strobe lights generally give better results than continuous illumination. Most experiments have centred on eels. Patrick *et al.* (1982, 2001) conducted experiments on American eels, A. rostrata. The first study aimed to determine whether strobe lights could be used to deter eels from entering a turbine unit during its shutdown period. The second involved initial laboratory tests followed by field trials at a fish ladder. Both investigations showed a reduction of eel movement of between 65% and 92%. The laboratory tests in the second study used flash frequencies from 66 to 1,090 flashes per minute (FPM): all were effective in repelling eels. The fish ladder trials used a flash rate of >800 FPM. The threshold light level for American eel repulsion was found to be $\geq 0.1\mu Em^{-2}s^{-1}$ ($\geq$5 lux). Further work is required to confirm the optimum flash rates and intensity thresholds for *A. anguilla*.

Strobe lights may be more effective when used alongside other forms of behavioural and physical screening. Combinations of bubble screens and strobe lights work well for some species, such as alewife (Alosa pseudoharengus), smelt (Osmerus mordax) and gizzard shad (Dorosoma cepedianum) (Patrick *et al.*, 1985). This combination has been tested at the Walton-on-Thames raw water intake: a reduction of 62.5% was observed in the entrainment of salmon smolts (Solomon, 1992). Strobe and bubble combinations do not appear to have been tested specifically for eel.

It is usually reported that strobe lights require clear water to work effectively (Turnpenny and O'Keeffe, 2005). However, a study by McIninch and Hocutt (1987) reported 'an interesting phenomenon was that fish avoidance to strobe light systems increased with turbidity over the range tested (clear, 39-45 and 102-138 NTU)'. The effect may be due to backscatter by particles making the illuminated area more visible. In this 1987 study, the strobes were used in conjunction with a bubble curtain.

The Environment Agency has recently issued an abstraction licence for a CCGT power station that is to be built at Pembroke in South Wales. The licence requires strobe lights to be used at the cooling water intake openings in an experimental measure to reduce eel ingress. The licence also requires a programme of testing once the power station has been commissioned. This testing should help us form a clearer of the usefulness of strobe lights.

Appendix D contains guidelines on the safe and environmentally-friendly use of strobes and other high intensity flashing lights for fish deterrence applications.

4.3.6.4 Design and operational best practice

This approach has been little used in the UK. Therefore 'best practice' is unclear. Important issues are:

- Water clarity: it is generally assumed that clarity should be high, but moderately turbid water may improve results as a result of backscatter. Most important is that the lenses can be kept clean, as this prevents attenuation.
- Install a lamp retrieval mechanism to facilitate cleaning the lights.
- When strobes are used, adequate testing is required to optimise the flash rate. There is a risk of attracting rather than repelling fish at some flash rates. Flash rates of 200 FPM appear to work best with a range of species, including eels, but rates up to and above 1,000 FPM also appear to work for eels. Owing to potential human health and safety risks associated with higher flash rates, rates should be kept at or below 240 FPM. Please read the health and safety advice in Appendix D.
- Use more lights than are strictly necessary, in order to allow for lamp failures.
- Provide warning systems, such as telemetry links, to inform plant operators of failure.
- Maintain equipment regularly. Display and log service intervals in the plant control room.
- Display visible indicators of operational status, such as the number of lamps operating versus failures. These indicators should be displayed at or close to the intake so that they are easily seen by operational and enforcement staff.
- Back-up power or interlocks with pump controls may be needed to ensure that pumping does not occur when the system has lost power.

The use of 'high-tech' computer-control systems is a promising development as these systems appear to enhance flexibility and control.

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4.3.6.5 Applications

Light-based techniques may be appropriate in situations where large flows are to be screened with zero headloss – for example at thermal power plant intakes.

From the limited research available, strobe light systems appear to work well in combination with bubble curtains. Recent improvements in strobe lamp technology have greatly extended operating life. This makes the technology potentially more useful.

4.3.6.6 Life stages

Although a number of other species can be deterred using strobe lights, light-based methods show particular promise for eel guidance. Consider combinations of Acoustic Fish Deterrent systems and strobe lights at sites where you need to deter eels as well as acoustically sensitive species.

4.3.6.7 Ease of retrofitting

Light-based systems of any kind are relatively easy to install and an attractive option for retrofitting.

4.4 'Fish-friendly' turbines

There has been some work done on how to make turbines more 'fish-friendly'. These laboratory investigations have looked at the individual biological stress factors associated with turbine passage. The findings are summarised below. However, building these features into turbine design is a balancing act: between achieving fish-friendliness and power extraction efficiency. It must be borne in mind that if more turbines are required to deliver the same quantity of power, the overall result may not be any more fish-friendly. We have included this information to give scheme engineers some insight into critical areas of turbine design. This may influence their choice or specification of turbines.

In the US, the Department of Energy's Advanced Hydro Turbine (AHT) Project has investigated 'fish-friendly' concepts in turbine design (Odeh, 1999; Cada and Coutant, 1997). The project has put forward some general measures to reduce or eliminate injury:

- Use fewer blades, so as to minimise the number of leading edges.
- Increase the radius of the runner's leading edge, to reduce the impact pressure on fish.
- Maximise the size of the flow passages.
- Avoid the use of a regulated runner. This reduces the risk of blade tip injuries caused by clearances at the runner tip.
- Reduce shear stress: fish in live tests were subjected to rates of strain up to 1,185 cm/s/cm. No significant shear-related injuries were found in fish subjected to rates of strain of less than 500 cms cm^{-1}.
- Cavitation can be minimised by properly designing the runner geometry. Key parameters include high velocity/low pressure zones, surface irregularities, abrupt changes in flow direction, and location or submergence.

- Allow minimum pressures within the turbine to fall to no less than 0.6 bar. This would protect most fish from the direct effects of low pressures.

A study of a 48 kW Archimedean screw turbine on the River Dart at Ashburton (Fishtek Consulting, 2007 and Kibel , 2008) demonstrated a low incidence of injury to fish. Based on this study, a well designed Archimedean screw turbine with appropriate protection to the leading edge of the screw (see Figure 4.18) may be considered a fish-friendly option.

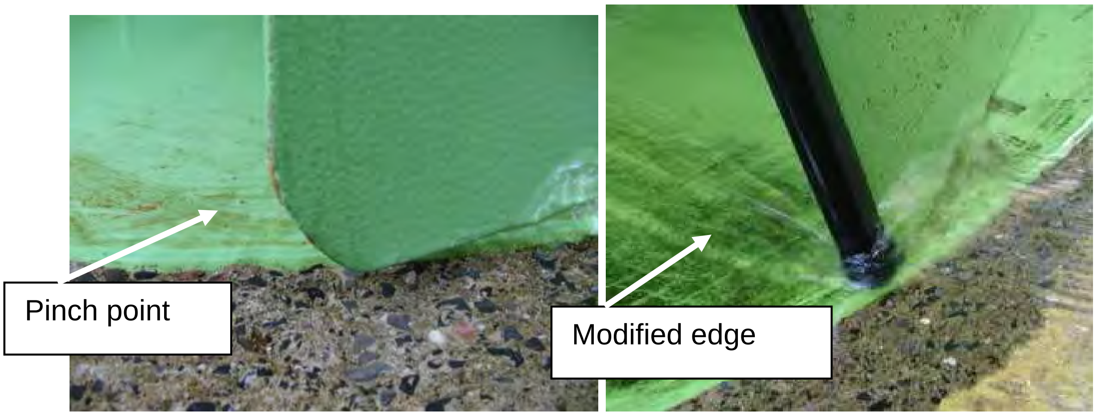

Figure 4.18: Photos of the leading edge of the Archimedean screw at R. Dart, Ashburton showing pinch point on leading edge and rubber 'bumper' modification (Courtesy of Fishtek, 2008)

160 downstream eel passages were recorded in the River Dart study. Most eels either orientated themselves tail up and head down or actively swam in the chambers as they passed through. 12% of passages were made with eels staying close to the bed of the chamber. One eel suffered minor damage in the form of a pinch 5cm from the end of the tail, probably caused by the tail sliding under the 5mm gap between the screw helix and the trough. All the eels were alive and appeared healthy after 7 days in holding tanks. The damaged eel was observed for a further 7 days (14 days in total) after which it was released into the river.

Effect on delay varied with the size of eel. Smaller eels generally passed into the turbine in less than 1 minute while larger ones, more able to resist the flow took up to 15 minutes to enter.

While fish screening may not necessarily be a requirement for a well designed Archimedean screw scheme, it may be appropriate to provide a "bywash" facility as an alternative, unhindered and safe downstream route for migrating eels. At sensitive locations, where there is the potential for a scheme to pass significant numbers of eels, diversion to a bywash should also be considered. An example would be where a scheme is located toward the lower end of a river system; while injury rate may be low, there is the potential for exposing high numbers of eels to the risk if the intake is unscreened.

However the Archimedean screw turbine is not suited to all flow and head conditions. Our Hydropower Guide discusses leading edge protection and relative ranking of turbines (Environment Agency, 2009). [11]

[11] See link

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4.5 Fish protection for temporary pumping operations

Most of the abstraction types covered in earlier sections of this report are permanent facilities. However, temporary pumping operations have the potential to kill or injure fish. These operations may be:

- for agricultural irrigation;
- pump-over for construction schemes;
- back-pumping over river weirs, to maintain upstream levels during drought or other purposes.

Where the water contains eels or other fish species, appropriate safeguards must be provided. The two alternative approaches are described below.

4.5.1 Screening of pumps

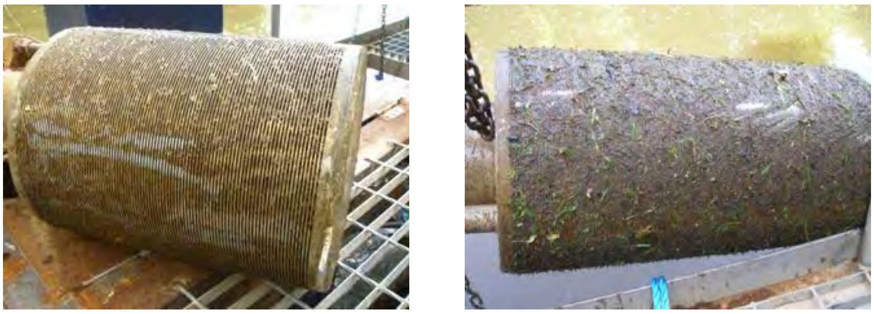
Some road schemes or temporary abstraction facilities over-pump water using submersible-drainage or surface-mounted pumps. Such pumps may entrain eel and other species. Typically these pumps are fitted with either integral or end-of-pipe suction strainers (Figure 4.19). These are primarily intended to exclude debris that could damage the pump. Although not designed to protect eel, the suction strainers may provide limited screening for larger specimens. However, they do not physically exclude elvers and small yellow eel, which may actively seek the cover given by pump accessories and then become entrained.

a

b

Figure 4.19: Typical pipe-mounted suction strainers designed for debris exclusion

Companies such as Johnson Screens® and Hendrick Screen Company manufacture stainless steel, pump guard screens of various sizes (Figure 4.20a). The Hendrick Sreen is distributed in the UK by Eimco Water technologies. These screens are fabricated in welded V-wire or Vee-wire ® with various mesh separations, down to 1 mm, which may physically exclude juvenile eel. This system works because it passes large volumes of flow through the screen face at low, uniform velocities. These products may however foul in low flows if not fitted with a screen-cleaning device (Figure 4.20b). Without such a device, the screen may need to be removed from the waterbody for regular manual cleaning.

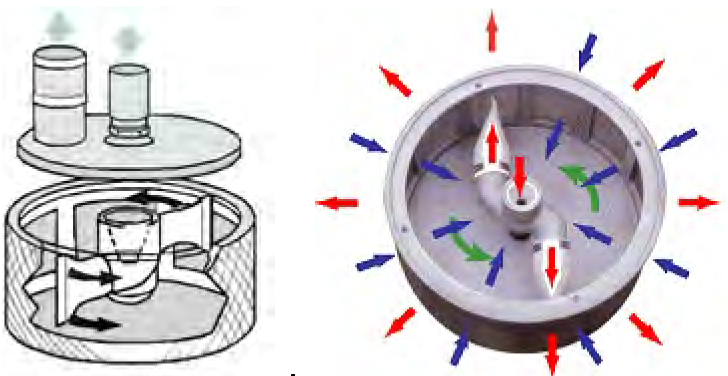


a b

Figure 4.20 a and b: V-wire pump guard screens. Figure 4.20b shows the fouling that may occur if the screen is not fitted with an automated screen-cleaning device.

On some schemes, the repeated fouling of suction strainers has resulted in their removal and this in turn has led to fish mortalities. Few manufacturers offer self-cleaning strainers that are appropriate to temporary works. One of the few available is the Rotorflush RF Series of self-cleaning inlet screens for surface-mounted pumps (Figure 4.21). The Rotorflush works by returning up to 20% of the pump output to the filter, in order to drive a rotating spray bar in the middle of the filter that continually backflushes the screen. The screens are designed for an intake velocity of 0.1 m/s at the screen face and the screen apertures currently available range from 1.5 to 6 mm.

Johnson Screens has developed the Hydroburst® system. When fitted to pump guard screens, Hydroburst® maintains screen cleanliness by generating a periodic blast of air through the screen assembly. However, this system is only appropriate on larger over-pumping schemes.



a b

Figure 4.21: The Rotorflush RF works by redirecting a percentage of the pumped water (red) to a dual head rotor. This creates jets that flush the filter screen up to 120 times per minute.

4.5.2 Fish-friendly pumps

Water pumps are mechanically similar to turbines, except that they operate with a reverse pressure gradient. They injure fish in much the same way. Fish-friendly pumps have been in use for many years, for example moving fish at fish farms and in some upstream fish passage facilities. Several types have a good proven track-record.

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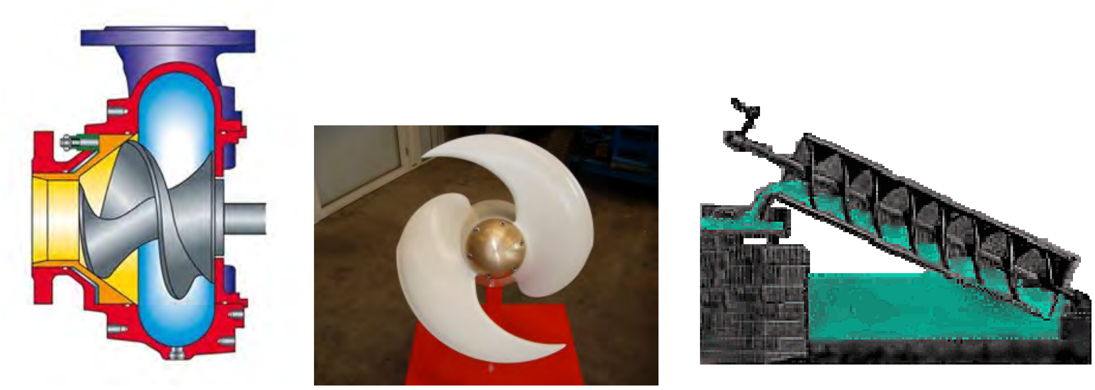
A fish-pump test facility at Red Bluff in California has looked at the performance of two types of pump over a number of years:

- a helical-impellor fish pump[12];
- an Archimedean screw pump.

Testers at Red Bluff have looked at mortality rates (Borthwick *et al.*, 1999) as well as sub-lethal effects, including plasma cortisol levels and behavioural responses (Weber and Borthwick, 2000).

Various proprietary designs are available. Most of the entrained fish were juveniles less than100 mm long. For these fish, the mortality associated with pump passage was estimated to be 5% for the Archimedean screw and 6% for the helical screw pump. No alteration of the behavioural metrics or plasma cortisol response could be detected as a result of pump passage. Eels were not present in the tests. However, the positive findings reported for Archimedean screw turbines – see Section 4.4 above – indicate that this type of pump should be suitable for eels to pass.

Axial fish pumps have recently been developed in the Netherlands, product literature claiming, through independent assessment, a 100% passage survival rate for eels of up to 82cm in length. The axial pump in question had a 800 mm impeller with a speed of 333 rpm[13].



a b c

Figure 4.22: Examples of "fish friendly pumps": a) Screw impeller fish pump b) FishFlow Axial Fish Pump impeller c) Archimedean screw pump

For further information on fish-friendly pumps see Appendix F.

4.6 Pumping Stations

There are numerous land drainage pumping station facilities throughout England and Wales that pose significant risk to eel passage. These create specific challenges when considering appropriate mitigation techniques.

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[12] See Link for example

[13] See Link

According to Solomon (2010) there are three basic options for protection:

- To utilise pump systems that cause less damage (“fish- friendly” pumps);
- To provide and encourage the use of alternative routes; or
- Capture downstream-migrating eels landwards of the pumping station and release them where safe seaward passage is available.

For more information refer to Appendix F.

4.7 Intake Siting

There is evidence that actively migrating silver eels swim close to the riverbed. Intakes that draw from near the bed are therefore likely to be particularly damaging to eels. The Environment Agency Best Practice Guide (Turnpenny and O’Keeffe, 2005) suggests adding a cill to mitigate this. A cill of 30-45 cm is preferred for eel. When reducing height through the use of curtains or cills, consider carefully how the change will affect intake velocity.

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5 Outfall screening

Water from outfalls and turbine tailraces may attract fish that are actively migrating upstream. Outfall screening is sometimes needed to prevent ascending fish from inadvertently entering the discharge.

The eels most at risk are ascending elvers, glass eels and yellow eels of up to 30 cm.

At outfalls it is generally not viable to install fine screens that use a small enough mesh size to exclude elvers (see Section 6.6). This is because of hydraulic head-loss and the risk of blockage.

Electrical barriers, such as the ‘Graduated Field Fish Barrier (GFFB™)[14], may be suitable for some outfalls (provided that they contain no descending fish). However, safety issues would need to be addressed and appropriate permissions secured. Due consideration must be given to potential impacts on other wildlife. Early consultation with your local Biodiversity officer is recommended.

Where possible, set outfalls above river level so that elvers will not be able to ascend. If the invert of the outfall is above the Q20 stage, this would normally ensure that river velocities were too high for elver to enter. Another approach is to keep the outfall discharge velocities higher than the burst swimming speeds of elvers. This should also ensure that elvers cannot enter (see Table 6.2).

[14] http://www.. smith-root.com/barriers/

6 Designing for performance

6.1 Introduction

This section provides general guidelines on screening requirements and the considerations for the operation and layout of fish screens. Some of the information given here, for example on mesh sizes and allowable water velocities, is specific to eels; for other species, refer to Turnpenny and O'Keeffe (2005).

6.2 Timing of fish movements

To be effective, screening must be targeted at the species, migratory form, sizes and life stages of the fish that are to be protected. These factors will determine: the method best suited; the critical times of the year (see Table 6.1); and the specific design details for the fish screen (mesh size, etc).

Life stage	**Vulnerability**	**Time of year**
Glass eel	Migration – dependent on tidal transport	Spring – timing varies with biogeography
Elver	Migration – active swimming upstream	All year round
Yellow eel	Migration – active swimming up and downstream	All year round
Silver eel	Descending adults	All year round, but mainly autumn

Table 6.1: Migration timings of eel found in UK waters and vulnerability to entrainment

If seasonal migrations are predictable, or if ongoing monitoring ascertains run timings, the design and use of screens can be more closely tailored to the needs of the site. It is common practice, established through byelaws in some localities, to install smolt screens only during the spring period of the smolt run. At other times of the year, the screens are replaced by coarser screens or bar racks, in order to ease operational problems. The same approach has been used to protect silver eel runs. For example, at the Backbarrow hydropower scheme (River Leven, Cumbria), eel screens are overlaid upon the inlet bar racks during the autumn period.

Knowledge of the timing of fish runs will allow operators to consider varying, or temporarily stopping, abstraction. For some operations, this approach is more cost-effective during critical periods than installing screens. For example, silver eel migration occurs

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predominantly between dusk and dawn in most rivers: it may be feasible to phase operations accordingly so that water is abstracted during the day.

6.3 Intake velocities and eel swimming performance

Eels are generally considered to be poor swimmers. They have performed less well in swimming trials than other species.

The swimming performance of eels is strongly influenced by the length of the fish and to a lesser extent by water temperature. Environment Agency R&D Project No W2-049 Swimming Speeds in Fish investigated the swimming speeds of various freshwater fish species, including elver and eel. The project used a computer program called SWIMIT (v3.3) which allows swimming speeds to be calculated for elvers and yellow eels according to body length and temperature. Table 6. presents data extracted from this program for eel. When considering swimming performance for intake design purposes, it is prudent to allow for the smallest size of eel likely to be present and the lowest water temperature band at which they are likely to migrate. Burst values are, by definition, speeds that can be sustained only for periods of up to 20 seconds. while Sustained values can be held for at least 200 minutes. Intermediate speeds can be held for periods between these limits.

Water temp. ^{o}C	**Parameter and percentile**	**Body length (cm)**							
		10cm		30cm		50cm		70cm	
		Sust.	Burst	Sust	Burst	Sust	Burst	Sust	Burst
<10	Mean	9	101	19	109	38	119	58	126
	90	<5	80	6	88	18	98	31	105
10-15	Mean	13	104	23	112	43	123	62	129
	90	<5	83	9	91	22	102	35	108
>15	Mean	18	107	27	115	47	125	66	132
	90	6	86	13	94	26	104	38	111

Table 6.2: Burst and sustained speeds (cms^{-1}) of adult yellow eel (*Anguilla anguilla*) in relation to size and water temperature, with median and 90th percentile values (from SWIMIT v3.3)

6.4 Advisory screen approach velocity

The impingement of eels may result in injury or death. To prevent this the fish approaching an intake should be able to swim fast enough and for long enough to ensure their escape. This may be via the bywash or any other route provided to return them to the main river flow. The screen approach velocity and screen’s angle-to-flow should be designed to allow fish to escape.

For screen design purposes, this approach velocity (Ue) (also known as ‘escape velocity’) is defined as the velocity 10 cm upstream of the screen, perpendicular to the screen face.

The screen should usually be angled diagonally across the intake/headrace flow. This ensures that the approach velocity is low even when the axial channel velocity Ua in the intake/headrace is high. This has the added benefit of guiding fish towards the bywash entrance (see Figure 6.1).

Note: where more than one species need to be protected, use the lowest common acceptable approach velocity. For information on the swimming speeds of other species, see our Good Practice Guidelines in the annex to Hydropower Handbook.[15]

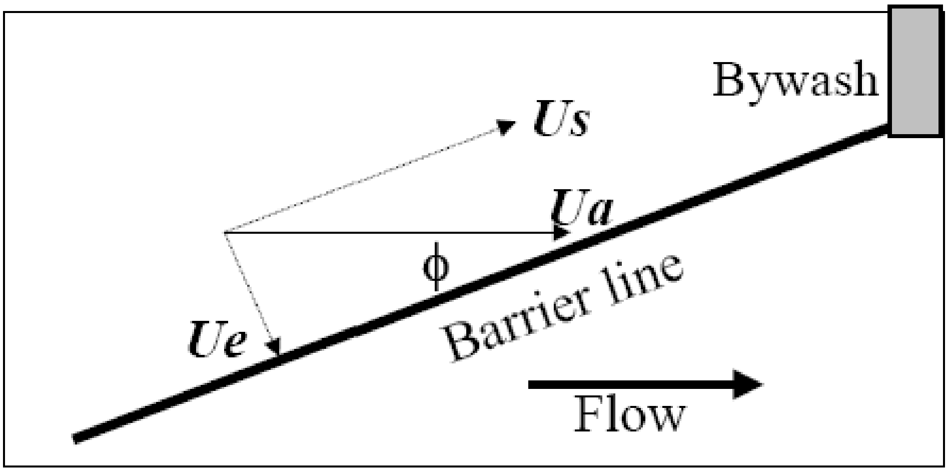

Figure 6.1: The flow velocity components in front of an angled fish screen or barrier. Ua is the axial channel velocity, Ue (=UsinΦ) is the fish escape velocity, and Us (=UcosΦ) is the sweeping velocity component along the face of the screen.

Please apply the following criteria to exclude eel at a specific life stage:

Life stage	**Screen angle Φ 21 to 90°**	**Screen angle Φ ≤ 20°**
Elver/glass eel	10 cms^{-1}	25 cms^{-1} (screen length <10 m)
Yellow >14cm	15 cms^{-1}	30 cms^{-1}
Yellow >30cm/silver eel	20 cms^{-1}	40 cms^{-1}
Silver eel	40 cms^{-1}	50 cms^{-1}

Table 6.3: Advisory screen approach velocities for eel.

Note: where salmonid smolts are present, the acceptable maximum is 60 cms^{-1}. For juvenile-adult coarse fish and shad, the limit is 25 cms^{-1}, and for lamprey it is 30 cms^{-1}. Velocities must meet the requirement for all species at the relevant times of the year.

[15] See Link

Environment Agency Website: www.environment-agency.gov.uk

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Burst speeds can only be sustained for short periods (20 seconds). So normally it will not be appropriate to use burst speeds in intake design: an eel may not be able to find a bywash within this time.

6.5 Accounting for debris

If screens become blocked with debris, water velocities will increase, particularly if the screen is at right angles to the flow. When determining the size of the screens, you must make some allowance for some blocking – so that the target approach velocity is not exceeded when screen performance is reduced by the accumulation of debris. For manually cleaned screens, the Hydropower Good Practice Guide (Environment Agency, 2009) requires 50% oversizing to allow for debris. The inclusion of an automatic screen cleaner will improve performance. The additional area of screen required can then be less, typically a maximum of 10% screen blockage.

6.6 Mesh sizes and bar spacings in screens

Appropriate mesh sizes and bar spacings will be dictated by the size of fish to be excluded and the angle of the screen to the flow.

Where the intake screen is flush with the riverbank, the natural sweeping flow of the river can provide the stimulus for guiding eels to safe downstream areas. In other situations, placing the screen across the channel along a narrow diagonal angle (preferably $\Phi \leq 20$ degrees to the channel axis) can generate the necessary sweeping flow. See Figure 6.1. At the downstream end of the screen, a suitable bywash must then be provided.

Sweeping velocity must allow fish to locate a bywash (or the downstream end of the screen for river bank intakes) within a reasonable time, recommended as 60 seconds. This is calculated by Time = Length of screen divided by Sweeping Velocity. This assumes fish are moving passively with the flow on encountering the screen. Under these circumstances, if water velocities in the approach to the screen are within the limits set out in Table 6.3, it is acceptable to use mesh sizes or bar spacings as shown in table 6.4.

This is based on the assumption that, although eels can force there way through apertures smaller than their head width, they will show behavioural avoidance of the screen after inevitable physical contact if some degree of compression is required to pass through the slot. Velocities will be low enough to allow them to swim away from the screen and the sweeping flow is sufficient to deflect to a closely located bywash.

Screening requirements are more demanding for water intakes whose design would not allow this arrangement or which have a screen angle to flow, Φ, that is between 21 and 90 degrees. In such cases a narrower mesh or bar spacing will be required to physically prevent eels from passing the screen..

The escape distance from any point on a 21 to 90 degree angled screen to a bywash entrance should be no more than five metres.

Table 6.4 gives suitable values for eels of different sizes and life stages.

For larger silver eels, several studies have shown that bar racks that have a narrow angle with respect to channel flow can deflect a high proportion of eels, even if they have bar spacings wide enough for eels to force their way through (Russon *et al.*, 2010; Horsefield

& Turnpenny, 2010; Dixon, 2006; Gosset *et al.*, 2005). This is provided that escape velocity is low enough to prevent impingement on the screen.

For the purposes of this manual screen angles of Φ ≤20 degrees are considered optimal to generate the necessary sweeping flow which allows wider mesh sizes to be used.

The bar-rack study presented by Dixon showed that the eel passage rate significantly improved – from 70% to 95% – if the bottom strip (~0.3 m height) was blanked off with a solid plate. This simple measure appears to offer a low-cost modification for a steeply angled (Φ ≤20 degree to the flow) bar screen, provided that the overall screen area is designed to achieve the maximum allowable approach velocity. The same effect could also be achieved by building the intake screen above the level of the riverbed. Further work may be required to develop appropriate design criteria.

Eel life stage (minimum size protected)	**Mesh size/bar spacing for exclusion (mm)**	
	Screen angle Φ >20 deg	Screen angle Φ ≤20 deg
Elver/glass eel	1-2*	1-2*
Yellow (14cm)	3	3
Yellow/silver eel (30 cm)	9	12.5
Silver eel (50cm)	15	20

Table 6.4: Selection of mesh sizes and bar spacings for eel of the sizes and life stages present. (Measurements are based on the use of rectangular section bars).

* See Section 4.2.2.5

7 Downstream bywash guidelines

7.1 Introduction

A good design for eel passage downstream should combine effective screening and diversion with a safe bywash route.

A screen bywash is usually required wherever:

- the intake screen is not located in the normal course of the river – for example, it is within the headrace;
- the structure will otherwise delay, restrict or block downstream migration.

In simple terms, a bywash should be a smooth and safe conduit that avoids damaging the eel (and other species that may use it), and delivers the eel safely back to the river downstream.

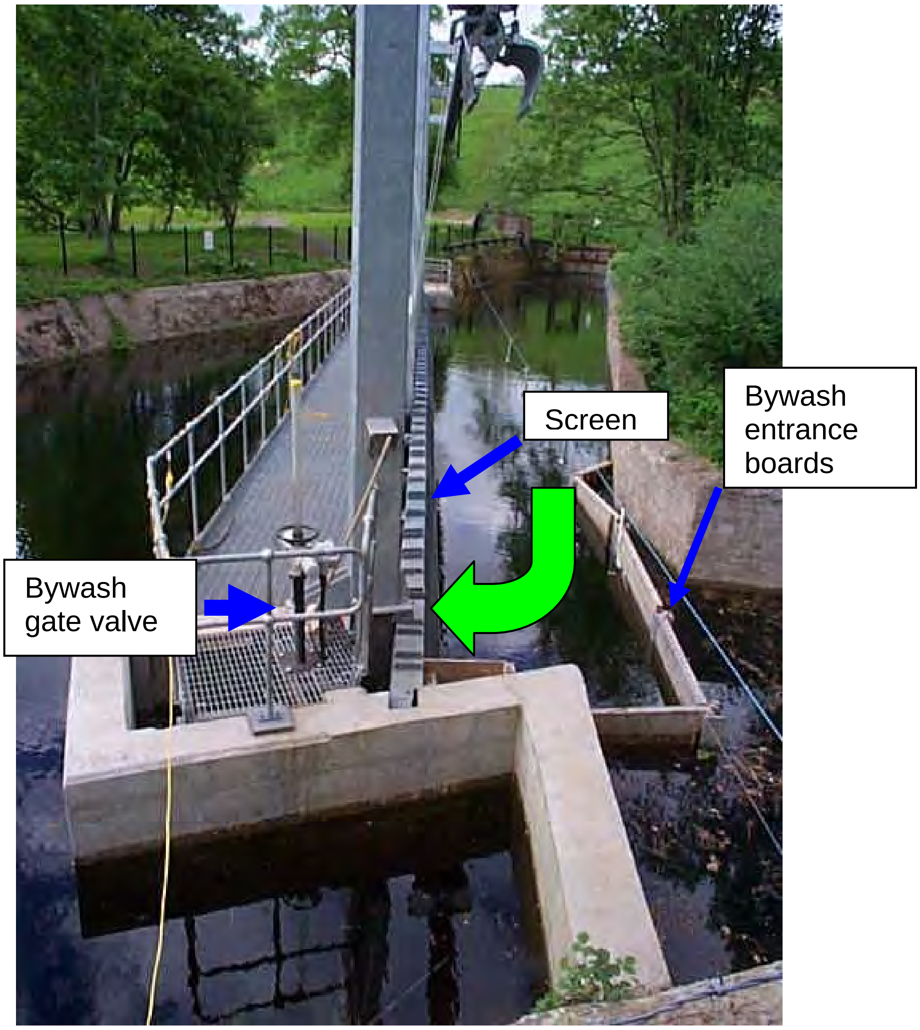

Figure 7.1: The Stanley Mills Hydro fish screen. The photo shows timber boards forming the mouth entrance of the bywash. This arrangement allows the entrance shape to be modified until as many fish as possible are diverted. The green arrow shows the direction of the river flow into the bywash. Flow then enters a buried bywash pipe

7.2 Bywash flow

The success of a bywash is strongly influenced by the amount of flow used: the larger the flow, the more likely the fish are to enter it.

Where screens are installed at a steep angle to the flow (Φ ≤20 degrees) and the bywash entrance is located immediately downstream of the screen, a discharge of at least 2% of the intake flow to the bywash may be satisfactory. Where the screen is installed at larger angles to the flow, the discharge to the bywash will need to be at least 5%.

A higher proportion (up to 10%) may be needed if by-pass design is poor – for example if the screen is aligned perpendicular to flow, is located away from the end of the screen, or there are poor hydraulic conditions at the bywash entrance.

7.3 Bywash entrance

Position the entrance to a bywash so that the eels and other species have the greatest chance of locating it. Intake screens should usually be set at a diagonal angle to the flow. This guides the fish towards the bywash entrance.

Where the angle of the screen to flow is $\Phi > 20$ degrees, there should be a bywash entrance every five metres along the length of the screen.

For screen angles to the flow $\Phi \leq 20$ degrees eels will need to locate the bywash within 60 seconds. This can be calculated by Time = Length of screen multiplied by Sweeping Velocity.

In the case of a perpendicular screen arrangement, where it is not possible to put the bywash entrance immediately next to the screen, the opening should be no more than a metre or two from the screen face. In such cases, the bywash discharge will need to be higher – at least 5-10% of channel flow – in order to attract eel.

Do not position the bywash entrance near areas of turbulence and plunging water flows. These conditions, which may occur near to turbine inlets, can create high levels of underwater noise that create conditions that may deter fish from finding the bywash entrance.

The bywash entrance should taper smoothly in from the sides and the bottom – in a flared 'bellmouth' shape (see Figure 7.2). For eels, the bywash entrance must extend to the floor of the channel. The bywash entrance should normally be a minimum of 0.4-0.5 m wide and deep. Flow should accelerate smoothly into the bywash channel.

The bellmouth design, with its vertically tapering entrance, is suitable for fish that move at the surface of the water and at the bottom. For this reason it is generally recognised to be the better option. An alternative arrangement would be to install an adjustable sluice gate at the upstream opening of the 'funnel'. This could be operated in either undershot mode for eels and bottom-moving species, or overshot mode for smolts and other surface-moving fish. The benefit of this approach is that it concentrates the flow that attracts the eel at the optimal level according to season. However it may be necessary to monitor performance in order to ensure that fish are not put off entering by turbulence around the gate.

There should not be any light/dark interfaces – such as shadows – particularly at the entrance of the bywash. Instead there should be a gradation of light level.

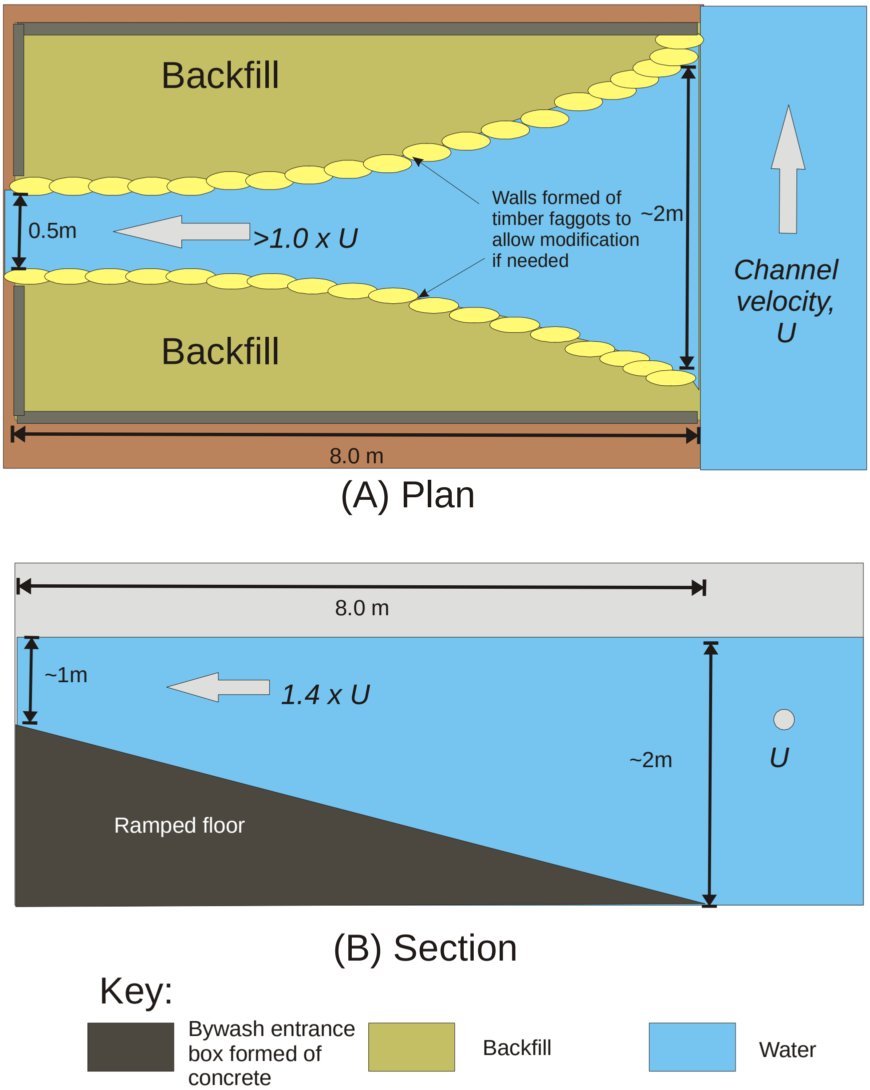

Figure 7.2: Sketch of profile of bywash entrance example.

7.4 The bywash channel

Fish handling should be as gentle as possible, both within the bywash and at the return point:

- Avoid sharp bends – the minimum radius should be 3 m.
- Avoid sudden drops – the minimum radius should be 3 m.
- Avoid rough surfaces and irregularities that might cause abrasion.

The channel should be designed so that it prevents predation but allows maintenance. For example, ensure debris blockages can be readily and safely removed. One way of doing this is to install a mesh grid over the bywash.

The design should deliver the fish safely and directly to the downstream point. Try to avoid an area where predators could accumulate. Any pools on the bypass are likely to delay and confuse the fish, particularly if turbulence is high.

Water within the channel should be accelerated smoothly to around 1.5-3 ms^{-1} in order to prevent fish from swimming back upstream.

7.5 Return point

The downstream exit from the bywash should be deep enough to prevent fish from becoming stranded or damaged on impact. The depth should be at least 25% of the differential head between the discharge point and the water surface, and not less than 0.9 m.

Set the downstream end of the bywash chute or pipe above the water level of the return pool. Maintain a height differential of at least 0.5 m (or Q1 stage, whichever is the greater). This prevents access to ascending elvers or migratory salmonids which might otherwise try to jump into the bywash. Note that this is usually more of an issue when the discharge is at a barrier/weir.

The terminal velocity from the returning plunging jet to the return pool should not exceed 7-8 ms^{-1}.

The returning jet (with fish) should avoid any still areas or back eddies in the receiving water, where predators may be encouraged to lurk. The bypass must not lead eels into an unsatisfactory environment.

7.6 Eel bottom bypasses

An eel bottom bypass channel may also encourage fish to enter the bywash. Although further research is needed into their use, eel bottom bypasses appear to offer a relatively low-cost solution and to merit further investigation.

There is an example of such a channel at the Backbarrow hydropower scheme on the River Leven in Cumbria (Spiby, 2004). It is claimed that this is based on a traditional eel fishing method. The bypass channel has a trough set in the floor of the headrace. This trough is just upstream of the screens at an angle of 60o to the flow. There are a 20 cm high wall on the downstream side (Figure 7.3) and a 20 cm bywash pipe at the downstream end. The effectiveness of this bypass is not known.

Richkus (2001) cites French and German examples that use this method to divert eel. The French example is the Halsou hydroelectric project in the Pyrenees, where a deep trough is set into the floor of the headrace upstream of the trash racks. This connects to a bywash which draws 3-5% of the turbine flow. From radio-tracking studies, it was estimated that between 50% and 80% of eels used the deep bypass.

In one German example, the eel bypass was formed by a steel half-pipe set into the floor of a turbine spiral chamber. When fully opened, the pipe carried 1,000 Ls^{-1} (the proportion of total turbine flow was unspecified). Using farmed (presumably yellow) eels, 41% of eels released upstream used the bypass. No further information is given. Another German example from the same author uses a bypass depression that was 50 cm wide and 15 cm deep across the width of the intake channel. This leads into a 25 cm bywash pipe. Studies carried out during silver eel migrations showed that this pipe was used by ‘a high percentage’ of eels at low and intermediate river discharge, but by a smaller percentage at higher flows. Richkus (2001) provides a comprehensive review of downstream eel migration and deflection technologies. The evidence from this is that concerted silver eel migrations tend to occur on high river discharges. This would suggest that this technique is not enough by itself to protect eels, but that it may help to increase efficiency of escapement.

A German company[16] has developed a design known as the Eel Bottom Gallery™. This provides a hydraulically designed channel placed a short distance upstream of the screen. The company claims that if the screen approach velocity is less than 0.5 ms^{-1}, eels will attempt to swim back upstream. The company claims that with their design the eels can be guided to safety along the gallery. Note that their marketing material provides no evidence of performance, other than photographs of laboratory tests.

Richkus (2001) concludes that there has not yet been any rigorous research to either optimise or evaluate the eel bypass technique. The information available suggests that:

- entrance velocities at eel bypasses should be the same as those occurring at the intake trash racks;
- bypass flows should be 3-5% or more of total river discharge.

[16] See link

Figure 7.3: The eel bypass trough at the Backbarrow hydropower scheme on the River Leven, Cumbria (Spiby, 2004). The trough is formed along a diagonal in the floor of the headrace canal, with a submerged bywash at its downstream end. The flow in this picture is from right to left.

7.7 Use of fish passes as bywashes

Some types of fish pass can be used as a bywash, if they can be suitably positioned.

Acceptable types include: the super-active bottom baffle (Larinier), vertical-slot, pool and traverse, and nature-like fish passes. However both the vertical slot and pool and traverse passes are prone to debris blockage. Avoid these if high levels of allocthonous debris are expected.

Denil type passes – including Alaskan A or side-baffle passes – may cause abrasion damage to fish by the nature of their baffles. They are therefore not suitable for use as a bywash channel. Recent screening trials on the River Test (Horsfield and Turnpenny, unpublished) show that silver eels are reluctant to enter the top end of a Denil pass. This is probably due to the turbulence generated by the upper baffles. A suitable solution where baffled fish passes are present may be to provide a parallel clear (unbaffled) bywash channel or pipe which merges at low velocity with the downstream fish pass entrance to augment attraction flow.

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Glossary

The following are definitions of certain words and abbreviations used in this Guide:

Acoustic fish deterrent – a behavioural screen or barrier exploiting the hearing sensitivity of fish.

Acoustic barrier – Barriers which exploit the hearing sensitivity of fish.

Approach velocity – The velocity of water approaching the screen.

Attraction flow – A water flow which attracts fish to a desired area.

Axial channel velocity – water velocity measured in a direction parallel to the centre-line of the flow channel

Backflushing – Reverse of flow to wash off debris from the screen.

Behavioural barrier or screen – A fish deterrent system which works by stimulating the senses of fish either by repulsion or attraction mechanisms.

Biofouling – the build up of aquatic organisms on a substrate.

Bubble curtain or barrier – A wall of bubbles used to deflect or guide fish.

Bypass – A channel or pipe which allows fish to pass by the obstruction unharmed via an alternative route.

Bywash – Synonymous with 'bypass' (see above) but more commonly used in Britain

Catadromous – migratory fish that live in fresh water and breed in the ocean

Channel velocity – The velocity in front of the screen measured axial to the flow channel.

Coanda effect – Principle of how fluids follow a surface, identified by Henri Coanda in 1910.

Epibenthic – Species that normally live close to the bed.

Escape velocity – The water velocity perpendicular to the face of the screen.

Entrainment – The drawing-in of fish of any lifestage at a water intake

Entrapment – entrainment and impingement

Flow velocity – water velocity measured in any specified direction

GFFB – 'Graduated field fish barrier' – a form of electric screen which presents an electric field of increasing intensity (voltage) as the fish gets closer, generated by means a series of separate pulse generators

Impingement – The accidental pinning of fish onto the surface of a screen by the water current

Infrasound – Sound with a frequency of less than 20Hz

Phototaxis – Movement in relation to light.

PWWC – Passive wedge wire cylinder – a type of fine aperture screen suitable for fish exclusion down to fry size

Retrofit – Addition of equipment to existing facilities.

Screening – prevention of entrapment of fish

Rheotactic – Movement (of fish or other animal) in relation to flow.

Shear (hydraulic) – Differential velocity field in water

Smolt – Young salmon of 2 or 3 years old.

Sound projector – an array of underwater transducers to produce a diffuse field of sound.

Strobe light – High intensity, short duration light pulses.

Sweeping velocity – water velocity measured in a direction parallel to the face of a fish barrier/screen

Teleost – A bony fish.

Transformer – Recently metamorphosed pre-adult lamprey

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Manufacturers

The following are manufacturers of screening solutions and components. This is not an exhaustive list and does not constitute a recommendation:

- **Beaudray Corporation**. Beaudrey USA. 25055 W. Valley Parkway, Olathe, KS. 66061 USA. Phone: (913) 390-5227
  Travelling screens
- **Dulas Hydro Limited** Dulas Hydro Ltd. – Dyfi Eco Parc, Machynlleth, Powys, Wales, SY20 8AX.
  Coanda screens
- Eel Bottom Gallery™. Bachstr. 62- 6452066 Aachen
  Tel: +49 241 949860
  Floecksmühle Ingenieursbüro (Consulting Engineers)
  Eel bottom galleries and migromat
- **Fish Flow Innovations** Fish Flow Innovations, van Twickelostraat 2, PO Box 423, 7400 AK Deventer, Netherlands. Tel +31 570 619292.
  Contact Guus Kruitwagen, g.kruitwagen@wittenveenbos.nl
  Fish friendly pumps
- **Fish Guidance Systems Ltd**. 7 Swanwick Business Centre, Bridge Road, Swanwick, Southampton. SO31 7GB. United Kingdom.
  Tel: +44(0)1489 880 420
  Fish guidance systems
- **Hendrick Screen Company** 3074 Medley Road, Owensboro KY 42301.
  Tel: 1-270-685-5138 . Johnson Screens®
  Screens
- **Hidrostal Ltd**. 4 & 5 The Galloway Centre, Hambridge Lane, Newbury, Berkshire, RG14 5TL.
  Contact Ian Skingley Tel 01635 550440
  Fish friendly pumps
- **Hydrolox**. E mail info@hydrolox.com. Tel Europe : +800 33445544
  Hydrolox travelling polymer screens
- **Optima International**. Optima House, Askern Road, Toll Bar, Doncaster. DN5 0QY. Tel: 01302 874128
  Wedge Wire Products
- **OVIVO** (Previously Eimco Water Technologies). Ovivo Municipal Water & Wastewater Treatment, Cornwallis Road, West Bromwich, West Midlands. B70 7JF Tel: +44 121511 2400
  Screens / guidance / recovery systems
- **Rivertec Ltd**. 21 Pottsmarsh Industrial Estate, Eastbourne Road, Westham, East Sussex. BN24 5NH. Tel: 01323 469000
  Smolt-Safe™ screen
- **Rotorflush** Rotorflush Filters, Langmoor Manor, Charmouth, Dorset.DT6 6BU. Tel 0044 (0)1297 560229
  Self cleaning pumps and strainers

- **Smith-root Inc**. Contact Support: 14014 NE Salmon Creek Ave., Vancouver, WA 98686. USA. Tel: 360.573.0202 support@smith-root.com
  Electric barriers

Appendix A: Legislative drivers for screening

Sections 14 and 15 of the Salmon and Freshwater Fisheries Act (SAFFA) 1975 set out specific powers to screen intakes and outfalls for the ingress and egress of fish. However, these measures apply solely to migratory salmonids.

The key pieces of legislation for eels are:

1. Article 2 of Council Regulation (EC) No. 1100/2007 (The Eel Regulation).
2. The Eels (England and Wales) Regulations 2009 Statutory Instrument No. 3344 (The Eel SI).
3. Part 7 (Fisheries), chapter 3 (Migratory and freshwater fish) of the Marine and Coastal Access Act 2009 (c.51) (The Marine Act).
4. The Water Framework Directive 2000/60/EC.
5. Sections 24 or 25 of the Water Resources Act (WRA) 1991 (c.57).
6. Land Drainage Act 1991 (c.59) section 61 A-D.
7. United Kingdom Biodiversity Action Plan (UKBAP) and The Natural Environment and Rural Communities (NERC) Act (2006).

1. Article 2 of Council Regulation (EC) No. 1100/2007

This has been adopted by the Council of the European Union. It requires member states to prepare an Eel Management Plan for every eel river basin within its national territory.

The objective of each Eel Management Plan is to:

‘reduce anthropogenic mortalities so as to permit with high probability the escapement to the sea of at least 40% of the silver eel biomass relative to the best estimate of escapement that would have existed if no anthropogenic influences had impacted the stock’

Eel management plans may contain, among other things, structural measures to make rivers passable and improve river habitats.

2. The Eels (England and Wales) Regulations 2009 Statutory Instrument No. 3344.

Under Section 17, the Environment Agency may require an eel screen to be placed within:

- a diversion structure capable of abstracting at least 20 cubic metres of water through any one point in any 24-hour period;
- any diversion structure returning water to a channel, bed or sea.

From 1 January 2015, it will be up to the 'responsible person' to ensure that there is an eel screen in place. For a diversion structure, this person is the owner, occupier or person in charge of the land on which the structure lies.

Under Section 18, if an eel screen is not located at the entrance of the diversion structure, operators must install a continuous bywash. This should allow eels to return, by as direct route as practicable, to the waters from which they entered the diversion structure.

Section 19 makes it an offence not to maintain the eel screen or bywash or to damage, interfere or do anything to the eel screen or bywash that may render it less efficient. The cost of screening intakes/outfalls normally falls to the responsible person.

3. Part 7 (Fisheries), chapter 3 (Migratory and freshwater fish) of the Marine and Coastal Access Act 2009 (c.51) (the Marine Act)

This makes amendments to a number of acts including the Salmon and Freshwater Fisheries Act 1975 (SAFFA) (c51), Water Resources Act 1991 (c.57) and Environment Act 1995 (c.25). The amendments allow for the appropriate protection of eels at water intakes and outfalls:

Section 223 of the Marine Act amends Section 41 of SAFFA (1975). It updates the definition of an eel to include any fish of the species *Anguilla anguilla*, including elvers and the fry of eels.

- Section 224 (Power to make byelaws) amends paragraph 6 of Schedule 25 to the Water Resources Act 1991. It gives the Environment Agency the power to make byelaws for the better protection, preservation and improvement of any 'fisheries of fish to which this paragraph applies', and not just salmon fisheries. This gives the us greater powers to protect eel and other species of freshwater fish.
- Section 230 amends Section 6 of the Environment Act 1995. It makes it a general duty of the Environment Agency to maintain, improve and develop fisheries of salmon, trout, eels, lampreys, smelt and freshwater fish.

4. The Water Framework Directive 2000/60/EC

This directive requires EU member states to take steps to prevent any deterioration in the status of all bodies of surface water. Moreover all surface waterbodies should aim to achieve Good Ecological Status (GES) or Good Ecological Potential (GEP) by 2015. The deadline can be extended to 2021 or 2027.

One of the indicators for assessing GES and GEP is fish stocks. Where a catchment fails to achieve GES or GEP, and entrapment is considered to be a contributing factor, then screening may be required (Defra, 2009).

5. The Water Resources Act (WRA) 1991

In recent years, we have often included the fitting of a fish screen as a condition to a new abstraction or impoundment licences (under sections 24 or 25 of the Water Resources Act (WRA) 1991 (c. 57)). This enables the Environment Agency to fulfil our statutory duty

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under section 6(6) of the Environment Act to 'maintain, improve and develop fisheries of salmon, trout eels, lamprey, smelt and freshwater fish'.

Such licence conditions may require not only the installation of screening systems at the owner's expense but also the installation of monitoring equipment and the carrying out of surveys.

The WRA allows us some flexibility in our approach. For example, we may place limits on the timing of abstractions to avoid critical fish migration periods. These could be times of day, tidal or seasonal. Or we may use more complex formulae related to available flows and water levels. We will normally negotiate operating conditions with the owners to achieve the most workable and effective solution. When time limited abstractions are up for renewal, we can reassess and modify them to take new legislation into account. We can of course re-assess a licence at any time, but we may have to pay compensation for any modifications that we require outside the normal renewal process.

Section105 (3) of the WRA requires us to have due regard for the interests of fisheries while exercising our power under Part IV (Flood Defence – General).

6. Land Drainage Act 1991 (c. 59) section 61 A-D

Land Drainage legislation does not protect eels directly. However, the appropriate authority must consider their general environmental duties in any land drainage application (Land Drainage Act 1991 (c.59) section 61 A-D). This means that eels and other conservation species are included within the assessment. If a Land Drainage Consent is required for a structure, such consent should not be issued if the structure would impede fish migration. The Environment Agency can insist on measures to allow migration as an integral part of the Land Drainage Consent process. Section 23 prohibits the obstruction or altering of flows on a watercourse without consent from the Environment Agency or Internal Drainage Board.

7. United Kingdom Biodiversity Action Plan (UKBAP) & The Natural Environment and Rural Communities (NERC) Act (2006)

The UK Biodiversity Action Plan, published in 1994, was the UK Government's response to signing the Convention on Biological Diversity (CBD) at the 1992 Rio Earth Summit. This convention recognised the need for specific biological targets and plans for the recovery of species and habitats. These targets and plans help drive forward conservation. The UK Biodiversity Steering Group has listed eel as a UK priority species and as such it is included under Section 41 (S41) of the NERC Act which requires the Secretary of State to publish a list of habitats and species which are of principal importance for the conservation of biodiversity in England. The S41 list is used to guide decision-makers such as public bodies, including local and regional authorities and statutory undertakers, in implementing their duty under section 40 of the Act, to have regard to the conservation of biodiversity in England, when carrying out their normal functions.

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Appendix B: Eel Life cycle and behaviour

1. The life cycle of the eel

We have much to learn about the life cycle of the Eupoean eel. However it is believed to breed in the Sargasso Sea, with the leptocephalus larva migrating across the Atlantic before metamorphosing into the glass-eel stage in continental waters (Figure B1). Research by Tesch (1975) found glass eels display a poor homing instinct during migrations, with no home-water 'printing'. All European eel can therefore be considered as a common stock

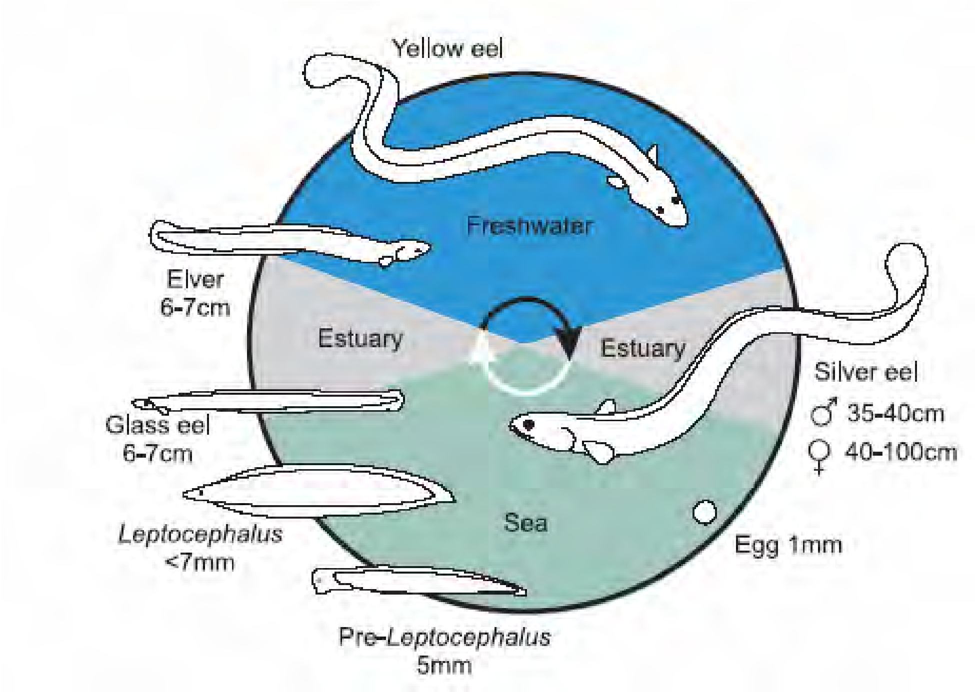

Figure B1: Life cycle of the eel (redrawn from White and Knights, 1994)

Once they are within transitional waters, the glass eels develop into pigmented elvers. At this stage, they may enter freshwaters (Knights, 2005). In estuaries, columns of elvers can often be seen ascending the margins on flood tides during the spring months. Gatherings of elver are commonly seen building up below obstructions such as weirs and sluices (Tesch, 2003). The highest concentrations of elver tend to occur in rivers close to the continental shelf – on the west and south coasts of England and Wales. Other juveniles may remain in transitional waters for a year or more, before travelling up into freshwater.

After the yellow eel growth stage, mature silver eels migrate seawards. In rivers, there can be some migration all year round. However, concerted migrations typically peak in autumn, when they are strongly modulated by the lunar cycle and river discharge.

The lifecycle of the eel has important implications for facilities such as power stations, refineries, chemical works and gasification and desalination plants. These are often located within transitional waters and the lower reaches of freshwater systems, and they abstract large volumes of water for cooling and other processes. There may be a greater density of eels within these zones than further upstream. Their average size (body length) may also be considerably smaller. The design of intake and outfall screens and the required efficiency will therefore depend on the site and be based on an assessment of the particular risks.

2. Elvers and glass eels

The average length of unpigmented elvers entering the freshwater environment is 6.4-8 cm (Naismith and Knights, 1988; Tesch, 2003). Their small body size and weaker swimming ability makes them vulnerable to entrainment. However, surveys of intake screens and entrainment monitoring have produced few reports of large numbers of entangled elvers and glass eels.

This may be partly due to the relatively large mesh sizes used by utilities on most band-cup- and drum-screens. Their mesh is typically 6-10 mm^2 and these mesh sizes would, in theory, allow elvers to pass. However their passage depends on their orientation as they contact the screen. A small proportion are generally retained because they strike the screen broadsides. Others are trapped among weed or other debris. Tesch, (2003) states that glass eel and elvers clearly orientate themselves in response to water movements (a strong, positive, rheotactic response). They swim into the main current. Their entry into intakes may therefore be accidental rather than through attraction to flow. However, the positive rheotaxis may result in an attraction to industrial outfalls, especially during periods of low river discharge. At such times, water at the outfall may have a higher velocity than the main river flow.

It is helpful if we can identify when migration upstream will start. This is when glass eels and elvers are likely to be entrained. Glass eels and elvers require a background temperature of between 9 and 11°C for upstream migration. February appears to be the earliest month for the onset of migration from the English Channel (Gascuel, 1986; Tesch, 2003). Glass eels can often remain within the estuary for at least a year, transforming into elvers before they start to migrate further upstream (Naismith and Knights 1988). Elvers – less than 14 cm long – migrate up the freshwater River Thames from April to October. Most migrate between May and June (Naismith and Knights, 1988). By the end of September, temperatures may start to drop too low for migration to continue (White and Knights, 1997).

Laboratory experiments have indicated that, at water velocities up to 0.38 ms^{-1}, elvers migrate upstream within the boundary layer created at the stream bed. They therefore avoid free stream velocities. If water speeds exceed 0.38 ms^{-1}, elvers move upstream by swimming in bursts in the water column. This requires much more energy, so the elvers then spend time recovering within the substrate. This allows them to pay back the oxygen debt. (Barbin and Krueger, 1994).

Glass eels and elvers naturally move away from light (a negative phototactic response). They therefore gravitate to the bottom of the water column during the day, where they spend much of their time within the substrate. Gascuel (1986) observed glass eels rising in the water column at night. They then remain close to the stream banks, where they risk being caught up in the water intakes that are sited in the middle and lower reaches of estuaries.

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As glass eels transform to elvers, migration occurs at greater depths. Although they use the edge of the midstream current, elvers are no longer found as close to the stream's banks (Tesch, 2003). This behaviour may reduce their risk of entrapment.

River migration is typically nocturnal. Dutil *et al.* (1989) have noted that river entry by the American eel, A. rostrata, mainly occurs between 21:00 and 23:00. Their entrapment is therefore most likely to occur at night.

Lunar cycles have been shown to influence migration activity. Tesch (2003) reported that the greatest activity was recorded during the last quarter of the moon and at new moon. The entrainment rates of elvers are likely to reflect these lunar cycles.

3. Yellow eel

The bodies of yellow eels are more than 10 centimetres long. They are large enough to become impinged at water intakes that use screens.

Yellow eels stop migrating upstream when they find suitable habitat or meet a physical barrier. The observed density of yellow eels therefore falls with distance upstream from the tidal limit (Ibbotson *et al.*, 2002; Chadwick *et al.*, 2007).

Smaller yellow eels prefer shallower habitats, compared with larger individuals (Chadwick *et al.*, 2007). They are therefore more susceptible to entrapment at intakes drawing water from the margins of rivers.

Yellow eels are most likely to become entrapped at night, when they are most active. They seek shelter during the day in burrows and cavities (Tesch, 2003).

4. Silver eel

The metamorphosis from yellow eel to silver eel is not linked to age. It occurs when a critical body size is reached (Vollestad and Jonsson, 1986). Silvering usually occurs between August and December and is associated with a drop in temperature (Van Den Thillart, 2005).

Todd (1981) identified close associations between silver eel migrations and lunar cycles. The greatest activity occurred during the last quarter of the moon and the lowest at full moon. However, other work questions the link with lunar phases. Vollestad and Jonsson (1986) found no correlation between the moon phase and silver eel descent. They suggested that there may only be a link when eels are deprived of other sensory inputs.

During the day, silver eels stay close to the river bed and can be found hidden under rocks and in debris (Sand *et al.*, 2000). While some have observed migrations primarily between sunset and midnight (Brautigam 1961; Volestad and Jonsson 1986; Berg 1987), others have reported eels to migrate both during day and night (Behrmann-Godel & Eckmann, 2003). Entrapment rates may be highest at night because – as for yellow eels – silver eels are more active then. Deep water can delay migration and low temperatures below 5oC can cause it to stop, making it less likely that silver eels will enter intakes at these times. (Vollestad and Jonsson, 1986; DWA 2005).

Silver eels tend to migrate in groups and a higher discharge increases the rate of migration (Behrmann-Godel and Eckmann 2003; DWA 2005). Tesch has also suggested a tendency towards active migration (1994). Tesch tracked eel travelling faster than the flow of the river and found that the migration of silver eels increased markedly when rain increased river flow (Acou *et al.*, 2008).

Within freshwater, silver eels tend to migrate close to the riverbed. However, they can be found at any depth. This makes it more difficult to choose the best depth for siting an intake to avoid entrainment (Haro 2000; DWA 2005). Moreover, silver eels follow the main current and their route selection is related to discharge. This may lower the entrapment risk when river flows are high, but is likely to put silver eels directly at risk of entrapment if they move when river flows are low (Tesch, 1994, Behrmann-Godel and Eckmann, 2003).

5. Eel size, density and sex determination

Eel size is related to their sex and sex is density dependent. If an eel is over 45cm it will, in all likelihood be female. Males will dominate where eel density is high whereas low eel density will tend to result in more females. Density, in turn, appears to be related to distance from the continental shelf and with distance upstream of the tidal limit. The greater the distances the lower the densities. Waters that are closer to the continental shelf, therefore, will generally have greater numbers of smaller male fish while those further away have a lower number of eels but with a greater proportion of larger females. This effect is noticeable in the UK with smaller males dominating the eel population far upstream in south west coast rivers and females dominating east coast eel populations.

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Appendix C: Additional Screening Techniques

Turnpenny and O'Keeffe (2005) describe a number of other positive exclusion fish screening methods are used or being trialled overseas, especially in North America, none of which have so far been introduced into the UK. In some cases this may simply be a matter of the larger scale of North American facilities and waterways but it is likely that we can learn from these techniques and adapt them for UK use. It would be premature to present them as "best practice" at this stage. Some of the material presented here has not been formally reported in publications. A number of the newer ideas were presented at a recent meeting on intake screening technologies organised by the Electric Power Research Institute (EPRI) at the Alden Laboratories in Massachusetts, USA (30 September 2004). Copies of the presentations are available on the Internet by EPRI (epri.com).

Modular inclined screens

The Modular Inclined Screen (MIS) is a new type of fish screen from the USA, designed by the Electric Power Research Institute (EPRI)[17] to suit a variety of different water intakes, fish species and sizes (Amaral *et al.*, 1999).

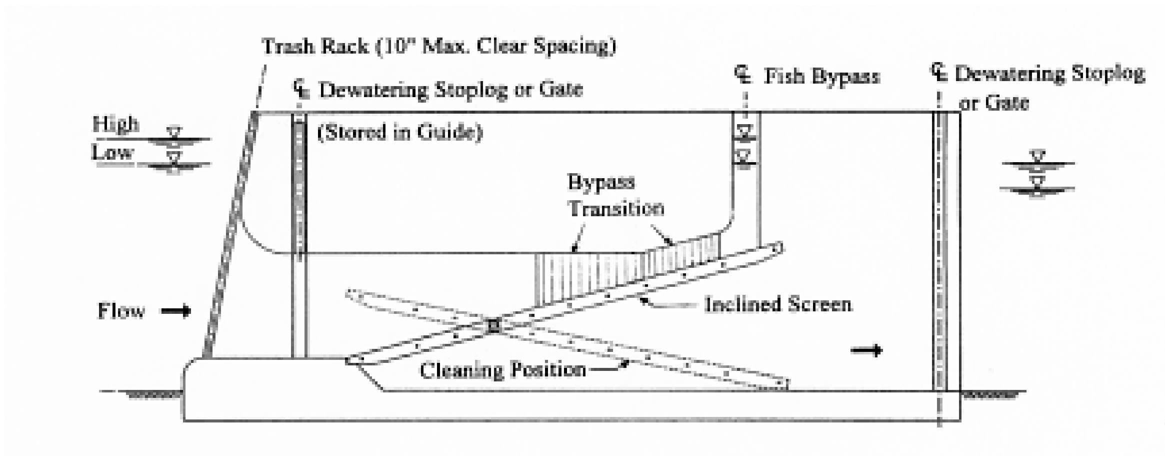

Figure C1 Diagram of a Modular Inclined Screen (www.aldenlab.com/scop-fisheries)[18]

The screen is formed from wedge-wire and is angled at 10-20 (relative to the horizontal) to the flow. The wires are spaced at approximately 1.9 mm to give 50% porosity. The screen is placed on a pivot to aid in rotation for cleaning via backflushing. A bypass system is provided for guiding fish to a diversion channel. A full-scale model of the screen will be approximately 9 m in length and 3 m in width. The system is completely enclosed

[17] Electric Power Research Institute (EPRI), 3412 Hillview Avenue, Palo Alto, California, 94304, USA.

[18] Alden Research Laboratory, 30 Shrewsbury street, Holden, MA 01520-1845, USA.

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and has a capacity of 2.8 m^3s^{-1} at 3 ms^{-1}. It is designed to operate at a velocity of 0.6-3.0 ms^{-1}.

Amaral *et al.* (1999) describe laboratory tests carried out in 1992 and 1993 to determine the efficiency of the system. The fish species evaluated included a variety of salmonid and clupeid species such as coho salmon (Oncorhynchus kisutch) and rainbow trout (Oncorhynchus mykiss). Diversion effectiveness was evaluated for a series of different approach velocities from 0.6 to 3.0 ms^{-1}. The percentage of live fish that were diverted exceeded 96% for all velocities. In particular Atlantic salmon smolts were diverted with a 100% survival rate for all test velocities.

The success of this laboratory investigation led to a prototype being investigated in the field. The prototype was installed at the Green Island Hydroelectric Project, Hudson River, New York in 1995 and 1996. The facility had a trashrack at the entrance of the MIS and a transition wall guiding fish to a bywash entrance. Tests were conducted at velocities of 0.6 to 2.4ms^{-1}. The passage survival and live diversion rates exceeded 95% for many riverine species tested (Amaral *et al.*, 1999).

In principle this would appear to offer a good solution to protecting juvenile fish such as elvers, lampreys and coarse fish at run-of-river hydroelectric projects but large size and high costs relative to flow may in practice limit application to higher head sites, where Coanda screens already have a track-record.

Labyrinth screens

Labyrinth screens are a variation on the flat panel screen or bar rack described in Sections 4.1 & 4.2. In this case, vertical bar racks are arranged in chevron-formations, rather like an array of fyke-nets. The fish are guided into bywashes located at the downstream angle of the 'V'. The bar spacing can be specified as usual, according to the sizes of fish to be excluded.

Meritec[19], source of the following information, recently reviewed the labyrinth screen for possible application at a large water intake on the River Waitiki, New Zealand. The river has the potential for six 90 MW capacity hydropower stations. A form of screen was needed in order to exclude 90% of the river's twenty indigenous and four introduced species from flows of >300 m^3s^{-1}, making this one of the largest fish screening projects in the world. The screen must exclude both adults and juveniles (25-1000 mm in length) of a range of species including salmonids and eels and be in place all year round. In order to avoid any impingement the maximum contact time has been specified at 60 seconds. The proposed screen gap size is 5 mm with bars orientated vertically.

The system is based on the 97-98% efficiency seen at the White River labyrinth screen in the USA. This screen is operated at a similar flow and angle as proposed for this installation and successfully excludes chinook salmon fry (Oncorhynchus tshawytscha) although using a slightly smaller screen gap of 3.1mm.

The proposed system (Figure C2) would consist of wedge-wire screen panels, a collection system and a return system to transport collected fish back to the river. To obtain a low approach velocity the screen would be angled at 8½ to the flow. The labyrinth arrangement confines the screen to a relatively short length of canal making both operation and fish collection easier. A total of 7 labyrinth bays would require 40 m of canal

[19] Meritec Limited, 47 George Street, Newmarket, Po Box 4241, Auckland, New Zealand.

whereas single line vertical screens would require 600 m. A full-height bywash opening and width of 600-900 mm allows fish collection over the full flow depth. Primary screens would consist of bars running perpendicular to the sweeping velocity in order to minimise head loss. An impermeable ramp on the bed angled at 45 ensures accelerating flow into the bywash.

The labyrinth screen concept could be of benefit in the UK at large intakes or where space is at a premium and a compact screening arrangement is required. Low-head hydro would be an obvious application.

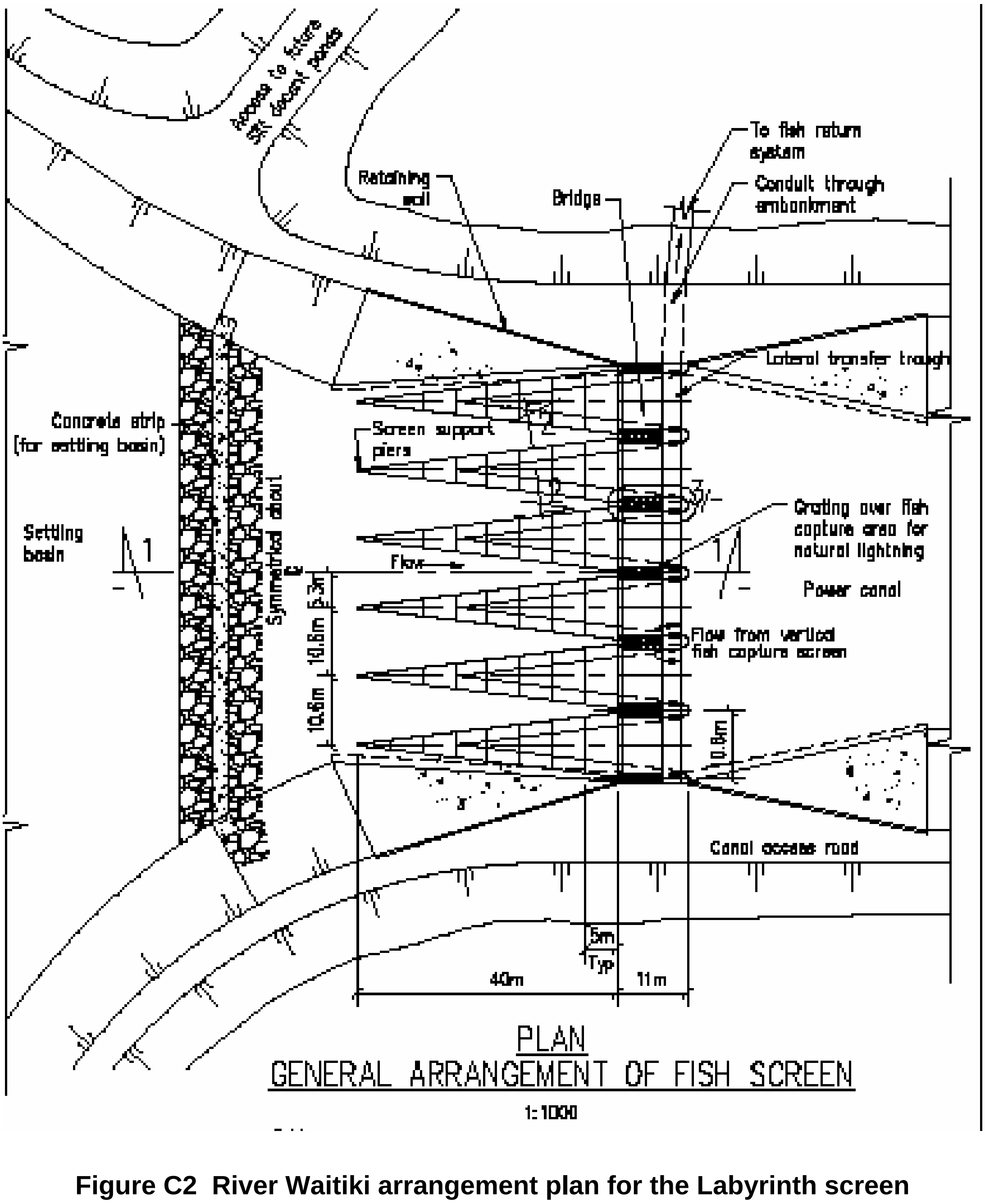

Figure C2 River Waitiki arrangement plan for the Labyrinth screen (www.ecan.govt.nz/consents/project-aqua)

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Appendix D: Health, safety and Environmental Issues Associated with Behavioural Systems

High Intensity Flashing Lights

Health, Safety and Public Nuisance

The operation of high intensity flashing lights (or ‘strobe’ lights) at certain flash rates can cause flicker-sensitive epilepsy and it is important to safeguard against this possibility when installing and operating strobe-light fish deterrent systems. Around one in ten-thousand people are susceptible. Published information and advice on this subject is published principally for use in the entertainment sector, where powerful strobe lights are sometimes used in theatres and discotheques. Guidance (it is not legally enforceable) for these applications exists in 'The Event Safety Guide - A guide to health, safety and welfare at music and similar events', published by the Health and Safety Executive .While not aimed at underwater applications, a number of guidelines relevant can be drawn from the HSE guidance and should be used when planning and operating fish deterrent systems:

- Provide warning signage at access points (e.g. on public right-of-way) on either side of the installation.
- Where possible keep the flash rate at or below 4 Hz (240 fpm): less than 5% of sufferers are susceptible at these rates. Higher flash-rates may be found to be needed for some species/lifestages.
- Where more than one light is used, ensure that the flash rate is synchronised across all lights.
- Where possible, keep lights out of direct line-of-sight of passing members of the public.

For use within buildings, HSE also advise that lighting should be diffused by reflecting off walls and ceilings. In underwater applications, suspended particles within the water body provide a high degree of natural diffusion. Light levels breaking out of the water are also greatly reduced by absorption within the water column and internal reflection off the water surface. Fish deterrent strobe systems should always be installed below water level and should not be suspended above the water surface. Where there is a risk that strobe light units may become exposed to air as a result of water level falling through tidal or other causes, water-level switching should be used to prevent the lights from flashing when out of the water.

Modern LED (light emitting diode) type strobe systems are generally of lower intensity than more traditional xenon-tube strobes and allow the use of a large number of small light sources rather than a small number of high-intensity sources. This allows creation of a more uniform light field across the intake entrance and better control of the light spreading out into the wider environment, thereby reducing risk to the public and other

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wildlife. LED systems are also safer in the event of cable breakages as they operate from low voltages (< 50V) rather than the kilovolt ranges used to drive xenon strobes. LED strobes should therefore be used in preference to xenon strobes for fish deterrent applications.

Adherence to these guidelines should minimise any public nuisance caused by use of strobe lighting.

Minimising Effects on Other Wildlife

Strobe light systems can be used to deter birds and mammals as well as fish and care must be taken to avoid unwanted side-effects ("overspill") on other wildlife, including e.g. migratory fish passing the site.

Recent Didson camera observations at Benacre pumping station indicate that the range of deterrent effect for an LED strobe unit for coarse fish is <5m (S. Lane, pers. comm.). Provided that the strobe light units are mounted directly onto the intake structure, overspill effects on external habitat should therefore be negligible and should reduce the risk of aquatic mammals and diving birds becoming impinged on screens and trash racks.

In some cases it may be necessary to mount strobe units on piles or other structures positioned out in the water body to avoid high water velocities at the intake entrance. More care will need to be taken in such cases to prevent overspill in to external habitats.

Acoustic Deterrents

Health, Safety and Public Nuisance

Underwater sound pressure levels (SPL) required for acoustic fish deterrence are high and consideration should be given to the potential noise level hazard for divers, swimmers or members of the public falling into the water.

Hearing damage (Permanent Threshold Shift – PTS) for transient exposure of humans underwater may occur at SPLs above180 dB re 1µPa (Parvin *et al.*, 1994) and source levels (referenced to 1 m from source) should be kept below this.

Where multiple sound sources (e.g. sound projectors) are used, the acoustic field should be checked to ensure that the combined sound field does not exceed this value at any point >1m distant from the sources. During the planning stages this can be estimated using an acoustic model such as PrISM™, or during commissioning by direct field measurement.

For sound sources deployed underwater, breakout of sound into the atmosphere will not generally be audible against background noise of wind, water movement, traffic, etc. In exceptionally quiet areas close to residences, care should be taken to minimise the amount of metal superstructure projecting above water, as the sound sources may cause noticeable 'ringing'.

Where there is a risk that sound sources may become exposed to air as a result of water level falling through tidal or other causes, water-level switching should be used to prevent the sources from sounding when out of the water.

Minimising Effects on Other Wildlife

Adherence to the above guidelines for human health and safety will also protect aquatic mammals and other wildlife from hearing damage.

Behavioural effects on other species can be minimised by use of acoustic modelling (e.g. PrISM™) to control the acoustic gradient in proximity to the intake. Parvin et. al. (1994) identified the following generic thresholds above the animal's hearing threshold for behavioural reaction in aquatic species:

- Onset of observable avoidance reaction - +50 dB
- Median avoidance reaction - +70 dB
- >90% avoidance reaction - +90 dB.

For general purposes, the +70 dB criterion should be applied to delimit the potential area of avoidance effect, calculated for the most sensitive species being considered.

For Natura 2000 sites, the Agency has used the precautionary +50 dB value as guideline, so that e.g. for an intake on the side of a river channel containing migratory fish, a guideline limit at the mid-width of the channel of +50 dB above the species' hearing threshold should be used.

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Appendix E: Recommendations for further work

Introduction

Our review of screening technologies (Section 4) shows clearly that there are many different approaches to screening and that there has been much innovation in recent years. New techniques have been developed to provide cost-effective solutions for an ever-widening range of circumstances. If a technique developed for a specific application proves successful, it is often tried out in other situations.

It could be argued that every situation is different and that the performance of every new fish screening system should be evaluated at the commissioning stage. In practice, comprehensive scientific testing can be very costly. It makes sense to first answer basic questions on effectiveness using data from soundly designed generic studies. The Environment Agency, as regulator, may then ask for targeted testing to answer some of the site-specific questions. The nature of work appropriate to generic trials and to site-specific commissioning trials is highlighted below.

Solomon (1992) proposed that it would be best to test different types and models of fish screens at a purpose-built facility, for example on a disused mill leat. This approach does not interfere with operation of an existing abstraction, and there are fewer operational constraints on the manipulation of flow conditions. In the case of eels, it will also be necessary to test screens at estuarine/coastal locations, for which water-cooled power stations probably offer the best test locations.

Priorities for generic trials

- A comprehensive review of the impingement/entrainment data from power stations and water undertakings to assess the importance of juvenile (elver and glass eel) losses.
- Detailed assessments of how changing key variables (approach velocity, screen angle and mesh/bar spacing) for mesh or bar screens affects diversion efficiency and injury rates.
- Assessment of the effectiveness of strobe lights at diverting juvenile and adult eels, including optimum flash rates and threshold light levels for deterrence.
- Investigation into the effectiveness of low-frequency acoustic stimuli in diverting juvenile and adult eels. To include signal types and threshold sound levels for deterrence and techniques for generating the required sound signals.
- Evaluation of existing drum and band-screen fish bucket designs for eel handling, future testing of new designs and checking for conflicts with designs for other species.
- Refinement and further evaluation of eel bottom channels including more detailed work on the engineering and hydraulics to improve effectiveness.

Scope of work for generic trials

Review of elver and glass eel losses to entrainment

There is a large quantity of entrainment/impingement data from power stations and other sites. Much of this data is unpublished or appears in 'grey' literature. All of this information needs to be reviewed and put into the context of the Eel Management Plans.

Positive exclusion screens

More information is required to better inform guidance on the relationship between screen angle and mesh size. In particular field trials are required to support data from testing carried out in laboratory flumes. Trials should include:

- observations of eels of a range of sizes;
- testing screen approach velocities from 0.25 to 0.5 ms^{-1};
- testing of screen angles from 15 to 90 degrees;
- testing of mesh sizes/bar spacings over a range, for example from 8 to 30 mm.

Trials for strobe-lights and acoustic deterrents

Behavioural deterrent trials are required, both to develop specifications for the use of strobe lights and acoustic deterrents, and to ensure that such deterrents are as effective as possible.

In the case of infrasound, there appears to be no reliable infrasound generator suitable for uninterrupted long-term use. Further evaluation of acoustic sources will therefore be necessary. However it would first be useful to establish the optimum frequency and intensity criteria across all life stages.

Recent developments in strobe technology, using low-voltage LED-based sources, have greatly improved longevity and reliability. However it will again be necessary to establish the optimum frequency and intensity criteria.

Experiments should ideally be carried out in semi-natural (leat or fish pass) river systems, as this minimises handling and environmental disturbances.

Designs for band drum-screen fish bucket

Most power station cooling systems use band- or drum-screens and all new ones are likely to require fish recovery and return technology. Testing bucket design is a high priority due to the potentially large scale impact on eel populations in saline waters.

Any proper testing of fish buckets will almost certainly need to be done on a full-scale installation. As band and drum screens are different sizes and shapes, they will need to be tested separately. Trials may be at power stations or other potable and industrial sites. However, issues of scale and geometry would need to be considered if testing were carried out at small installations.

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Ideally field trials on both types of screens should be conducted within the same river basin. Potential sites include:

- Barking (band) and Tilbury (drum) on the Thames;
- Marchwood (band) and Fawley (drum) on the River Test/Itchen (Southampton Water).

Tests should concentrate on the larger silver eels (40-80 cm): any system that can handle these will also be suitable for smaller yellow eels. The testing process should be repeated at high and low tidal levels for comparison. The following data should be recorded:

- bucket design;
- eel length;
- time taken from introduction to recovery from launders;
- all visible injuries (photographs);
- any evidence of repeated cycling of eels through the screenwell.

The last item may be difficult to identify using only the above method: further testing may be required.

A design is satisfactory if the testing shows that existing fish recovery buckets successfully remove a high percentage of silver eels at the first attempt – that is without eels falling off and going through the system again. A high percentage would be at least 80%. Where more than 20% of the eels are recycled, it will be necessary to review and modify the fish bucket design. This may involve enlarging the buckets or altering their shape.

Eel bottom channels

Techniques such as the Eel Bottom Gallery™ and other generic bottom guidance channels appear to have some effect. However, there has been little or no scientific testing of these devices. A good hydraulic design is likely to be an important requirement. Consider using wet flume models or numerical Computational Fluid Dynamics modelling techniques before undertaking costly biological trials. Biological testing within a flume may be feasible, but the limited scale of such tests may mean that tests would be better carried out on a larger scale in a small headrace channel – such as Backbarrow in Cumbria – where hydraulics are well controlled and the natural run of silver eels can be used.

Bottom channels may be tested as an independent guidance technique or in association with a bar or mesh screen as proposed in the case of the Eel Bottom Gallery™.

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Appendix F: Screening solutions at pumping stations

Excerpt from Solomon, D.J., 2010. Eel Passage at Tidal Structures and Pumping Stations, Report for Environment Agency, Thames Region.

What are the issues?

The first fundamental issue for pumping stations is the scope for fish passing through the pump impeller to be killed or damaged by physical contact with moving or fixed parts of the machine. In this respect the situation is similar to that of fish passage through low-head turbines, though that situation has been studied in greater depth than passage through pumps. In the case of low-head turbines, effects other than collision, for example pressure change and shear, are not considered to be a risk for robust fish such as adult eels (Solomon 1988 ; Turnpenny *et al.* 1992). It is assumed that this is also the case for low-head pumps, though it would be prudent to investigate this further. Klinge (2006) reports on fish passage observations at a pumping station in the Netherlands where all fish over 10 cm passing through the pumps were killed. This is clearly site-specific and recently further investigations have been conducted in the Netherlands.

A major study has recently been completed by consulting groups ATKB and VisAdvies on behalf of the Dutch government research organisation for water authorities, De Stichting Toegepast Onderzoek Waterbeheer (STOWA). The final report of the study has not yet been published but some general results are presented here taken from a summary report (van Weeren, 2010) with the agreement of STOWA. The study involved making observations on fish passage at 24 pumping stations throughout the Netherlands, covering many types of pump. Nets were used to collect all fish passing through the pumps to determine levels of damage and mortality of different species and sizes of fish.

Overall, 265,470 fish, mostly cyprinids, were recorded passing through the pumping stations during the study; of these, 28,390 (10.7%) were killed, and a further 2576 (1%) were damaged. Larger fish suffered disproportionately, with fish over 15 cm experiencing a 22.9% mortality.

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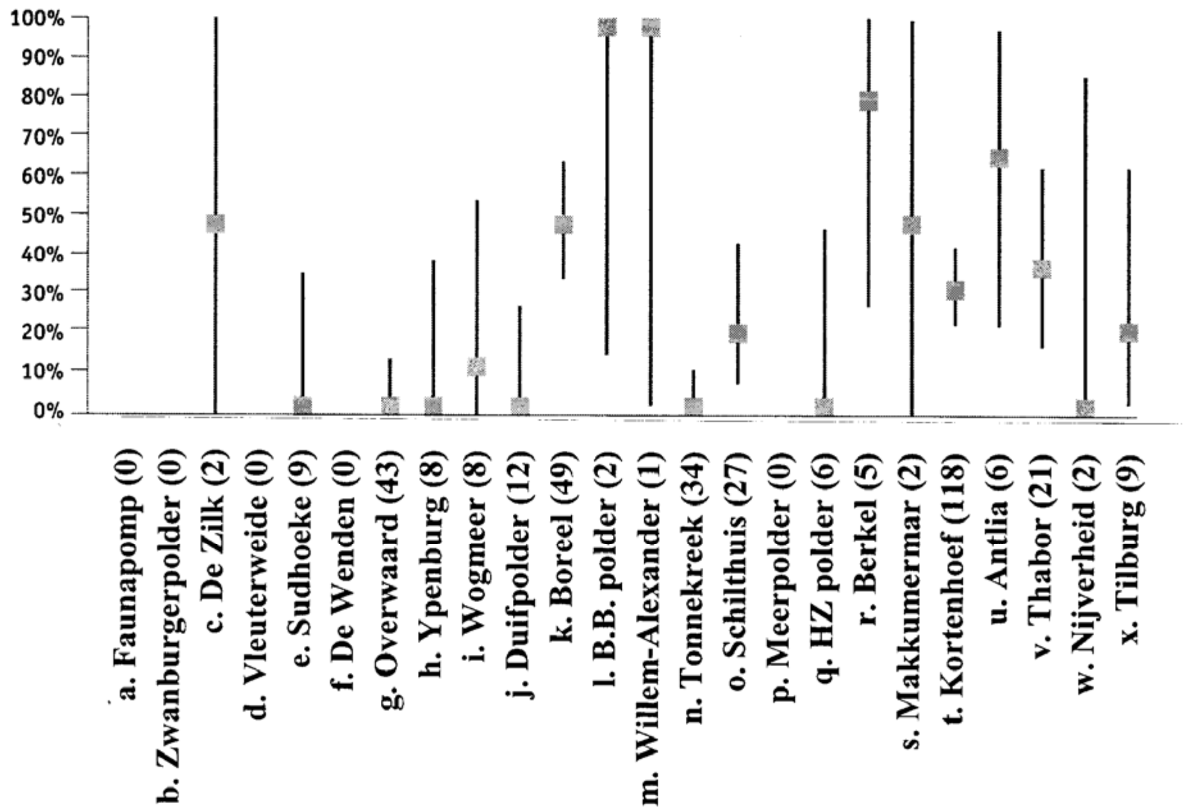

Figure F5.2. Percentage of eels killed at each of the sites in the STOWA study. The total number of eels passed at each site is shown in brackets after the site name; note that no eels were seen at five of the sites. Pump types:- a = airlift; b = shrouded Archimedes screw (see section 5.3.2); c = reverse-flow pump; d = modified Archimedes screw; e, f and g = conventional Archimedes screw; h and i = Hidrostal (See section 5.3.4); j and k = centrifugal pump; l, m, n and o = centrifugal/axial; p, q and r = compact closed axial; s, t and u = closed axial pump; v, w and x = open axial pump.

The results for mortality of eels are shown in Figure F5.2. At most sites the numbers of eels passing during the period were low, and thus the confidence limits on the mortality rate are wide; indeed, at five of the stations, no eels were observed at all. Combining the results for all the stations indicated a mortality rate for eels of about 25%. Although the numbers are small it is clear that the Archimedes screw and its variants are generally eel-friendly (no mortality observed) while the centrifugal, centrifugal/axial and open axial, while of variable performance, are generally less so, averaging around 25%. It is this latter group that have most often been deployed in the UK.

As part of the STOWA study, fish populations upstream of the stations were examined to compare with the fish passing though the pumps. It was noted that the fraction passing through the pumps generally contained a much lower proportion of larger fish (more than 150 mm in length) than the population as a whole, and it was concluded that this was due to avoidance behaviour, with fewer of the small fish being able to resist being drawn into the pumps with the flow.

A separate study with a major eel component has recently been conducted at the IJmuiden pumping station at the seaward end of the North Sea Canal. Many low lying areas pump water into the canal, and IJmuiden station drains the canal to the sea via sluices when levels allow, and by pumps when required. The eight axial flow pumps at IJmuiden are very large (see Figures F5.3 and F5.4), have five blades and rotate at 60 rpm. They have a combined capacity of 260 m^3s^{-1}, making this the largest pumping station in Europe. The fish passage studies were conducted on behalf of the water authority Rijkswaterstaat Noord-Holland, and unpublished results are discussed here with the agreement of their water adviser Marco van Wieringen. As with the STOWA study, the effects of passage through the pumps was investigated by capturing fish in nets set in the outflow.

Figure F5.3. Pump impeller from one of the eight axial-flow pumps at IJmuiden, removed for maintenance.

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Figure F5.4. Impeller housing from one of the pumps at IJmuiden.

During the tests in November and December 2009, 251 silver eels passed through the pump under test, with a length range of 31 to 100 cm. Overall mortality was 40.6%, but this was size dependent, with very low mortality of 30 cm fish, rising to 50 % at 70 cm. However, the overall mortality of eels leaving the canal is less than these figures as only about 25-33% of the total seawards flow passes through the pumps, with the remainder passing by gravity through the sluices and locks. Further, eels appear to tend to avoid passage through the pumps. DIDSON behavioural studies showed that many eels approaching the trash racks (250 mm bar spacing) return upstream, before or after passing through the trash rack, without being drawn through the pumps; the maximum water velocity at the racks of about 0.8 m/sec. Overall, it was calculated that only about 14% of the eels passing seawards from the canal did so through the pumps, compared to the 25-33% of water passing via this route.

During this study 3912 river lampreys, with a mean length around 30 cm, passed through the pumps. Only 14 (0.4%) were killed.

Overall, these Dutch studies indicate that losses of eels passing through land drainage pumps can be considerable, and that a widespread belief that passage through large axial pumps is benign is not justified. On the other hand some types of pump show a much lower level of impact on eels than do others, so there is scope to limit damage and losses through equipment selection.

A second major issue for eel passage has already been alluded to and is ironically almost the opposite of the first, that of fish being discouraged from passing through the pump by virtue of the noise and vibration of the operating machine. For most freshwater species this is not an issue as they have no absolute requirement to pass through to complete their life cycle; indeed, if the station is close to the sea, passage may be a strong disadvantage. Land drainage pumps in some areas are fitted with additional devices, such as strobe lights, to further discourage fish passage. Evidence for avoidance behaviour comes from observations that fish kills are more often observed as pumps start up than when they have been running for some time. However, any eel that declines to make seaward passage through a pumping station is effectively removed from the potential spawning population, unless there is an alternative route for emigration. This clear dichotomy in the interests of different species, with eels requiring seaward passage and freshwater fish being disadvantaged by it, poses a real fishery management challenge.

Figure F5.5. Eels killed during passage through IJmuiden pumping Station. Picture reproduced with permission of Marco van Wieringen, Rijkswaterstaat Noord Holland.

In many situations, e.g. at IJmuiden described above, there are gravity-operated structures draining the area in addition to pumps; the pumps are in theory used only when level difference precludes gravity drainage, or in floods. In this situation, depending upon the location, frequency, timing and duration of gravity drainage, the best solution may be to discourage passage through the pumps. However, in the course of discussions contributing to this study several references were made to alternative gravity drainage installations that were of doubtful value due to lack of maintenance and silting-up; in such situations migration via the pumps is the only option. Further, even when gravity discharge is feasible pumps are often run at the same time, as such “assisted gravity” flow represents a cheaper option in terms of fuel costs than pumping later in the tidal cycle. It was not feasible in this investigation to establish how many of the thousand or so pumping stations in England and Wales fell into these three categories:-

- Those with no alternative route for eels;
- Those with effective gravity drainage in addition to pumps, which represents a viable alternative route for eels;

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- Those with gravity drainage in addition to pumps, which does not represent a viable alternative route for eels, by virtue of being minor and unlikely to be located, lack or maintenance, siltation, or operating protocols.

The implications of these different situations are fundamental to applying the appropriate solution.

Information is available for the Lindsey March IDB and the Isle of Axholme IDB (to the West of the tidal Trent), supplied by Chris Manning of the Lindsey Marsh Board. Of the 48 pumping stations operated by these two boards, 25 have a gravity bypass which at least in theory can drain some of the area when levels allow. However, of these 25, 11 are not currently effective due to siltation or because of current operating protocols or levels managed. It is not known if this situation is typical of other Boards.

The three basic options for dealing with the problem of fish damage passing through pumping stations are:-

- To utilise pump systems that cause less damage (“fish- friendly” pumps);
- To provide and encourage the use of alternative routes; or
- Capture the eels landwards of the pumping station and release them where safe continued seaward passage is available.

These will now be considered in turn.

F5.3 Fish-friendly pumps

F5.3.1 Introduction

For recent developments in “fish friendly” pumps we have to turn to the Netherlands. Of the total area of the country of 41,785 km^2, about 670 km^2 is water, and a further 17,500 km^2 is below high tide level. The Dutch are heavily dependent upon pumping for drainage, and freshwater fish and eels have been a major food crop for thousands of years. It is therefore understandable that they are at the forefront in addressing the problems of fish damage caused by pumping stations.

F5.3.2 Archimedes screw pumps

One of the oldest forms of water-lifting apparatus is the Archimedes screw, and there has been a great resurgence of interest in this technology for both lifting water and deployment for hydro-electric power generation. They are widely used for land drainage in Europe, and in sewage treatment works in the UK and elsewhere. There has always been the belief that such a machine used for either lifting water or for power generation is relatively benign for fish passage (a belief supported by the results of the STOWA study described in Section 5.2), but there have been a number of developments which have attempted to improve the situation further. Kibel, Pike and Coe (2009) were able to reduce the damage caused by collision in an Archimedes screw being used for power generation, by modifying the shape and material of the leading edge, though this is of course a different situation from that associated with pumping.

There are two main areas for potential damage to fish in a conventional Archimedes screw pump. The first is the entrance (downstream end) where collision may occur with the blade leading edges, and where pinching between the blade ends and the trough is most likely. The second is the gap between the edge of the spiral blades and the trough throughout the length of the screw; the runner is supported at each end only, and clearance has to be allowed for some flexion, especially in larger units. This gap varies from a 3-4 mm in a 0.8 m in diameter and 8 m in length, to 10 mm or more in a large unit (say 5 m diameter and 25 m in length). Leakage through this gap affects efficiency, and represents a zone where fish can become trapped and damaged.

Figure F5.6. Archimedes screw runners at the Landustrie factory for refurbishment. These are about 1.8 m diameter, but they have been made up to 5 m in diameter and 25 m in length.

A development with respect to the first problem area has been undertaken by Landustrie Sneek BV, in the form of their "Landy" screw pump. A prototype "fish-friendly" version has been constructed and installed. The modifications are mainly to the lower part of the structure, which the fish experiences as it enters the screw (Figure F5.3).

Sharp edges have been replaced with large radiuses, and the lower part of the screw has a rotating shroud so that the risk of fish being jammed, pinched or squeezed between moving and fixed parts is eliminated in this critical zone. Further, the screw is designed to rotate at full speed only when necessary for pumping flood flows, and for most of the time it operates more slowly, reducing turbulence within the water column. The prototype has been installed in a new canal system where the fish fauna still has to develop, so the fish-friendly claims are so-far untested in the field. Currently the Landy range of pumps have a capacity of up to 11.5 m^3s^{-1}.

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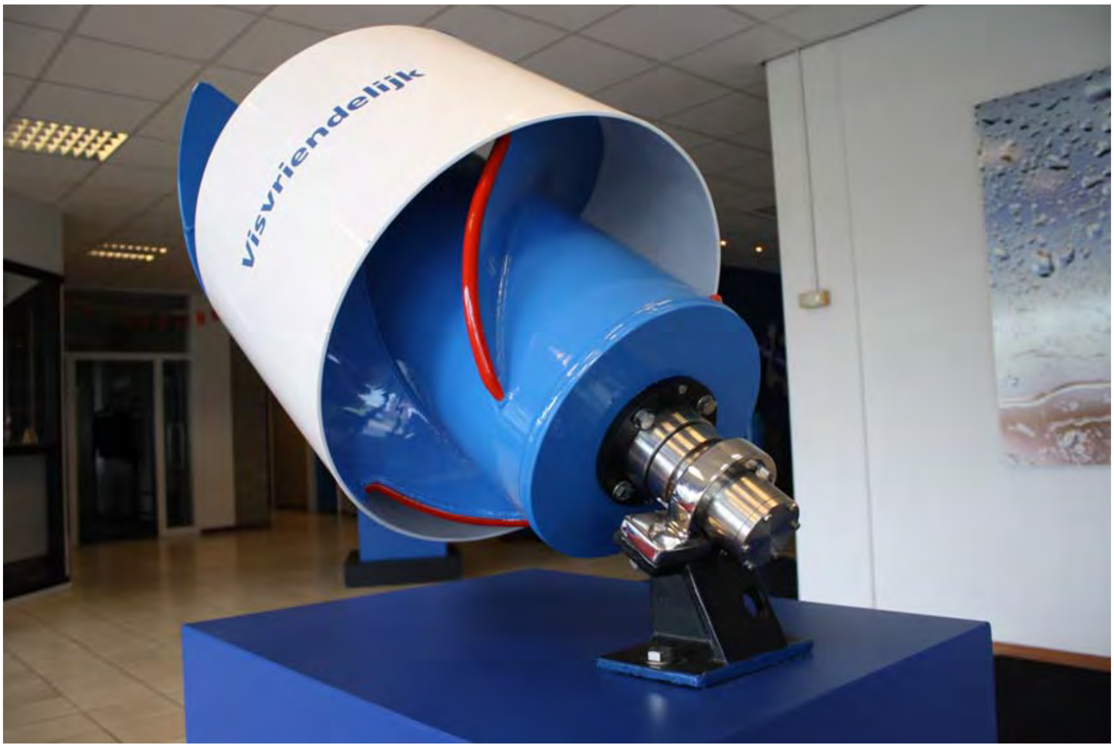

Figure F5.7. Lower end of a "fish-friendly" Landy Archimedes screw pump, showing the specially-designed leading edges (red) and the rotating shroud (the grey structure with the word "visvriendelijk"). Photograph courtesy of Landustrie Sneek BV.

Another Dutch development that increases the fish friendliness of the Archimedes screw has been undertaken by Fish Flow Innovations. This has addressed both the areas for potential fish damage. The blade leading edges have been designed to minimise collision damage (Figure F5.8), and the whole screw is fitted into a tube or shroud that rotates with the screw, eliminating all gaps and all possibility of fish becoming squeezed (Figures F5.9 and F5.10); the manufacturers claim 100% fish survival. The unit is manufactured in a composite material on a steel central axis.

The use of a composite material reduces weight and minimises the maintenance requirement. The shrouding of the screw enables placement on a light steel frame and makes the construction of a supporting trough unnecessary. The units so far built have generally been of limited size (less than 2 m diameter) but there is no reason why they cannot be built as large as conventional designs – up to 5 m diameter. The fact that all the water being pumped is supported within the tube means that the working runner becomes very heavy, but deflection could be managed in a very large unit by having bearings at intermediate points along the tube. The efficiency is high (80-85%) and the system can cope with a wide range of hydraulic heads and flow rates. Operation is very quiet, and the manufacturers claim that fish do not hesitate to enter the pump.

Figure F5.8. Lower end of a Fish Flow Innovations Archimedes screw pump under construction. The shape of the blade leading edge minimises collision risk and damage. The whole screw will be fitted within a rotating tube so that blade-edge gaps are eliminated. The diameter is 1.4 m, and the pumping capacity is 0.26 m^3s^{-1} at 38 rpm over a head of 1.24 m.

Figure F5.9. Top end of an Archimedes Screw pump with a fixed tube or shroud throughout its length. Photograph courtesy of Fish Flow Innovations.

A limitation of the Archimedes screw pump is that it is efficient over only a limited range of tailwater levels. If the level is too low, little or no water is pumped, and if it is too high efficiency drops as the lower part of the runner revolves submerged in water. In fact, the shrouded design is more sensitive still, and the pump will work sub-optimally if the downstream end of the shroud is completely submerged. A way around this is to have the lower end of the pump liftable. This allows the pump to follow changes in the tailwater level so that it is always optimally submerged; this is of course only possible in designs with the runner totally enclosed within a tube.

Figure F5.10. Fish Flow Innovations Archimedes screw pump at a pumping station at Zwanburgerpolder, Netherlands. Photograph courtesy of Fish Flow Innovations.

F5.3.3 Axial flow pumps

Another development from Fish Flow Innovations (jointly with pump manufacturer Nijhuis Pompen) is a design of a fish-friendly axial pump (Figure F5.11). These pumps include both impeller and guide vanes with designs optimised to pass fish undamaged. The manufacturers state that in tests the pump has been demonstrated to pass undamaged 98% of fish; 100% of eels, 100% of coarse fish smaller than 300 mm, and 88% of coarse fish larger than 300 mm. Efficiency is above 80% operating under optimal conditions, and pumped heads of up to 8 m are possible. The pump is very quiet. An 800 mm diameter impeller operating at a head of 2.22 m will pass 4281 m^3/hour (1.19 m^3s^{-1}) with an efficiency of 80.8%. The first permanent installation, with a 1 m diameter runner, will be commissioned shortly at Mijndense Sluis. Significantly larger versions are feasible, and the impeller and guide vanes can be retro-fitted to a range of existing pumps. No price details are available but the manufacturers indicate that the price is similar to that for other custom-built pumps though a little higher than standard off-the-shelf models. This is partly because of the heavier build to reduce noise and increase durability, and the higher initial cost is compensated by lower running costs.

Figure F5.11. "Fish-friendly" impeller for an axial flow pump. Photograph courtesy of Fish Flow Innovations.

Significant advances have been made in the USA with respect to developing "fish-friendly" turbine runners. One development is the Alden/NREC Advanced Turbine runner (Hecker and Cook 2005; Figure F5.12). This has greatly reduced fish mortality by, inter alia, designing-out gaps at the tip and base of the blades which caused fish to be squeezed or pinched, fewer blade leading edges, and a slower rate of revolution and thus collision speed; the consequences of blade collision are minor at relative velocities of 5 m/sec and below (Amaral *et al.* 2008). It is not known to what extent this development could contribute to design of pump impellers.

F5.3.4 Hidrostal pumps

Hidrostal is a Swiss company with a UK subsidiary. They specialise is manufacturing pumps for handling specific products such as foodstuffs and live fish. The specialised pumps that are used to pump fish at fish farms are probably too small to be useful in most land-drainage situations. However, some of their larger pumps have many of the fish-friendly attributes of the specialist fish pumps. They are fitted with a spiral vane impeller with few opportunities for collision and close fitting tolerances which minimise impingement risk (Figure F5.13). The water passageways are large (Figure F5.8). Monitoring large pumps in Sacramento, California, over a 29 day period involved pumping of 20 species of fish with an overall survival of 96.2% - however, this did not include eels. Two Hidrostal pumps were included in the STOWA study (Figure F5.2), but numbers of eels at these two sites were low; only 16 were passed, of which one was killed. The manufacturers suggest that trials would be required to establish suitability for passage of eels. The largest pumps available have a capacity of the order of 2 m^3s^{-1} pumping at a head of 10 m.

Figure F5.12. The helical runner in the Alden/NREC Advanced Turbine. This rotates in a tapered chamber with minimal gap between the outer edge of the blades and the chamber wall.

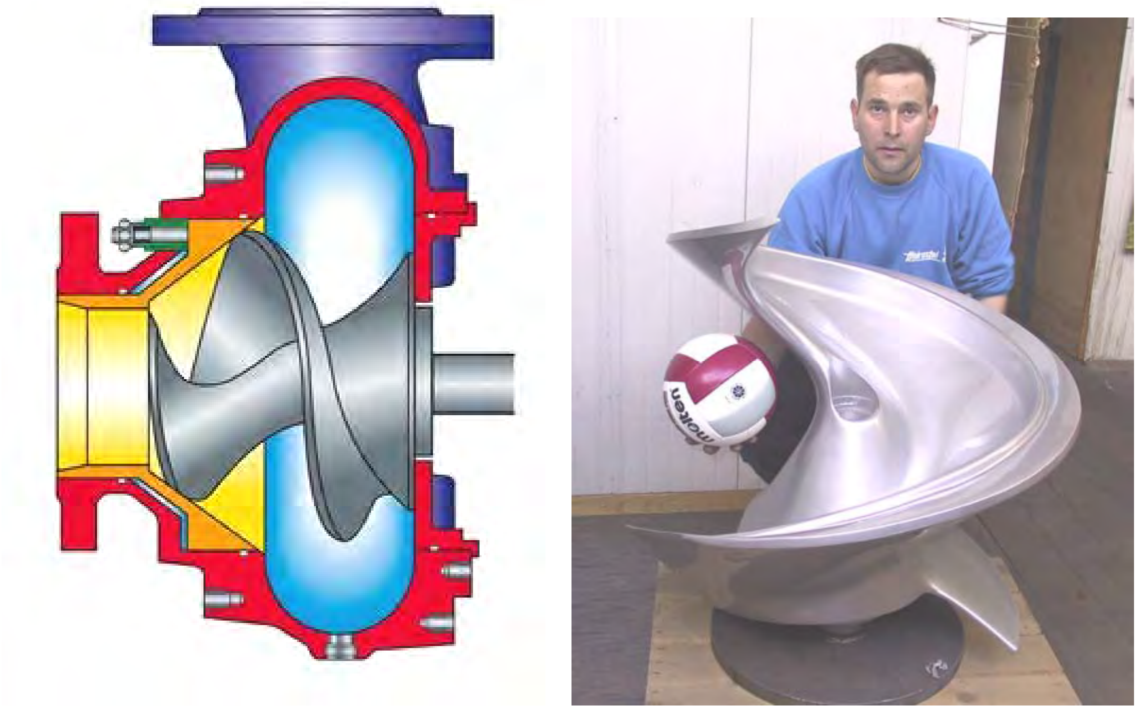

Figure F5.13. (Left) Cross section through a Hidrostal spiral vane pump. (Right) The spiral vane impeller from a large Hidrostal pump, showing the large water spaces.

Another possibility would be to use one of the smaller Hidrostal pumps that are specifically designed for fish, to pump part of the flow, especially if a physical or behavioural screen could be deployed to guide fish away from the main pump and towards the smaller one. Patrick and McKinley (1987) evaluated such a pump for transferring live American eels, length range 270-520 mm. The only injuries were non-fatal abrasions of about 3% of the fish. This style of pumps have a capacity of up to 160 l/sec (0.16 m^3s^{-1}) with a 10 to 20 m head.

F5.4 Alternative routes

F5.4.1 Introduction

The second approach to fish passage at pumps mentioned above is provision of an alternative route. This is inherently difficult in this situation as downstream migrants will be looking to “go with the flow” and are unlikely to use a fish pass in which they are obliged to swim upstream. However, there are some options worthy of consideration.

The extent to which the “alternative route” concept is appropriate will be site specific, and will depend upon the following:-

- Just how potentially damaging for adult eels is passage through the particular pumps installed at the site;
- What is the location and accessibility of alternative gravity outfalls, and how often, how long and under what conditions do they operate;

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- Can passage through the pumps be prevented or discouraged.

As already discussed, many areas that are drained mainly by pumping do have some alternative gravity routes seawards, although there is some doubt in many cases regarding their effectiveness as routes for adult eels.

If the widespread perception of gravity alternatives becoming ineffective due to failure or siltation is true, it is a matter warranting examination. Not only does it represent a potential loss of a safe route for emigrating eels, it also would presumably also lead to increased pumping with both monetary and environmental costs.

As already mentioned, eels and other fish may tend to avoid passage through operating pumps due to the noise and vibration, and it may be possible to reduce entrainment further by use of physical screens or behavioural deterrents (Solomon 1992; Turnpenny and O'Keeffe 2005).

A factor that may complicate this solution is the tendency for eels to emigrate at times of elevated flow, when pumps are likely to be operating at something approaching full capacity. Approach velocities may be high, and diversion mechanisms inefficient. For example, it is difficult to envision effective screening or diversion of eels at the Wiggenhall St Germans Pumping Station (Section 5.1) operating at anything like its full capacity of 100 m^3s^{-1}.

F5.4.2 Fish flow fishway

There are some options for avoiding passage through the impeller of land drainage pumps that do however depend upon pumping. One is what the developer, Fish Flow Innovations, call a "fishway for pumping stations". This uses the venturi effect of a pumped flow to induce flow through bypass channels which rejoin the main flow just downstream (up-hill) of the pump (Figures F5.14 and F5.15).

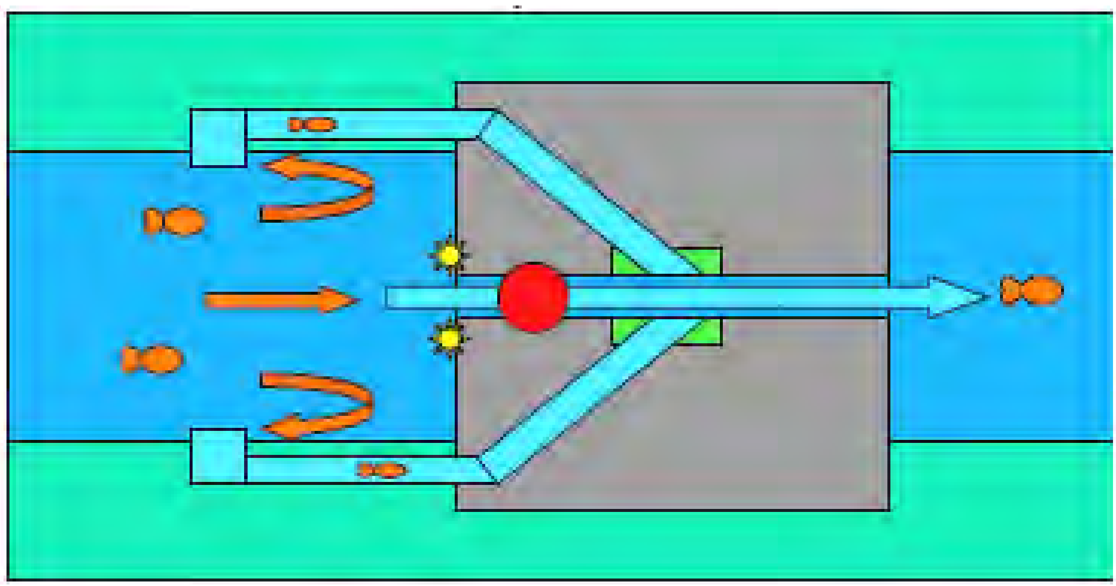

Figure F5.14. "Fishway for pumping stations" developed by Fish Flow Innovations. The red circle is the pump. Fish are discouraged from passing through the pump by strobe lights. Diagram courtesy of Fish Flow Innovations.

Figure F5.15. Part of the structure of the "Fishway for pumping stations". The pumped flow comes along the pipe in the centre of the photograph The flow containing the fish comes up pipes on either side; one can be seen on the left. Photograph courtesy of Fish Flow Innovations.

Fish are discouraged from passing through the pump itself by their inherent avoidance of noise and vibration discussed above, and by strobe lights. Instead they choose the darker and quieter bypass routes. A prototype was installed in 2007 at the Meerweg pumping station on the Oude Aa River near Groningen. In trials, mortality of coarse fish that passed through the pump itself when the bypasses and deflection system were not in operation was about 18%, and for eels about 50%. With both operating, 8272 coarse fish (mortality < 1%) and 150 eels (0% mortality) were passed. Limitations of this system are the relatively low head limit (about 1 m), and the relatively low efficiency (50-60%).

F5.4.3 "Fish Track"

The second "pump-based" alternative route option is another Dutch development, the Tauw "Fish Track". This uses a two-chamber system each of which operates in turn as a fish lock, in a cycled operation (Figure F5.16). In the first part of the cycle water is pumped from the first (left-hand) chamber, through the cylindrical mesh screen, into the second chamber. The water level rises in the second chamber and flows via the tunnel in the end wall into the receiving water. Fish are drawn into the first chamber with the flow, but cannot pass through the screen, so they collect there. After a set time (30 minutes or so?) the first chamber is sealed off from the lower water level, and the water pumped instead through the second chamber and into the first.

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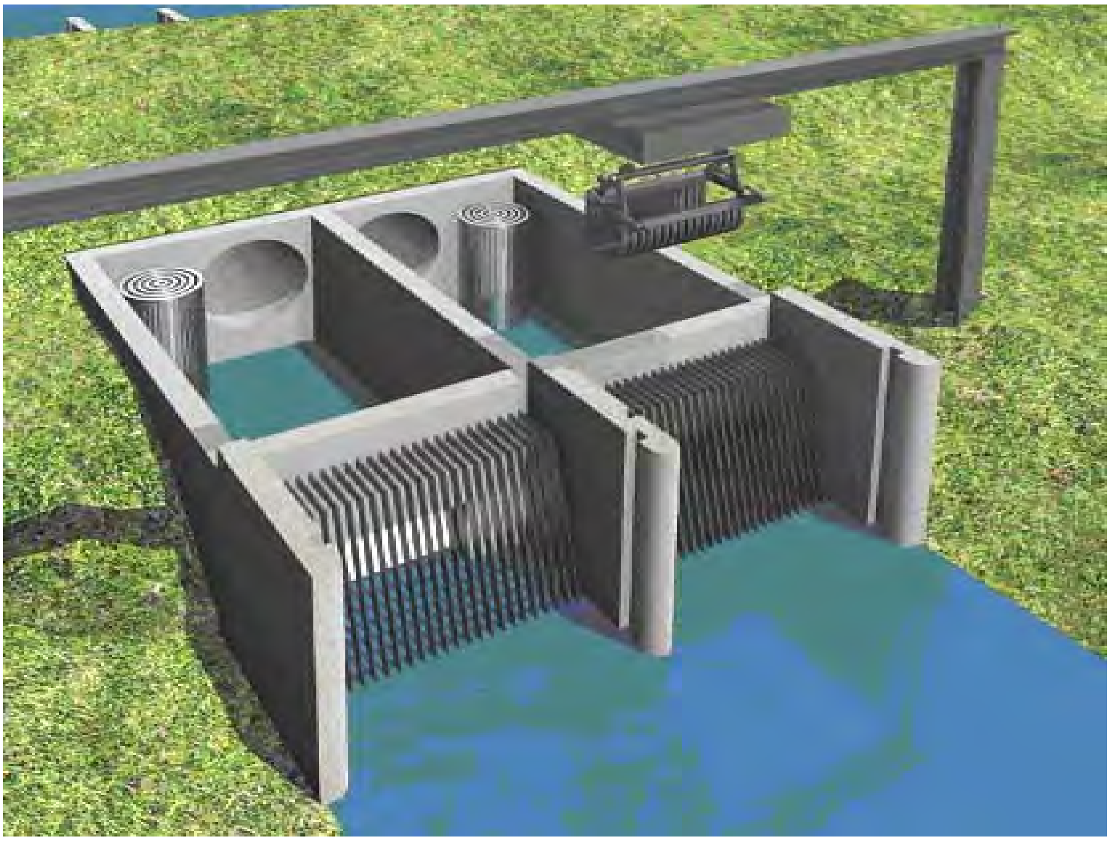

Figure F5.16. Schematic of the Tauw "Fish Flow" system. See text for an explanation of the operation. Diagram reproduced with permission of Tauw BV.

The fish that had collected in the first chamber can now pass to the receiving water with the flow, and fish begin to collect in the second chamber. After another set period the cycle is complete, and starts again. The prototype had two pumps, and a further development may involve a single pump. There are no full-scale operational installations as yet, but installation is currently (June 2010) in progress at the Offerhaus Pumping Station in the Netherlands; the site is expected to be operational in November 2010. A second station, this time a new build, is scheduled for Henswoude with a capacity of 0.5 m^3s^{-1}.

F5.5 Trap and transfer

This is probably not a sustainable long-term option but may be viable as a short-term operation where alternative arrangements are planned for the future. It may also be a useful technique to identify if and where numbers of eels build up during migration.

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