Environment Agency, Thames Region

Eel passage at tidal structures and pumping stations

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Cover picture. Tidal flap at the mouth of Mar Dyke, Essex. Such installations represent a significant impediment to the landward passage of elvers and small eels.

Contents

1 INTRODUCTION

1.1 Background

In England and Wales there are many thousands of hectares of potentially productive freshwater eel habitat in waterways that lie below high tide level of adjacent estuaries and coastal waters. These are drained by tidal flaps, which allow seaward gravity flow at low tide, or by pumping. Both these scenarios represent potential problems for eel migration either into or out of fresh water, and are likely to be limiting the contribution of these areas to production of the species. The aim of this project is to assess the scope of problems for passage of elvers and adult eels, and to identify and promote potential solutions.

1.2 Terms of reference

Initially the project was conceived to cover only tidal gates and flaps. However, during contact negotiations the Agency requested that pumping stations were included in the study. The following Terms of Reference have been modified from the original version that was included in the project specification to reflect this modification:-

- Review the published and grey literature regarding operation of tidal flap gates and pumping stations and the associated issues of fish passage. Include any contacts with scientists or manufacturers outside of the UK where new technology may be developing.

- Gather the experience and views of appropriate Flood Risk Management and Fisheries staff working within Environment Agency Regional and Area offices through face to face meetings or extensive telephone conversations. Identify issues, concerns and misconceptions about the operation of tidal gates and pumps so that FRM and Fisheries are fully aware of the wishes and requirements of the other function.

- Identify situations where some tidal exchange could be achieved and where this would not be considered under any circumstances

- Initiate contact with a number of manufacturers of tidal gate and land-drainage pump technology to identify available products, experience of deployment and potential for innovation that will improve eel passage. If possible, identify the difference in cost of eel passing technologies compared with traditional impassable flap gate and pumping station designs

- Carry out a small number of field observations and measurements of the operation of existing tidal gates and, where available sites with eel passage enabling adaptations.

1.3 Approach

The project was conducted to include the following sources of information:-

- Review of the published and "grey" literature regarding operation of tidal flaps and land drainage pumps, and associated issues of fish passage. There is a fair volume world-wide, including publications from the UK, Europe, North America and Australia.

- Gathering of the experience and views of appropriate Flood and Coastal Risk Management and Fisheries staff within each of the Environment Agency Regions and Internal Drainage Boards. There is a major but uncoordinated fund of knowledge and experience within these organisations, and contacts were established by mail, email, telephone discussions, meetings and site visits.

- Discussions with manufacturers in the UK and Europe regarding what products are available, experience of their deployment, and potential for innovation to improve eel passage success.

- Field observations of the operation of a number of existing installations, including assessment of the passage opportunities.

- Observations on other species. Although eels are the main focus of this investigation, observations with respect to other species will be made where appropriate. In the case of tidal flaps these are likely to include adult salmon , sea trout, bass, mullet and lampreys. In the case of pumps the species are likely to be juvenile lampreys.

1.4 Eel terminology

Several terms are used for the young stages of the European eel, including glass eels, pigmented elvers, elvers and pencil eels. To save repeating the list each time, the term "elvers and small eels" will be used throughout this report; this phrase includes fish in the year of arrival in coastal waters and over the next year or two when they are likely to be migrating landwards past tidal structures.

2 A LITTLE HISTORY

We know that the Romans had land drainage schemes in Britain, and Anon (1954) suggests that they used side-hung tidal doors to allow drainage by gravity and to exclude tidal water. The same source describes side-hung tidal doors in use near Selby before the year 1127. However, the earliest large-scale drainage of marsh land commenced in the 1630's with the draining of the fens. At first the land was drained by gravity, using tidal doors or flaps to keep out the tide and flood water. However, as the land dried out the peat shrank and the ground level fell, and by the end of the 17th century much of the reclaimed land was once again under water. Windmill pumps were introduced to aid drainage. These drove scoop wheels (Figure 2.1), which were paddle wheels mounted in close-fitting brick channels very much like a conventional undershot waterwheel arrangement, running in reverse The maximum lift that was practical was of the order of five feet, and as the land level fell further it was often necessary to have two or more scoop wheels in series to gain the necessary lift. A real breakthrough came in the 1820's with the introduction of steam power; at first driving scoop wheels similar to the wind pumps. The more powerful steam engines could drive larger wheels, the largest being 50' in diameter and weighing 50 tonnes, which would provide a lift of the order of ten feet, but these were soon superseded by centrifugal pumps. The steam engines were gradually replaced with diesel powered centrifugal pumps early in the 20th century, and then electric pumps. Most pumping stations now use axial-flow pumps, effectively a vertical or inclined tunnel up which the water is driven by a fan or propeller, though there are a number of Archimedes screw pumps in operation. The issues for fish well-being are similar to those associated with passage through low-head turbines.

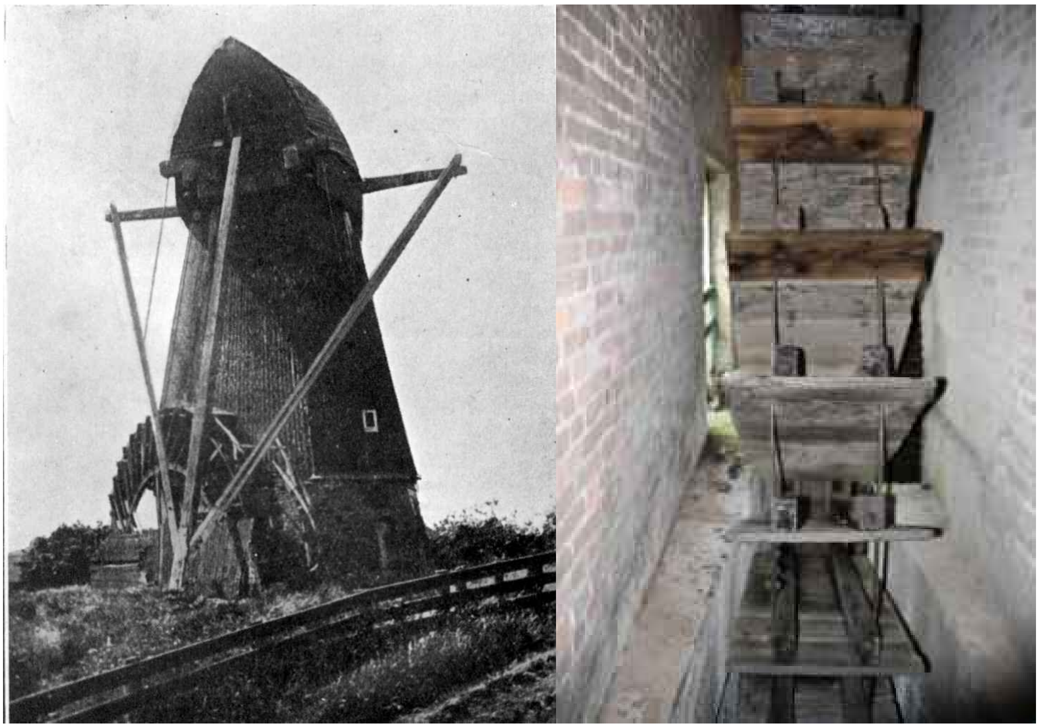

Figure 2.1. Scoop wheels. (Left) A fenland windmill-driven pumping station, operating a scoop wheel; From Farrar (1921). (Right) 22 foot diameter scoop wheel at the Pinchbeck Pumping Station, Lincolnshire. This was driven by a steam beam engine until the station closed in 1952; it is now a museum.

Top-hung tidal flaps and side-hung tidal doors are still in very widespread use, and the principles of design and deployment have been almost unchanged for hundreds of years. The main developments have been in the materials used and the precision of manufacture, and it is these changes that represent the main issues for passage of eels.

3 TIDAL FLAPS AND GATES

3.1 Definitions

There are many terms used to describe structures that allow water to flow seawards by gravity, but not landwards, including tidal flaps, tidal gates, tide gates, flap gates, flap valves and tidal sluices. From here on in this report, "tidal flap" is used to describe a top-hinged flap, and "tidal door" to describe a side-hung flap. "Tidal sluice" is used to describe a structure where gates are lifted or lowered according to the relative levels of water on each side, under either manual or automatic control. There are of course situations where these structures are located away from tidal influence, and they are used to isolate the area to be drained from high river levels in the channel to which they drain. The issues for eel passage are similar to those in tidal water.

"Level equalisation" refers to the water levels each side of the tidal flap or other device being the same, so that there is no tendency for water to flow in either direction. With tidal flaps it is for short periods around equalisation that the only scope for small eel passage may arise, and this window of opportunity may last for minutes only. Typically, level equalisation will occur twice in each 12-hour tidal cycle, once on the ebbing tide, and once on the flood.

In this section we are considering installations where the intention has been to exclude or minimise any inflow from the tidal side, and the remedies considered aim to continue to maximise the level of exclusion while allowing landward passage of elvers and small eels. In some situations consideration is being given to allowing some significant level of tidal intrusion to re-establish the drained area as intertidal or saltmarsh. This would of course allow free access for eels and other species. Approaches to this are considered in Section 4.

3.2 Description of construction and operation of tidal flaps and tidal doors

Tidal flaps are designed to allow run-off to flow seawards when the landward water level is higher than the tide level, but to prevent landward flow of tidal water. Their deployment has allowed development of large areas of very productive farm land from areas that were previously flooded by the tide, or were at least poorly drained. Significant areas of England and Wales lie below the high tide level, and are drained through tidal flaps, tidal doors, tidal sluices or by pumping. Tidal flaps may range from a matter of tens of centimetres to several metres in width and depth, and are generally rectangular or circular in shape (Figure 3.1). Being top-hinged they tend close under their own weight, and the seating face may be sloped back towards the top to encourage positive seating. For hundreds of years tidal flaps were made of wood, with larger installations reinforced with iron straps. From Victorian times onwards cast iron was commonly used for small and medium sized gates, and is still a much-used material. Increasingly however a wider range of materials are being used including cast or pressed stainless steel, cast aluminium, rubber, HDPE, co-plastix and other plastic materials. Many flaps are fabricated rather than cast, especially where non-standard sizes or designs are required.

The size of the flap, or more precisely the dimensions of the culvert that the flap controls, is determined by the highest flow that it is considered necessary to convey.

This may be equivalent to the flood flow of the system following heavy rain, or it may be greater than this where it is considered necessary to cater for draining of a flood caused by overtopping of the barrier by storms or exceptional tides (Thorn, 1959). This generally means that for the great majority of the time the flap is only carrying a very small fraction of its maximum capacity, and the flap is only just "cracked" open even at low tide.

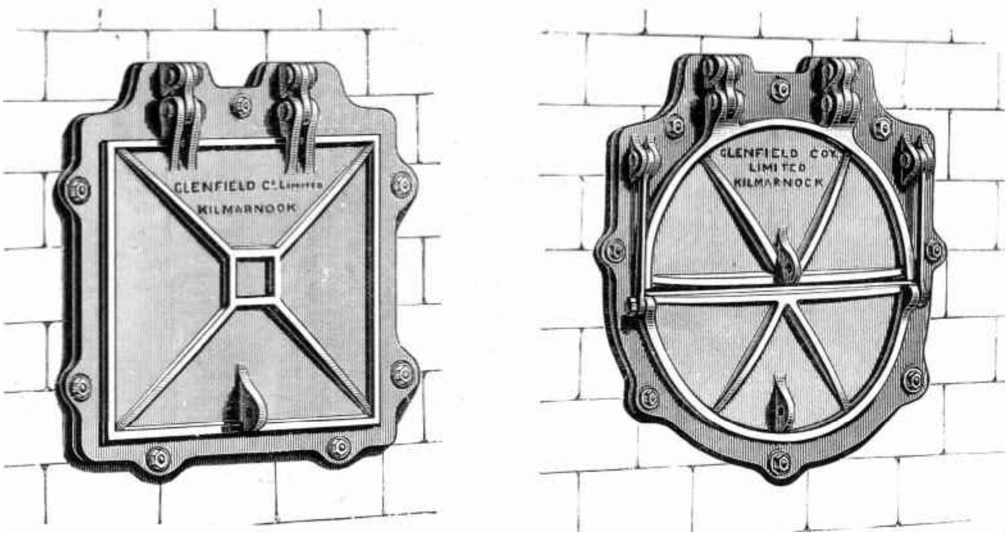

Figure 3.1. Drawings of cast-iron tidal flaps from a 1910 catalogue from Glenfield and Kennedy of Kilmarnock. Note the double-hinge link arrangement that allows self-seating of the flap, the lifting eyes, and the split-flap arrangement of the circular flap.

Figure 3.2. A large wooden flap being removed from a structure incorporated into a road bridge over the Chinook River at Ilwaco, Washington State, USA. Photograph courtesy of Jeff Juel, Juel Tide Gates, Seattle.

Fabricated wooden flaps and frames were generally imperfect in their sealing capability, allowing some landward flow when outside water levels were higher than those landwards of the structure. Thorn (1959) described the construction of large wooden flaps:-

"On the larger outfalls they usually comprise an outer skin of vertical timber, felt, and an inner skin of horizontal timber, the whole strengthened by mild steel angle or channel bracing with steel suspensions".

A large wooden flap is shown in Figure 3.2, being removed from a site in Washington State, USA. It is clear that in this condition the seal would have been far from perfect, even though the gate was still effective at minimising back-flow when closed.

Cast iron flaps and surrounds had better seating properties, but still often represented an imperfect seal. The latest generation of flaps have ground seating faces and neoprene seals, and when closed are effectively waterproof .

Tidal doors, often referred-to as pointing doors, tend to be larger than tidal flaps, and are generally of wooden construction, looking very like lock gates. However, there has been a recent trend to side-hung smaller gates, and in some cases top hung flaps have been converted to side-hung gates (see Figures 3.7 and 3.17). Gates tend to remain in the position to which they were last pushed by the flow, and may remain open until beyond level equalisation (Figure 3.3). This may result in the gates slamming shut once the tide really starts to flow landwards. They may also tend to swing with wave action when there is little flow in either direction, so are often limited to more sheltered sites.

Figure 3.3. Tidal doors on the estuary of the Lymington River in Hampshire, in an open position. The tide has started to flood, and there was noticeable landward flow (towards the right of the picture) through the structure when this picture was taken. A few minutes later as the landward flow increased, the doors slammed shut.

As part of this study, the situation over a low tide period at Lymington Causeway (location of the tidal doors shown in Figure 3.3) was investigated. In addition to the tidal doors there are three counterweighted tidal flaps, shown in Figures 3.12 and 3.13. On this tidal cycle, which may be considered typical, the tidal doors remained open for about 26 minutes after level equalisation on the flood tide, when a seaward head difference of 80 mm closed the gates Figure 3.4). This period represents a major opportunity for landward passage of small eels.

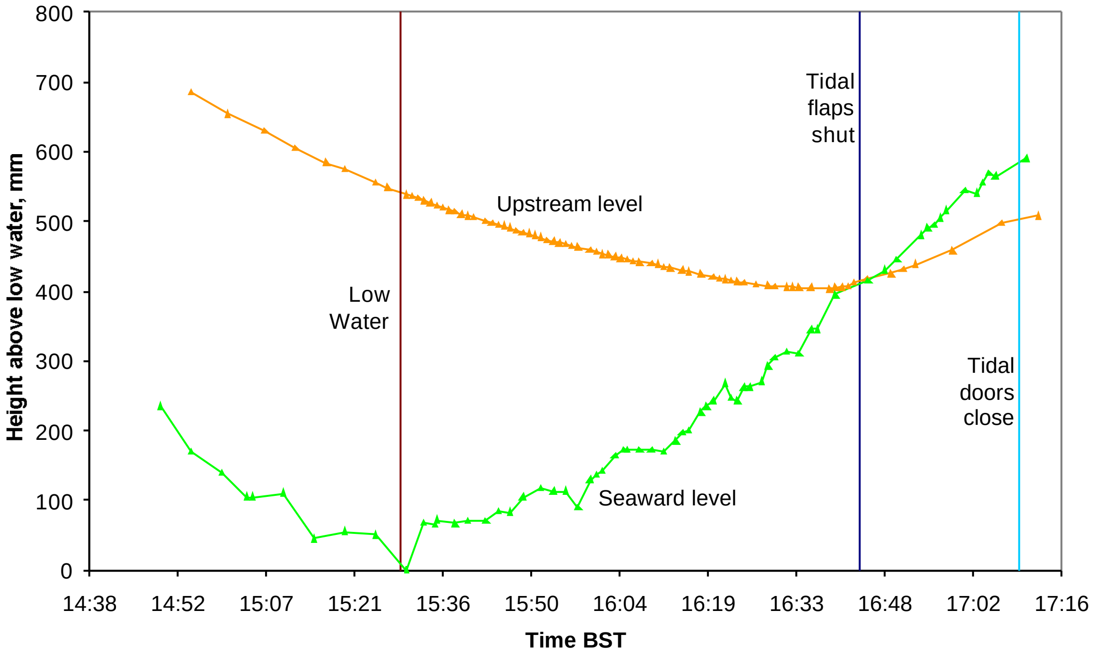

Figure 3.4. Water levels and tidal flap and door operation at Lymington Causeway, April 11 2010.

3.3 What are the issues?

Tidal flaps represent obstructions to free movement of fish and other biota. Small eels migrating landwards are particularly vulnerable because of their limited swimming ability. Information on elver swimming ability was reviewed by Solomon and Beach (2004a). Burst speed (a speed that can typically be maintained for 20 seconds) of an 80 mm elver is generally of the order 0.5 m/sec, varying with temperature and between individuals. The theoretical relationship between hydraulic head and velocity of water passing through an orifice is shown in Figure 3.5; this suggests that head difference of only 12.7 mm will generate a velocity of 0.5 m/sec. In fact the velocity through a narrow gap will be less than this due to edge effects, but this indicates that very small head differences will generate velocities that will be impossible for elvers to overcome. These figures are in close agreement with the conclusions of Wood and Blennerhassett (undated), who concluded that heads in excess of 15-20 mm will defeat elvers.

As already described, the commonest form of tidal flap is a circular or square top-hung gate which closes under its own weight, and is held open by the seaward flow when the landward level exceeds the seaward. The seating face is often sloped to aid self-closing. This means that the door closes while there is still a positive head on the landward side, and as the gate closes the flow around the gate is still of fairly high velocity, and beyond the swimming ability of a small eel. The situation is further complicated by the route that water takes during low freshwater flows. Tidal flap apparatus has of course to be installed of a size to pass the highest flow that is likely to occur. This means that, for the great majority of the time, it is handling only a very small fraction of its maximum design flow. This is particularly true during the period of landward migration of small eels, typically April to September. This means that the flap is only open to a minor extent, with the flow "squirting" sideways through a small gap (Figure 3.6). This is in fact a worse situation for larger fish of all species than it is for small eels.

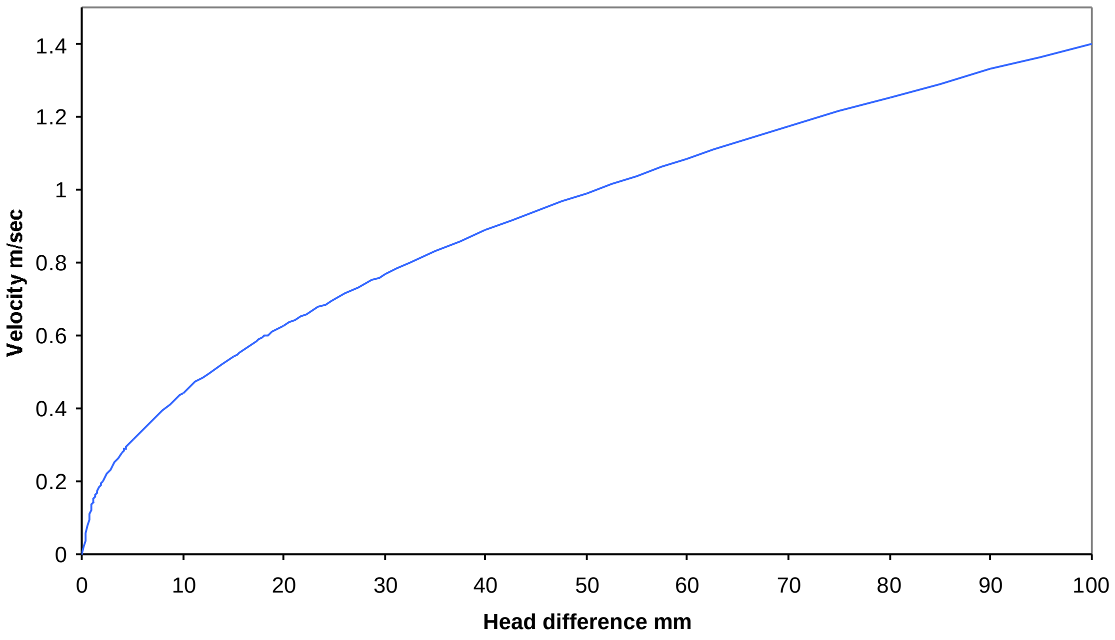

Figure 3.5. Theoretical relationship between head difference and velocity of flow through an orifice, based on the standard formula $v = (2gh)^{0.5}$, where v is velocity, g is the acceleration due to gravity, and h is the head difference.

Figure 3.6. Water squirting through the gap of an almost-closed rectangular tidal flap at the mouth of a marsh drainage channel on the Thames Estuary. Even when the tide rises to the bottom of the door, this flow is too fast for elvers to overcome. As the tide rises past the bottom of the door and the velocity starts to fall, the gate shuts.

A complicating factor is the increasing tendency to install a structure with two tidal flaps in series (Figure 3.7), especially where industrial or residential property is at risk if a single control device failed. This rules out the possibility of occasional landward flow and passage of elvers which might be expected with a stick or plastic bottle holding a single flap slightly ajar for a tide or two (Figure 3.8).

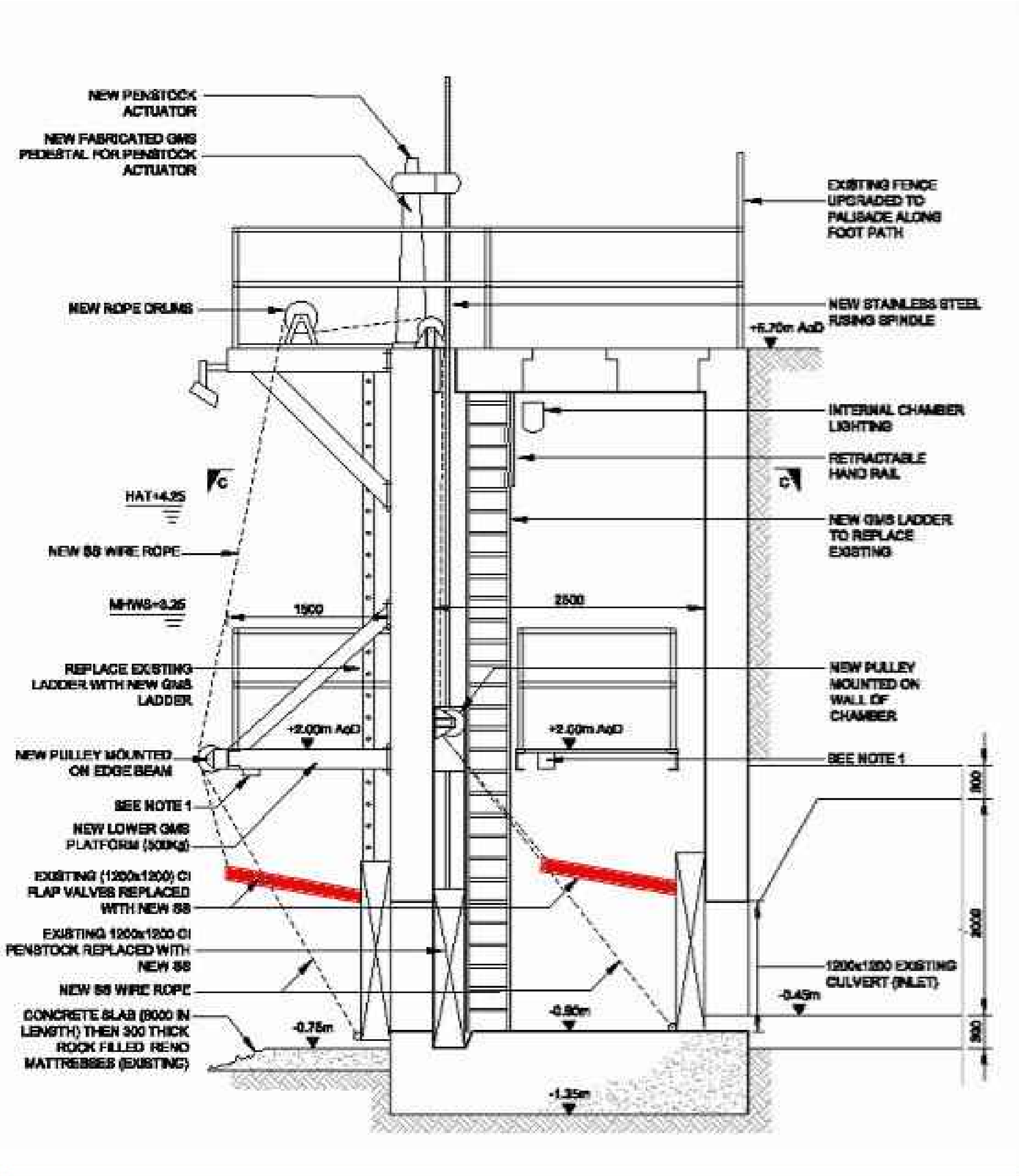

Figure 3.7. Section through the tidal control structure at the outlet of a marsh drainage system into Barking Creek in Essex. There are two 1200 mm square-section cast-iron flaps in series (highlit in red, held wide open), with a penstock between.

Although it appears that tidal flaps are a major impediment to the landward movement of elvers and small eels there are few observations of a complete lack of eels within areas protected by tidal gates. Elvers are remarkably adept at exploiting small leakage flows and occasional failures of defences such as debris holding a flap slightly open for a tide or two. However, the presence of some eels within an area should not be interpreted as indicating that there is no problem – they may have arisen from a short window of opportunity that may occur only once every several years. Further, the author has learned of many unauthorised and otherwise unrecorded or poorly recorded instances of restocking with elvers. Bailey (1992) records an eel fisherman regularly stocking marshland waters in Norfolk, and similar activities are known to have taken place in several areas of South West, Southern and Thames Regions over the past twenty years. The presence of eels in many waters may be due to, or enhanced by, such activities. Further, as already discussed, tidal flaps in the past have represented imperfect seals which are likely to have allowed regular passage, whereas modern designs may effectively be fish proof. The ideal situation is that that elvers and young eels have some opportunity of landward passage for at least a short time on each tide; the rest is up to them.

Figure 3.8. The outer flap in the structure shown in Figure 3.4. Note that the flap is being prevented from complete closure by two plastic bottles jammed in the gap, one on each side. While this serendipitous situation would allow some landward flow and passage of elvers were this a single flap, the presence of a second flap a couple of metres behind this one, prevents this.

Tidal doors are generally considered benign for eel and elver passage, and indeed for other species of fish. Their tendency to remain fairly wide open throughout the ebb tide and ensuing slack water allows landward passage of strong swimmers, such as salmon and sea trout, throughout the ebb tide. It also allows a significant period of access for weak swimmers such as small eels and elvers towards the end of the ebb, over slack water, and for a short time on the flood until the doors close, as described above for the installation at Lymington Causeway. Firth (undated) examined the fish access situation at 59 tidal structures on waterways draining to the Humber Estuary between Spurn Head, and Boothferry Bridge on the Ouse and Keadby on the Trent. He concluded that in most situations, tidal doors were of minimal impact on fish movement, in contrast to tidal flaps.

3.4 The extent of the issues in England and Wales

Attempts were made to ascertain the numbers of various types of tidal control structures in England and Wales, and the extent of the potential eel habitat that is affected. A approach was made to the Asset Management Section of the Environment Agency requesting information on the following:-

1) The number of tidal flaps in each Agency Region or Area.
2) The number of land drainage pumping stations in each area.
3) The area of land drained by each of these approaches in each area.
4) If possible, an idea of the length of water channels and water surface area drained by each of these approaches in each area.

Much of this information was not available, although some information on the number of pumping stations in each region was received – this is presented in Section 5. It is understood that the Environment Agency is currently developing a database containing much of this information to support System Asset Management Plans (SAMPs). This will be very valuable for future assessments.

Similar information was requested from Internal Drainage Boards. Many boards made helpful responses but again no clear national picture of the numbers of tidal flaps and doors, and the area drained in this way, was forthcoming. As for the Environment Agency a much clearer picture of the situation for pumping stations has emerged and is discussed in Section 5.

From the responses that were received it is clear that there are thousands of tidal flap and tidal gate installations in England and Wales.

3.5 Options for fish passage at tidal flaps

3.5.1 Replace with tidal doors

As discussed in Section 3.3, side-hung tidal doors overcome many of the problems for passage of elvers and small eels. They would not appear to have any inherent disadvantages compared to tidal flaps so this simple alternative is recommended wherever it is viable, especially when work is being done for other reasons. If major refurbishment is being undertaken anyway the additional cost of conversion to doors is likely to be minimal.

Figure 3.9. Side hinged gates being fitted to replace top-hung flaps at Schneider Creek, Washington State, USA. The issue here was passage of coho salmon. The right-hand gate is fitted with a Muted Tidal Regulator (see Section 4.4). Photograph courtesy of Tom Slocum, Washington Conservation Districts NW Region Engineering Program.

3.5.2 Pegging of flaps

The "unofficial" practice of pegging of flaps, to cause them to remain slightly open throughout the tidal cycle, was once fairly widespread on the Essex marshes (Information from John Claydon, recently retired from ASM team, EA Kelvedon Office). The practice involved placing a small piece of wood to hold the door ajar (Figure 3.10). This was done to allow some landward flow to keep the field ditches wetted in dry weather – they often acted as stock fences between adjacent fields. When major rainfall caused the flap to open further, the piece of wood would be released and washed away.

There may be scope to use this practice, subject to appropriate agreement, as an approach to improving elver passage during the relevant months of the year. However, caution must be exercised as pegging on one side of the flap, as opposed to at the bottom or in a balanced manner on each side, may cause damage to the gate structure especially where the head on the tidal side of the flap is considerable.

Another potential undesirable side-effect of pegging and indeed several of the other of the options being considered here is that of siltation. In many cases the tidal water outside the flap may be turbid with a high silt load. Allowing some tidal intrusion could result in silt carried landwards being deposited in the quieter flow regime there.

Figure 3.10. A pegged tidal flap ; note the piece of wood at the 3 o'clock position holding the flap ajar.

3.5.3 Lightweight flaps

The lighter the material from which the flap is manufactured, the further it will open, and the longer it will remain partially open towards level equalisation; this might provide a few minutes of access for elvers on each tide which would otherwise be denied. Aquatic Control Engineering (ACE) supply a range in HDPE, with stainless steel reinforcement which are much lighter than their cast iron equivalents (Figure 3.11). Bates (1992) compared the extent of opening of two 1.2 m diameter flaps, one made of cast iron and one of aluminium. With a head differential of 300 mm the aluminium gate had a maximum opening of about 750 mm, compared to 150 mm for the cast ion one. Perhaps the greatest scope for lightweight flaps to aid in eel passage is in their potential for the cat-flap approach (Section 3.5.6).

3.5.4 Counter-weighted flaps

Counter-weighting of flaps, as in Figures 3.12 and 3.13 (Lymington Causeway), effectively reduces the tendency to close compared to the same door without the weights. Thus for any given flow of water the gate is likely to open further, and remain open longer. The performance of the Lymington gates in this respect is shown in Figure 3.4, where it can be seen that the flaps remained slightly open right up until level equalisation. With appropriate adjustment of the size and position of the weights it would be possible to arrange for the gate to be slightly open under neutral conditions – see Section 3.5.5 below.

Figure 3.11. A range of lightweight HDPE tidal flaps, supplied by Aquatic Control Equipment (ACE) Ltd. Photograph courtesy of ACE.

Figure 3.12. Counter-weighted tidal flaps on the Lymington River, Hampshire. These tend to open further and remain open longer than conventional flaps of similar weight.

Figure 3.13. The counter-weighted flaps on the Lymington River, fully open during a spate. The flow of water in the middle distance is from the tidal gates shown in Figure 3.2.

3.5.5 Naturally-open flaps

Most tidal flaps are naturally closed under neutral conditions, by virtue of their own weight, and in some cases a backward slope to the sealing face. However, there are ways in which the gate can adopt a naturally open position under neutral conditions, closing only when a seaward head builds up and/or there is significant landwards flow. One approach is to slope the sealing face with a forward slope, such that the gate hanging in a vertical position is slightly open. Any significant flow landwards will cause the gate to close. A simpler approach that does not require any significant modification to the installation is to use a chain or cable rigged to an eye on the flap, and supported some way in front of the flap (Figure 3.14). The weight of the chain, or weight attached to the cable, can be adjusted until the gate is just held open under neutral conditions by a catenary action; again, any significant landward flow would shut the gate. This option is probably only realistic where the structure readily allows the cable to be held well in front of the gate, for example where the flap lies within a channel as in Figure 3.14.

Figure 3.14. Two metre square section tidal flap at Havering, Essex, draining an area of Havering Marshes to the Thames Estuary. Although this was not the intention, the weight of the chain and cable effectively reduces the closing weight of the door, delaying closure. Additional weight would hold the flap open beyond level equalisation on the rising tide.

3.5.6 Cat flap

The principle of a built-in "cat flap" has been much explored as an approach to allowing flow of some water through a larger flap. The idea is that the smaller flap is light and the flow of water, which is very much less than the capacity of the "parent" gate, holds the smaller flap open much wider, and for a longer period, than the large gate. Depending on the size of the cat flap it can be made of very lightweight material. There is also the scope to have a mechanism to hold the cat flap open for much longer than it would stay open naturally; rather like an SRT which delays closure of the whole of a large flap (Section 4), but the mechanism can be very much lighter and cheaper. The consequences of failure are also very much reduced compared to a mis-hap that causes the main gate to remain open when it should be closed.

A float-operated cat flap has been installed in a massive tidal flap on the River Gilpin in Cumbria. The gate was manufactured by Aquatic Control Engineering and was installed in 2009; some details are shown in Figure 3.16. The cat flap is relatively large (1000 mm wide and 400 mm tall) and is designed for passage of sea trout. It is top-hinged and is held open by a sliding float arrangement. The float is fitted with a pipe which allows it to fill with water. When the tide rises to the top of this pipe, water flows down a pipe into the float, causing it to fall, allowing the cat flap to close.

The float drains on the next low tide, commencing the cycle once more. It is understood that a decision has recently been taken that the flap should be allowed to remain open at all times, and the float-closure mechanism has been over-ridden.

Figure 3.15. Tidal flap at Maydays Farm, Essex. This is an interesting installation as the flap is separately hinged in two halves, and the lower half is fitted with a small "cat-flap", presumably designed to operate at very low flows. However, in this case the construction of the cat flap is too heavy (cast iron) to really be a useful contribution to elver passage.

Figure 3.16. Details of the cat-flap fish pass on the tidal flap on the River Gilpin, Northwest Region. Reproduced with permission of ACE.

The scope for using a bottom-hinged cat flap, which is naturally open until lifted by a float, has been explored in the USA and more recently in the UK; it appears to have been originally proposed for fish passage by Charland (1998), though many of the recent designs are remarkably similar to a 1976 US Patent for a self-regulating tidal gate (see Section 4.1). According to Jeff Juel of Juel Tide Gates the few installations that were made in the USA subsequently failed and were removed, but no details of the problems are available. A design of similar concept has recently (May 2010) been installed in the tide gate on the river Stiffkey in Norfolk, to allow access for sea trout. Details are shown in Figures 3.17 and 3.18. The device was designed, constructed and installed by Sandy Cowie, Anglian Region, Environment Agency. It's performance, and the salinity landwards of the installation, are being monitored.

Aquatic Control Engineering have recently developed a number of models of bottom-hinged cat flaps for elver passage (Figures 3.19 and 3.20). Several have been or are being supplied to the Environment Agency and UK Rivers Trusts. Cost of supply of such a cat flap, and additional cost of inclusion within an appropriate parent gate during manufacture, is of the order of £1,000.

Figure 3.17. Bottom-hinged cat flap in tidal flap on the River Stiffkey in an open position. The timing of closure can be adjusted by altering the position of the float. Photograph with permission of Ros Wright, Environment Agency.

Fig 3.18. Bottom-hinged cat flap in tidal flap on the River Stiffkey in an open position, with the float being lifted by the tide. As the tide rises further, the flap will close. The dimensions of the opening are 600 x 300 mm. Photograph with permission of Ros Wright, Environment Agency.

Figure 3.19. An ACE HDPE tidal flap fitted with a 300 mm internal diameter cat flap. The cat flap door is open, and is operated by a float which would be attached to the hinged metal rod attached to the front edge of the flap. Photograph courtesy of ACE.

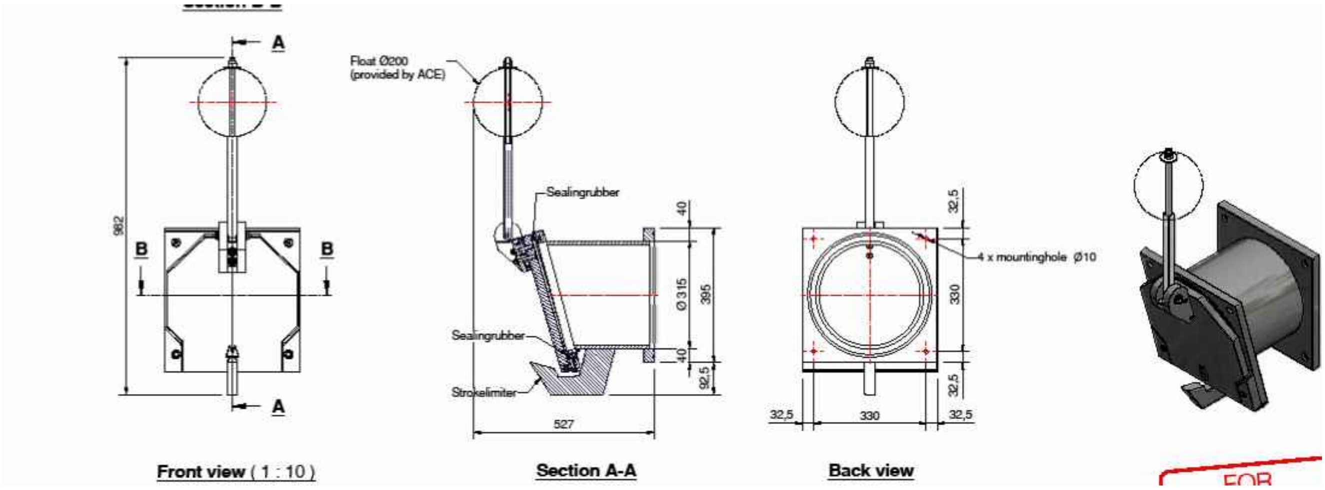

Figure 3.20. Drawing of a bottom-hinged cat flap, supplied by Aquatic Control Engineering (ACE). Reproduced with permission of ACE.

3.5.7 Permanent gap

There are a range of options for maintaining a small gap, either permanently or seasonally, to allow elvers and small eels access when water levels allow. This emulates the imperfect seal that most flaps suffered before modern materials and manufacturing methods resulted in well-sealing installations (Section 3.2). Possibilities include holes drilled in gates, and devices to hold the door open a small amount. For elvers a gap of just a few mm is likely to be enough to allow passage for a short period around equalisation. It may be more effective if the gap were fitted with a crawling substrate, which could allow elvers and small eels to make progress against a stronger flow, and thus at greater heads and for longer on each tide, than if they were free swimming. An arrangement of rigid pins, perhaps of varying diameter and spacing for eels of a range of sizes, may be more effective that conventional flexible substrates. Costs are likely to be minor, and minimal if this arrangement were included in manufacture.

A good approach might be to develop a device that can be readily fixed and removed from a flap, to allow seasonal deployment. This is basically an extension of the pegging principle (Section 3.5.2).

A simple system along these lines has been installed at flaps draining Lodmoor lagoon and marsh to tidal water near Weymouth, Dorset. This has been undertaken by RSPB who own and manage the bird reserve at Lodmoor. The device comprises a length of chain which is wrapped in garden mesh (Figure 3.21); costs were just a matter of a few pounds.

Figure 3.21. Chain wrapped in garden mesh prior to installation at Lodmoor.

The chain is anchored and laid through the flap and associated culvert, to provide both a small permanent opening and a crawling substrate for the elvers (Figures 3.22 and 3.23). Nick Quintrell of RSPB has provided data on catches from a small elver trap upstream that showed an increase in catches when the bare chain was installed in the tidal flap, and a further increase when mesh was added to the chain.

Figure 3.22. Chain wrapped in garden mesh laid through tidal flap at Lodmoor. The chain, covered in algal growth, is visible on the far side of the flow.

Figure 3.23. Chain wrapped in garden mesh laid through a culvert at Lodmoor. The chain extends through the tidal flap at the seaward end of the culvert (Figure 3.21), and is anchored to a stake in the stream bed.

A limitation of the permanent gap principle is that it allows an ingress of water for much longer than it is actually useful for migration. Elvers are likely to be attracted to an outfall by the seaward flow of fresh water. Once the tide starts to flood, the small gaps left around the flap would be unlikely to attract elvers from very far afield; this is in contrast to a strong landward flow that would occur if the flap were fully open or not installed at all. The "permanent gap" in reality is likely to be effective for elver passage for a relatively short time around level equalisation. This leads to the next principle, that of slow-closing flaps.

3.5.8 Slow-closing flaps

As discussed above, this is a logical extension of the permanent gap principle. By having the gap open only when eels and elvers could utilise the facility, rather than throughout the tidal cycle, the extent of tidal intrusion is greatly reduced. This may in turn allow the gap to be somewhat larger when passage was possible. No examples of this approach have been identified but it may be a viable future option, and costs are likely to be minor.

It may be possible to arrange for the flap to have "stiff" hinges for the last (say) 10^o of closure, so that a positive pressure was required to close it. The engineering options for this have not been explored , and it may prove difficult to make such a device reliable or fail-safe. Perhaps a better approach would be to have a device away from the hinges that delayed closure; possibilities include coil springs, or rubber ball set into a cup mounted just inside the pipe away from the hinges. The increasing pressure as the tide rose would compress the spring or ball, closing the gate. The same mechanism would open the gate slightly just before equalisation on the falling tide, again giving an window of opportunity for elver access.

3.5.9 Mitigator fish passage device, Nehalem Marine

This device should perhaps be under self-regulating tidal flaps (SRT, Section 4), but is included here as the overall intention is to allow fish passage and not to allow significant tidal intrusion. Floats mounted on a lever system attached to the gate operate cams which bear upon the bulkhead upon which the flap is mounted, to hold it open a short way for part of the tidal cycle (Figure 3.24). As the tide rises to lift the floats, the cams are turned allowing the water pressure to shut the gate.

Figure 3.24. The nearer flap is fitted with a Mitigator Fish Passage device, which holds the door ajar until the rising tide lifts the floats. The further culvert has a side-hinged gate, converted from a top-hinged flap – the remains of the flap hinges can be seen on top of the concrete bulkhead. Photograph courtesy of Guillermo Giannico, Oregon State University.

3.5.10 Elver passes

Provision of an elver pass may be a viable option at some sites, as an alternative to passage through a flap culvert. This may be a preferred option where any risk of landward flow, as is likely to happen with many of the options discussed so far, is unacceptable. Conventional elver passes are not described here as this is a large subject that has been covered elsewhere (Solomon and Beach 2004 a and b),and it is understood that a new eel pass manual is being prepared by the Environment Agency. However, a couple of recent development of particular relevance to passage at tidal limits are now briefly described.

Where the headwater level is maintained within fairly close limits for much of the eel and elver migration season, an eel pass may be operable on a simple overflow system This has been done at Three Mills Weir on the River Lee. This was feasible as there were several alternative routes for flood water to pass seawards., so that the loss of flood capacity at one flap posed no additional flood risk. A schematic of the design is shown in Figure 3.25. Installation was recently completed at a cost of about £12k.

An alternative is to construct a pumped-supply pass to lift the fish to above the retained water level. This would require a source of power, though the flow requirements are not great and a supply from solar panels or a wind turbine may suffice. Design criteria are provided by Solomon and Beach (2004 a and b).

Figure 3.25. Schematic diagram of a proposed gravity-fed elver pass at a tidal flap at Three Mills Weir at the tidal limit of the River Lea in London. This option is made possible by the carefully-maintained head in the navigation channel upstream, and the availability of alternative routes for flow so that the reduction in flood flow capacity is of no consequence.

Finally, an intriguing option was described by Bult and Dekker (2006). They compared the effectiveness of a siphon pass and a pumped-supply trap at two sites in the Netherlands. The 110 mm diameter siphon pipe was arranged so that flow passed at all times from the side of the sluice with the higher water level; thus fresh water would pass seawards when the landward level was above the tide level, and vice versa. The authors argued that passing landwards with the flow was an extension of the selective tidal stream transport mechanism that elvers use to approach the tidal limits of rivers. More elvers used the siphon route than entered the traps, by a factor of about 7.4 at one site, and 1.5 at the other; significant numbers of three-spined sticklebacks also used the siphon passage. The volume of water passing through the siphon in each direction each tide was between 226 and 284 m^3. The freshwater flow passing through the trap was only of the order of $15m^3$ per tide; catches are likely to have been greater with a greater pumped flow. Nevertheless, this approach appears to offer some strong advantages over pumped-supply traps or passes in such situations, including lower cost and no requirement for a power supply once the siphon has been established.

4 SELF-REGULATING TIDAL FLAPS AND GATES

4.1 Background

There have been a number of developments in recent years of tidal flaps that allow controlled tidal intrusion, in order to allow a degree of tidal interchange and saline intrusion in the area draining to the structure, usually for conservation purposes. A number of studies have examined the ecological changes that follow tidal and saline exclusion (e.g. Johnston *et al* 2003; Giannico and Souder 2004; Kroon and Ansel 2006), and there is increasing interest in allowing some tidal intrusion (termed regulated tidal exchange, or RTE) into wetlands at present cut-of from tidal influence by tidal flaps and gates. Rupp and Nicholls (2007) include a map showing the location of such proposals throughout NW Europe, including several in England and Wales. Where there are gates under manual or automatic control the operating regime can be modified to manage RTE. There have also been a number of developments of self-regulating tidal gates, which are basically modified tidal flaps that allow RTE without the need for power or supervision. Most designs are fitted with floats that hold the gate open for part of the tidal cycle, but close the gate at some stage during the flood. The earliest reference found to such a device is a US patent dated 1976; a drawing of the device is shown in Figure 4.1.

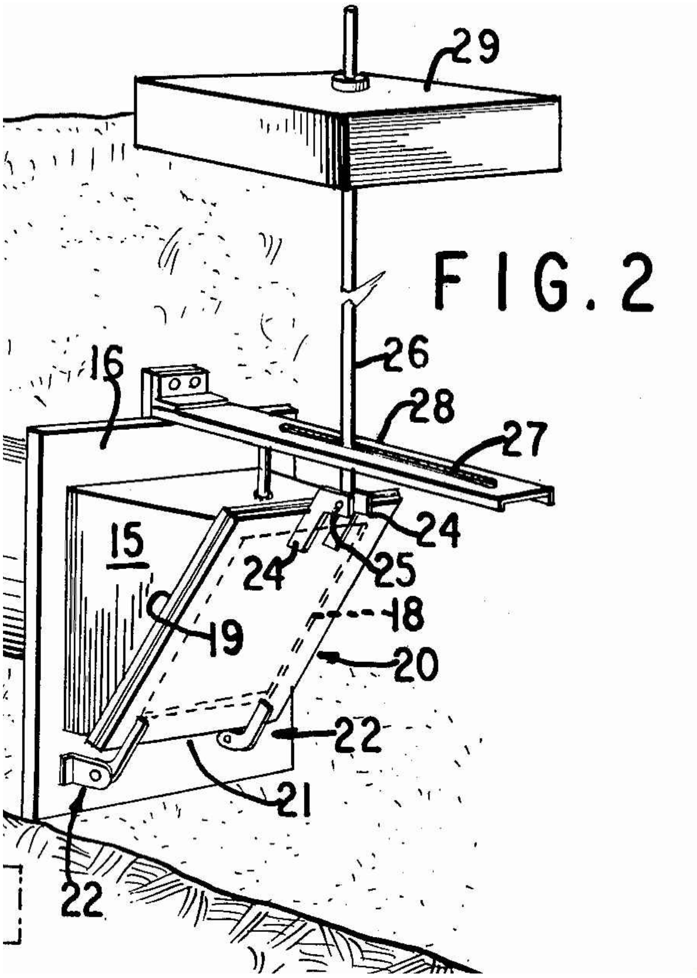
FIG. 2

Figure 4.1 Drawing from US Patent 3,974,654, "Self regulating tide gate", dated August 17 1976.

An Australian development of this type is shown in Figure 4.2 (Green and Pease 2007). The gate is held open during the first part of the flood tide by the weight of the float and its associated metalwork. As the tide rises it lifts the float, gradually shutting the flap. On the falling tide the weight of the float opens the flap wider than it would otherwise be, even at very low seaward flows. The device is adjustable with respect to outside water level at time of closing by re-arranging the alignment of the float.

Figure 4.2. Automatic tidal flap in New South Wales, Australia. From Green and Pease (2007).

4.2 The Waterman SRT gate

Similar in principle is the Waterman SRT gate, manufactured by Waterman Industries in the USA. Two of these have been installed in the UK; one at Goosemoor on the estuary of the Exe, the other at Cone Pill, a small stream draining into the Severn Estuary (Figure 4.3). The Cone Pill structure was the first to be installed in 2004, and Matthews and Crundwell (2004) describe the installation, operation and lessons learned.

Figure 4.3. Waterman SRT gate installed alongside a much larger tidal flap at Cone Pill. The tendency for the gate to remain open can be adjusted by swinging the floats forwards or backwards. The gate closes when the tide level rises to lift the floats. The tide level at which the gate closes can be adjusted by raising or lowering the floats. Soon after installation the floats were raised on long extension arms to keep the gate open for longer as this site has an extreme tidal range.

4.3 Williams/Stoneman SRT gate

A somewhat different SRT device has been developed by Mike Williams of the South West Region of the Environment Agency. The requirement was somewhat exacting, with the gate being closed at high and low tides, but open at an intermediate stage such that the water passing landwards was saline rather than backed-up fresh water. The design and operation of the structure are described by Williams (2009). The device is fundamentally a steel plate that rotates across the mouth of a circular-section culvert (Figure 4.4). The rotation is effected by a weighted float, and the operating sequence is shown in Figure 4.5. The prototype was installed on an outfall on the estuary of the River Axe in January 2009, and has so far operated without significant problems. A second device is shortly to be installed to replace one of the three tidal flaps in the Lymington causeway in Hampshire, to allow RTE into the reedbed area which had formerly been part of the tidal estuary of the Lymington River until the causeway was built in 1731.

Figure 4.4. Williams/Stoneman SRT gate during installation on the Axe Estuary, Devon

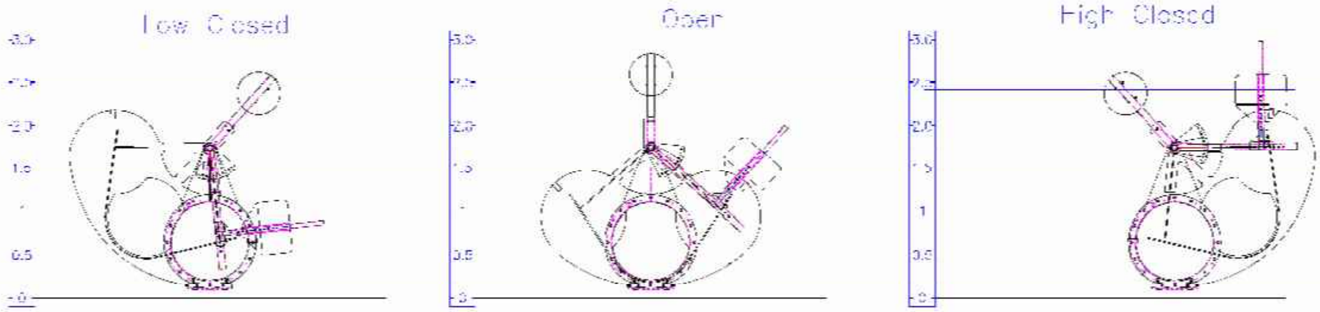

Figure 4.5. Operating cycle of the Williams/Stoneman SRT gate. Drawing reproduced with permission of Mike Williams and Stoneman Engineering.

4.4 Muted tidal regulated (MTR) gate, Nehalem Marine.

This development of the SRT gate principle is interesting as the gate operation is controlled by the water level on the landward side of the structure, which is of course usually the target of regulation. A float on the landward side operates the gate by a series of levers and a rod that projects through the structure. The mechanism is illustrated in Figures 4.6 and 4.7. This device is patented (US Patent 6,988,853 B1).

Figure 4.6. Float mechanism for an MTR gate at Schneider Creek, Washington State, USA. Photograph courtesy of Tom Slocum, Washington Conservation Districts NW Region Engineering Program.

Figure 4.7. Gate actuating mechanism for an MTR gate at Schneider Creek, Washington State, USA. The door is being held open. This is the right-hand door in Figure 3.9. Photograph courtesy of Tom Slocum, Washington Conservation Districts NW Region Engineering Program.

4.5 Variable Backflow Flap Gate (VBFG™), Juel Tide Gates.

This is basically an extension of the principle of the slow-closing flap described in Section 3.5.8. In the original design the gate was held open by a hydraulic cylinder until the flow of water landwards, and the head acting upon the open gate, exerted enough force to overcome it and close the gate. Current models use a shock-cord rigging arrangement to create the same effect. When correctly balanced the tension increases as the gate closes, preventing the gate from slamming shut. A major advantage of this design is that the gate is either fully open, or is closed. The rigging can be adjusted to effect closing with almost any level of tidal intrusion.

Figure 4.8. Juel Variable Backflow Flap Gate (VBFG ™). The gate is fully open, on the ebb tide. Photos reproduced with permission from Juel Tide Gates of Seattle, Washington, USA (www.jueltide.com).

The gate is made from heavy-duty 316 stainless steel and copolymer, and is designed to require minimal maintenance.

5 PUMPING STATIONS

5.1 Background

Land drainage pumping stations in England and Wales are for the most part operated by the Environment Agency and by Internal Drainage Boards.

Disappointingly little information is available regarding stations operated by the Environment Agency. We have information on the numbers in each region (Table 5.1), but no collected information on types of pump or their capacity. The 471 stations contain a total of the order of 1000 individual pumps. This table excludes pumping stations operated by IDB's, but may include a small number operated jointly with IDB's.

Region	**Number of EA pumping stations**
Anglian	77
Midlands	88
North East	40
North West	44
Southern	105
South West	54
Thames	43
Welsh	20
Total	**471**

Table 5.1. Number of pumping stations operated by the Environment Agency in each of its regions.

There are 177 Internal Drainage Boards in England and Wales. Between them they are responsible for draining 1.2 million hectares of land in England (representing about 9.7% of the total land area) and about 28,500 hectares in Wales (1.4%). They range in size from 182 hectares (Cawdle Fen IDB) to 52,498 (Lindsey Marsh IDB). Of the 177 IDB's, about one third drain entirely by gravity, while the remainder require some level of pumping; 53 have more than 95% of their area dependent on pumping. The largest pumping station is at Wiggenhall St Germans in Cambridgeshire, operated by the Middle Level Commissioners. This pumps water from the Middle Level drain system into the tidal Great Ouse. The station has just been completely rebuilt (Kitching 2008); the old installation had four pumps with a total capacity of 70 m^3/sec, and the new one six pumps with an astonishing capacity of 100 m^3/sec. There is no alternative gravity outlet.

The areas covered by IDB's contain a disproportionate fraction of the optimal eel habitat in England and Wales. To illustrate this situation further, the IDB's covering the coastal areas of Lincolnshire and the lower reaches of the Rivers Witham and Welland are explored. The boards concerned are shown in Figure 5.1; those covering the area upstream of Lincoln (Upper Witham and Newark IDB's) are not included in this assessment. The nine boards between them cover an area of 2656 km^2. A total of 4635 km of channel are maintained, and they operate a total of 147 pumping stations (Table 5.2). It is not possible to assess what proportion of the area and maintained waterways are drained by pumps or gravity, though pumping predominates. Many pumped areas also have provision for gravity drainage when relative levels allow, but this is likely to be a small proportion of run-off from these areas.

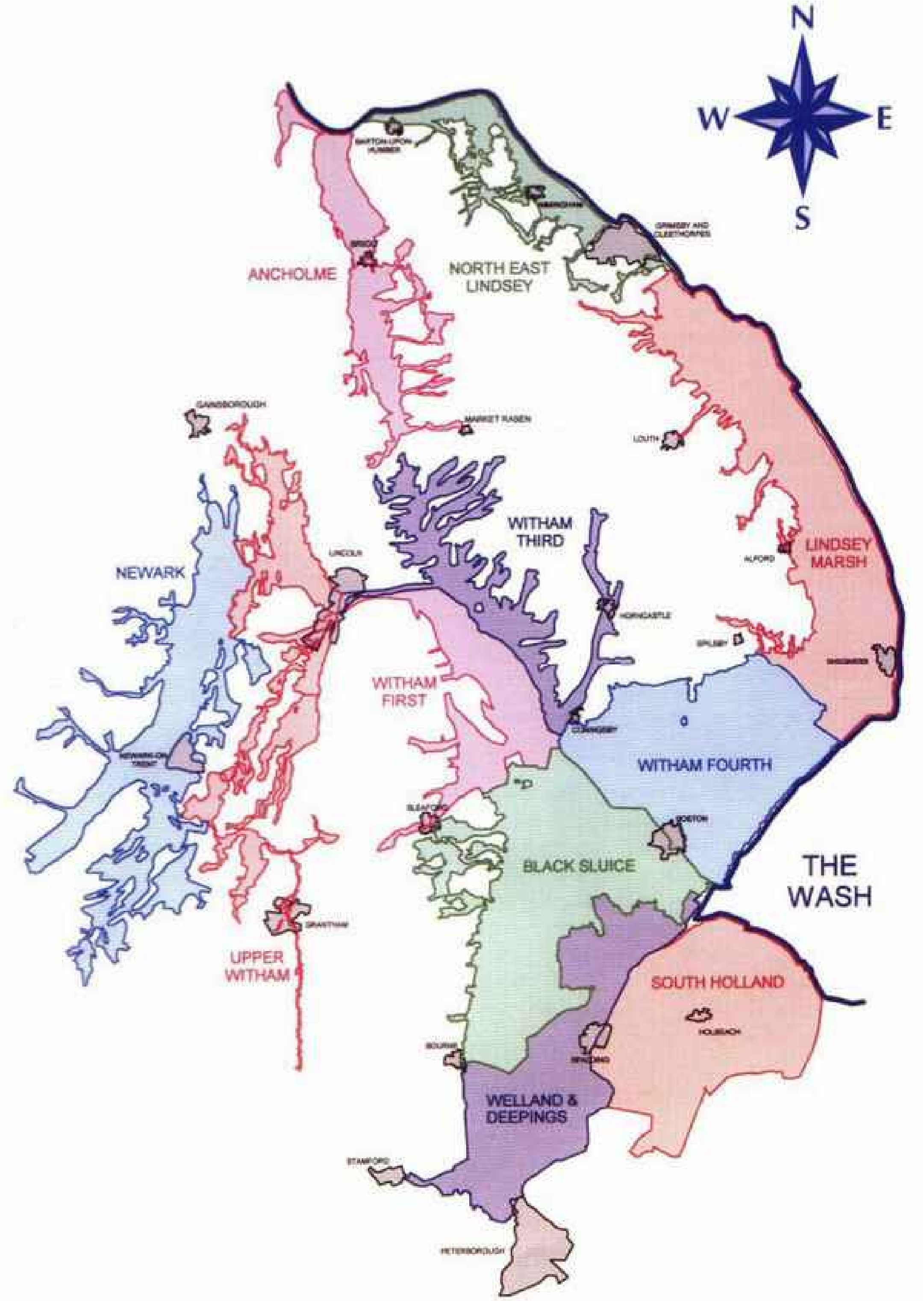

Figure 5.1. Lincolnshire Internal Drainage Board areas (Association of Drainage Authorities).

The total area of maintained channel, assuming a mean width of 5 m, is about 2300 ha, and smaller and private drains would represent a greater area again, perhaps a total water area of 5,000 ha or 50 km^2. This represents about 6.25 % of the surface water area of England and Wales, even though the proportion of the land area covered by these boards is only about 2%. Further, these lowland drains represent optimal eel habitat and can support very dense populations. These figures highlight the importance of assuring free access for eels both into and out of these waterways.

Board	**Area km^2**	**Length of maintained waterways, km**	**Pumping stations**
Ancholme	158	191	15
Black Sluice	435	800	34
Lindsey Marsh	525	973	30
NE Lindsey	112	130	3
South Holland	384	709	16
Welland and Deepings	324	631	14
Witham First	158	269	12
Witham Third	151	230	16
Witham Fourth	409	702	7
Total	**2656**	**4635**	**147**

Table 5.2. Statistics for the Internal Drainage Boards draining the coastal areas of Lincolnshire and the lower Witham and Welland catchments.

A total figure for the volume of water pumped at stations in England and Wales is not available. The volume pumped in the largest IDB area, Lyndsey Marsh IDB, ranged from 44.7 to 135.3 million cubic metres per year between 2001 and 2009, with an average of 80.8 million cubic metres per year.

Trudgill (2009) provides a useful background to the legal aspects of pumping stations and fish.

5.2 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.

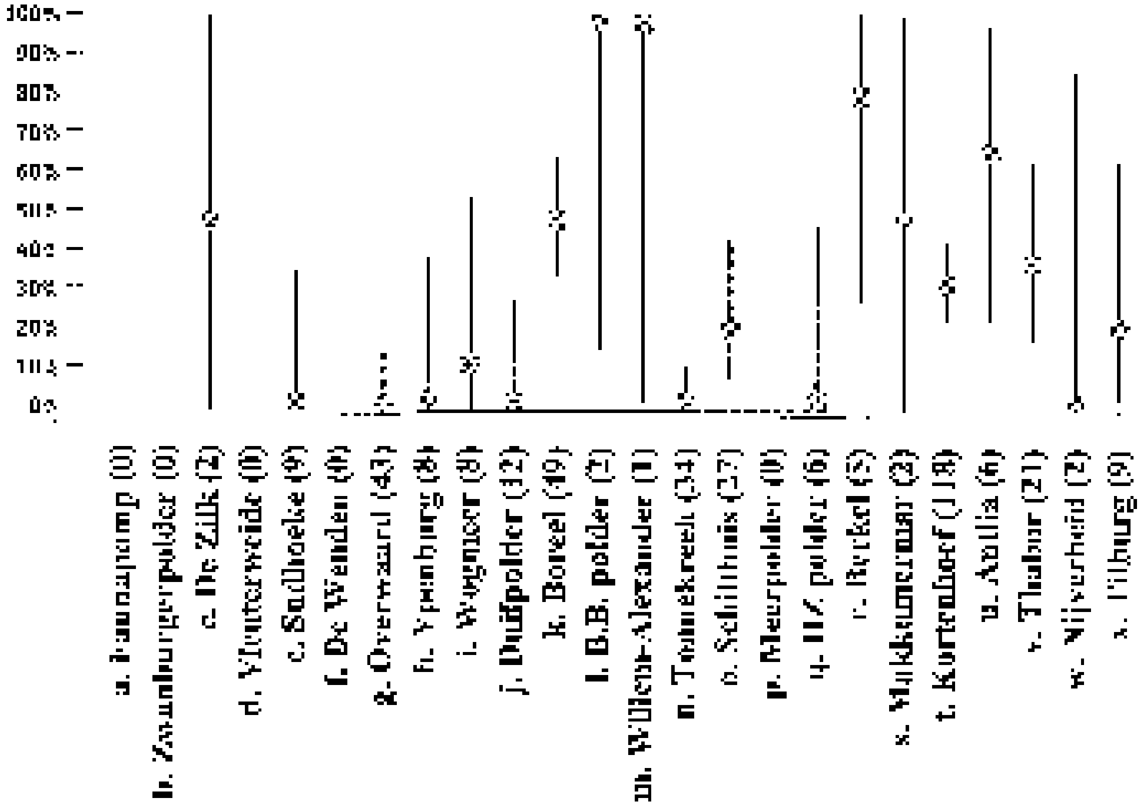

Figure 5.2. Percentage of eels killed at each of the sites in the STOWA study. The total number of eels passed at each site is shown in brackets after the site name; note that no eels were seen at five of the sites. Pump types:- a = airlift; b = shrouded Archimedes screw (see section 5.3.2); c = reverse-flow 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 5.2. 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 5.3 and 5.4), have five blades and rotate at 60 rpm. They have a combined capacity of 260 m^3/sec, 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 5.3. Pump impeller from one of the eight axial-flow pumps at IJmuiden, removed for maintenance.

Figure 5.4. 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 was 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 5.5. Eels killed during passage through IJmuiden pumping Station. Picture reproduced with permission of Marco van Wieringen, Rijkswaterstaat Noord Holland.

In many situations, eg 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;
- 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 (See figure 5.1) 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.

5.3 Fish-friendly pumps

5.3.1 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.

5.3.2 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 3-4 mm in a unit 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 5.6. 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 5.3).

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^3/sec.

Figure 5.7. 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 5.8), 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 5.9 and 5.10); 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 5.8. 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^3/sec at 38 rpm over a head of 1.24 m.

Figure 5.9. 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 5.10. Fish Flow Innovations Archimedes screw pump at a pumping station at Zwanburgerpolder, Netherlands. Photograph courtesy of Fish Flow Innovations.

5.3.3 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 5.11). 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^3/sec) 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, but the higher initial cost is compensated by lower running costs.

Figure 5.11. "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 5.12). 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.

5.3.4 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 5.13). The water passageways are large (Figure 5.8). 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 5.2), 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^3/sec pumping at a head of 10 m.

Figure 5.12. 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.

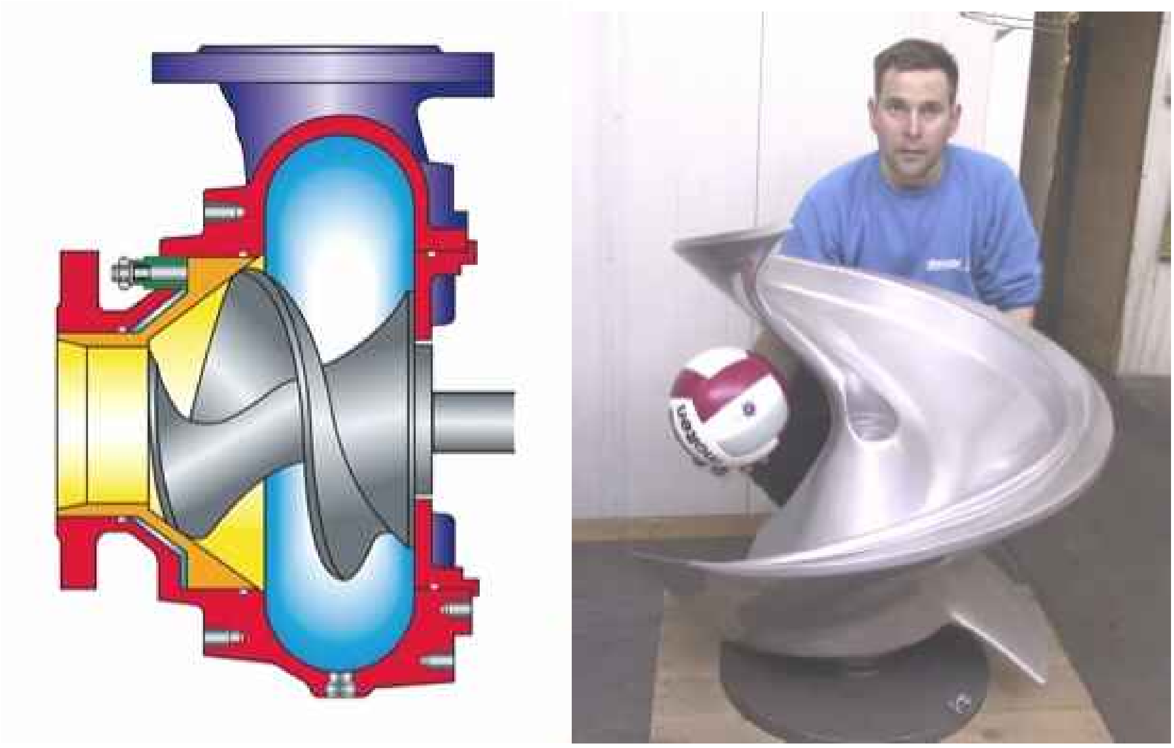

Figure 5.13. (Left) Cross section through a Hidrostal spiral vane pump. (Right) The spiral vane impeller from a large Hidrostal pump, showing the large water spaces.

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^3/sec) with a 10 to 20 m head.

5.4 Alternative routes

5.4.1 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;
- 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^3/sec.

5.4.2 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 5.14 and 5.15).

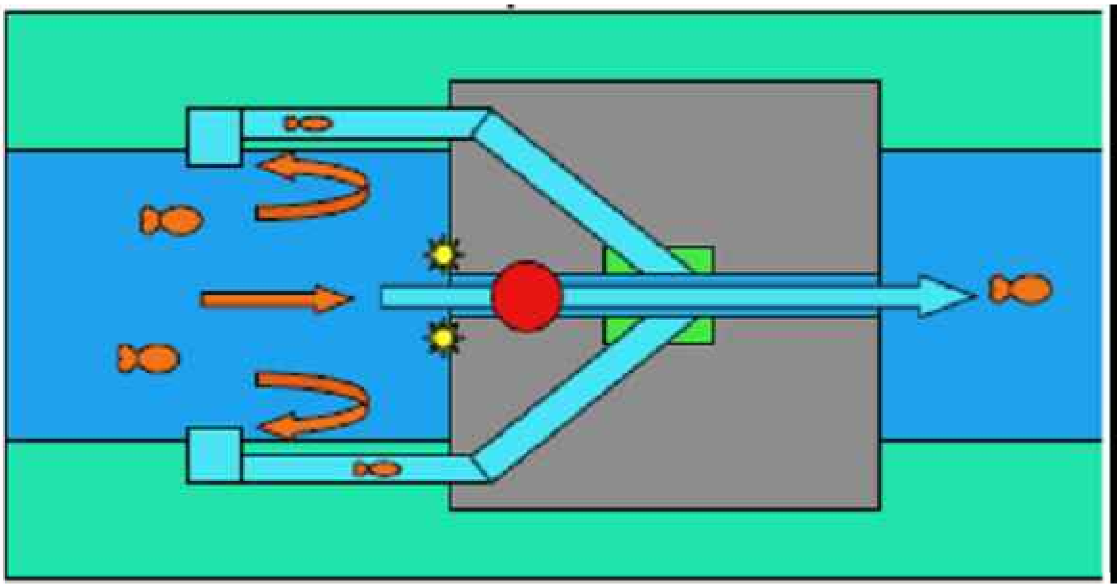

Figure 5.14. "Fishway for pumping stations" developed by Fish Flow Innovations. The red circle is the pump. Fish are discouraged from passing through the pump by strobe lights. Diagram courtesy of Fish Flow Innovations.

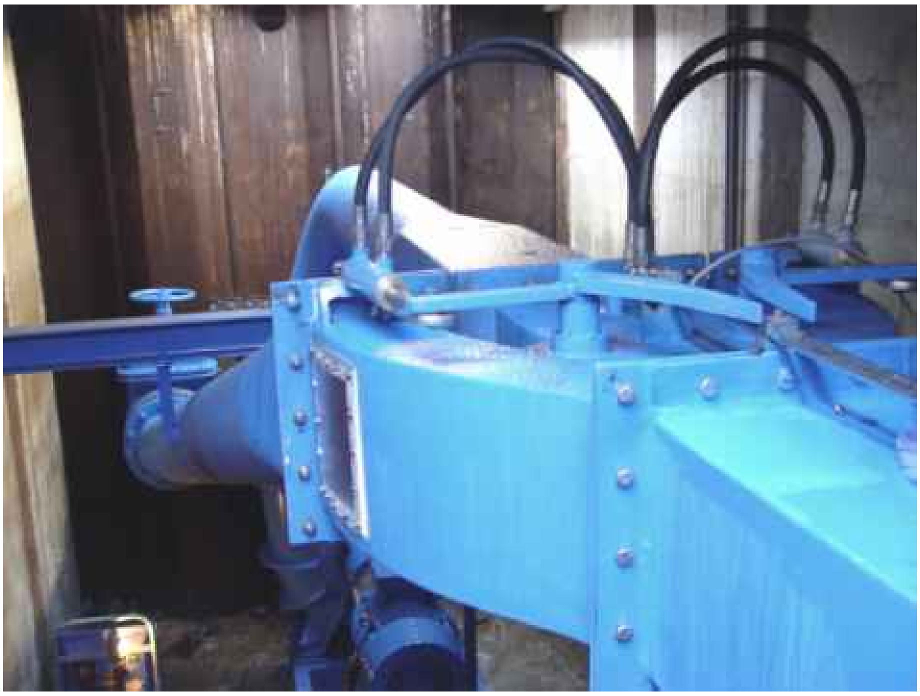

Figure 5.15. Part of the structure of the "Fishway for pumping stations". The pumped flow comes along the pipe in the centre of the photograph The flow containing the fish comes up pipes on either side; one can be seen on the left. Photograph courtesy of Fish Flow Innovations.

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%).

5.4.3 *"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 5.16). 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.

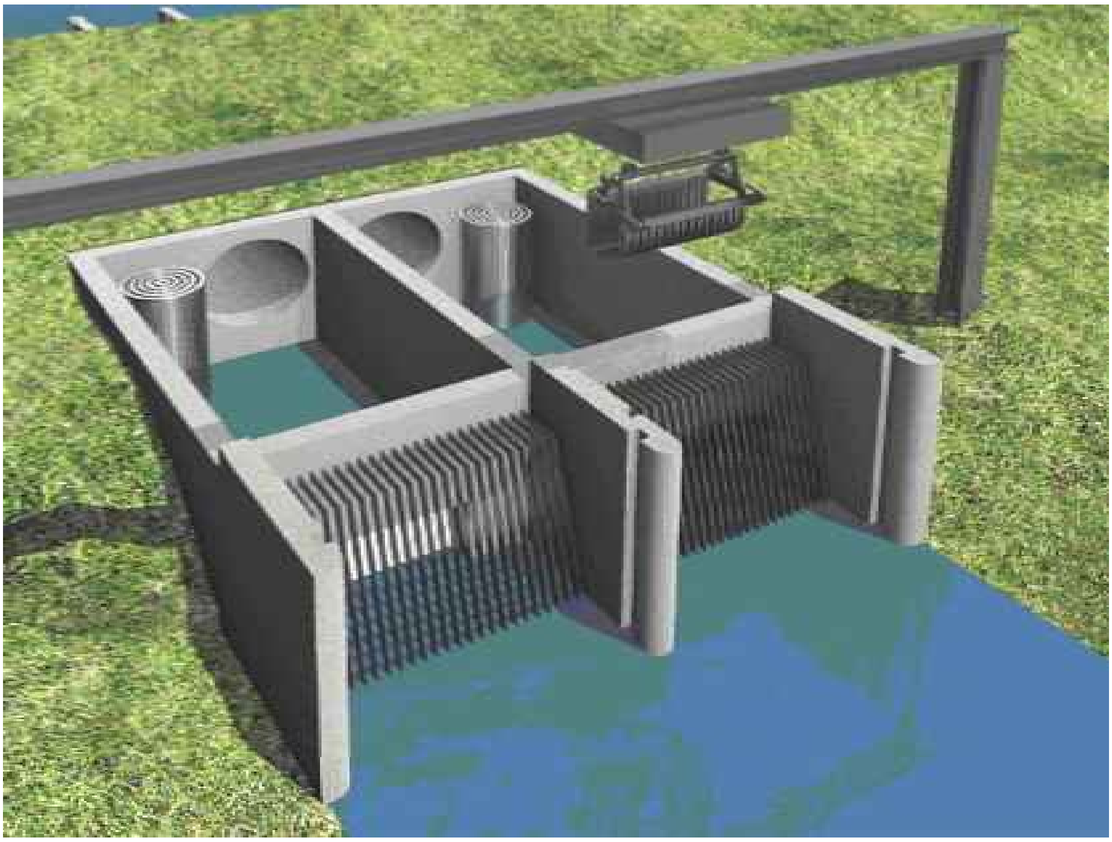

Figure 5.16. Schematic of the Tauw "Fish Flow" system. See text for an explanation of the operation. Diagram reproduced with permission of Tauw BV.

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^3/sec.

5.5 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.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions with respect to tidal flaps and gates

Tidal flaps represent a major obstruction to landward migration of small eels, with a head difference of a few centimetres creating a velocity that is impossible for the fish to overcome. As the head difference starts to fall to levels that represent conditions suitable for access the flaps close completely. In the past, imperfections in the sealing faces and other minor operating flaws allowed some access. Modern designs of flap, with machined faces and rubber seals, often installed in pairs in series, represent a more serious threat.

There are many potential approaches to allowing some landward access for small eels, which are reviewed in Sections 3 and 4. These include mechanisms to maintain small gaps either throughout the tidal cycle or for part of it, installing a "cat flap" to allow fish access, and fitting tidal doors rather than flaps. Where a level of tidal exchange is considered desirable for reasons beyond fish access, self-regulating tidal (SRT) flaps and gates are a good solution. Several cat flap and SRT devices are proven in the North America and Australia, and others are currently being assessed in the UK.

There is a need for more trials of innovative low cost designs in the UK, and a careful record should be maintained of current trials.

Side-hung tidal gates appear to represent no significant impediment to the free movement of eels, and their use if recommended where conditions allow.

6.2 Conclusions with respect to pumping stations

More than a thousand pumping stations drain huge areas of potentially very productive eel habitat in England and Wales, and often represent the only realistic route for adult eels from fresh water to the sea. Eels may be killed during pumping, but the level of mortality is strongly dependent upon the size and type of pump; in a study in the Netherlands mortality ranged from 0 to 100 %, with a mean of the order of 25%. Options for addressing these losses are use of fish-friendly pumps, diversion of fish to other safe routes of passage, or trapping and transferring to safe routes. Preventing passage without providing an alternative route is not a viable option for eel stock management. There are some recent significant advances in pump design that offer considerable scope for improving the situation.

6.3 Recommendations with respect to databases and further assessments

A frustration during this study was the lack of a single accessible database of relevant structures (tidal flaps, tidal doors and pumping stations) including numbers, location, dimensions, areas drained, areas of waterways drained etc. It is understood that the Environment Agency is currently developing a database containing much of this information to support System Asset Management Plans (SAMPs). This will be very valuable for future assessments. Hopefully it can be extended to include structures operated by other authorities such as the Internal Drainage Boards.

However, it is recommended that this, or an equivalent data base is developed to include an assessment of fish passage issues, such as passability at various states of tide and under various operating conditions with respect to eels and other species, and the availability and extent of use of alternative routes. This, coupled with the information on extent of waterways will allow priorities to be set for action. This will be very valuable in terms of compliance with the Water Framework Directive and the Eel Regulations.

6.4 Recommendations for further investigations

There is an urgent requirement for development and trials of some of the options for easing passage at tidal flaps that are identified in Section 3. These trials would check both the effectiveness with respect to passage of eels, and the engineering and flood risk implications. It is likely that much of the testing could be undertaken in the field, but some laboratory testing may be required. It is worthy of note that suitable facilities may exist at the School of Civil Engineering and the Environment, University of Southampton (Contact Dr Paul Kemp). For example, his group were involved in flume testing a half-size model of the Stiffkey cat flap described in Section 3.5.6.

Several Self Regulating Tidal (SRT) devices are currently under trial in the UK and elsewhere. It is strongly recommended that a continuing watching brief is maintained to report on the effectiveness and limitations of various installations.

There has been a major initiative in the Netherlands assessing fish passage through land drainage pumps, including some claiming to be fish-friendly. The study was commissioned by STOWA (contact Bas van der Wal) and is due to report later in 2010. It is recommended that access to the outcome of this study is negotiated and made available to UK interests.

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