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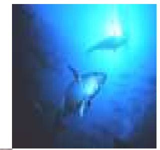

Archimedes Screw Turbine Fisheries Assessment. Phase II: Eels and Kelts.

Client: Mann Power Consulting Ltd.

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Author: Pete Kibel BSc. (Oxon) MSc. Fish Biology. MIFM

Reviewed by: Toby Coe BSc. (Oxon) MSc. Aquatic Resource Management.

Fishtek Consulting Ltd. Unit 3D Betton Way, Moretonhampstead, Devon, UK.
TQ13 8NA. Tel. 01647441020. Fax. 01647441040. Email. info@fishtek.co.uk

1 Executive Summary

The Archimedes Hydraulic screw turbine, supplied by Mann Power Consulting Ltd. on the River Dart in Devon, is the first of its kind operating in the UK. In view of the fact that screw turbines are considered to be fish friendly, the Environment Agency has permitted the turbine to run unscreened for 12 months while monitoring is undertaken. A rigorous monitoring plan was developed in consultation with the EA and members of the National Fish Pass Panel were present during some of the testing on site.
The first phase of monitoring, published in September 07, found the turbine to be safe for trout across a wide range of sizes and operating speeds. Smolts naturally passing through the device were monitored by underwater camera and trapped at the outflow. Limited and recoverable scale loss occurred in 1.4% of fish. However, these were wild fish and it is possible some scale loss was already present.
Turbulence within the screw was very low and unlikely to cause disorientation or increased predation at the outflow.

Phase 2 of the monitoring, assessed the effect on eels and kelts. After modifications to the leading edge, the turbine was found to be extremely safe for eels; one out of 160 (0.64%) suffered minor and recoverable damage to the tail.
Kelts naturally migrating downstream were monitored as they approached and entered the turbine and then trapped at the outflow. They all passed through unharmed, including the largest at 7.6kg (98cm). The delay at the intake was short, generally less than 15 minutes and would not have a significant effect on downstream migration.
Modifications to the leading edge, including cutting back the trough overhang and installing fish bumpers, prevented small fish and eels from being caught in a pinch point, improving fish safety.
Overall the turbine proved to be extremely safe for salmonids and eels, with an insignificant risk of injury.

2 Introduction

Background information including design specifications for the Archimedes screw, previous fishery assessments and site characteristics are covered in Phase 1: "Fish monitoring and live fish trials of the Archimedes turbine". Phase 2 extends the monitoring to eels and kelts.
Both are important down stream migrants in many rivers throughout the UK and have to be screened from entering conventional turbines such as Kaplan and Francis machines to avoid high levels of mortality.
This investigation aims to assess how they approach and enter the turbine and if any damage is caused by passage through the screw.
The work was conducted between July 07 and January 08. Members of the Environment Agency Fish Pass Panel, namely Kelvin Broad, Alan Butterworth and Adrain Fewings, were present during some of the trials and were consulted regarding modifications to the leading edge.

3 Eel Monitoring

3.1 Method

Eels were trapped from the wild using Fyke nets and stored in 1000 liter tanks with river water pumped through at the rate of 40 litres per minute, see figure 1.

Figure 1

Figure 2

They were introduced approximately 1m behind the leading edge via a 110mm diameter fish pipe referred to in Phase 1 (See Phase 1 DVD). This ensured eels entered the turbine near the base, maximising exposure to the leading edge and hence the risk of injury. A screen of 10mm x 10mm galvanized steel mesh was installed in the forebay tank to prevent them escaping into the leat, see figure 2. A second screen at the outflow trapped the eels after they had passed through.

Eels were introduced in batches of 4 or 5 at a time. After each passage they were netted out and assessed for damage, including pinch marks, scuffing to the skin, haematoma and strike marks from the leading edge. Each batch passed through several times (maximum of four), with a rest period of 2-3 hours between passages. Technically this is a form of pseudo-replication, however, it was deemed very unlikely that eels would learn how to negotiate the screw from one passage and reduce the risk of injury in subsequent passages. If this had occurred it would have been evident from the results, in that the probability of damage would not be distributed randomly across the first, second, third or fourth passage. The benefit of passing them through more than once was first to increase the quantity of data, providing a more robust assessment and secondly to represent multiple passages through turbines, which is possible on rivers with several installations. After a maximum of four passages, they were placed in holding tanks and observed for 7 days after which they were released into the river.

The behaviour of eels entering the turbine, moving down inside the chamber and being issued from the end of the screw, was monitored by underwater cameras. These were trained on the following areas:

- Forebay Tank
- Leading Edge
- Inside the Helix of the Turbine
- Outflow

3.2 Pilot Study

A pilot study was conducted earlier in the summer to assess the general approach and highlight any fine tuning necessary.
The results are shown in table 1. One out of a total of 12 eels (8%) suffered a severe pinch mark behind the head and a damaged spine, see figure 3. It is unlikely the eel would have survived long term. The scuff marks on the skin suggested that the eel had been trapped by the overhang of the leading edge, shown in figure 4. Placing the eel under the overhang confirmed this, as it fitted exactly into the 20mm gap.
Footage from the cameras revealed that >90% of eels entered the turbine along the base, making them very vulnerable to a pinch point.

Length (cm)	Weight (g)	Damage
43	90	None
47	170	None
48	165	None
48	185	None
53	210	None
54	235	None
57	310	None
59	340	None
64	410	Severe pinch behind head. Not recoverable.
70	490	None
72	720	None
73	950	None

Table 1. Results of pilot study showing length, weight and damage to eels.

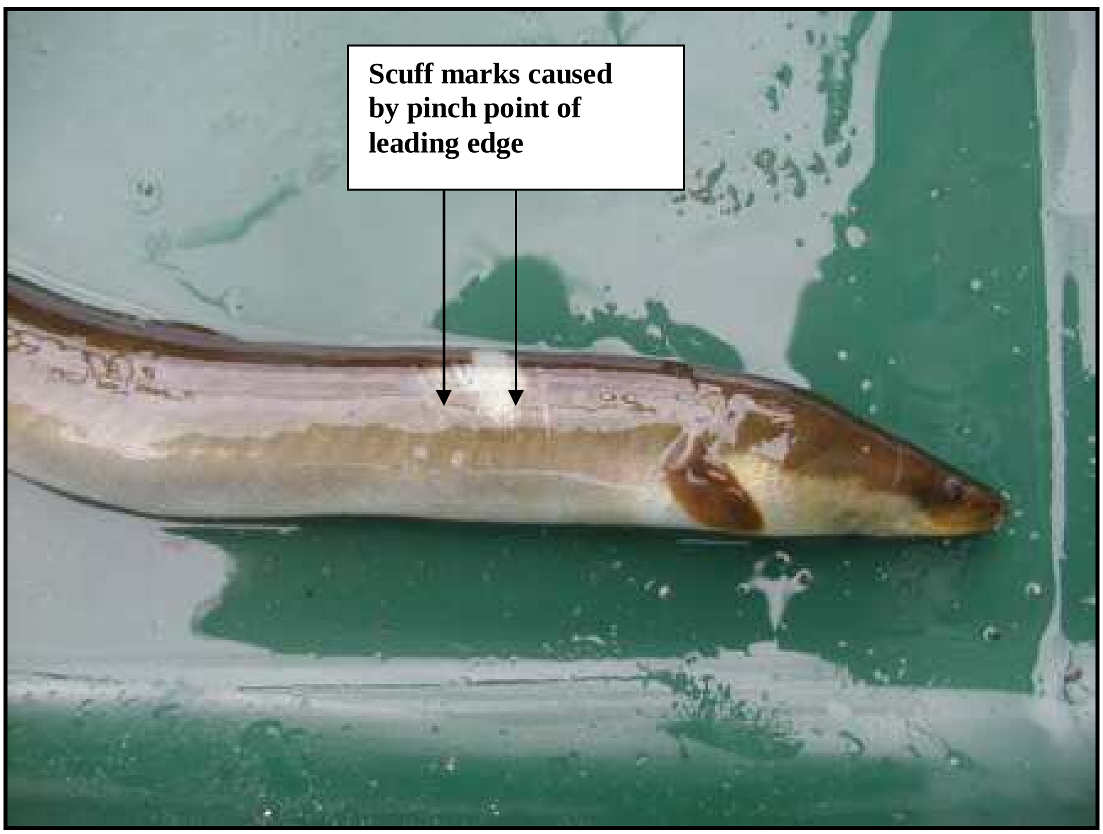

Figure 3. Eel caught in pinch point

Figure 4.

Figure 5. Modified edge

Before continuing with the trials, it was decided to modify the edge by cutting it back so it ran within the trough, removing the bevel and pinch point. The modified leading edge is shown in figure 5.

3.3 Results of Eel Monitoring

The length distribution and length to weight relationship are shown in figures 6 and 7 below.

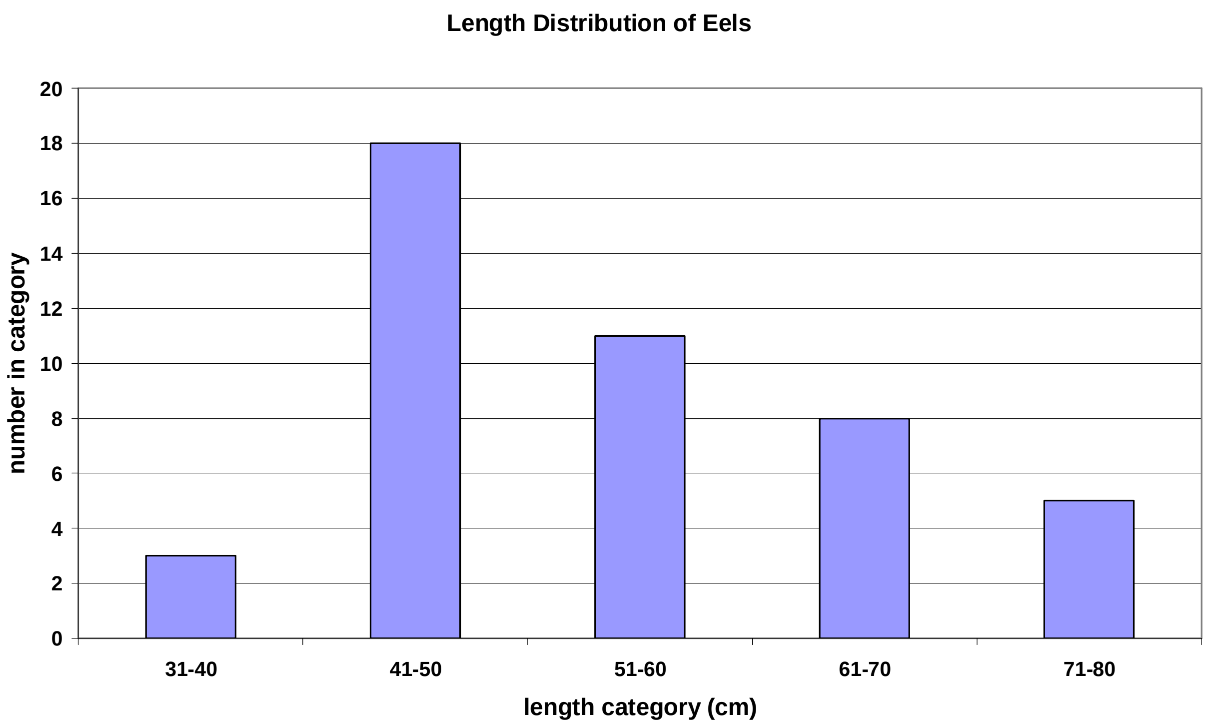

Figure 6. Length distribution

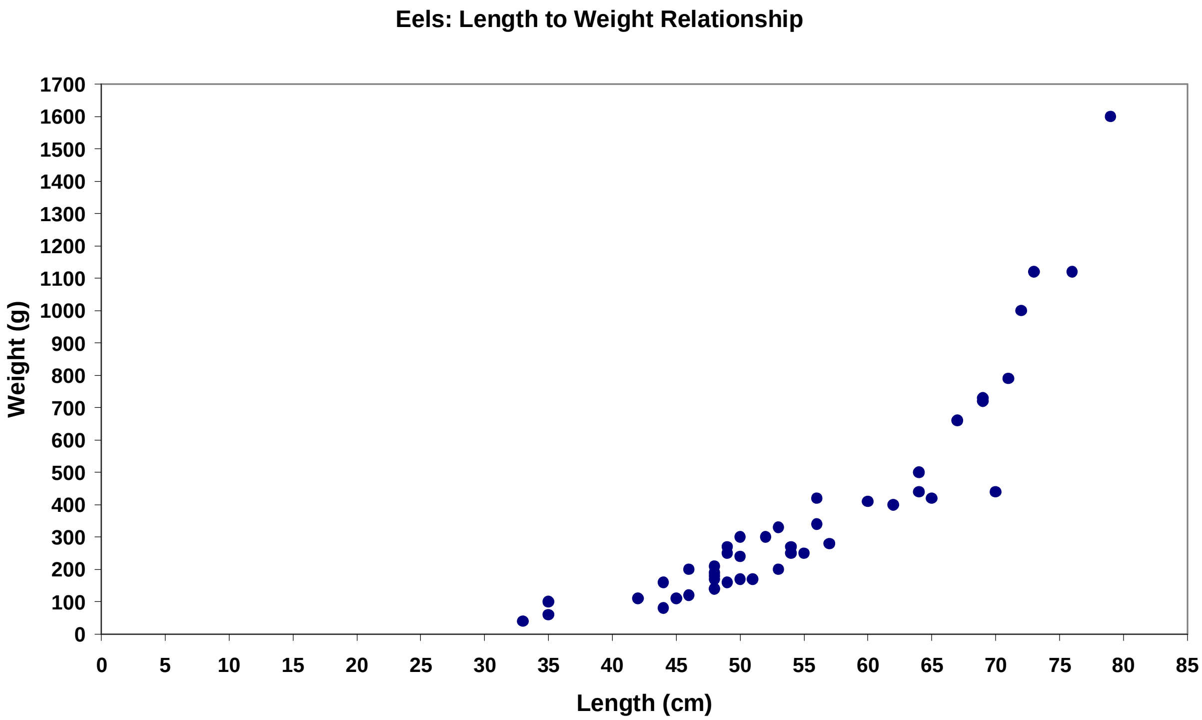

Figure 7. Length to weight relationship

160 passages through the turbine were recorded across a range of speeds as shown in table 2. One eel suffered minor damage in the form of a pinch 5cm from the end of the tail (see figure 8), 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. It was concluded that the damage to the tail was recoverable and the risk to eels from passing through the screw negligible. Overall the mortality rate was 0%, with less than 1% (0.64%) suffering minimal and recoverable damage.

Turbine speed	Eel passages	Number damaged	Damage sustained
Slow (23-25 rpm)	42	0	
Medium (25-27 rpm)	51	0	
Fast (29-31 rpm)	67	1	pinch to tail

Table 2. Results across different operating speeds

Figure 8. Eel with pinched tail

3.4 Evaluation of Leading Edge Modification

It was evident that modifying the leading edge had resolved the issue of eels being trapped and damaged by the pinch point. This was confirmed by a Chi-squared comparison of results before and after modification. (Chi-squared test, $p=0.02$).

3.5 Analysis Of Camera Footage

Eels entered the turbine along the floor of the forebay tank as expected. The majority passed through without being bumped by the leading edge, approximately 28% were struck, as shown in figure 9. No damage was inflicted, suggesting that the maximum speed of 3.8m/s towards the periphery of the helix is too low to cause injury.

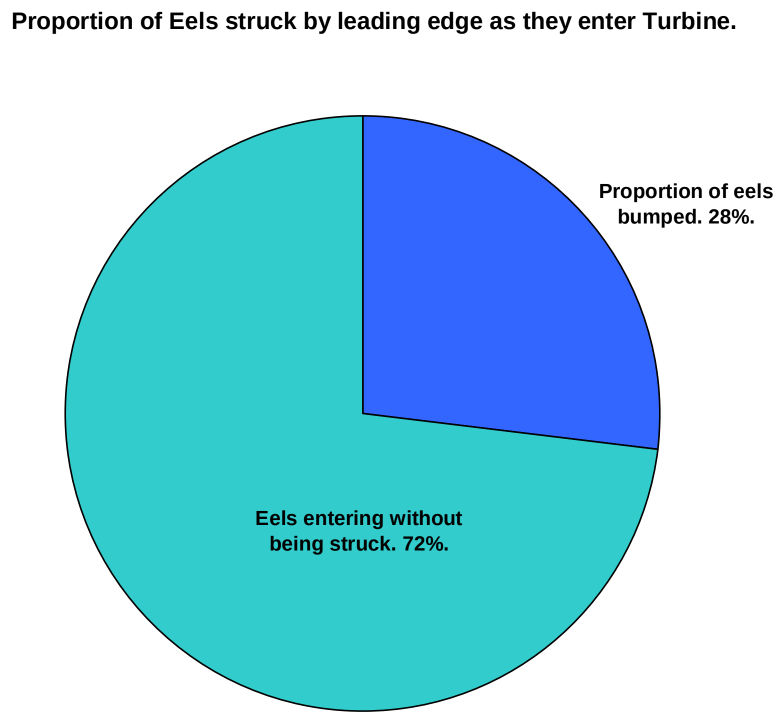

Figure 9. Proportion of eels struck by leading edge

Inside the chamber, eels behaved in an unexpected way. Rather than remaining close to the bottom with heads facing upstream and tails down stream, most held their tails well up in the water column and heads towards the bottom of the trough, or actively moved around the chamber. It is likely this was due to the circulation of water from the trough floor to the surface, with the eels holding station against the flow. This is interesting, as it explains why very few (0.64%) suffered pinched tails. By actively swimming around the chamber, the tails are held away from the gap between the helix and the trough.

The proportion of time spent within a few cm of the trough compared to swimming actively in the water column is shown in figure 10.

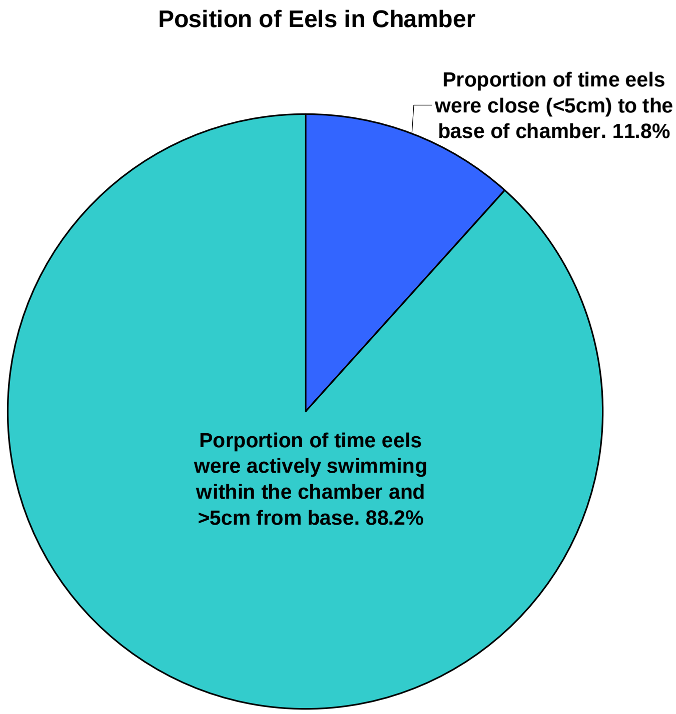

Figure 10. Position of eels as they pass through turbine

It was clear that turbulence levels inside the turbine were very low and it is unlikely eels suffered any significant disorientation. In this sense, I would not expect them to be more prone to predation after passing down the screw.

3.51 Delay at Intake

Smaller eels generally passed into the turbine in less than 1 minute. Larger ones, more able to resist the flow took up to 15 minutes to enter. These were wild eels trapped from a stillwater in September and probably not in migratory mode. It is possible that Silver eels actively migrating downstream would enter more readily. In any case a short delay would have a negligible impact on downstream migration.

4 Kelt Monitoring

4.1 Method

Kelts naturally moving downstream were monitored for a period of 4 weeks during December and January. Infra red sensitive cameras were positioned in the forebay tank and focused on the leading edge to capture the behaviour of fish as they enter the turbine. Cameras were also trained on a natural holding area at the end of the leat, approximately 5m before the intake. If kelts were reluctant to pass into the screw it is likely they would remain in this region before either moving back up the leat or into the turbine.
In addition the leat was walked regularly from the top (intake off weir) to the bottom and the numbers of fish recorded.

A grid of 50mm x 50mm weld mesh formed a holding area to trap fish in the outflow box, see figure 11. The trap was checked every morning and evening. Fish were assessed for turbine induced damage, such as scale loss, strike marks from the leading edge and haematoma. They were photographed, weights and lengths recorded and then released.

Figure 11. Trap at the outflow box

4.2 Results

A total of 11 kelts passed through the turbine over the 4 week period. The size distribution is shown below. There was no evidence of turbine damage on any of the fish.

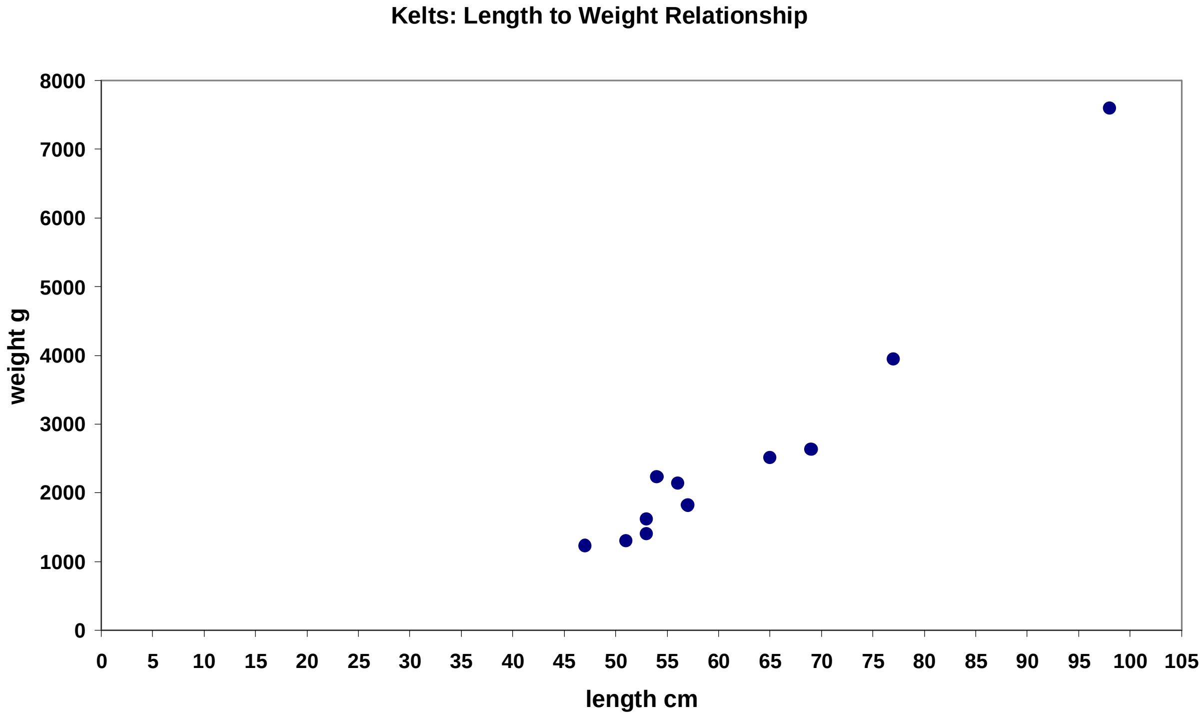

Figure 12. Kelts : Length to weight relationship

More fish passed through at night (7 of 11), however, considering the short day length of approx. 8 hours, the ratio actually indicates that fish were moving through without any apparent day/night preference and the numbers correlated with hours in the day. I.e. 16 hours night =66% of fish (7.25), 8 hours day =34% (3.75).

Length (cm)	Weight (g)	Turbine Damage	Passed Through
98	7600	None	Night
77	3950	None	Night
69	2630	None	Day
65	2510	None	Night
57	1820	None	Day
56	2140	None	Day
54	2230	None	Night
53	1620	None	Night
53	1400	None	Night
51	1300	None	Day
47	1230	None	Night

Table 3. Results of kelt monitoring.

While none of the fish were damaged by passing through the screw, some were in poor condition, with bacterial/fungal lesions and fin rot. This is not unusual, especially for spring run fish that may have been in the river for at least 6-8 months. One of the smaller sea trout kelts at 51cm and a 77cm salmon kelt are shown in figures 13 and 14 below.

Figure 13. Sea trout kelt.

Figure 14. Salmon kelt

4.3 Analysis of Camera Footage

Fish were recorded on camera passing the leading edge and into the first chamber. During the day they passed through relatively quickly, delaying for less than 15 minutes. At night several flashes were seen (infra red glare from scales), indicating that fish passed by quickly, but little useful data could be collected. During the day, footage was very clear. Some fish drifted into the screw with no delay, while others were put off from entering immediately and delayed for 10-15 minutes before swimming into the chamber. However, there was too little footage for a robust assessment of behaviour at the intake.

4.4 Walking the Leat

Throughout the 4 weeks of monitoring, the leat was walked 10 times. Only 3 kelts were seen, suggesting they were not delaying here for extended periods. The water was shallow enough to be waded and very clear, so fish could easily be spotted.

5 Discussion

The range of kelts and eels was typical of sizes found on many rivers. Some of the largest silver eels would be bigger than the 1.6kg maximum size tested, however, it is unlikely that they would suffer damage in view of the fact that salmon kelts up to 7.6kg passed through unharmed.
The maximum peripheral velocity based on 31rpm is 3.8m/s, just below the 4m/s regarded as the critical fish contact injury velocity, (Turnpenny 2000). This value, however, was determined using salmon smolts passing through Francis machines. The extent of injury is a function of fish length and weight in relation to the thickness of leading edge and speed of impact. While I would expect the risk of injury to be greater if the leading edge had not had the rubber sections, this was not assessed. A previous study by Dr Spah (Spah, 2001) in Germany involved a screw turbine with the standard 5mm edge section (No bumpers) and recorded no damage to eels up to 58cm. It is probable that around 28% of the eels would have been struck, indicating that even without the bumpers the turbine does not cause any injury to eels up to this size. The risk of injury, however, increases with fish weight and the largest eels used in Dr. Spah's study were only 400-500g. Silver eels at 1500-2000g may well have been bruised by the unmodified leading edge.

The number of kelts trapped was lower than expected; more fish would have provided additional camera footage allowing a thorough evaluation of bahaviour. Over the 4 week period, there were a number of days when the river was >1.5m above normal levels and significantly overtopping the screen in the outflow box. In addition the water was too coloured to make sense of the camera footage. It is likely that kelts passed through, but escaped over the top of the screen. A higher screen may have helped, although the sides of the outflow box were also underwater and would have needed additional screening.

The results indicate that eels and kelts may delay for relatively short periods of 15 minutes or so in the forebay tank or at the end of the leat. While this study has shown that salmonids and eels entered the turbine relatively quickly, a previous study in Holland (Vries, 2007) found that larger fish (mainly cyprinids) avoided the screw in preference for the fish pass. By netting at the end the screw and the pass, the study only recorded preference and not delay or the numbers that swam back upstream. The average size of fish passing through the screw was 5.6 cm, and 11.2 cm for the fish pass, suggesting that larger fish were avoiding the turbine. However, 83% of fish passing through the screw were small bream, averaging 4.8cm that would have contributed significantly to the low average size. The table below (table 4), compares the average and maximum size for fish passing through the screw and the fish pass. It is evident from the results that while the maximum size is similar for both, more of the large fish are opting for the pass, especially eels which avoided the screw altogether. The results raise some interesting questions that merit further study. Additional monitoring planned at Howsham Mill in Yorkshire will hopefully provide some answers.

Fish Species	Size of fish passing through screw (cm).		Size of fish passing through fish pass (cm).	
	Average	Max.	Average	Max.
Stone Loach	11	11	9	11
Bitterling	4.6	5	-	-
Bream	4.8	7	5.8	10
Roach	7.8	12	11	14
Stickleback	3.6	5	4.3	5
Crucian Carp	11.5	14	11	17
Carp	11.5	19	13.3	16
Gudgeon	11	11	11.2	15
Chub	7.5	11	10.5	12
Pike	39	39	-	-
Sunbleak	4.5	5	-	-
Orfe	11	14	-	-
Tench	10.3	20	14.9	27
Eel	-	-	36.4	60
Ruffe	-	-	11.3	12

Table 4. Results from the Vries 2007 study at Hoidonkse Mill , showing average and maximum size of fish passing through the turbine and fish pass.

6 Conclusions

After modifications to the leading edge, the turbine has proved to be extremely safe for eels and kelts. The risk of damage is very small indeed, with less than 1% of the eels suffering minor and recoverable pinch marks to the tip of the tail and no damage at all to kelts. The fact that eels tended to swim actively inside the chamber, keeping their tails away from the gap between the helix and the trough explains why only one suffered a pinched tail.
Both eels and kelts delayed for short periods of up to 15 minutes before entering. The effect on downstream migration would be insignificant.
The behaviour of eels inside the chamber, indicated that turbulence was very low and they would not have been disorientated and prone to predation at the outflow.
The bumpers fitted to the leading edge were assessed after 8 months of continuous operation. They were in perfect condition (see appendix) and could be expected to last for 5-10 years.

7 Recommendations

The results from this investigation confirm my earlier recommendation (phase 1) that no intake screening is needed.

The leading edge must be modified by removing the bevel and any overhang of the trough. Extruded rubber profiles (fish bumpers) should also be fitted to protect larger fish in particular.
While the bumpers are extremely durable, they should be inspected during routine maintenance, every 6 to 12 months.

8 References

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Turnpenny,A.W.H, Clough,S. Hanson, K.P. Ramsay, R. and McEwan, D. (2000) Risk assessment for fish passage through small low-head turbines. Contractors report to the Energy Technology Support Unit, Harwell Project No. ETSU H/06/00054/REP

Vries, T. (2007). Dir. Vis Advies BV, Gebouw Vondelparc 1, Vondellaan 14, 3521 GD Utrecht, Holland

9 Appendix

Rubber extrusion (fish bumper) after fitting

After 8 months of operation

Fishtek Consulting Ltd. Unit 3D Betton Way, Moretonhampstead, Devon, UK.
TQ13 8NA. Tel. 01647441020. Fax. 01647441040. Email. info@fishtek.co.uk