FISHTEK consulting

Fish Monitoring and Live Fish Trials.
Archimedes Screw Turbine, River Dart

Phase 1 Report: Live fish trials, smolts, leading edge assessment, disorientation study, outflow monitoring.

Client: **Mann Power Consulting Ltd.**

Project: **River Dart (Ashburton)**

September 07

Report Summary

The Archimedes hydraulic screw turbine installed on the River Dart in Devon is the first of this type operating in the UK. These turbines are generally thought to be fish friendly, having a slow rotational speed, and no significant shear forces or pressure changes. Several studies have concluded that they are safe for fish and will generally allow fish to pass unharmed.

In view of this, the Environment Agency (EA) has permitted the turbine to run unscreened for 12 months while monitoring is undertaken.

A monitoring plan was developed in consultation with the EA and subsequently members of the Fish Pass Panel were present during some of the testing on site.

Fish passage through the turbine was assessed using brown and rainbow trout across a broad spectrum of sizes (10g- 4400g, 8cm to 63cm) and turbine speeds.

Over 1000 fish passages through the turbine were recorded, many of them captured on film with underwater cameras.

No damage was caused by passage through the turbine and it was found to be fish safe across the full range of operating speeds of up to 31 rpm.

Smolts naturally passing through the device on the sea ward migration were monitored by underwater camera and trapped at the outflow to assess the condition. Limited and recoverable scale loss occurred in 1.4% of the fish.

The smolts were wild fish, passing through the device naturally and were not assessed before entering. It is highly probable that some may have already had pre-existing scale loss before entering the screw and therefore it is likely that fewer than 1.4% were affected by the turbine, possibly none at all.

Smolt monitoring highlighted the issue of the pinch point caused by the leading edge of the helical screw overhanging the trough. This appeared to be an anomaly on this installation. After consultation with the EA it was decided to modify the leading edge to remove the pinch point. Evaluation of the modified leading edge proved that the pinch point had been removed and it could no longer trap small fish. Rubber extrusions were fitted to protect the leading edge from stone damage and further improve the fish safety.

Turbulence within the screw and the effect on fish behaviour were assessed with cameras inside the chamber of the turbine. It was found that turbulence levels were very low and within the range normally experienced by salmonids and probably most riverine species. The fish were not disorientated and therefore unlikely to be any more prone to predation.

The behaviour of salmon and sea trout at the bottom of the turbine was monitored with underwater cameras. While some fish were attracted to the outflow channel, they did not try and ascend the turbine and none were observed jumping at the end of the screw. The average residence time in the outflow region was relatively short at just under 8 minutes and would not have any significant effect in terms of delaying upsteam migration.

In conclusion, this investigation has demonstrated that the Archimedes Screw turbine is extremely fish friendly, causing very limited if any damage to salmonids.

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1 Introduction

A hydro electric device (Archimedean screw turbine) has been installed by Mann Power Consulting Ltd. on the River Dart at the Dart Country Park near Ashburton in Devon. Grid ref SX735712.
The site has an existing abstraction licence for 1100 litres per second. An older Kaplan turbine has recently been replaced by the Archimedean screw supplied by Mann Power Consulting Ltd.
Section 14 of the Salmon and Freshwater Fisheries Act (SFFA), requires that hydro electric turbines need to be screened to prevent the entry of migrating salmonids, unless it can be shown that fish can pass through unharmed. The Environment Agency has therefore allowed abstraction without screens for 12 months, while monitoring is undertaken to assess the impact on fish.

1.1 Archimedean Turbines

This type of Hydraulic screw turbine is generally considered to be very fish friendly, having a slow rotational speed of 28-30 rpm and no rapid pressure changes or hydraulic shear forces. After passing the leading edge, fish remain in the same chamber of water until released at the outflow.
The Archimedean screw installed on the Dart at Ashburton is 2.2m in diameter and 11m long with a head of 4.5m. It is inclined at an angle of 22^0.
Water from a weir upstream is diverted from the mainstem river via a leat approx. 500m long. Water flow is regulated by a sluice gate at the top of the leat and a second sluice at the intake to the turbine.
A diagram of a turbine is shown in figure 1. Water enters at the top and drives the screw as it moves down the trough towards river level at approx. 1 m/s^{-1}. A gearbox steps up the speed and drives a generator producing electricity. These turbines are typically between 1.5-3.5m in diameter and are particularly well suited to low head sites of up to 8m. The length of the screw is determined by the head height.

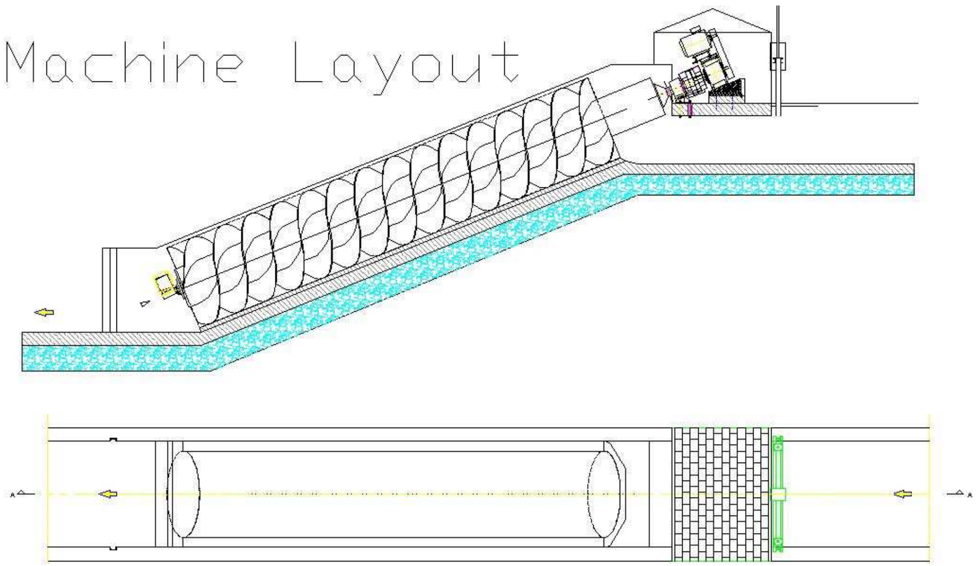

Figure 1. Diagram of Archimedes hydraulic turbine

1.2 Fishery Assessments

The first assessment of fish passage through Archimedes turbines was conducted by Dr. Hartmut Spah of Bielefeld, Germany in 2001 (Spah, 2001). 158 fish of nine species were electro fished from the river, passed through the turbine and netted at the outflow. 4.4% of the fish suffered limited damage, mainly scale loss that was deemed to be minor and probably recoverable. Chub and roach were the only species to suffer any damage; eels that traditionally experience problems passing through turbines suffered no damage at all. Dr. Spah concluded that the damage was most likely due to the leading edge of the screw that had become sharpened by stones after prolonged operation.

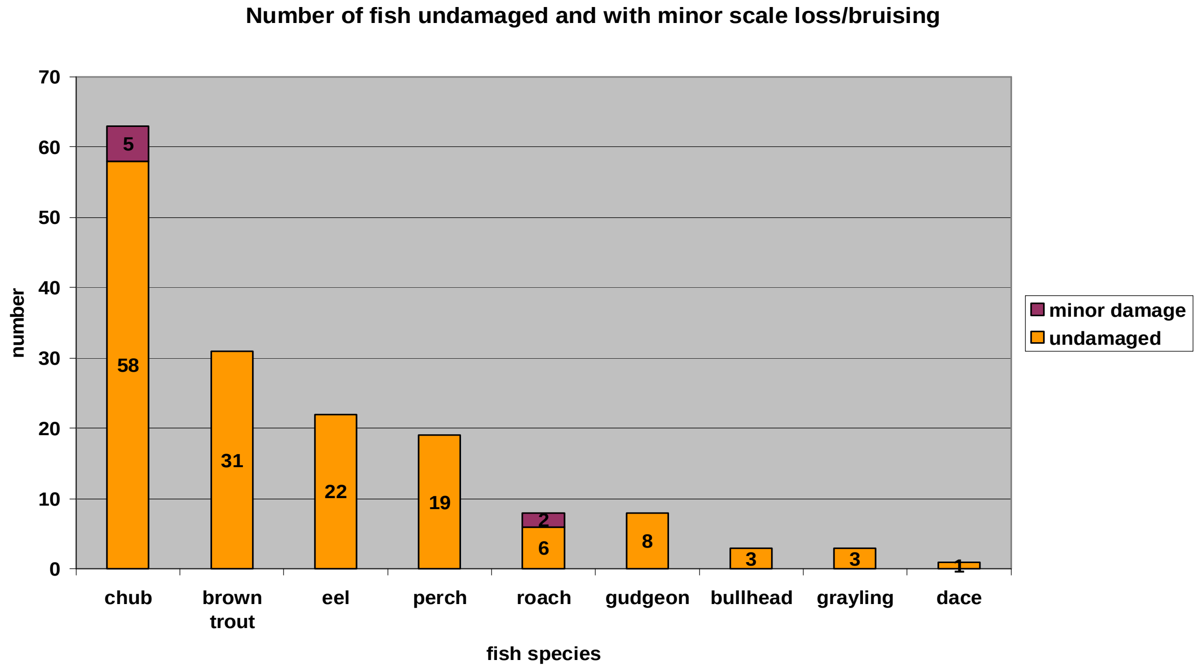

Figure 2. Results from Dr. Spah study showing species, number and number with damage.

A more recent study conducted by VisAdvies (Merkx and Vriese, 2007), netted fish naturally passing through an Archimedean screw at Hooidonkse Mill on the River Dommel in Holland. A total of 289 fish, mainly small bream passed through the screw. None of the fish suffered any damage at all and it was concluded that the turbine was safe for fish passage. The average size of fish passing through was 5.6cm, compared to 11.2cm for fish passing over the fish pass. It was thought that some of the larger fish able to resist the water velocity at the intake, tended to avoid the screw.
Species, size range and number netted at Hooidonkse Mill are shown in figure 3.

Species	Size range	Number	Number of fish with damage
Bitterling	4cm-5cm	5	0
Bleak	4cm-5cm	2	0
Bream	3cm-7cm	239	0
Carp	7cm-19cm	11	0
Crucian carp	9cm-14cm	2	0
Gudgeon	11cm-11cm	1	0
Orfe	8cm-14cm	2	0
Pike	39cm-39cm	1	0
Roach	5cm-12cm	9	0
Rudd	4cm-11cm	2	0
Stickleback	1cm-5cm	5	0
Stone Loach	11cm-11cm	3	0
Tench	4cm-20cm	7	0

Figure 3. Results from Vis Advies study showing fish species, size range and number.

Archimedes screws are also used as fish lifts or pumps to transfer fish between waterways. An extensive study by McNabb et al (2003), on the Sacramento River in California, involved passing 7000 fish through an Archimedes lift. It was found to be very fish friendly and damage levels were extremely low across 27 riverine species.

1.3 Site Characteristics

The River Dart is a fast flowing upland river, rising on Dartmoor as the East and West Dart and merging at Dartmeet. The catchment area upstream of the site is 187.1 km^2 , with average rainfall of 1800mm per annum.
It is primarily a salmonid river, although other species are also present as shown in the table below.
Mean flow at Ashburton is 8.4 m^3s^{-1}. Q95 flow is 1.13 m^3s^{-1}, Q10 is 18.5 m^3s^{-1} .
The river rises rapidly after heavy rainfall and can increase from Q90 to well above average daily flow and drop back again, within a few days.

Fish Species		**Migration**	**Migration period**
Salmon	(*Salmo salar)*	Anadramous	
Spring fish	ascending		spring
Grilse	ascending		summer
Kelts	descending		winter early-spring
Smolts	descending		spring.
Sea trout	(*Salmo trutta)*	Anadromous	
Upstream	ascending		summer
Post spawned	descending		winter
Brown trout	(*Salmo trutta)*		
Eel	(*Anguilla anguilla)*	Catadromous	
Adults	descending		mainly autumn
Juveniles	ascending		spring-summer
River lamprey	(*Lampetra fluviatilis)*	Anadromous (ascending)	spring and autumn
Transformers	(macrophthalmia)	descending	late winter-early summer
Sea Lamprey	(*Petromyzon marinus)*	Anadromous (ascending)	spring-early summer
Tranformers	(macrophthalmia)	descending	autumn-winter
Minnow	(Phoxinus phoxinus)		
Stoneloach	(Barbatula barbatulus)		
Bullhead	(Cottus gobio)		

Figure 4. Fish species present with life stages and times of migration.

1.4 Scope of Investigation

This study is designed to assess the impact of the Archimedes turbine on salmonids and eels. It has been split into two sections, phase 1 and 2. Each report has a DVD showing footage of fish behaviour captured by the underwater cameras.

The monitoring plan was developed in consultation with the Environment Agency to ensure it was rigorous and would provide a thorough evaluation of the potential fisheries impacts. It was amended several times until it was deemed acceptable.

A number of EA staff, in particular Kelvin Broad, Chris Lawson and Alan Butterworth were present during some of the on site monitoring.

Phase 1:

- Trials with brown and rainbow trout passing through the screw.
- Modification and assessment of the leading edge.
- Levels of turbulence within the screw and the effect on fish behaviour.
- Passage of smolts through the turbine as they migrate downstream.
- Monitoring numbers and behaviour of salmon and sea trout at the outflow.

Phase 1 report DVD.

- Leading edge
- Smolts
- Passage through turbine
- Outflow monitoring

Phase 2:

- Assessing the effect on eels of passage through the turbine.
- Monitoring kelt behaviour at the intake and condition after passing through.

Phase 2 report DVD.

- Kelts
- Eels

2 Method

Brown trout were sourced from Torr Fish Farm on Exmoor. These were reared in water with similar pH to the River Dart. Fish were kept in large 1000 litre tanks (see fig 5), with water pumped through continuously from the leat at the rate of 40 litres per minute. Two pumps were used to ensue that in the event of one failing, the fish would still receive enough water.

Most studies on the effects of turbine passage and shear force have all used farmed fish.

One issue resulting from the use of farmed fish, however, stems from the fact that the conditions in which they are raised can lead to a degree of fin damage, characterized by rounded fins and tails. It is easily distinguishable from recent damage such as scale loss and haematoma that can be caused by turbines. However, to ensure that any damage caused by the screw could easily be assessed, each fish was photographed on both sides before passing through and photographed again afterwards.

Length and weight measurements were recorded and related to each photo ID. This enabled fish netted at the outflow to be matched with the same fish at the intake. The condition was assessed on a 4 point scale (see appendix). Level 1 representing the most extreme damage and level 4 no damage. The photographs were compared before and after to double check there was no pre existing damage, although fish with obvious scale loss were not used in the investigation.

Screens were secured to the sides of the forebay tank to prevent fish from swimming back up the leat (see fig 6).

Fish were placed in the intake, a meter above the leading edge, one at a time, in batches of 8 -12. It took up to 5 minutes for them to pass through the system and to be netted at the outflow. After passing through the screw, fish were caught in the cod end holding box of a large Fyke net as shown in Figure 7.

A secure frame of 20mm steel box section was constructed to hold the net in place and prevent any fish escaping around the edges of the net. A slot running down the edge of the frame allowed the net to be lowered into place and easily removed for cleaning.

After each passage through the screw, fish were placed in 1000 litre resting tanks for 48 hours. They were observed for any delayed effects such as listing, poor swimming, remaining on the bottom and infection.

Fish were used again after a rest period of at least 48 hours. Any with scale loss were excluded. Fish were used up to several times, although the batch results were recorded to ensure there was no effect from multiple use.

There are several advantages of using fish more than once. Firstly, fewer need to be obtained and stored and therefore less holding tanks are needed. Secondly, if a river has several Hydrodynamic screw turbines, a fish migrating downstream may pass through more than one within a relatively short period. If multiple passage had caused a problem for the fish, this would have been evident in the batch results.

To determine that using fish more than once was not influencing the results, a Kruskall-Wallis test was used to assess if there were any differences between batches. The non normal distribution of data required the use of a non parametric test.

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Figure 5. 1000 litre fish holding tanks.

Figure 6. Intake with fish screens

Figure 7. Fyke net at outflow.

Fish were monitored using infra red sensitive under water cameras, as shown in figure 8 and 9 below. These record in colour during the day and switch to black and white at night. Infra red LED's built into the cameras provide a light source for night viewing, although this was boosted with additional underwater IR lights.

Cameras were installed in different positions for the various monitoring regimes.

- Before the intake and looking directly onto the leading edge to view fish passing into the first chamber.
- Within the screw to assess if fish are exposed to high levels of turbulence that may cause disorientation.
- In the outflow box to monitor fish behaviour as they are issued from the bottom of the turbine.
- In the outflow channel and outflow box to monitor sea trout and salmon as they approach the turbine from the outflow channel.

Figure 8

Figure 9

3 Assessing the Effect of the Net

The outflow channel is shallow, averaging 40cm in depth with a high water velocity. It was not possible to easily baffle the net to create an area of reduced flow in the holding box. Even if some degree of baffling had been possible, it would not prevent fish being forced through the Fyke sections as they passed down the net. In view of this and results from preliminary tests that indicated small fish were being pushed against the netting in the fast water, it was important to assess any background level of damage that may have been caused by the net.

3.1 Method

100 fish varying in size between 8cm and 20cm, were photographed and placed into the outflow box at the end of the screw in batches of 10-12 at a time. They passed through the net having by passed the turbine and were removed from the holding box after 15 minutes and the condition assessed.

3.2 Results

The length distribution is shown in Fig 10.
All the fish were healthy after 48 hours in the holding tanks.
Three fish had limited scale loss of less than 10% (category 3). They were 12, 15 and 19cm.
This gave a background level of 3% net damage. If the level of net damage had been high (>20%) it is possible it would have obscured a component of any damage caused by the turbine. A high element of net damage, combined with a low component of turbine damage, would make the results difficult to analyse. However, 3% would have a negligible masking effect. Across sufficient numbers of fish (100), any turbine damage would be statistically discernable above the background net component.

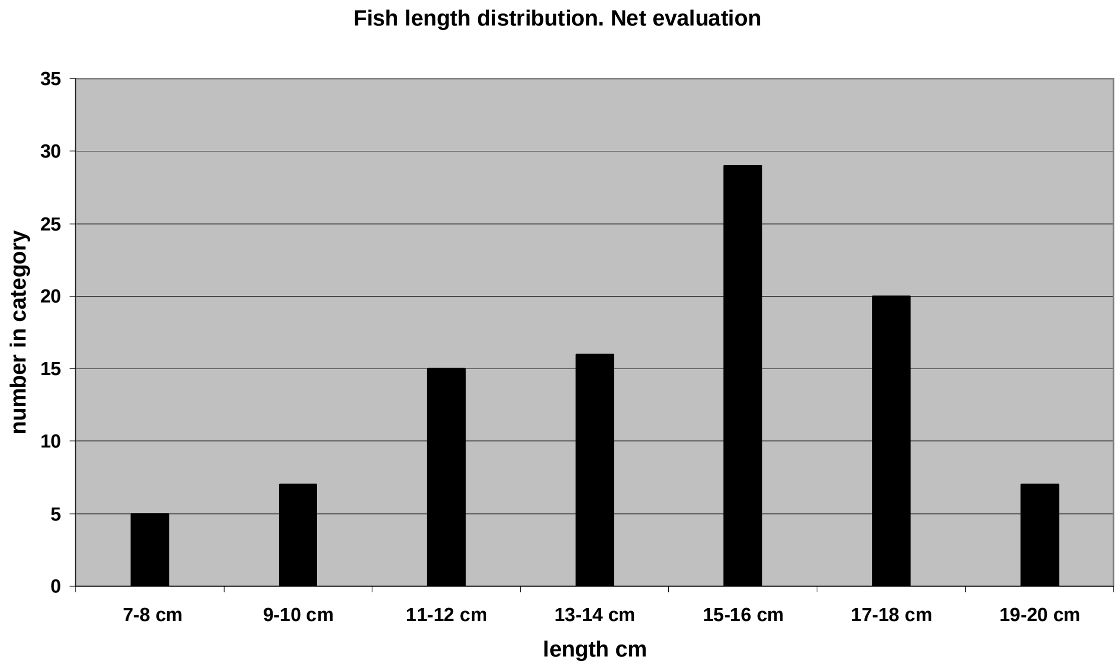

Figure 10.

4 Passage of Trout through the Turbine

4.1 Method

Fish were photographed on both sides and introduced in batches of 8-12 at a time as outlined in the general methodology. The turbine speed was recorded for each batch. The fish were netted at the outflow, photographed again and the condition assessed. They were placed in holding tanks and monitored for 48 hours. Fish were tested across a wide spectrum of turbine speeds, representing the full range of operating conditions. The speeds were grouped into 3 bands, slow, medium and fast.

Speed	Turbine revolutions per minute (rpm)
Slow	20-23
Medium	25-26
Fast	29-31

4.2 Results

4.21 Slow speed

132 fish passed through the device at this speed. The weight and length distributions are shown in figure 11 and 12. Four fish suffered limited scale loss of 5-10% (category 3). These were 17cm, 19cm, 22cm and 24 cm. The number of fish with scale loss was very low and almost the same as the net component, indicating that passage through the turbine caused no damage.

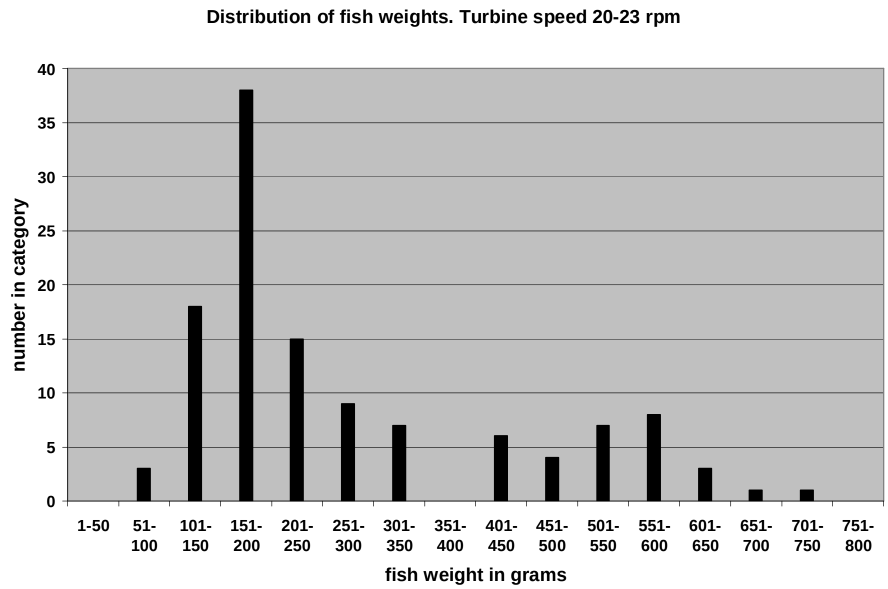

Figure. 11

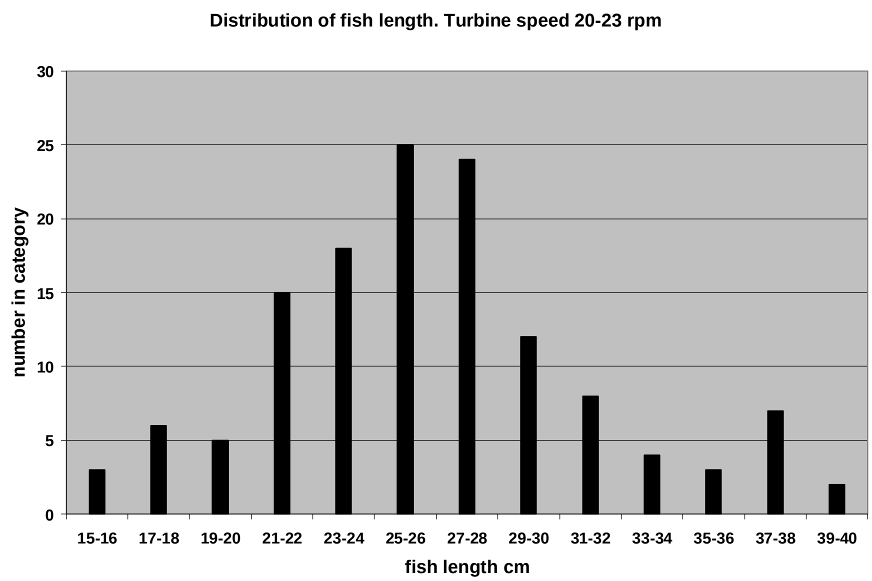

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Figure. 12

4.22 Medium Speed

120 fish passed through at this speed. The weight and length distributions are shown in figures 13 and 14. Three fish suffered limited scale loss of 5-10% (category 3), 2.5% overall. They were 23cm, 23cm and 25 cm. Again the percentage was within the net damage component and therefore it was unlikely any scale loss was caused by the turbine.

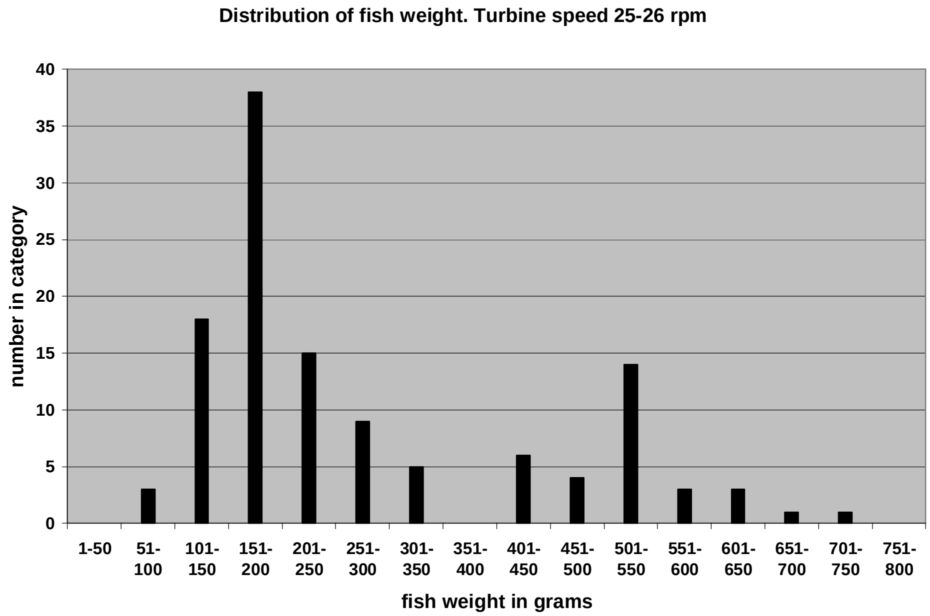

Figure 13

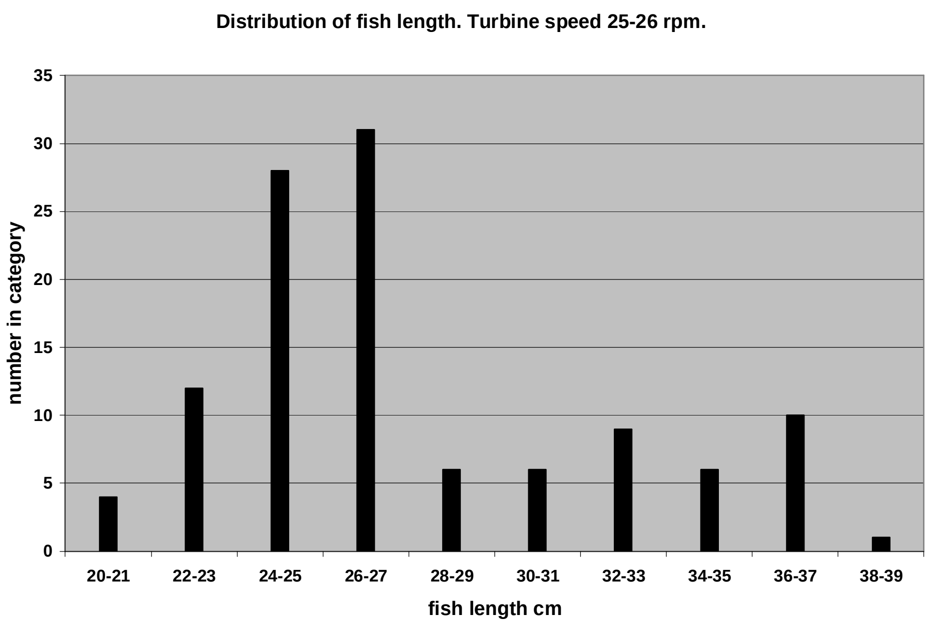

Figure 14.

4.23 High Speed

125 fish passed through the turbine. The weight and length distributions are shown in figures 15 and 16. Four fish suffered minor scale loss of 5-10% (category 3). These were 18cm, 20 cm, 22 cm and 25 cm. This gave an overall value of 3.02% and was almost within the net component.

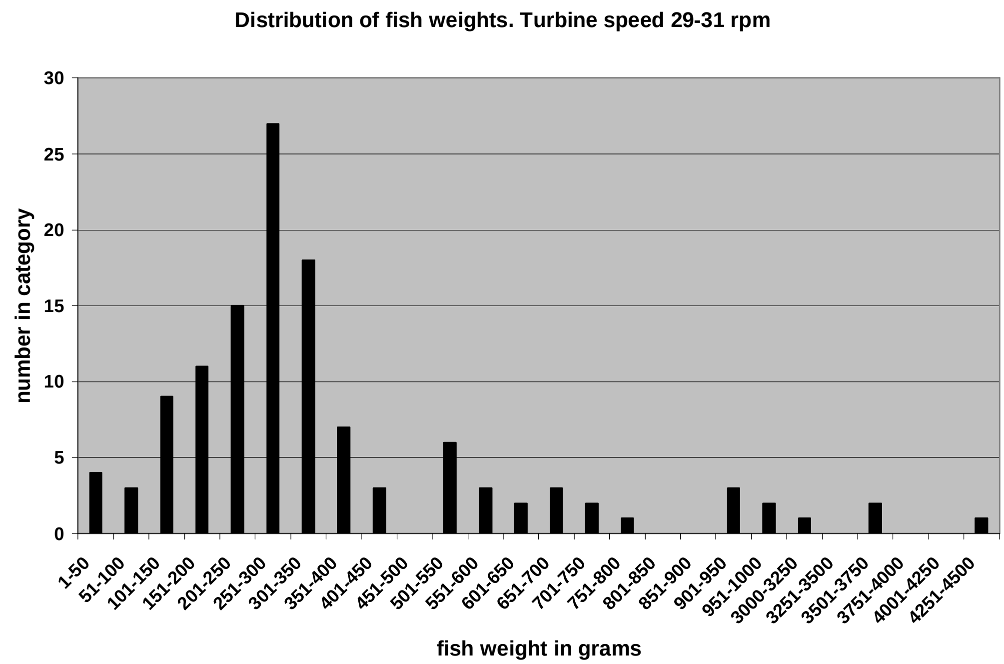

Figure 15.

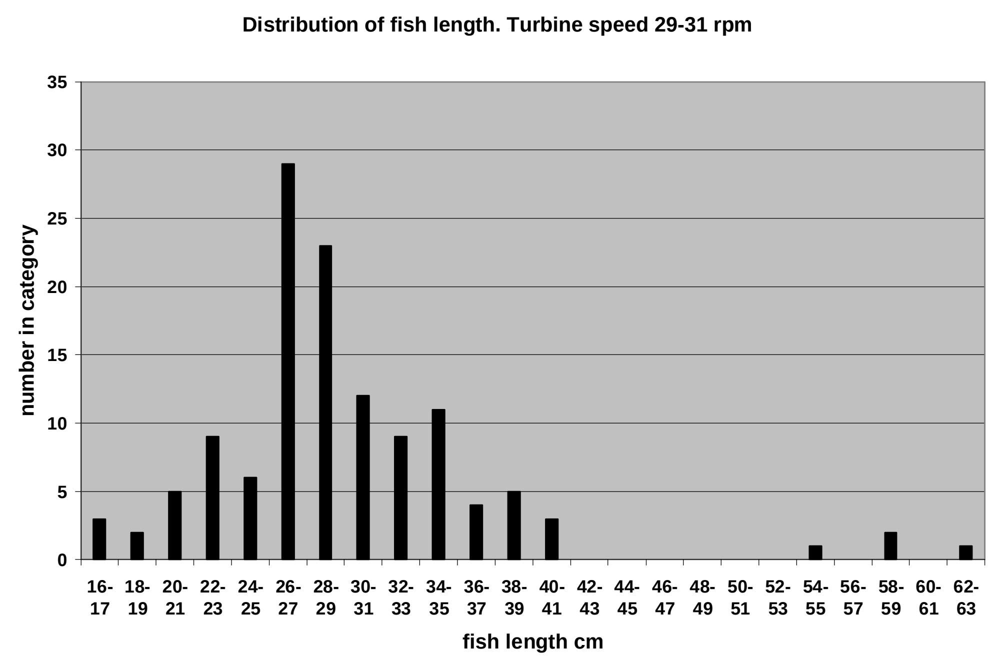

Figure 16

4.24 48 hour Tank Test

All the fish were alive and appeared healthy after 48 hours in the holding tanks. None displayed any behaviour such as listing to one side, lethargy or remaining motionless on the bottom for long periods that might indicate a delayed effect.

A Kruskall-Wallis test was used to compare the results from each turbine speed. (H=0.22, df=1, p=0.895). The high P value showed that there was no significant difference between slow, medium and high speed.

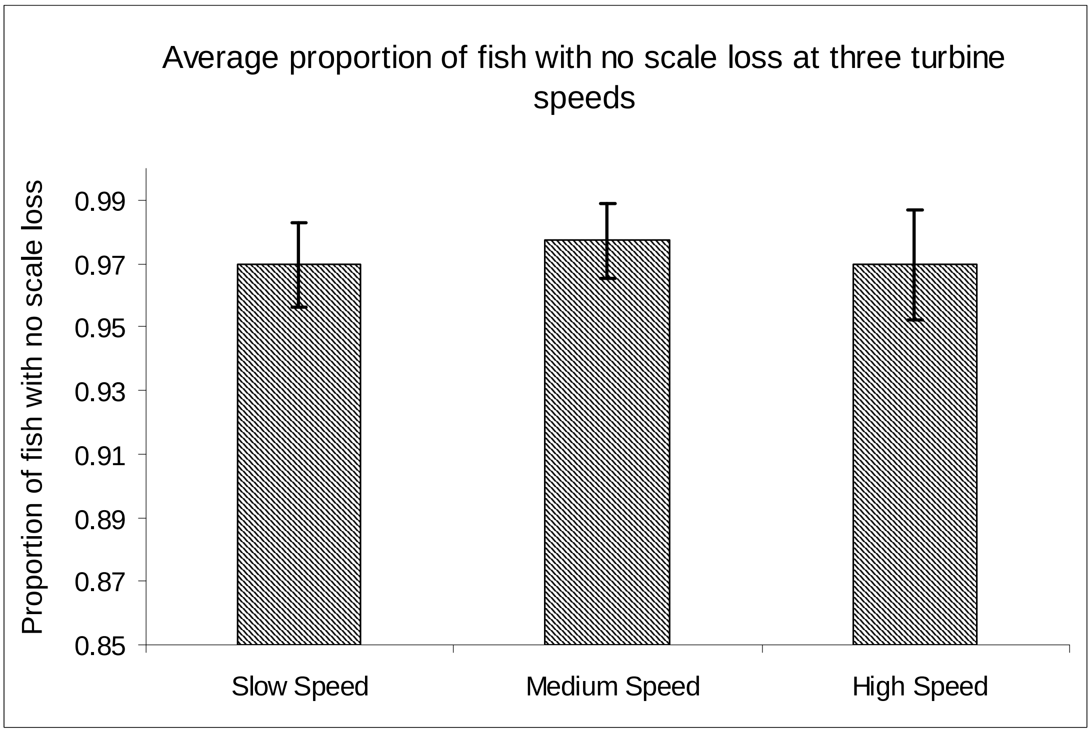

Figure 17.

The results from trials at 3 speeds are compared in figure 17 above. The error bars are +/- one standard error of the mean.

Evaluating the batch results using a Kruskall-Wallace test, gave a very high p value (H=0, df=1, p=0.953), showing that there was no difference in scale loss between batches and that using fish more than once did not effect the results. It also showed that fish can pass through a number of times without increasing the risk of damage.

4.25 Comparing results with the net test

Figure 18 compares the number of fish that sustained limited scale loss (category 3) across the 3 different speeds with the number in category 3 from the net test. It is evident from this that any scale loss sustained is within the net damage component and that passage through the screw caused no damage at all.

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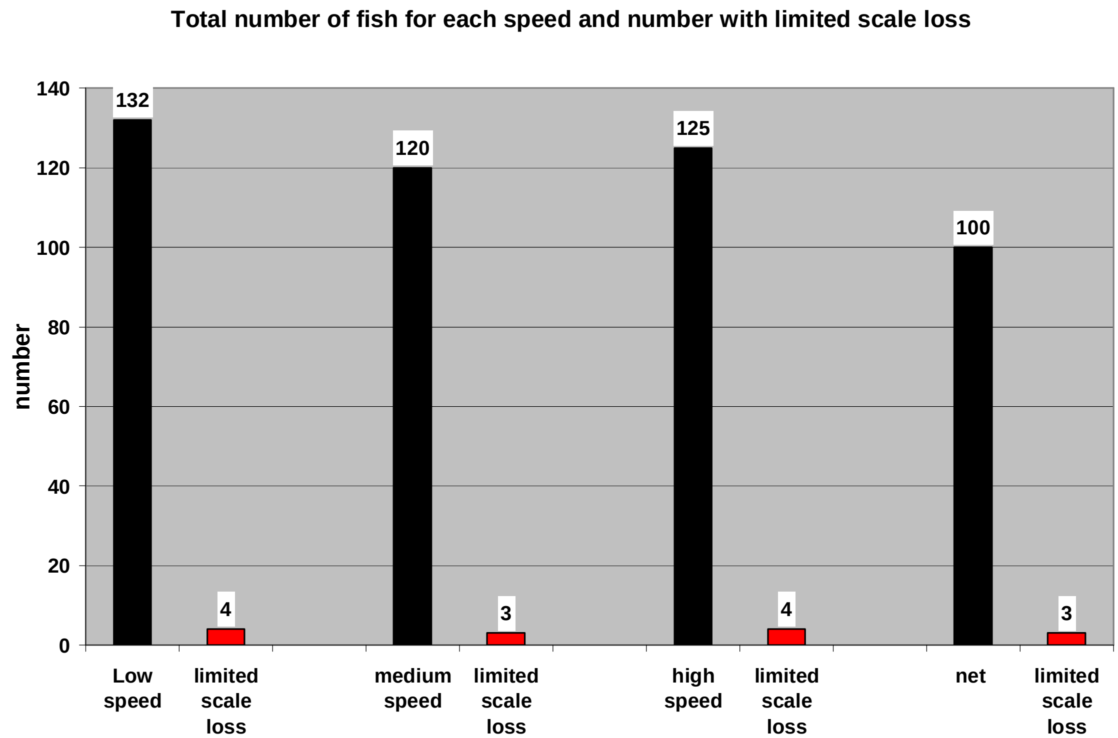

Figure 18.

An example of a fish before and after passing through is shown in Figure 19 below.
A fish showing minor scale loss, typical of those in category 3 is shown in Fig. 20.

Figure 19. The same fish before and after it has passed through the turbine.

Before

After

Figure 20 A fish with category 3 damage showing limited scale loss towards the tail.

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5 Passage of Smolts through the Turbine

5.1 Method

Smolts were monitored on the 24 and 25 April, 2007 and again on the 3 May.
From mid April smolts began to accumulate in the leat and forebay tank. Rainfall on the 22 and 23 April increased river levels by 15-20 cm. Increasing river levels after a dry period, is one factor that can stimulate the seaward run of smolts and it was considered to be a good time to begin monitoring.
The depth of water at the intake was 850mm, with total flow in the river estimated at 5000 l/s^{-1} and proportional take about 20% . The rotational speed of the screw was 22-24 rpm. Monitoring began at 5pm and continued through to 4am.
The behaviour of fish as they entered the device was recorded using an infra red sensitive underwater camera. Fish were removed from the holding box of the Fyke net, photographed and the condition assessed.

5.2 Results

Smolts were trapped throughout the evening and night, however, the majority of fish passed through between 2 am and 4 am as shown in Figure 21 below.
To reduce the stress caused by handling and time out of the water, fish were only photographed; they were not measured or weighed. A few of the larger and smaller fish were measured to give an indication of the size range. The smallest were 8cm and the largest 19cm.

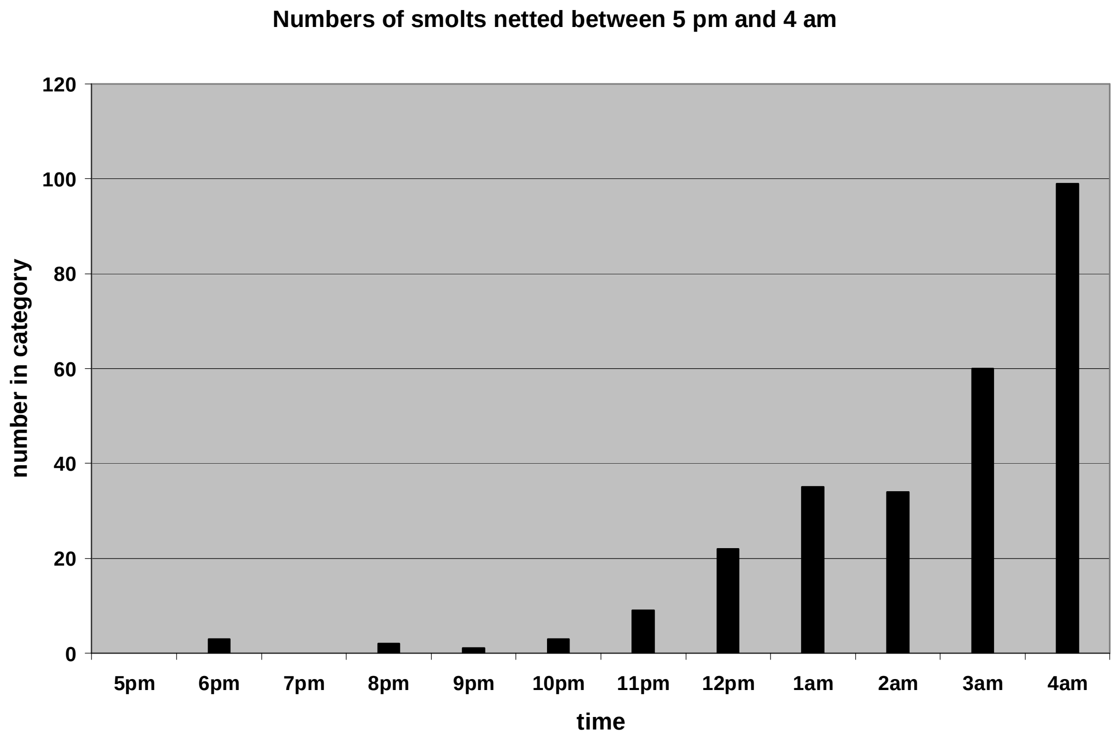

Figure 21

The fish holding box at the cod end of the net was emptied hourly. After a number of fish had been through it was apparent that being left in the net for an hour was too long, as the fish were being forced against the netting by the current and suffering stress and scale loss.

Figure 22 shows diagonal stripes and scale loss across the flank of the fish, corresponding to the net pattern. This was caused by the pressure of water forcing the fish against the netting.

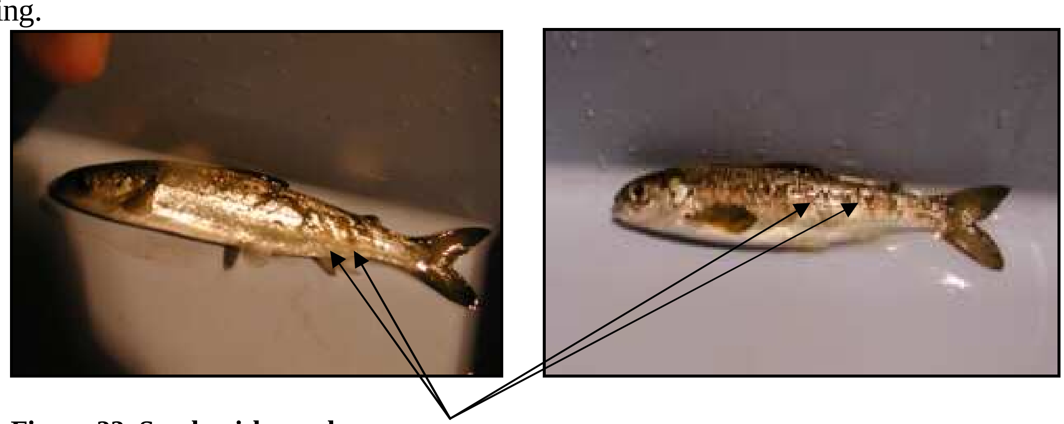

Figure 22. Smolt with net damage

For the rest of the study, the box was emptied every 15 minutes to reduce this effect.
In total 18 fish were trapped during the period in which the box was emptied hourly.

Of these, 3 suffered scale loss at the category 3 level (1-15%) and 1 at category 2 (above 15%). Overall 4 fish out of 18, or 22% suffered some damage.
After the procedural change, the level of scale loss decreased significantly. In total 249 fish were trapped after the procedure was changed to emptying the box every 15 minutes. 11 suffered minor scale loss of between 5 and 15%. (Category 3). Overall 4.4%, (1.4 % after adjustment for the net component). The dramatic reduction in scale loss after changing the procedure, suggests that the net was contributing to fish damage.
A Chi Squared comparison of the results from the first batch of fish compared to the second supports this.
Chi Sq. value 20.2, 2 df, $p<0.001$.

Other variables such as the turbine speed and river levels that may have influenced the result remained the same throughout the monitoring period.
Figure 23 shows the total number of smolts trapped, the number without any damage and the number with limited scale loss after correcting for the net component.

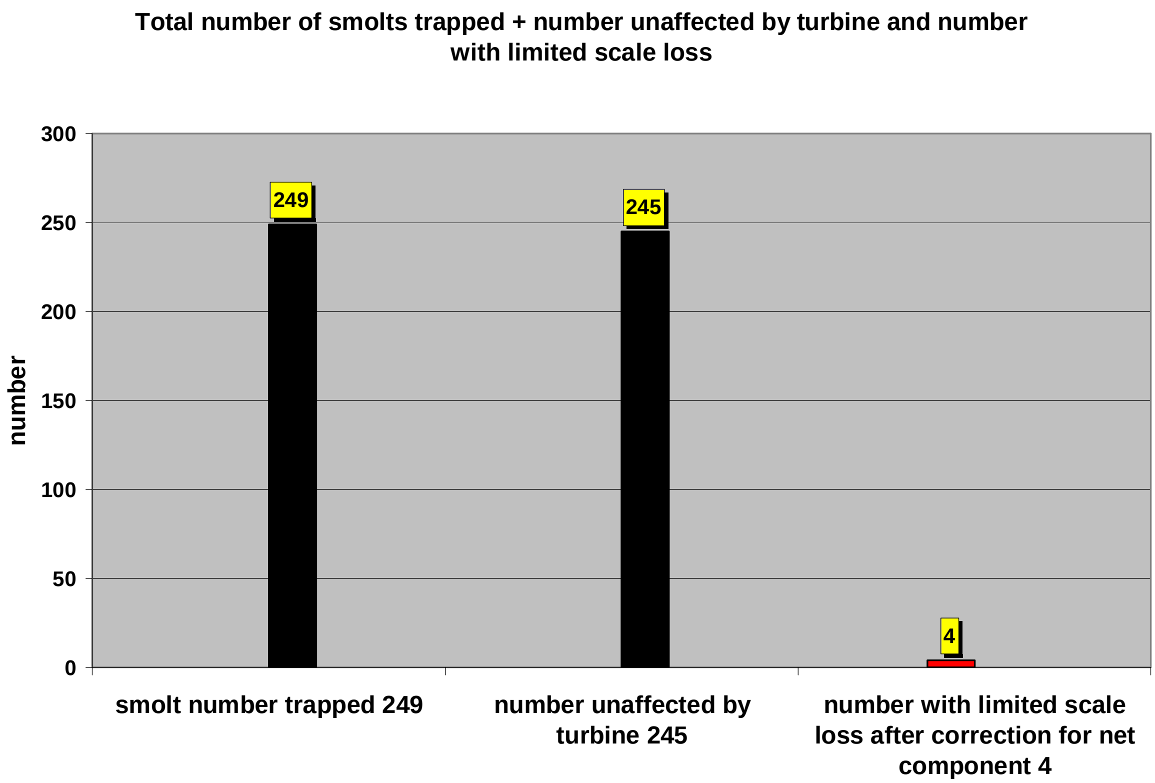

Figure 23

Pictures typical of the vast majority of fish that passed through the screw without any damage (category 4) are shown in Figure 24.

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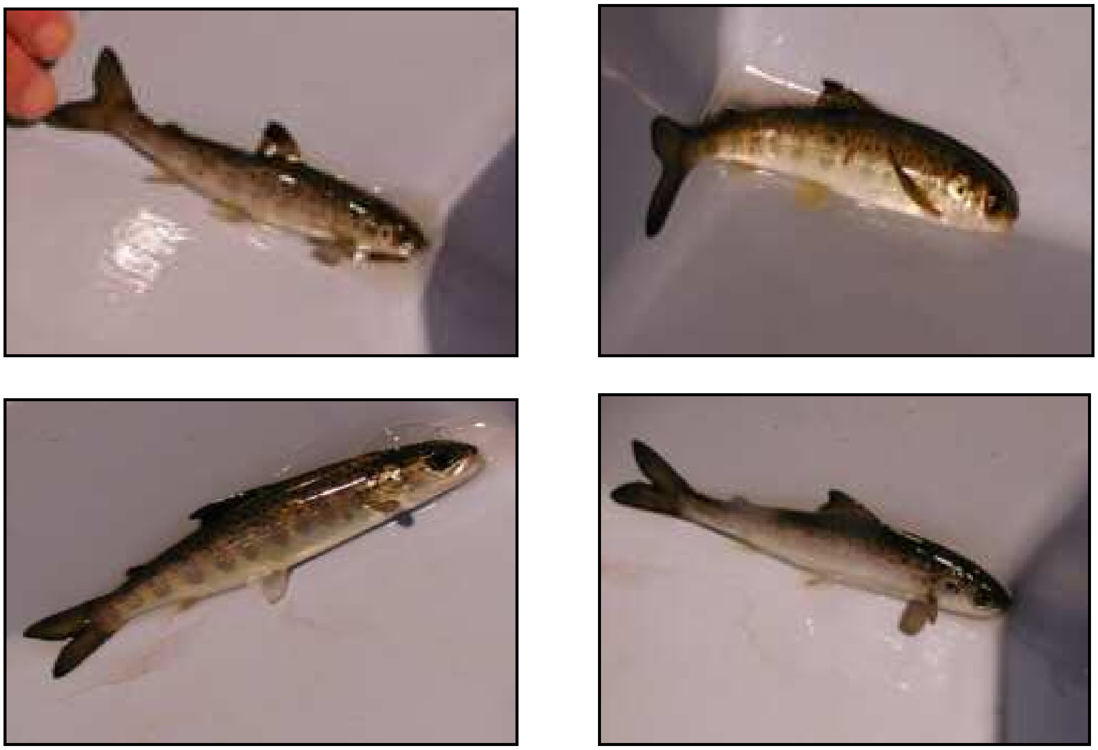

Figure 24. Smolts netted after passing through the turbine

Overall 1.4% of the smolts suffered limited and recoverable scale loss of less than 10%. It is generally considered that fish usually recover from scale loss of below 20%. (Kostecki, 1987). If more than 20% are lost, the fish is prone to bacterial and fungal infection that may reduce long term survival.

While 1.4% is very low, it is probable that the actual figure is even lower, as the fish were not checked before hand and it is likely that some had already lost scales during the passage downstream.

Most of the fish assessed at Hooidonkse Mill were small bream of between 4 and 7 cm that would have been prone to scale loss if forced against netting or rough surfaces. Tim Vries, the lead investigator for the study, confirmed that each fish was carefully checked for any sign of damage including limited scale loss, but none was found. (pers comm.) Unlike the River Dart site, the outflow channel fed directly into a large still basin and fish were not subjected to high water velocities in the net. This is probably why no net damage was observed by VisAdvies.

5.21 Start Up Procedure

During maintenance, the turbine is shut down and re-started by an automatic start up procedure. The turbine is powered up and spins to about 15 rpm, before the sluice gate is opened, allowing water to rush in.
Smolts accumulating at the end of the leat are sucked into the turbulent water when the gate opens.
An automatic start up was conducted on the 3 May, with a number of smolts evident in the forebay tank at the end of the leat. 12 fish passed through the screw and were netted at the outflow. One sustained bruising that could only have been caused by the pinching action of the leading edge. The fish suffered category 1 damage and was unlikely to survive beyond 24 hours. The others were not harmed. The single damaged fish is shown below.

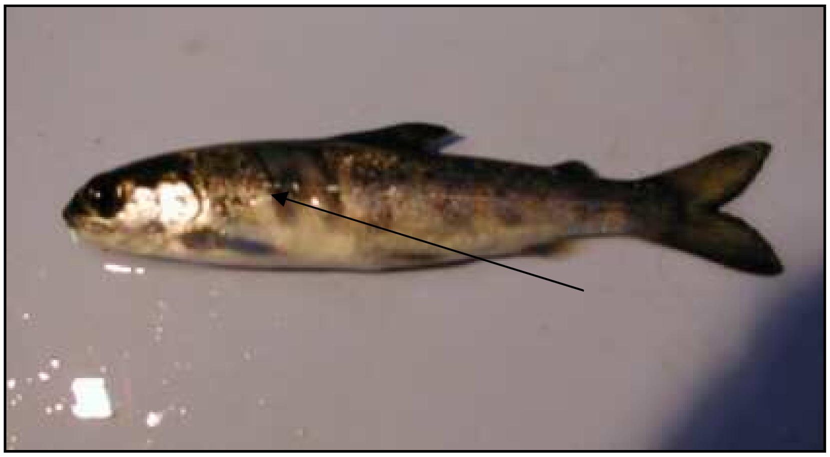

Figure 25 clearly shows the diagonal mark across the flank of the fish, corresponding to the width of the leading edge.

Figure 25

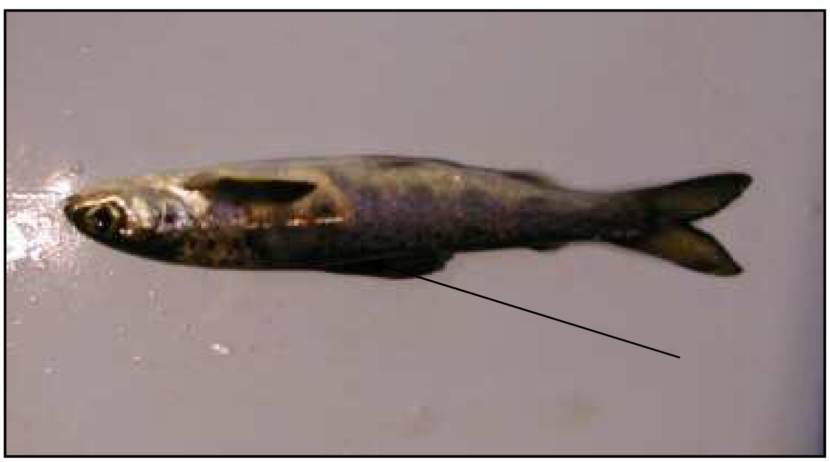

Figure 26 shows the scale loss resulting from the fish being scraped along the base of the turbine.

Figure 26

A statistical comparison of the start up data (1 of 12 trapped) and normal operating conditions (0 of 249 trapped), gave a **Chi Sq. value of 22.34, 1df. Prob. <0.001.**
This proves that conditions particular to the start up significantly increased the chance of fish being trapped by the pinch point of the leading edge.
The pinch point, shown in figure 27 is the only area of the screw that is likely to trap small fish and eels, especially if they enter swimming near the concrete base of the

forebay tank. A small number of eels were used in this study, revealing that they were susceptible to the pinching action.

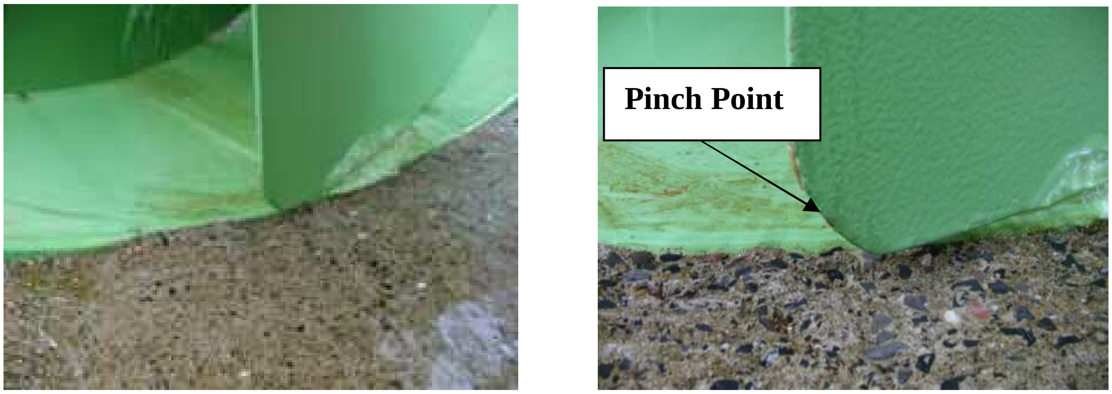

Figure 27. Pinch point created by overhanging leading edge and bevel.

After consultation with the Environment Agency, it was decided to modify the leading edge to remove the pinch point.

5.22 Analysis of camera footage

The footage shows that larger fish are able to swim actively against the flow and generally pass into the device after a few minutes of swimming. The largest fish (over 40cm) resisted entering for long periods and on occasion had to be "encouraged" into the screw.

The fact that some fish swam against the flow and moved away from the leading edge indicates that larger fish moving downstream would not automatically pass into the screw, but would have the option of turning around and swimming away from the fast flowing water at the intake.

It was evident from monitoring the smolts that they entered fairly quickly, generally delaying for less than a minute before descending. This was determined by estimating the number of smolts in the forebay tank every 15 minutes and comparing this to numbers trapped in the outflow net. There were never more than a dozen or so in the intake area, while up to 30 or more were often found in the net after 15 minutes. Had they been delaying by more than a few minutes, significant numbers would have been evident in the forebay tank. This is not surprising, considering the strong urge smolts would have to migrate downstream.

Smolts entered the screw in a similar way to brown trout, generally within 10 cm of the base and often drifting back tail first or passing through head first. There was one noticeable difference, however, in that smolts were sometimes seen to drift towards the screw tail first then turn at the last second and enter head first.

Smaller brown trout (<25cm) generally passed into the screw within a few minutes, however, they were often less keen to do so than smolts.

The study at Hooikdonkse Mill, found that larger fish tended to avoid the screw, possibly due to the low thumping noise produced. Water velocities at the intake are about $1 m/s^{-1}$. The burst swimming speed of fish, generally around 5-10 times body length depending on species would determine the size range of entrained fish. During the winter I would expect larger fish to pass through as they are less able to resist the flow in cold water due to reduced swimming speeds.

The response of fish to the intake has a number of implications for hydro sites.
Firstly, on salmonid rivers such as the R. Dart most fish moving down the leat/intake would be migratory smolts, kelts and possibly eels. Numbers of brown trout moving towards the intake would be minimal, therefore as long as fish actively migrating downstream readily enter the screw, it is unlikely there would be a build up of fish in the forebay tank and probably no need for a bywash channel.
(Note: the behaviour of kelts and eels at the intake will be evaluated in phase 2 of this study).
Secondly, Rivers with large populations of coarse fish species that have long unscreened intake channels/leats may need a bywash channel or fish pass to provide an alternative route for larger fish that will not readily enter the screw. If no alternative is available some fish may enter the screw, while others would probably swim back up the intake channel, especially if it is relatively short. The maximum length of channel that fish of a particular size and species could ascend, would be a function of water velocity, maximum sustained swimming speed, and water temperature.

6 Modification and Evaluation of Leading Edge

6.1 Modification of the Leading Edge

The leading edge overhangs the beginning of the trough by approx. 50mm. The bevel on the blade end creates a potential trapping action for small fish and eels as the blade sweeps around. This appears to be an anomaly on this installation, which is probably why other studies have never encountered this problem. A comparison with other Archimedes turbines revealed that the screw should not overhang the trough at all.
To rectify the problem, the leading edge was cut back by 50mm so it was within the trough and the bevel removed to create a straight end. In addition a rubber extrusion (see figure 28) was fitted along the entire length of the leading edge to soften any direct impact with fish, particularly large fish such as kelts with more mass and inertia. By spreading the impact over a larger area it is unlikely to cause bruising or scale loss. Dr. Spah concluded that the limited damage observed in his study was most likely caused by the leading edge becoming sharpened by stones after prolonged operation. The rubber extrusion protects the leading edge from stone damage.

The modified edge is shown in figure 28. The pinch point is removed and the extrusion (fish bumper) brushes within a few mm of the trough, preventing fish from being trapped.

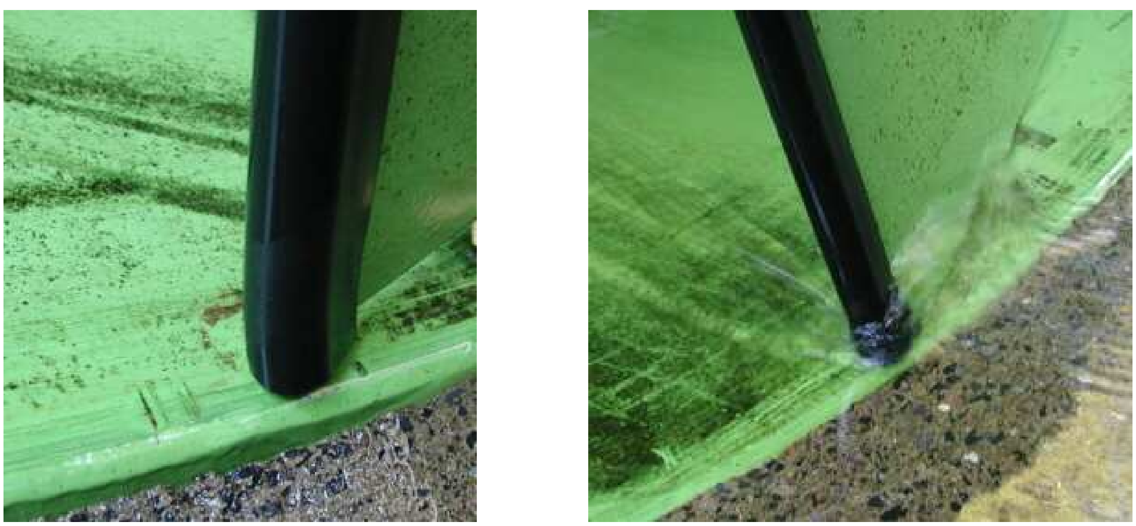

Figure 28. Modified leading edge removing the pinch point.

6.2 Evaluating the modified leading edge

6.21 Method

To determine if the modifications to the leading edge have resolved the pinching action, cameras were installed to record fish as they approached the edge and as they passed into the first chamber. It was important to ensure that the trout entered near the base of the intake, in the same way as smolts.

The trout were introduced via a 110mm diameter pipe with an escape window cut into the bottom. They emerged from the window within a few cm of the base and entered the screw naturally. The pipe was set 1 meter back from the leading edge to allow the fish to orientate before moving out into the flow.

Instead of using the Fyke net, fish were trapped in the outflow box by a frame of 10mm welded steel mesh. After each trial, the sluice gate was closed and the fish netted out of the outflow box and examined. This meant fish were not forced through the net and any issue of net damage was avoided.

6.22 Results

220 brown trout between 12 cm and 28 cm were recorded passing the leading edge and into the screw. Fish passed through at turbine speeds of between 25-30 rpm.

Analysis of video footage revealed that over 85% of the fish passed straight into the screw without swimming back towards the screen. Fish that swam against the flow and remained in the intake area behind the screens, were netted out after the sluice gate was closed and the water drained. Fish remaining in the intake area as the turbine is shut down are sometimes drawn into the screw with the residual water. It was noted that small fish (<12cm) are occasionally drawn into the small gap between the helix edge and the trough, resulting in scale loss. This is only likely to occur during trials and would be very unlikely to happen in normal operation. In this respect it represents an insignificant risk to fish, as firstly the turbine is only shut down occasionally for maintenance and secondly it would be rare that small fish would be in the forebay tank at the moment of shut down.

93% passed the leading edge within 10cm of the base, the rest entered higher than this. The orientation of fish as they entered the screw is shown in figure 29. 49% drifted back and entered tail first, 45% head first. 6% moved towards the edge head first and turned to face upstream before entering tail first. The vast majority seemed to avoid the leading edge, only 4% were touched by the rubber extrusion as they entered.

None of the fish suffered any damage at all and they were all alive and behaving normally after 48 hours in the holding tanks.

This confirmed that the modifications to the leading edge have removed the pinch point for small fish. It is likely that eels can also pass the modified edge safely, although this will be fully evaluated in phase 2 of this report.

Trapping the fish by screening the outflow box was more effective than using the Fyke net. There were adequate areas of reduced flow for fish to shelter and they were easily netted out when the turbine was shut down.

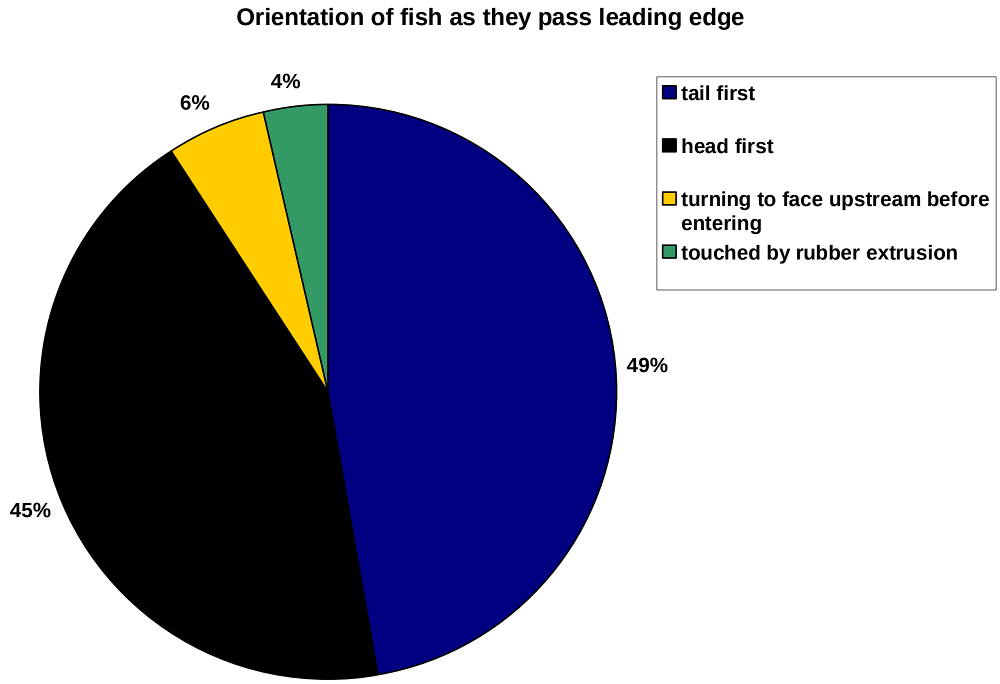

Figure 29.

7 Fish Passage and Disorientation

Disorientation of fish can occur in highly turbulent water, if they are rotated, tumbled and generally buffeted by the irregular flow patterns. High levels of disorientation for prolonged periods can affect the fishes ability to respond to predators, the so called startle response time (SRT).

Smaller age - 0 fish are usually more prone to behavioural impairment such as disorientation as they have a smaller mass and so sustain larger accelerations. They are often less prone to physical injuries for the same reason, eg they sustain smaller forces as they have less mass and inertia. (Guench et al, 2002). For this reason, it was deemed important to include a range of fish sizes in the study.

The ability to cope with a degree of turbulence and shear stress (fluids moving at different rates) is important for fish, especially riverine species. It has been estimated that brown trout rushing into fast flowing water to grab food items, experience rate of strain exposure of up to 5 m/s/m. (Hayes and Jowett, 1994). This is a measure of the exposure of fish to shear stress and turbulence. Fast flowing rivers can have near bed shear stresses of up to 30 N/m^2 (Statzner and Muller, 1989).

An extensive study into the effects of turbulence on disorientation by Odeh et al (2002), involved subjecting a range of fish species including juvenile Atlantic salmon and rainbow trout to jets of water of $3.2m/s^{-1}$, $8.3m/s^{-1}$ and $10m/s^{-1}$. The fish were monitored by camera and the effect on startle response time assessed by comparison with control fish. They calculated that a jet of $3.2m/s^{-1}$ created a shear stress of $30N/m^2$, equivalent to levels in fast flowing rivers, but well below turbulence levels during flood conditions. They found that $3.2m/s^{-1}$ had no effect on the startle response time of juvenile Atlantic salmon and rainbow trout compared to control fish. Higher levels of turbulence corresponding to shear stresses of $50N/m^2$ and above did begin to influence the SRT. It was noted that after exposure to high turbulence levels likely to cause disorientation, fish usually swam to the bottom and rested, often exhibiting listing behaviour with bodies tilted by up to 30^0 from vertical.

7.1 Method

To assess the degree of turbulence experienced by fish as they move down the screw and the likely disorientation, fish were introduced at the top and monitored by underwater camera as they moved down. The orientation of fish and behaviour as they descended was analysed in terms of the criteria listed below.

- **Rotated about the dorso-ventral axis.**
- **Rotated about the head-tail axis.**
- **Forced against the rotating edge or trough**.
- **Swimming normally and in the correct orientation.**

In addition, the behaviour in the outflow box, after they had passed through was also assessed in terms of signs indicative of disorientation such as abnormal swimming, listing from vertical, and resting for long periods.

7.2 Results

80 brown trout were filmed passing down the screw. The length distribution is shown in figure 30.

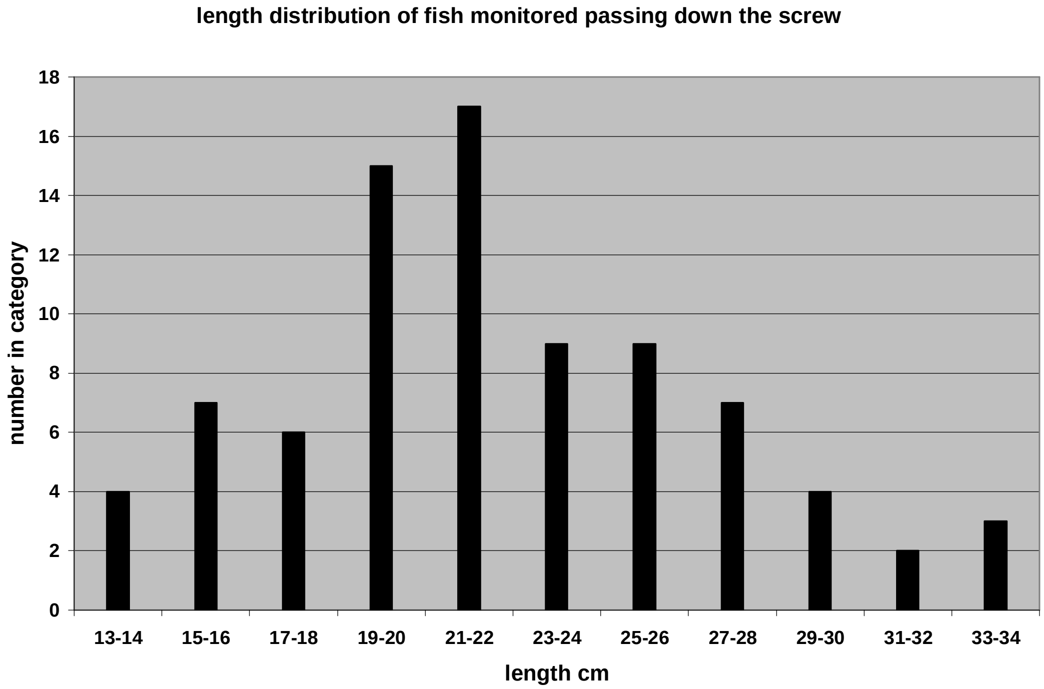

Figure 30

The behaviour of fish in camera view was analysed using the JOG feature on the recorder. This allows the image to be moved forward one frame at a time (0.08 sec.).
A camera with wide angle lense was used, however, it was still only possible to see approximately 50% of the chamber at any one time. Fish would drift into and out of view, so data from fish that remained in view for one second or more was analysed, avoiding the difficulty of assessing fish that were not in full view.

Over 200 units of footage of more than 1 second were recorded. In none of them were fish either rotated dorso-ventrally or head to tail or forced against the trough or screw. The fish swam normally and easily held position within the chamber. It was evident from the footage that levels of turbulence within the screw were low and very unlikely to cause disorientation that would affect the SRT. (see DVD)
Furthermore the footage of fish released at the end of the screw show them to leave swimming normally and in the correct orientation. They did not exhibit any of the symptoms indicative of disorientation.

I would conclude from the analysis that the turbulence within each chamber of the screw is very low indeed and well within the range experienced naturally by salmonids and probably most riverine species.(see calculations in appendix).
While it was not possible to remove fish fast enough from the end of the screw to make a SRT test worth while (the 5-10 minutes recovery time in the outflow chamber would have invalidated the test), I would conclude that it is very unlikely the SRT would have been affected. Comparison with video footage of fish moving through turbulent water in a Denil fish pass, suggests that fish are exposed to significantly lower levels of turbulence within the screw.

8 Monitoring the Outflow

8.1 Method

Water velocity at the outflow is high, averaging 2.5m/s^{-1}. To reduce the attractiveness of the tailrace to ascending fish, it is recommended that outflow velocities should be below 0.5 m/s^{-1}. (Turnpenny et al, 2005). To determine if significant numbers of fish are attracted to the outflow, how long they remain in the outflow region and if they try and jump at the end of the turbine, the area was monitored at different flow regimes.

Four infra red sensitive underwater cameras monitored fish movements. One was placed just below the outflow box to monitor fish passing up and down the channel. Another was placed in the middle of the outflow region, 1.5m below the end of the screw and facing upstream towards the screw. Two more were positioned above water and focused on the portion of the turbine above the waterline to capture any fish attempting to jump.

The area was monitored at different water levels, as during low water conditions, the leat takes proportionately more water and so may be more attractive to fish.

Monitoring was conducted for 6 days in July with water levels well below average daily flow and again in August for 6 days when water levels were above average daily flow for some of the time.

8.2 Results

The results are shown in the figures 31 and 32 and on the DVD that accompanies the report. A total of 25 fish, mainly sea trout, but including at least 3 salmon were seen throughout the period.

All the fish moved up the channel at night, between 10.30pm and 4.30am. Interestingly fish movements were mainly between 10pm-1am and again 3am-4.30am.

The average time spent in the outflow area was 7 minutes and 53 seconds. The standard error was 1 minute and 19 seconds. No fish were seen jumping at the end of the turbine.

More fish were seen in the outflow during higher river levels, probably because there were more moving upstream generally. Salmon and sea trout are usually stimulated to move upstream when river levels are over 40% average daily flow (ADF). On the R.Dart this corresponds to 3360 l/s^{-1}.

Fish would often move into the outflow box and back out several times before swimming down the channel to the main river. They were seen swimming close to the end of the screw for short periods, before heading back down the channel head first. This usually indicated they had left the outflow permanently as they were not picked up again on the cameras.

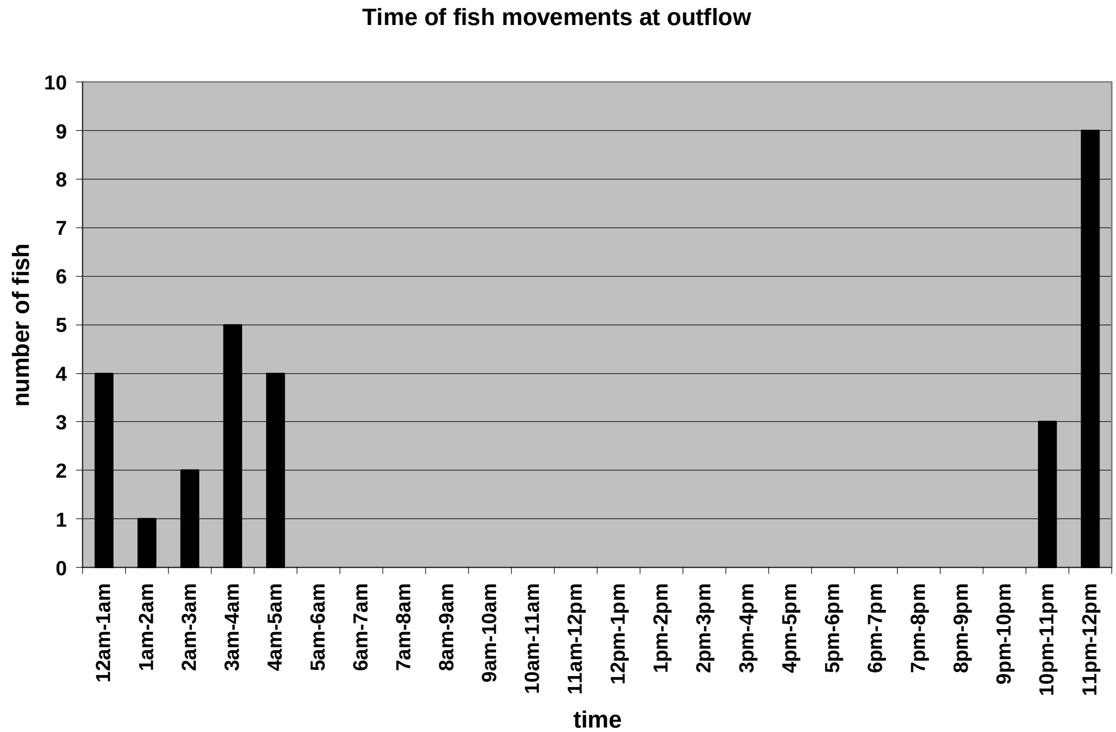

Figure 31

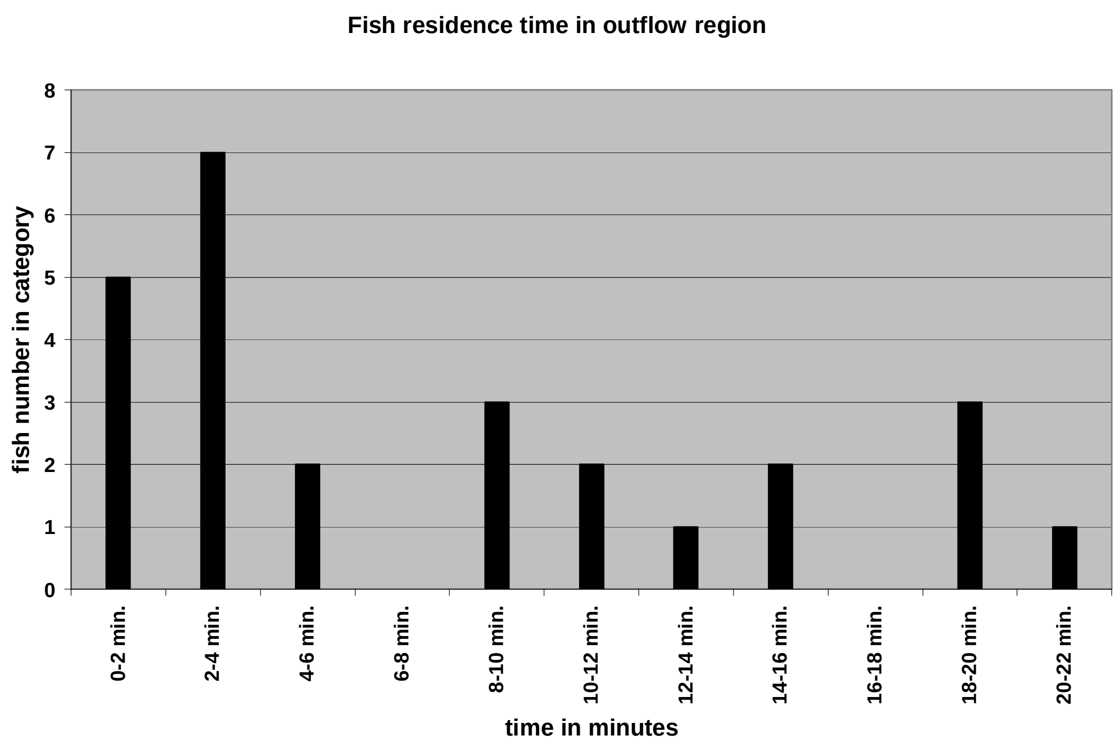

Figure 32

9 Discussion

Damage caused to fish by turbines is generally either mechanically induced or due to changes in flow characteristics.

Mechanical injuries are caused by direct strikes with the leading edge of runner blades, stay vanes or wicket gates or by abrasion or grinding. The extent of injury or death due to strikes is a function of fish length in relation to the leading edge thickness and speed of impact (Turnpenny et al 1992). Archimedes Screws have a slow rotational speed and only one significant point of contact, the leading edge of the Screw. The maximum peripheral speed is $3.8m/s^{-1}$ towards the tip of the helical blade. This is below the $4.0m/s^{-1}$ generally regarded as the threshold speed below which fish are not damaged.

Flow induced injuries are caused by velocity gradients producing shear forces. In conventional Frances and Kaplan turbines, these can be significant, disrupting swim bladders and contorting fish. The pressure differentials across regions of the screw are negligible and unlikely to cause any problems. As water flows down the trough at approx. $1m/s^{-1}$, it flows over a smooth steel surface and is divided into chambers by the moving sides of the screw that are also smooth. The velocity gradient occurs over a very short distance resulting in low levels of shear and turbulence. Shear forces are approximately $0.32N/m^{-2}$ within 13mm or less of the surface of the helix, it is therefore impossible for the turbine to generate highly turbulent water within the screw. (see appendix for mathematical calculations).

While this study has focused on salmonids and found little if any damage caused by the turbine, it is possible that other species are more susceptible. However, the two previous studies in Germany and Holland, referred to earlier in the report have found either no damage at all (Holland) or very minimal injury attributed to a damaged leading edge (Germany). Table A in the appendix combines results from all three studies, giving a total of 1341 fish across 15 species.

10 Conclusion

This study has shown that trout up to 63cm (4.4kg) can pass through the turbine safely, without sustaining any damage. The turbine was safe for fish across a wide range of operating speeds, up to 31 rpm. The only damage evident was limited scale loss caused by the outflow net. All of the fish with net induced scale loss were under 25cm long. It was surprising that none of the larger fish sustained any scale loss as they passed through the net, considering that over 50% of the fish used in the trials were above 25cm. The most likely explanation for this is the high water velocity in the net. Water velocities were approximately 2.5 m/s^{-1} at the outflow and through the net. Speeds increased in this region compared to the intake area because the outflow channel is shallower, averaging 400mm.

The burst swimming speeds of salmonids is approximately 10 times body length (Env. Agency Fish Pass Manual). All of the fish with limited scale loss were in the 8cm-25cm range, giving burst swimming speeds of between 0.8 m/s^{-1} and 2.5 m/s^{-1} Flow rates of 2.5m/s^{-1} at the outflow would have been too high for smaller fish to resist. Unable to swim against the flow, they were more prone to being forced against the netting when passing through to the holding box. This was confirmed by observation, as smaller fish could be seen pressed against the net.

The effect of the net was confirmed by a procedural change, that involved using a screen to trap fish in the outflow box, instead of the Fyke net. Out of a total of 220 fish that passed through and were retrieved from the outflow area, none sustained any damage.

Large numbers of smolts were able to pass through the device unharmed; at most 1.4% of fish sustaining limited and recoverable scale loss. I say at most, because these were wild fish and may already have sustained some scale loss before entering the screw.

Smolts and eels highlighted the issue of the pinching action of the leading edge, an anomaly on this installation, which has since been rectified. The modified leading edge was evaluated using small trout, introduced in such a way that they entered the screw in the same way as smolts (low down near the base). It was found to be safe and did not cause any problems. (Note, eels will be evaluated in phase 2 of this report).

The behaviour of fish as they pass down the screw was assessed with cameras inside the chamber. Levels of turbulence were very low and easily within the range experienced by most riverine species. Fish were not buffeted or disorientated as they passed down and displayed normal swimming behaviour after emerging at the bottom. While the startle response time was not measured, it is very unlikely that passing through the screw would have had any effect on the fishes ability to avoid predators.

Monitoring at the outflow indicated that some salmon and sea trout will swim up the outflow channel and remain there for over 20 minutes, however, the average residence time was under 8 minutes and fish did not attempt to jump at the screw. The delay in upstream migration is minimal and would not have any significant effect.

Overall, I would conclude that Archimedes turbines are extremely fish friendly and allow fish across a range of sizes to pass safely.

11 Recommendations

While the study has demonstrated that the Archimedean screw turbine is very fish friendly indeed, it has also highlighted the problems arising from the pinching action of an overhanging leading edge. It is important that the edge is within the trough, otherwise small fish and particularly eels are prone to being trapped as the blade sweeps around.
A check list for new installations should include.

- **Leading edge is at least 10mm within the perimeter of trough before rubber extrusions fitted.**
- **Rubber extrusions fitted correctly and sweeping within 5mm of trough.**
- **Removal of bevel on leading edge.**

The addition of the rubber extrusion along the entire leading edge protects it from stone damage, preventing it becoming sharpened. The extrusions have been evaluated for several months and seem very durable, however, it is important that they are checked during routine maintenance and replaced if damaged.

Screens

Intake:

Based on the results of this investigation, I would suggest that no intake screening is necessary. However, I will have to defer my final recommendations until phase 2 of the report (kelts and eels) is concluded.

Outflow:

Outflow screens are not needed, as the end of the turbine and outflow channel did not cause any problems for upstream migrants.

12 References

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13 Appendix

Damage categories

Damage level	Nature of damage
1	Death or serious injury likely to cause death within 24 hours. Deep wounding exposing internal organs
2	Moderate damage, including abrasions to skin. Fin damage and significant scale loss above 15%
3	Very little damage. Limited if any fin damage. Between 1% and 15% scale loss
4	No damage

Species	Maximum Length	Number	No. affected	Damage sustained
Bitterling (Rhodeus sericius)	5cm	5	0	
Bullhead (Cottus gobio)	14cm	5	0	
Brown trout (Salmo trutta)	44cm	708	0	
Bream (Abramis brama)	7cm	239	0	
Carp (Cyprinus carpio)	19cm	2	0	
Chub (Leuciscus cephalus)	43cm	63	5	limited scale loss/haematoma
Dace (Leuciscus leuciscus)	21cm	1	0	
Eel (Anguilla anguilla)	58cm	22	0	
Grayling (Thymallus thymallus)	36cm	3	0	
Perch (Perca fluviatilis)	18cm	18	0	
Rainbow trout (Oncorhynchus mykiss)	63cm	4	0	
Roach (Rutilus rutilus)	21cm	17	2	limited scale loss
Salmon, smolt (Salmo salar)	18cm	249	4	limited scale loss
3 Spined Stickleback (Gasterostues aculeatus)	5cm	5	0	
Stone Loach (Barbatula barbatula)	11cm	3	0	

Table A. Combining results from all 3 investigations. The River Dart, German (Spah, 2001) and Dutch (Vis Advies, 2007) studies.

Calculation of Shear force and Turbulence within the screw

Effect of screw blade movement relative to water body
This effect is considered the most significant and quantifiable, since it is common throughout the transit of the body of water through the machine, and will be the result of the fastest relative movements within the machine. If we reduce the problem to a two dimensional situation, where the blade is considered to be a smooth flat plate of unit width moving parallel to the direction of the oncoming fluid, we are able to quantify some effects.

The flow Reynolds number Re_x is defined as $Re_x = u_\infty x/v$

Where u_∞ is relative flow velocity
x is distance along surface
v is fluid kinematic viscosity

For the value of x_∞ we can take the worst case scenario as being close to the outer radius of the screw, where the relative velocity will be ωr or 3.46 ms^{-1} at 30 RPM, and given a 2.2m diameter. x can be taken to be again the worst case figure, and since the boundary layer thickens as the value of x increases, we will take it to be the maximum possible. This can be considered to be five rotations along the periphery, approximately $10\pi r$, 34.5m. v can be taken as $1.5x10^{-6}m^2s^{-1}$ at 0ºC, again a worst case.

Thus $Re_x = 79.6 \times 10^6$ at the bottom of the screw. This will mean that the boundary layer will be in the turbulent regime, which will limit its thickness, but locally mean that there are significant shear forces close to the surface of the blade. Because the velocity within the boundary layer increases toward main stream velocity asymptotically , an arbitrary convention is made to define the 'edge' of this layer. It is generally considered that the 99% point (whereby the flow velocity is 99% of the main stream velocity) allows for complete disregard of the viscous stresses, and is denoted by δ.

We can use Blasius' relation $\delta=0.37(v/u_m)^{1/5}x^{4/5}$, this being an approximation which can be taken to be true for turbulent boundary layers with Re_x values of up to 10^8.

Thus δ = 0.33m. This is large enough that a fish could be within this zone, so some consideration can now be given to the magnitude of the shear stress in this region. In a wholly laminar boundary layer, the shear stress is often assumed to be constant throughout the layer, in a turbulent boundary layer the shear stress is concentrated in the thin viscous sublayer, which is effectively laminar. The thickness of this can usually be taken to be 0.04δ, above which the shear stress rapidly reduces toward nil. This is a thickness of 0.013m or 13mm. Within this region shear stress can be taken to be $\tau_o = \tau = \mu(\partial u/\partial y)_{y=0}$, in this case $(\partial u/\partial y)$=158.9, and for a worst case of water at 0ºC, $\mu = 2x10^{-3}$, therefore $\tau_o = 0.32Nm^{-2}$ within the 0.013m viscous sublayer, and lower than this in the remaining part of the boundary layer up to 0.37m. This is significantly lower than levels experienced by riverine fish species.