Environment Agency

Evidence

Testing the effectiveness of fish screens for hydropower intakes

Project SC120079

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Miranda Kavanagh

Director of Evidence

Executive summary

Where hydroelectric power (HEP) schemes are used in any aquatic environment fish could be drawn into the turbines used to generate electricity. All HEP schemes in England are regulated by the Environment Agency, which has developed guidance on how to screen a range of structures such as hydropower turbines, intakes and outfalls to reduce the potential for environmental impacts including those on fish and eels.

This project was undertaken to quantify the level of protection provided to fish species by the screen designs recommended in the current Environment Agency hydropower guidance. This involved a literature review and field-based experimental evaluation. The focus of the study was on Atlantic salmon (*Salmo salar*) smolts (young fish ready to migrate out to sea) and European silver eel (*Anguilla anguilla*) (adult eels turn silver when they are ready to migrate out to sea). We chose these life stages of fish as they have a drive to swim downstream and will want to swim past our experimental site.

The existing guidance for screening run-of-river HEP schemes is based largely on understanding of intake and outfall screens. A literature review indicated that few studies have tested the effect of bar spacing (mesh aperture) on how easily fish bypass screens (fish deflection efficiencies), particularly in relation to the bar spacing guidance for silver eels and salmon smolts in the UK. Where studies have been undertaken, the results in terms of deflection efficiencies were highly variable and used a range of different screen sizes. We investigated the performance of two mesh aperture screens of 10mm and 12.5mm as these are the spacings recommended in Environment Agency guidance for the life stages of fish described above.

We tested how well fish were able to navigate past screens which involved the capture and tagging of individual fish, their subsequent release upstream of an experimental screen, monitoring of their movements through the site and recapture downstream.

We selected a study site (Abbey Mills on the River Test) with an experimental channel that provided something close to a realistic situation but where we could control the introduction and capture of tagged fish. Two trials were carried out: one for salmon smolts in spring 2014 and one for silver eels in winter 2014. Two screen apertures were tested during the smolt trials (10mm and 12.5mm) and one screen aperture (12.5mm) during the silver eel trials. Vertical stainless steel wedge-wire screens angled to the flow (at approximately 18°) were trialled in the experiments with screen apertures as defined within the Environment Agency guidance.

A review of available tagging methods confirmed the use of hydroacoustic tags as having a number of advantages over other tagging and assessment approaches. Some studies use only capture nets and we compared our results to this approach; capture nets alone would have underestimated the deflection efficiencies in our study. We used tags which provided real-time data, allowing the tracking of fish through the experimental area. The experimental site setup provided flow conditions that were representative of hydropower water intakes, with mean escape velocities of $0.44ms^{-1}$ (smolt) and $0.39ms^{-1}$ (eel). These were less than the maxima defined in the guidance, but still adequate to assess screen deflection efficiency and fish behaviour. Escape velocity needs to be within a range that the fish can swim away from.

We released 294 smolts during the trials; 15 tags failed and 64 smolts were used in a control trial without the screens in place. Of the remaining 215 smolts; 2 appeared to be trapped or impinged on the screen (one in the 10mm the other in the 12.5mm trial); 4 appeared to pass through the screen indicating potential entrainment (2 in the 10mm screen trial, 2 in the 12.5mm screen trial) and 1 fish did not move downstream. Some fish remained upstream of the deflection line in the experimental channel (5 in the12.5mm trial); hence these fish could not be considered to have been successfully deflected.

A total of 67 silver eel releases were carried out over the course of the trials, 16 tags failed and 24 eels were used in a control trial without a screen in place. The remaining 27 eels all successfully bypassed the installed 12.5mm screen; none were trapped or drawn through the screen.

To calculate the true deflection efficiency of the screens in our trials we took account of sample size and the possibility that some fish bypassed the screen by chance.

- We measured an overall deflection efficiency of at least 92.4% (with 95% confidence) for salmon smolts with a 10mm aperture screen and an overall deflection efficiency of at least 87.7% (with 95% confidence) for a 12.5mm aperture screen.
- We measured an overall deflection efficiency of at least 89.5% (95% confidence) for a 12.5mm aperture screen for silver eels.

Under the test conditions experienced both the 10mm and 12.5mm screens for salmon and the 12.5mm screen for silver eels provided minimum deflection efficiencies for downstream migrants of between 87% and 92%.

Acknowledgements

We would like to thank Jon Hateley (Environment Agency) for his support in using the acoustic tagging technology and interpreting results.

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1 Introduction

Where hydroelectric power (HEP) schemes are used in any aquatic environment it is possible that fish will become entrained into the turbines used to generate electricity. All HEP schemes in England are regulated by the Environment Agency and the Environment Agency guidance for run-of-river hydropower development has been developed to reduce the potential for environmental impacts including those on fish (Environment Agency 2013).

One specific area of the Environment Agency guidance for run-of-river hydropower development covers the need to provide appropriate screening to prevent fish injury or mortality by restricting access to HEP turbines where this is considered to be a risk. Fish screens are fitted to protect resident fish and those moving past the site and most are positive exclusion screens, which form a physical barrier to fish to divert them away from the turbine to a suitable bypass or fish pass. Fish migrating downstream are at risk from entrainment into the turbine channel as they are often using areas of faster river flow to aid their migration. Fish may also attempt to migrate upstream through the turbines where the turbine flow provides the main flow over the barrier.

Where fish passage may be impeded as a result of an abstraction or impoundment (as required for hydropower installations), the Environment Agency can invoke Sections 24 and 25 of the Water Resources Act 1991 and place conditions on the owner/operator to install a suitable form of screen to prevent fish entrainment. This allows the Environment Agency to comply with its statutory duty under Section 6(6) of the Environment Act, 1995 (as amended by the Marine and Coastal Access Act, 2009) to 'maintain, improve and develop fisheries for salmon, trout, eels, lamprey, smelt and freshwater fish' (Environment Agency 2010). Part 4, Regulation 17 of the Eels (England and Wales) Regulations 2009 broadly requires that 'eel screens' and/or bywashes are placed in qualifying diversion structures.

The Environment Agency has published guidance on screening for fish in the following documents:

- *Guidance for run-of-river hydropower development*, which contains an overview of Environment Agency guidance and a glossary of technical terms and associated guidance notes (Environment Agency 2013)
- *Screening at intakes and outfalls: measures to protect eels* ('The eel manual', Environment Agency 2011)
- *Environment Agency fish pass manual* (Environment Agency 2010)
- *Screening for intakes and outfalls: a best practice guide* (Turnpenny and O'Keeffe 2005)

Fish screens can harm fish if they are not appropriately designed. For example if the escape velocity (also referred to as escape velocity) is too great, fish may become impinged on the screens. A poorly designed screen or bywash (the outlet where fish move downstream past a screen) can also result in a delay to downstream migration. The design requirements for the bywash and screen arrangements are given in the Environment Agency guidance for run-of-river hydropower development (Environment Agency 2013), but there is currently only limited supporting evidence of their deflection efficiencies.

Existing guidance on fish screen design is not prescriptive as to what fish passage efficiencies are required for different structures. This is because the dynamics of the fish populations affected by the structure will vary according to site and species, as will the practicality of installing effective measures. However, for rare or threatened populations, particularly for life stages which occur in relatively small numbers, the aim should be to achieve as close to 100% passage as possible. The aim of this project is to focus on providing supporting evidence of deflection efficiencies of salmon (smolts) and eels (silver) in response to the screen dimensions recommended in the guidance for run-of-river hydropower development.

1.1 Project aims

This project aimed to quantify the level of protection provided to fish species by the screen design recommended in the hydropower guidance. The work has been conducted through a literature review and field-based experimental evaluation. The focus of the study was on Atlantic salmon smolts (*Salmo salar*) and European silver eel (*Anguilla anguilla*).

The principal objectives were to:

- undertake a literature review focusing on the efficiency of screens for deflecting fish
- develop a protocol to measure the efficiency of two vertical screen apertures (10mm and 12.5mm for Atlantic salmon smolts and 12.5mm for silver eels) using experience and information collated during the literature review
- apply this protocol under experimental conditions for salmon smolts and silver eel
- report the experimental outcomes with a focus on screen efficiency in preventing entrainment and impingement of two fish species at key migratory life stages
- determine the deflection efficiencies of the recommended screens

1.2 Project context

The ideal way to test the effectiveness of a fish exclusion screen is to establish a monitoring programme at a variety of hydropower sites. The full variety of screen orientations and screen parameters (angle, inclination and aperture) would be tested, while also assessing the responses of different species and life stages. This would give a thorough view of the effectiveness of the recommended screens at hydropower sites across the UK. However, this is expensive and difficult to achieve as real world settings are very hard to control and measure and to achieve this would require excessive costs and time, and would not always be acceptable to operators of hydropower installations.

Instead we established an experimental arena that mimics, as far as possible, the general conditions experienced by a fish passing a hydropower screen system, as designed following the guidance for run-of-river hydropower development (Environment Agency 2013). It is accepted that this arena would be unable to directly mimic a real hydropower setup, not least because no single mimic can address all possible site format/arrangement scenarios, flows and conditions experienced by real hydropower sites.

1.3 Current Environment Agency guidance

The current guidance provided by the Environment Agency specifies the bar spacing for screens based on the species requiring protection, geographical locations (which affects fish size) and turbine characteristics. This information is summarised in Table 1.1, which is taken directly from the current Environment Agency best practice guidance for hydropower screening (Environment Agency 2013).

Table 1.1 Summary of the current Environment Agency best practice guidance for hydropower screening (taken from Environment Agency 2013)

<table>
<tr><th>Situation</th><th colspan="3">At intake – fish screening requirements</th></tr>
<tr><td>Traditional waterwheel
Most Archimedes screw designs</td><td colspan="3">Trash screen (100mm) – see also detailed guidance in Tables S6, S7 and S8 as in some cases smaller aperture screens will be needed to provide protection for larger fish</td></tr>
<tr><td>Impulse turbines, such as Pelton and Turgo</td><td colspan="3">Drop through screens ≤3.0mm (for example Coanda style)</td></tr>
<tr><td rowspan="5">All cross-flow turbines and other turbines with a maximum turbine flow <1.5m³ per second</td><td rowspan="3">Migratory salmonids</td><td>Region*</td><td>Screen aperture</td></tr>
<tr><td>Y and NE, NW, SW (D and C) and Wales*</td><td>≤10.0mm</td></tr>
<tr><td>Mid, Ang, SE, SW (Wessex)*</td><td>≤12.5mm</td></tr>
<tr><td>Other species, including eels</td><td colspan="2">≤12.5mm (see notes)</td></tr>
<tr><td>Where protection of salmonid parr or young of year coarse fish (O+) is required</td><td colspan="2">Default is 6.0mm
Such screening can be used for part of the year when parr or young of the year fish require protection</td></tr>
<tr><td rowspan="4">Any other turbine with a maximum turbine flow ≥1.5m³ per second (excluding cross-flow turbines)</td><td rowspan="3">Migratory salmonids</td><td>Region*</td><td>Screen aperture</td></tr>
<tr><td>Y and NE, NW, SW (D and C) and Wales*</td><td>≤10.0mm</td></tr>
<tr><td>Mid, Ang, SE, SW (Wessex)*</td><td>≤12.5mm</td></tr>
<tr><td>Other species, including eels</td><td colspan="2">≤12.5mm (see notes)</td></tr>
</table>

Notes (taken from Environment Agency 2013):

*Environment Agency Regions: Y and NE – Yorkshire and North East; NW – North West; SW (D and C) – South West (Devon and Cornwall); Mid – Midlands; Ang – Anglia; SE – South East; SW (Wessex) – South West (North and South Wessex); Wales – Environment Agency Wales

The screen aperture necessary to protect eels is dependent upon the size of eels and the orientation of the screen (its angle to the flow). Screen apertures for adult eels can range from 9mm to 20mm. For further guidance, please refer to the Environment Agency eel screening guidance, *Screening at intakes and outfalls: measures to protect eel* (Environment Agency 2011).

Further protection may be required for species protected under specific legislation – such as lampreys, shad and bullhead where they are designated features of Habitats Directive sites. If there are no eels or salmonid smolts present, a default screen aperture size of 12.5mm is recommended. Where protection of young of year fish is needed, smaller screen apertures may be required depending upon the type of turbine used.

The use of other screen aperture sizes must be based on evidence and linked to the size of fish which need to be prevented from passing through the screen. The values provided in Table 1.1 assume that screening best practice is followed (e.g. screens are angled to the flow where appropriate).

In addition to the bar spacing of the screen, guidance on escape velocities is also provided in the Environment Agency guidance (2013). Maximum acceptable escape velocities for the species being protected by the screen are given for salmonids, coarse fish and shad, eel and lamprey (Table 1.2). The escape velocities are based on the swim speeds of each of the species; the fish must be able to swim away from the screens to avoid impingement. Smaller fish which are not physically excluded from the turbine by the screens may still be diverted. This may occur where the screen acts as a behavioural deterrent provided escape velocities are low enough to avoid entrainment.

Table 1.2 Maximum acceptable escape velocities. Taken from Environment Agency hydropower screening guidance (Environment Agency 2013)

Fish species	**Maximum escape velocity (ms^{-1})**
Salmonid	0.60
Coarse fish and shad	0.25
Eel	0.50
Lamprey	0.30

Environment Agency guidance for screening intakes and outfalls to protect eels gives the advisory escape velocity for silver eel as $0.4ms^{-1}$ at screen angles between 21° and 90° and $0.5ms^{-1}$ for screens angled at ≤20° (Environment Agency 2011).

2 Literature review

2.1 Screen properties

This section provides a review of available literature on the effects of bar spacing, screen angles and screen inclinations on fish deflection. Particular attention is paid to studies which have reported on screen properties recommended in the Environment Agency guidance (Environment Agency 2013), and which report on salmonid smolts and silver eels. A summary of the studies reviewed, including details on screen properties and key findings, is provided in Appendix A.

The following definitions have been provided for screen properties. Definitions of other terms are provided in the Glossary:

- **Bar rack screen –** a screen design made from bars instead of mesh.
- **Bar spacing –** the space between bars (also known as slot width).
- **Bar width** – the width of the individual bars.
- **Bywash** – the outlet where fish move downstream past the screen.
- **Louvre system** – typically a series of vertical steel slats set with their broad faces at right angles to the direction of flow.
- **Mesh size** – mesh is used on a number of screens such as traditional passive mesh screens and wedge-wire mesh screens. Mesh size can vary from a course mesh with large gaps to a fine mesh with small gaps. The size of the mesh will influence the ability to prevent fish of different sizes moving through the screen.
- **Screen deflection efficiency** – the percentage of fish deflected by the screen (i.e. not impinged or entrained), instead moving down past the screen and through the bywash.
- **Screen angle** – the angle of the screen relative to the river bank or channel wall (Figure 2.1).

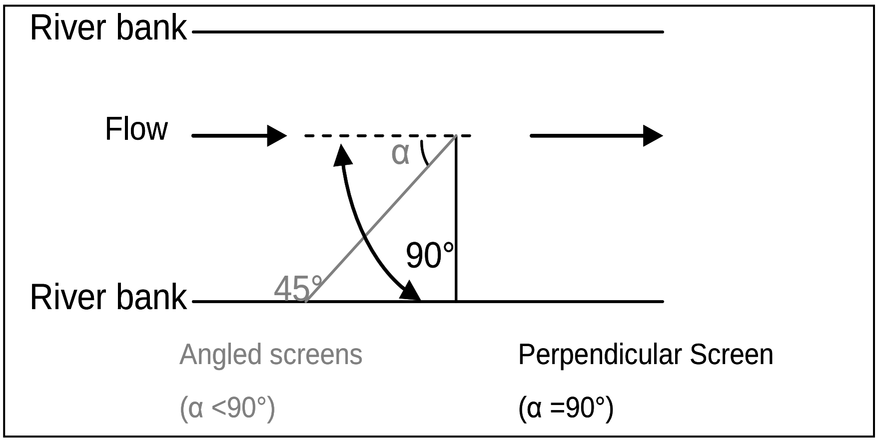

Figure 2.1 Bird's-eye view from above the river to show screen angle. Angled screens α<90° (45° in this example), perpendicular screens α=90°

Perpendicular (on non-angled) screens are installed at a right angle to the channel wall, whereas angled screens have an angle of less than 90° between the screen and the channel wall.

When screens are positioned at right angles to the flow they are often affected by blinding (build-up of debris) and also provide no assistance to fish moving past the screen into a bywash. Having the screen at an angle can ensure that the escape velocity is kept below the required design value. An angle of 30° or less provides the best screening properties (Environment Agency 2013).

- **Screen inclination** – the angle of the screen relative to the channel bed or to vertical (Figure 2.2).

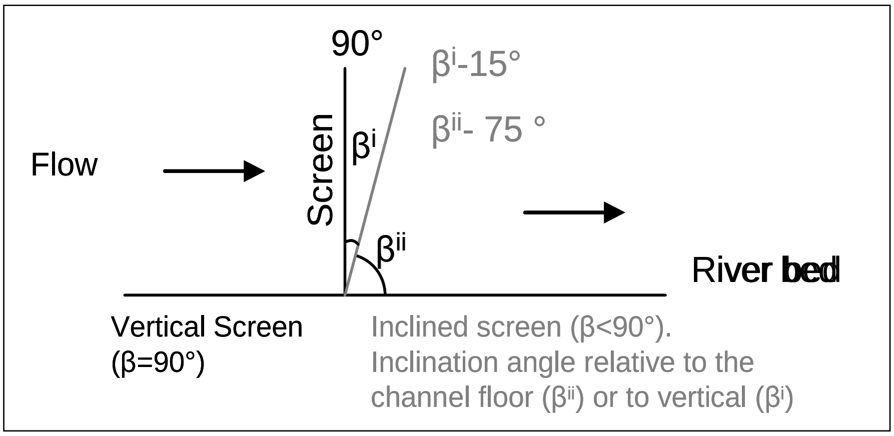

Figure 2.2 Cross-sectional view to show screen inclination Vertical screens β=90°, inclined screens β<90°

2.1.1 Bar spacing

Bar spacing refers to the distance between the bars on a screen. Few studies have investigated 10mm and 12.5mm bar spacing on salmonid smolts and silver eels. Four UK studies are of particular relevance: the field flume trials carried out on downstream migrating juvenile salmonids with 10mm and 15mm bar spacing (Turnpenny 2010); the laboratory flume tests looking at responses of downstream migrating adult European eels to bar racks with 12mm spacing (Russon et al*.* 2010); the field tests with salmon smolt at a HEP site in Scotland with 10mm spacing; and the comparison of 10mm and 12mm bar spacing on salmon smolt in an experimental setup on the River Gaur, Scotland (Clough et al*.* 2000). These four studies provide the most extensive literature on testing of bar racks in the UK, and they are summarised in Appendix A.

The studies of screens of bar widths between 10mm and 15mm showed positive results indicating high levels of deflection of salmonids. Clough et al. (2000) used Atlantic salmon smolts (*Salmo salar*) of between 135mm and 190mm, Turnpenny (2010) used 61–122mm rainbow trout (*Oncorhynchus mykiss*) and Turnpenny et al*.* (2004) employed 95–145mm Atlantic salmon smolts. Silver eel of size range 583–806mm have also been found to experience high fish deflection efficiencies with such bar screen sizes (Russon et al*.* 2010).

Turnpenny (2010) found screen efficiencies for rainbow trout, *Oncorhynchus mykiss* (in the absence of available Atlantic salmon smolts) (length 60.9 to 121.8mm, mean 90.83mm) varied from 88.35% to 100%, with higher performances for the smaller bar width tested (10mm) compared to 15mm (Table 2.1). During the experiments no fish were seen to be impinged on the screen at any time: reported mean escape velocities were <0.6ms^{-1} during the experiment, within the maximum value detailed in the Environment Agency guidance (Environment Agency 2013).

Table 2.1 Fish deflection efficiencies for all tests (18°, 45° and 90°). Table from Turnpenny (2010)

Slot width (bar spacing) (mm)	Screen angle (°) relative to the flow	Fish deflection efficiencies (%)
10	18	94.41
10	18	94.41
10	18	97.20
10	18	94.41
10	45	97.67
10	45	100.00
10	45	100.00
10	90	95.34
10	90	100.00
10	90	100.00
10	90	88.35
15	18	97.20
15	18	100.00
15	18	98.14
15	18	94.41
15	18	96.27
15	18	96.27
15	45	97.20
15	45	94.41
15	45	96.27
15	90	90.68
15	90	95.42
15	90	95.42

Turnpenny et al. (2004) found 10mm screens (angled at 15° and inclined 10°) to be highly efficient at deflecting salmon smolts (length range 95–45mm, mean 177mm), with the exception of one undersized hatchery smolt (100mm). No impingement was recorded and no fish were entrained.

Clough et al. (2000) tested 10mm and 12mm screens at different angles (section 2.1.2) and inclinations (section 2.1.3) on Atlantic salmon smolts (length range 135–190mm, mean 162mm). No fish were impinged on the screen during any of the setups tested; however, deflection efficiency (in the 30 minute experiment duration) varied from 7.7% to 87.7% with a large variability between replicates under each setup.

Russon et al. (2010) found 12mm bar spacing to be highly effective at deflecting European silver eels (length range 583 to 806mm, mean 660mm), with no eels passing through the bar rack at any of the screen angles or inclinations tested. However, angling of the screens was required to prevent impingement; further details of screen angles are given in sections 2.1.2 and 2.1.3.

There are a number of published reports on screen testing outside the UK on a range of screen types, mesh sizes, fish species and setups. These are also of relevance and are discussed here.

A study of European silver eels (length range 560–860mm, mean 663mm) migrating downstream through the Tange hydropower station on the River Gudenaa in Denmark found very low passage efficiency (35.5%), attributed to a combination of screen and bypass design and setup (Pedersen et al*.* 2011). The trashracks[1] had 10mm spacing between bars (the maximum spacing permitted under Danish legislation). Although the deflection efficiency of the bar rack was not measured, during high flows escape velocities typically reached $1ms^{-1}$. This is above the maximum escape velocity recommended by the Environment Agency (2011), and resulted in impinged eels being removed by the automatic debris cleaner.

A number of studies have reported on fish passage with bar spacing wider than 12.5mm. One of the most commonly studied setups is trashracks with 30mm bar spacing. This type of rack is commonly found at hydropower sites around the world, and is usually designed to prevent larger debris entering the turbines rather than to prevent entrainment of fish.

It is widely acknowledged that trashracks with >30mm bar spacing do not prevent entrainment of downstream migrating silver eels (Boubée and Williams 2006 – shortfin eels length range 630–1,210mm, longfin eels length range 640–1,300mm; Gosset et al*.* 2005 – European silver eels, size range not specified; Haro et al*.* 2000 – American silver eels, size range not specified; Travade et al*.* 2006, 2010 – European silver eels, length range 450–750mm). However, results on the effectiveness of these trashracks as a behavioural deterrent are less conclusive. For example in field evaluations at HEP sites Gosset et al. (2005) found a high deterrent effect with only 28% to 36% of European silver eels (size range not specified) passing through the turbine when 80% of the eels used could physically fit through the bars. Travade et al. (2010) undertook a three-year experiment with European silver eels at a hydropower station in southwest France with 30mm bar spacing. In 2004, 60% of the eels passed through the turbines when 95% of the eels had heads less than 30mm wide. In 2005, 53.9% passed through the turbines when 80% of the eels had heads less than 30mm wide. In 2006, 76% of the eels had heads larger than the 30mm bar spacing; only 8.1% passed through the turbines.

Differences in the effectiveness of trashracks as behavioural deterrents can be attributed to a number of factors such as escape velocity, screen angle (see section 2.1.2) and inclination (see section 2.1.3), and bypass type and location. Despite the variation in effectiveness, the overall conclusion remains that narrower bar spacings are required to prevent entrainment of eels. A number of studies recommend bar widths of <20mm (Gosset et al. 2005; Travade et al*.* 2006, 2010), based on the measurements (see Appendix A) of downstream migrating silver eels caught at the sites.

Field trials at a HEP site in Sweden showed that replacing the existing racks with 20mm bar spacing inclined at 63.4° by racks with 18mm spacing inclined at 35° reduced downstream migrating silver eel (length range 510–1,060mm) mortality rates from >70% to <10% with no impingement occurring on the new racks during the study period (Calles et al*.* 2013). However, it is not possible to separate the effect of the change in inclination of the rack from the reduction in bar spacing. It was also noted that injured eels were still encountered, highlighting the need for improvements.

The effect of trashracks on salmon smolts has also been reported. Croze (2008) studied four HEP sites in France with bar spacing typically between 30 and 40mm, although bar spacing was often uneven, with up to 60mm gaps. Larger smolts (>175mm) were less likely to be entrained than the smaller smolts. With an even bar spacing of 30mm and escape velocity of $1.2ms^{-1}$, the trashrack did not act as a

[1] Trashracks are a method of screening coarse debris from a water intake to prevent damage or reduced operational efficiency. These are usually use more coarse spacing than would be suitable for an effective fish screen.

behavioural deterrent for smaller smolts (<175mm); however, at lower approach velocities (<$0.9ms^{-1}$) no influence of smolt size was observed.

None of the studies reviewed looked at the effect of the width of screen bars on fish behaviour, entrainment, impingement or damage. Bar widths where reported are given in Appendix A.

2.1.2 Screen angle

Screen angle refers to the angle of the screen relative to the river bank or channel wall. Perpendicular (on non-angled) screens are installed at a right angle to the channel wall whereas angled screens have an angle of less than 90° between the screen and the channel wall (see Figure 2.1). The aim of an angled screen is to guide fish towards a bypass located at the downstream end. A summary of setups including screen angles and key results from reviewed literature is given in Appendix A.

The angle of the screen relative to the flow has been investigated in a number of studies. It is widely acknowledged that angling the screen relative to the direction of flow increases the efficiency of the screen in guiding fish to the bypass at the downstream end by creating a sweeping flow, aiding guidance efficiency and reducing impingement and entrainment (EPRI 2001, Turnpenny et al. 2004, Turnpenny and O'Keeffe 2005, Russon et al. 2010, Turnpenny 2010, Environment Agency 2013, Raynal et al. 2013). However, no studies undertaken at hydropower sites have directly tested the difference in fish deflection efficiencies between screen angles, with the majority testing the existing setup.

Current Environment Agency guidance for hydropower screening states that an angle of 30° or less provides the best screening properties and that screens at right angles to the flow can be used for small screens (<2m wide) (Environment Agency 2013). This guidance is provided alongside maximum approach velocities for each species. Environment Agency guidance on the screening for intakes and outfalls to protect eels recommends angling the screen at ≤20° (Environment Agency 2011).

Turnpenny (2010) investigated three screen angles (18°, 45° and 90°) on rainbow trout (in the absence of available Atlantic salmon smolts) (length range 60.9–121.8mm, mean 90.83mm) using vertical bar rack screens in a field flume test. Two bar spacings were tested, 10mm and 15mm. High efficiencies were seen for all setups, ranging from 88.35% to 100.00%, with the highest for the smaller bar spacing screens. No fish were impinged on the screens under any of the setups. Significant differences in the efficiencies between the 10mm screen at 45° and 15mm screen at both 45° and 90° were found. Fish deflection efficiencies across all setups did not significantly differ between the two screens (10mm and 15mm). There was no statistically significant difference between screens with the same bar spacing but at different angles. This was attributed to the low approach velocities (<$0.75ms^{-1}$) under which the screens were tested, which were low enough for the racks to be perpendicular (Turnpenny and O'Keeffe 2005). Environment Agency guidance states the maximum acceptable escape velocity for salmonids is $0.6ms^{-1}$ (Environment Agency 2013).

Multiple screen angles were also tested by Russon et al. (2010) on downstream migrating silver eel (length range 583–806mm, mean 660mm). Four screen angles were tested (15°, 30°, 45° and 90°) with a 12mm spacing bar rack in a laboratory flume setup. Angled racks (<45°), rather than those which were placed perpendicular to the flow, were shown to be more efficient for guiding eels to the bypass and in avoiding impingement. During the experiment impingement only occurred when the racks were placed perpendicular (90°) to the flow. The results indicated that with angled racks the eels were able to avoid impingement at velocities up to $0.9ms^{-1}$ and that more extreme angles for bar racks could be used under low velocity conditions. This is a much higher escape velocity than the maximum acceptable escape velocity of 0.5ms^{-1} given for eels in the Environment Agency (2013).

Clough et al. (2000) tested the effectiveness of bar racks with 10mm spacing and 12mm spacing at angles of 90°, 75° and 0° for salmon smolts (length range 135–190mm, mean 162mm) in a field flume setup. No fish were impinged under any of the setups tested and the behaviour of the fish was found to be similar between screen types and positions; only the orientation of the fish varied between the screen positions. The effect of screen angle on orientation of smolts approaching the screen was attributed to flow patterns created by the angle of the screen and the position of the bypass.

In the USA, 25mm and 50mm bar spacing tested at 45° and 15° in a laboratory flume study with a range of species (see Appendix A) found guidance efficiencies were low (mostly <50%) at 45° compared to 15° for all species. Silver phase American eel (*Anguilla rostrata*) (length range 151–781mm) showing the greatest guidance efficiencies (deflection efficiencies) (up to 73%) at this angle; at 15° guidance efficiency was often >70% with the exception of lake sturgeon (*Acipenser fulvescens*) (length range 82–161mm) (EPRI 2001).

2.1.3 Screen inclination

Screen inclination refers to the angle of the screen relative to the channel bed or to vertical; both measurements are commonly used in the literature (Figure 2.2). Vertical screens are (as the name indicates) installed vertically in the water column whereas inclined screens are tilted back. As with angled screens the aim of an inclined screen is to guide fish towards a bypass located at the downstream end of the screen.

Environment Agency hydropower screening guidance does not currently recommend if the screen should be vertical or horizontal in relation to the channel bed. It does state that horizontal screens should have the bywash at the top of the screen and the screens may require smaller screen apertures.

Data on the effect of inclination of fish screens on fish deflection efficiencies is very limited, although some studies have tested more than one inclination angle of bar rack (e.g. Clough et al. 2000, Russon et al. 2010, Calles et al. 2013). However, in these examples other properties of the screen were also changed between tests so the effect of the incline of the screen is not independently assessed.

Calles et al. (2013) highlighted the lack of published reports on implementing and evaluating inclined racks (<45° relative to the channel floor, Figure 2.2) designed to facilitate silver eel passage (length range 510–160mm, mean 776mm). As discussed in section 2.1.1, field trials at a HEP site in Sweden showed that replacing the existing racks consisting of 20mm bar spacing inclined at 63.4° with racks with 18mm spacing inclined at 35° reduced eel mortality rates from >70% to <10%. No impingement occurred on the new racks during the study period (Calles et al. 2013). However, it is not possible to separate the effect of the change in inclination of the rack from the reduction in bar spacing. It was also noted that injured eels were still encountered, highlighting the need for improvements.

A modular inclined screen inclined at 15° (to the vertical) was tested at the Green Island HEP site in the USA (EPRI 1996). It was found to be successful, with golden shiners (*Notemigonus crysoleucas*, mean length 71mm) and rainbow trout (mean length 95mm) showing diversion and survival rates approaching 100% under most test conditions.

Clough et al. (2000) tested screens at different angles and inclinations. Screens included vertical screens (one wire mesh screen and two bar screens) tested in three positions. Screens were angled at 75° to the flow in the vertical and angled at 90° and 0° to the flow while inclined 10° to the vertical in a downstream direction . No Atlantic salmon smolts (length range 135–190mm, mean 162mm) were impinged on any of the screen types and the behaviour of fish was similar between screen types and positions.

Russon et al. (2010) concluded that racks which were inclined and angled (<45°) rather than perpendicular were most effective at guiding downstream European silver eels (length range 583–806mm, mean 660mm) to the bypass and avoiding impingement. Fish deflection efficiencies were on average 98.3% with vertical screens (angled 15°, 30° and 45°), and no impingement or entrainment occurred. When the screens were perpendicular to the flow (vertical and inclined 30° to the channel floor) 46.8% of fish were impinged on the screen for >5 seconds and 25% were entrained.

2.1.4 Screen design

There are a number of screen designs including mesh screens, vertical or horizontal bar racks and louvres. Screens can be fixed or have moving parts (e.g. travelling band screens) or have devices for removing debris or fish which become impinged on the screen. The majority of the literature reporting on fish deflection efficiency of hydropower screens refers to vertical bar screens (see Appendix A). However, two of the studies (Clough et al. 2000, EPRI 2001) compared the screen type, rather than variation of properties of one screen type.

Clough et al. (2000) compared a vertical bar screen with 12mm bar spacing to a mesh screen with 12 × 25mm rectangular mesh using Atlantic salmon smolts (length range 135–190mm, mean 162mm) on the River Gaur, Scotland, and found the behaviour of fish was similar across screen types. The orientation of the fish in front of the screens varied between screen angles (0°, 70° and 90° to the flow), but not between screen types. No smolts were impinged on either screen type; the results suggested no difference in fish deflection efficiency between bar screens and rectangular mesh screens.

The EPRI (2001) undertook a laboratory study using a range of fish species, comparing 50mm bar racks with 50mm louvre arrays. There was no distinct difference in guidance efficiency between the bar rack and louvre arrays.

2.2 Monitoring

In order to measure the effectiveness of a screen, fish movements and/or behaviour around the screen must be monitored. There are numerous methods that have been used in studies to date but the majority have involved tagging and/or video footage in either flumes, experimental river setups or on site at existing hydropower plants. The choice of method used to determine screen efficiency depends on several factors including turbidity, channel topography/experimental setup, fish species, availability of fish and the type of data required. This section examines some of the methods described in the literature including any reported problems and limitations.

2.2.1 Experimental location (flume/field)

The majority of studies reviewed have carried out screen tests at HEP sites using the screen (usually trashrack) which is currently in place. Studies testing the efficiency of screen properties have in the majority of cases been carried out under experimental conditions either in a river channel or experimental flume.

The ability to easily control factors such as escape velocity and screen properties and the ability to closely monitor fish behaviour is an advantage of flume setups. However, the artificial setup introduces factors which may influence the behaviour of fish. Few studies have compared the difference in results of screen tests between laboratory flume tests, experimental field testing and testing undertaken at HEP sites, mainly because conditions experienced across these facilities may not generally be directly comparable.

Evaluation of the modular inclined screen at the Green Island Hydroelectric Project (EPRI 1996) found the results of the on-site screen testing were comparable to those obtained in laboratory flume experiments using a smaller scale model of the Green Island setup. This indicated that the larger size and the presence of debris were not factors affecting passage success. Comparison of the hydraulic testing results between the scale model flume study and the installed screen on site found no significant differences between the two configurations.

2.2.2 Tagging

Fish tagging is commonly used to study fish passage. The main types used are radio, PIT (passive inductive transponder), acoustic and float tags. With the exception of the float tags which are always attached externally, tags can be attached internally or externally. Internal tags involve surgical insertion of the tag under anaesthetic. Fish are allowed a recovery period before being released into the test area. External tags still involve the use of sutures or stitches to attach the tag, but avoid making an incision. Studies on fish screening commonly report on the success of the tagging method used including tag losses and any injury or other impacts on the tagged fish. Here we review the success of these monitoring methods in fish screen testing rather than giving a detailed review of each tag type.

Radio tags

Radio tags are small radio transmitters (e.g. 45mm long, 11mm diameter, weight 8g radio tags used by Gosset et al*.* 2005 and Calles et al*.* 2013) which can be attached internally or externally to the fish. The radio signal is constantly emitted from the transmitter and can be picked up by fixed or mobile receivers.

External tagging of fish is often used in an attempt to minimise stress from handling and surgery. However, external tags can cause irritation and get entangled (Haro et al*.* 2000) and are also more easily shed.

Travade et al. (2010) used ATS (Advanced Telemetry System) radio transmitters and PIT tags surgically implanted into silver eels but found the method did not provide sufficiently high resolution data (i.e. 3D data) on the behaviour of the eels and the depth at which they were approaching and passing through the trashracks.

Radio tags have been used to track silver eels migrating downstream through HEP stations in Sweden and France (Gosset et al*.* 2005, Calles et al*.* 2013). Tagged eels monitored for between 1 and 5 hours after tagging prior to release showed no signs of injury during this period (Calles et al*.* 2013). Comparison of tagged and untagged eels migrating through a HEP station has shown that downstream migration of the radio-tagged eels occurred at the same time as the untagged eels (Gosset et al*.* 2005).

Passive inductive transponders (PIT)

Unlike radio tags, PIT tags do not emit a continuous signal. When the tag passes the electrical field of the receiver the information stored in the PIT tag is received. PIT tags have some key advantages; they can store the unique pit tag number which is used to identify the fish, they do not require batteries so can be used to track fish over longer periods of time and they are a low cost method of fish tagging. However the receivers require a continuous power source which may not be available at the required receiver locations and batteries can prove unreliable. Additionally, the aerials are vulnerable to damage as fish pass through confined spaces.

The tags are surgically inserted into the fish. PIT tags have been successfully used to monitor Atlantic salmon smolts passing through hydropower stations (Boubée and Williams 2006, Croze 2008). The disadvantage is that the fish cannot be continuously followed using this method and the range between PIT tag and the receiver over which they can be detected is low (about 0.5m). Travade et al. (2010) found PIT tags did not provide sufficiently high resolution data on the behaviour of the eels approaching and passing through the trashracks.

The use of PIT tags as an assessment method for the deflection efficiency of fish screens therefore depends on the type of data required and the experimental setup. Where a continuous recording of fish movement throughout the system is required an alternative method such as acoustic tracking would be more appropriate.

Acoustic tags

Acoustic tags release an acoustic signal which is picked up by hydrophone receivers. A major advantage of this method over radio and PIT tags is that with the correct setup of receivers it is possible to determine the exact location of the fish and produce 2D or 3D tracks of fish movements. Other advantages are that acoustic tags are often smaller than radio tags, have large detection ranges (up to 1km compared to 10m for radio tags) and do not have an antenna on the fish, which reduces behavioural influences on the fish (HTI 2015). Accuracy of the spatial positioning using this technique depends on the equipment and setup used but sub-metre resolution and position-fixing down to approximately 25 times per second can be achieved.

Figure 2.3 shows some examples of 2D fish tracking using acoustic tags and the position of deflectors taken from an acoustic fish tracking project looking at upstream fish passage past a HEP scheme and through a fish pass (Noble et al*.* 2013).

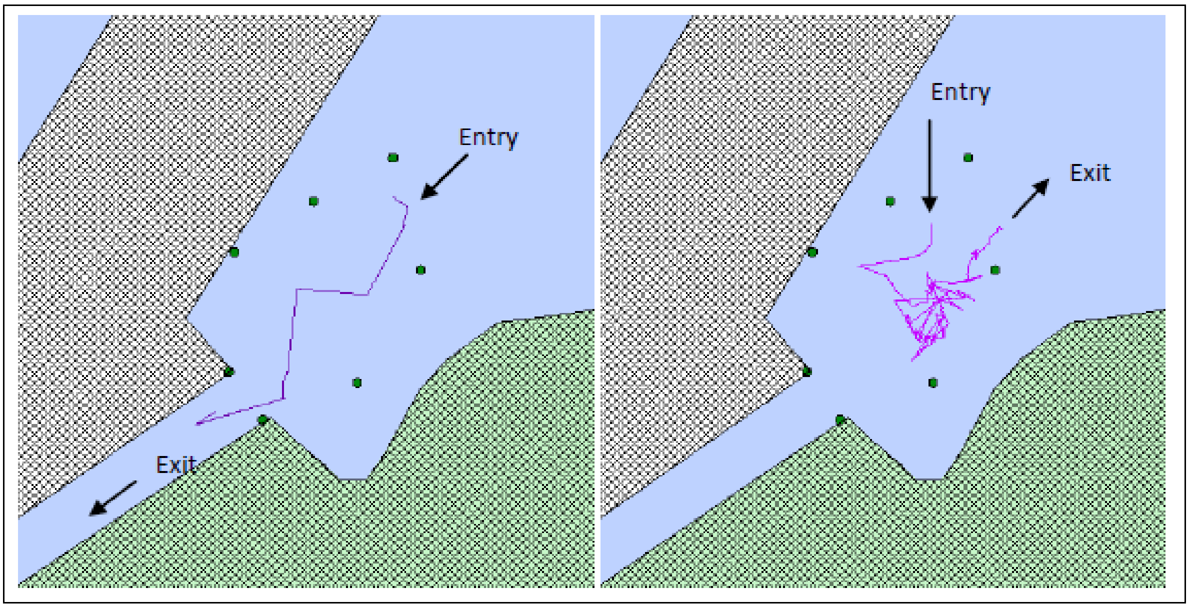

Figure 2.3 Examples of 2D fish tracking using acoustic tag tracking (taken from Noble et al. 2013)

Acoustic tags have been used to assess fish movements including passage through hydropower stations (Haro et al. 2000, Pedersen et al. 2011, EPRI 2012) and over weir structures (Gauld et al. 2013). Pedersen et al. (2011) used pairs of hydrophone buoys to divide the river into sections, and fish (internally tagged European silver eel) were only recorded when they passed these stations. However, not all eels tagged with the acoustic tags were picked up by the hydrophone buoys and adverse effects of capture, handling, tagging or transmitter malfunction could not be ruled out.

Acoustic tags can be attached internally or externally. Haro et al. (2000) attached tags externally to American silver eel in order to minimise stress from handling and surgery. Each transmitter was attached with sutures at each end of the transmitter through the skin on the dorsal surface approximately 30–50mm anterior to the origin of the dorsal fin. However, external tags can get entangled in vegetation and on structures, and are more likely to be lost or cause irritation to the fish. Haro et al. (2000) found a number of tags became stationary soon after the fish were released, likely to be the result of shed tags.

Data collected by an array of hydrophones has been used to triangulate a 2D position for each fish as it moves through the test area, with spatial accuracy at sub-metre resolution but ultimately determined by the arrangement and number of hydrophones employed. This method was successfully used by EPRI (2012) to assess the impact of turbines on fish. Atlantic salmon smolts were externally tagged with acoustic tags without anaesthetic, and a single suture thread was made behind the dorsal fin. The acoustic monitoring proved very successful and highlighted the benefits of Advanced Telemetry Systems particularly in turbid water where video monitoring is less successful.

Gauld et al. (2013) used internal acoustic tags together with automatic listening stations and manual tracking devices to track salmon smolt over low head weirs. Loose tags were released into the river prior to the release of tagged fish. This enabled testing of tag operating duration and understanding of the movements which would be detected if tags were shed during the experiment. These tags were easily detected, remained active for the expected duration and moved very little during the study. Average detection efficiencies for the automatic listening stations were ≥89%. Manual tracking was carried out on foot by wading in shallow stretches and by boat in the deeper sections.

Float tags

Float tags are a floating object that is attached externally to the fish and monitored visually. The advantage of this method is the ability to monitor the fish in real time (Turnpenny et al*.* 2004) and the low costs associated with the equipment.

This method was used by Turnpenny et al. (2004) to assess passage of Atlantic salmon smolts at a small hydropower station on the lower River Tay in Scotland. The test smolts (wild and hatchery) were fitted with float tags to allow their position to be seen from above; their movements were monitored by CCTV cameras.

The float tags were made from 10mm diameter polystyrene balls which were attached to the root of the dorsal fin via a length of very fine monofilament line. The floats were sprayed with a fluorescent paint to aid visibility (Figure 2.4). For tests conducted during darkness, the float tags were fitted with small chemical lights. The swimming ability of the fish was reported not to be markedly affected by the tags and tagged fish were able to dive to the bottom of the channel.

Figure 2.4 Float tags (taken from Turnpenny et al*.* 2004)

The benefit of this experiment was that it allowed detailed real-time monitoring of smolt behaviour in the headrace and as they encountered the screen. However, there were some problems with fish shedding tags and floats getting snagged on vegetation.

2.2.3 Video

Video monitoring of fish can provide detailed information on not only the location of fish but their behaviour. This includes visual evidence of contact with the screen and impingement, orientation and location in the water column. Video monitoring has been used in a number of studies (e.g. EPRI 1996, Clough et al*.* 2000, Russon et al*.* 2010, Turnpenny 2010) either as the sole monitoring method or in conjunction with tagging.

Various camera types and setups have been used to obtain images of fish movements and behaviour.

Fish trials using silver eels are commonly undertaken in darkness to re-create natural migration conditions. To allow recording in these conditions a number of studies have successfully used infra-red light to illuminate the study area with infra-red sensitive cameras to capture the video (e.g. Clough et al. 2000, Turnpenny et al. 2004, Turnpenny 2010). In the USA, low light video cameras and incandescent lights were used in a screen trial monitoring a number of species (see Appendix A) at a HEP site (EPRI 1996) to allow monitoring at night.

Studies undertaken in the field present problems with turbidity, glare, surface turbulence and increased difficulties with camera locations when compared to laboratory flumes. This can make video monitoring an unreliable monitoring method.

Video recording from CCTV cameras on wires above the channel, undertaken at a HEP site on the lower River Tay in Scotland (Turnpenny et al. 2004) was able to capture float tags attached to salmon smolts but not wild migrating smolts, despite their visible presence upstream. This was attributed to the reduced visibility caused by water movement when the turbine was running. The study used underwater Perspex camera boxes (800mm height x 450mm width x 400mm depth) with three submersible concept monochrome CCTV cameras mounted in a vertical line within each of the boxes. Infra-red lamps mounted vertically above each camera box provided illumination during the night and low light conditions.

EPRI (1996) used low light video cameras and incandescent light to monitor impingement of a number of species (see Appendix A) on a modular inclined screen at a HEP site in the USA. Cameras were mounted on the walls and roof of the modular inclined screen facility in several locations to cover up to 90% of the screen area. Although some camera positions were successful, because of water turbidity the underwater video cameras located on the walls of the modular inclined screen did not offer a clear enough view of the screen to provide a visual estimate of impingement.

In order to avoid some of the problems associated with recording video in field trials, Clough et al. (2000) employed a number of techniques in an experimental setup to improve the quality of images recorded. This included overhead shading to reduce glare, a float board to reduce surface turbulence and a reflective material on the base of the flume. This technique was successful, and provided clear results on fish (Atlantic salmon smolt) passage and behaviour. Night-time recordings clearly showed the fish as a silhouette against a bright background.

There are fewer problems to overcome in laboratory experiments where glass-sided flumes are used. Cameras can be mounted overhead and on the flume sides rather than underwater. This technique has successfully been used by Russon et al. (2010) to monitor the effectiveness of bar racks with European silver eels; again infra-red lighting was used to monitor the eels under low light.

2.2.4 Test fish

There are three main options for sourcing fish: monitoring of naturally migrating fish (without capture), monitoring of naturally migrating fish caught and put through the test area (often with tags) and monitoring of hatchery fish through the test area. The majority of studies reviewed have used the target species but where this is not possible a surrogate species may be used.

The majority of field-based studies aim to use wild migrating fish of the target species; however, this is often not possible due to the timing of the study, presence of eel traps, number of wild stock in the river or size of fish available.

Turnpenny (2010) could not obtain wild salmon smolts due to delays in the timing of the study. Brown trout (*Salmo trutta*) were identified as the best substitute but none of suitable size were available and instead rainbow trout (length range 60.9–121.8mm, mean 90.83mm) sourced from a hatchery were used. However, the authors highlight the importance of future testing with naturally migrating salmon smolts.

Atlantic salmon smolts are often sourced from hatcheries due to the low availability of naturally migrating salmon smolts. The disadvantage is that the fish are not captured during natural downstream migration and this may affect the downstream passage times through the test area (Turnpenny 2010). There may also be differences in behaviour and swimming abilities as a result of being reared in a low velocity environment (Clough et al*.* 2000).

Studies using eels have sourced silver eels from commercial trappers (ideally on the same river) for field testing (e.g. Travade et al*.* 2010, Pedersen et al*.* 2011), from trappers on nearby rivers (e.g. Russon et al*.* 2010) and from collection points at HEP schemes (e.g. Haro et al*.* 2000, Gosset et al*.* 2005, Boubée and Williams 2006, Travade et al*.* 2006, Calles et al*.* 2013).

The majority of studies have aimed to use each fish once during the testing of the screens; however, reuse of fish has occurred when the numbers of a particular species have not been sufficient and for control runs without a screen in place (e.g. EPRI 2001). Using fish only once avoids problems associated with fish learning the route downstream and any impacts from damage caused from the previous passage and recapture.

The effect of fish behaviour will be influenced by the species and source of the test fish. Fish which naturally migrate in groups are more likely to behave as they would under natural conditions if they are tested under conditions as close as possible to natural. The benefits of releasing fish in batches for species which naturally migrate as a shoal include increased efficiency: fish are likely to follow other fish that find a route through and have increased confidence when moving as part of a group. Releasing groups of salmon smolts is also used to limit risk of predation (Croze 2008). The influence on fish behaviour will also depend on the experimental setup; flume studies will often be undertaken in a confined space compared to studies undertaken in the field, particularly at large HEP sites. It has been recognised that little is known about the effect of group size on fish passage study outcomes (Russon 2011). Comparison has been made between brown trout released in groups and those released individually negotiating screens in a test flume. It was found that nearly one-fifth of approaches during group trials involved fish entering the observation zone in close proximity to at least one other individual. Group integrity was lost as individuals either passed or avoided conditions created by a weir orifice. It was noted that the avoidance behaviour exhibited by the remaining individual left behind was greater than for fish that had not previously been part of a group (Russon 2011).

Monitoring has been undertaken on Atlantic salmon smolts passing downstream over weirs in laboratory flumes. Smolts in groups attempted to maintain cohesion within the accelerating flow field, but some individuals were swept over the weir and separated from the group. Haro et al.(1997) found that designs which had a larger flow transition zone in front of the bypass reduced delay as larger groups of smolts were able to pass through together. This also reduces stress and predation (Haro et al*.* 1997). Delay was not investigated as part of this study.

2.2.5 Uncertainty

A number of variables in the field trials can affect confidence in the results. These include the number of replicates with the setups tested, number of fish used in the trial, and the applicability of the results to the final screen application, for example due to the trial location (see section 2.2.1) and source of test fish (see section 2.2.4).

The variation between results is demonstrated in the number of salmon smolts reaching the bywash under the nine screen setups tested on the River Gaur, Scotland (Clough et al. 2000) as shown in Table 2.2. The large variation between replicates highlights the importance of undertaking replicate experiments, with the mesh screen at 0° to the flow varying from 87% of the fish reaching the bywash in replicate one, to only 20% and 23% reaching the bywash in replicates two and three respectively.

Table 2.2 Number of fish recorded in the bywash at the end of each experiment (30 minutes). Number of fish per test = 30. Table from Clough et al. (2000)

Screen type	Angle to flow (°)	Rep 1	Rep 2	Rep 3	Mean
Standard wire (12x25mm mesh)	0	26	6	7	13.0
Standard wire (12x25mm mesh)	75	2	8	-	5.0
Standard wire (12x25mm mesh)	90	15	10	3	9.3
Bar screen 12mm spacing	0	29	21	29	26.3
Bar screen 12mm spacing	75	6	3	2	3.7
Bar screen 12mm spacing	90	10	0	5	5.0
Bar screen 10mm spacing	0	17	15	19	17.0
Bar screen 10mm spacing	75	3	2	2	2.3
Bar screen 10mm spacing	90	17	16	3	12.0

Experiments undertaken in the field are subject to a number of variables that cannot be controlled such as river flows and fish behaviour. The variability in efficiency between years is highlighted by the evaluation of surface and bottom bypasses to protect downstream migrating eel at a small HEP site in France where the bypass efficiency varied between 40% and 80% over the three years studied (Travade et al. 2006).

Variation in the size of the fish used in the experiments has also been shown to have a significant impact on the results. Travade et al. (2010) found the variation in downstream passage of eels at a HEP in France between years was closely correlated to river discharge (relating to the spill flow which provides an alternative downstream migration route) and the size of the eels, which affected the proportion of eels which could fit through the bar rack (30mm bar spacing).

The use of statistical tests to ascertain significant differences between treatments is important in determining outcomes. Where the experimental setup is not located at a hydropower site, a control run can be used to ascertain the average number of fish which actively migrate downstream without the screen in place. This is particularly relevant where the fish used are not a naturally migrating downstream stock (see section 2.2.4).

2.3 Recent research

The existing guidance for run-of-river hydropower development (Environment Agency 2013) is based predominantly on the descriptions and recommendations put forward within the *Screening for intake and outfalls: a best practice guide* (Turnpenny and O’Keeffe 2005). Here we consider additional and more recent literature to better understand the relevance and efficiency of screen prescriptions for fish deflection. This will help determine areas where more experimentation may be needed to demonstrate the deflection efficiencies expected from the guidance for run-of-river hydropower development.

Turnpenny and O’Keeffe (2005) proposed a simple method for determining mesh aperture size and the orientation of screening operations to best effect, based on international knowledge of similar situations and fish behaviour.

Mesh apertures recommended in the guidance for run-of-river hydropower development were based on the repeatable relationship between the fish length and its fineness ratio[2] and therefore the potential for the fish to get its head trapped in the screen aperture (Turnpenny 1981). For salmon smolts of at least 120mm in length an aperture of 12.5mm is considered sufficient, whereas smaller and different shaped fish (with different fineness ratios) require different minimum aperture dimensions; juvenile chub of 50mm in length would require a minimum screen aperture of 7.2mm, whereas for adult eel 335mm long this would be a minimum of 12.5mm. Specifications in the guidance for run-of-river hydropower development for minimum aperture dimensions were therefore considered protective with 12.5mm minimum aperture recommended for migratory salmonids (in the central, south, east and south-east of the country) and for adult eel (Environment Agency 2013). Adaptations required for migratory salmonids in other parts of the country, and undersized salmonids such as a parr/smolt of 79mm in length, would require a more protective 10mm aperture (Environment Agency 2013).

The use of a fineness ratio to determine the screen apertures provides a tool for generic protection from entrainment for an identifiable range of fish species of defined lengths. However, other factors play a role in the suitability of fish deflection: such as variation in fish sizes, altered behaviour, impingement in the screen structure, or delay to migration. This means that in reality different deflection efficiencies may at times be observed outside this generic range of values.

Studies into the effectiveness of fish screens are few in number, providing only limited opportunity to confirm the actual effectiveness of the recommended screen apertures across the range of conditions experienced at such installations. In addition, identified studies took place with different escape velocities, river flows, fish sizes, screen apertures, angles and inclinations, in waterbodies of different sizes or in flume or in field conditions. All these factors will influence the results, along with the variety of hydropower installations. In this section we identify the principal findings from the recent literature since 2005, when the best practice guidance was published, summarising the extent to which the guidance recommendations are supported in field trials and experimentation.

The best practice guide (Turnpenny and O’Keeffe 2005) and guidance for run-of-river hydropower development (Environment Agency 2013) recommend screens of ≤12.5mm to protect migratory salmonids (from the east, middle and south of the country) and adult eel from entrainment (Table 1.1). No studies since the best practice guidance was written have provided further information for salmonids. The only UK

[2] Fish fineness ratio is a measure of how elongate a fish is relative to its transverse sectional diameter. This is defined here as the standard length divided by the maximum depth of the fish (Turnpenny and O’Keefe). The fineness ratio formula is presented in Turnpenny and O’Keeffe (2005).

example to examine the effectiveness of this approximate screen aperture dimension was undertaken in 2000 on Rannoch Moor in Scotland and used 12mm screens with escape velocities of $0.3ms^{-1}$ to $0.4ms^{-1}$ and variations in angle to the flow. This found deflection efficiencies for the 12mm screen ranged from 0% to 96.7%, with the best results achieved with the screen at 0° angle to the flow (70% to 96.7%), despite considerable variability between replicates under the same conditions (Clough et al. 2000). This study used hatchery reared smolts rather than wild smolts. The hatchery reared smolts were larger (about 160mm) than wild smolts (about 120mm). Both factors will lead to different behaviours and reduce the validity with respect to mimicking deflection efficiencies that may be expected from wild salmon smolts. The method of recording was to count the fish that came past the bywash; there was apparently no counting of those that went through the screen, or those that did not attempt to pass the screen area. The study was also designed for a different purpose which was to confirm whether or not the 12mm bar screen was any more effective at deflecting fish than the existing rectangular 12x25mm mesh at the site. The variability of results within replicates in this single study demonstrates how a generic approach may not identify the true deflection efficiencies achieved in each scenario. There remains no further evidence to confirm the effectiveness of the generic approach in the best practice guide (Turnpenny and O'Keeffe 2005) and guidance for run-of-river hydropower development (Environment Agency 2013) for migratory salmonids and the 12.5mm screen.

There are a few more studies that have considered deflection efficiencies for the 10mm screen with respect to migratory salmonids. These all show an increase in deflection efficiencies when compared with those seen for larger apertures. Efficiencies between 88.4% and 100% were achieved using a 10mm screen which is angled to the flow at 18°, 45° and 90° (Turnpenny 2010), although this was using farmed rainbow trout to approximate the response of salmon smolts. Clough et al. (2000) showed that no salmon smolts were impinged on 10mm screens, regardless of the screen angle to the flow. However, deflection efficiency (proportion of test fish travelling past the screen into the bywash during each 30-minute trial) was highly variable (6.7% to 63.3%) with the best deflection achieved when the screen was angled at 0° to the flow (50% to 63.3%).

Russon et al. (2010) found that no eels were entrained when examining deflection efficiencies for silver eel (≥583mm long) with a 12mm screen, except where high escape velocities were combined with a vertical (non-inclined) bar rack. Impingement was found to be a risk due to the tendency of eels to make contact with obstructions before moving past them. Russon et al. (2010) found that impingement could be reduced by inclining the screen by 30° in relation to the river bed and that impinged eels escaped the screen even at escape velocities around $0.85ms^{-1}$ to $0.95ms^{-1}$. These results support the recommendations in the guidance for run-of-river hydropower development (Environment Agency 2013) in this case, but this study alone does not examine the effectiveness of the recommended 12.5mm screen aperture on eel of other sizes or of silver eel in other flow conditions or aperture sizes.

2.4 Summary

The key points of the literature review can be summarised as follows:

- Several studies indicate that in many cases existing trashracks with bar spacing commonly 20mm or more will not prevent fish entrainment.
- Few studies have experimented with the effect of bar spacing on fish deflection efficiencies, particularly in relation to the bar spacing guidance for silver eels and salmon smolts in the UK. Guidance is based on a

combination of the likelihood of entrainment based on the fish fineness ratio and the few experimental studies that have been undertaken.

- Behavioural differences between salmon smolts and silver eels when approaching and encountering screens have been highlighted. Unlike salmon smolts, eels are bottom-dwelling species which generally approach in contact with the bed or channel sides (Russon et al*.* 2010). This must be taken into account when designing screens and bypass systems to protect both species.
- The behavioural deterrent effect of screens is less for eels than salmon smolt; salmon smolt rarely make contact with the screen whereas eels are often shown to contact the screen before moving away (or passing through) (Haro et al*.* 1997, Russon et al*.* 2010).
- Fish screens have been assessed using a variety of setups from experimental laboratory flumes to on-site testing with a variety of fish monitoring methods used.
- Assessing fish behaviour around screens is made difficult due to various factors including water turbidity affecting camera footage, entanglement and loss of external tags, lack of data resolution particularly in relation to fish behaviour around the screens and problems with sourcing suitable test fish.
- Acoustic tags have advantages over other tagging methods including the ability to record continuous tracks of fish movements and to record either 2D or 3D positioning.
- Reported deflection efficiencies are as varied as the parameters tested. 10mm screens have resulted in deflection efficiencies for rainbow trout (61–122mm) of between 88% and 100% at 90° angle, 98% to 100% at 45° angle and 94% to 97% at 18° angle (all using vertically inclined screens). Studies of 10mm screens with salmon smolts varied from 50% to 63% passage from the flume past the screens to the bywash with considerable variation between replicates. Other angles and inclinations did not reliably improve efficiencies within the same study.
- Deflection efficiencies for 12.5mm screens have not been examined, but 12mm screens have been considered in a few studies. These suggest 12mm screens give deflection efficiencies of between 70% and 97% (0° angle, vertically inclined screens) for rainbow trout. Other angles and inclinations in the same study seemed reliably less efficient (0% to 33% deflection efficiencies). Studies of 12mm screens with salmon smolts varied from 70% to 97% passage from the flume past the screens to the bywash.
- Deflection efficiencies of 100% have been achieved in an experimental flume set up for silver eel with 12mm screens, although impingement was a concern at elevated escape velocities (about $1ms^{-1}$).
- There have been no studies on the influence of 10mm screens on silver eel passage. Similarly, no studies were found that specifically aim to confirm the effectiveness of the recommended screen apertures for the downstream migration of salmon smolts or silver eel. The logic of the fineness ratio to prescribe an aperture dimension is as yet unconfirmed in experimental or field conditions through repeatable study.

3 Methodology

This chapter outlines the methodology used during experimental field trials to quantify the level of protection provided to fish species by the screen design recommended in the hydropower guidance (Environment Agency 2013). The experimental site and its adaptation approximates to an experimental version of a typical hydropower screen setup, using parameters defined within the guidance for run-of-river hydropower development (Environment Agency 2013). Two trials were carried out: one for salmon smolts in spring 2014 and one for silver eels in winter 2014. Two screen apertures were trialled during the smolt trials (10mm and 12.5mm) while one screen aperture (12.5mm) was trialled during the silver eel trials. Screen apertures were as defined within the Environment Agency guidance.

3.1 Location and arrangement of trial site

The experimental site was located in a short side channel on the River Test in Romsey, Hampshire. There were two Denil (baffle) fish passes in the channel, one upstream and one downstream of the experimental location, along with a series of sluices and stop log channels that permitted considerable control over the flows and water velocities in the vicinity of the screen.

A schematic of the site arrangement and photograph of the screen in place are shown in Figures 3.1, 3.2 and 3.3. The water level shown in Figures 3.2 and 3.3 was at a low level in order to demonstrate the arrangement of the screen and hydrophones, but water levels during experimentation reached nearer, but not over, the height of the screen. Two video camera boxes each containing three cameras were located at the entry to the screen net and bywash deflector net (video data was captured as a back-up should the acoustic tracking system fail). The experimental area of the channel was 2.2 m wide, 1.5 m high and about 15 m long.

The screens used in the trial were constructed of 316 grade stainless steel wedge-wire. Each panel measured 0.75 m in width and 1.0 m in height and six panels were used.

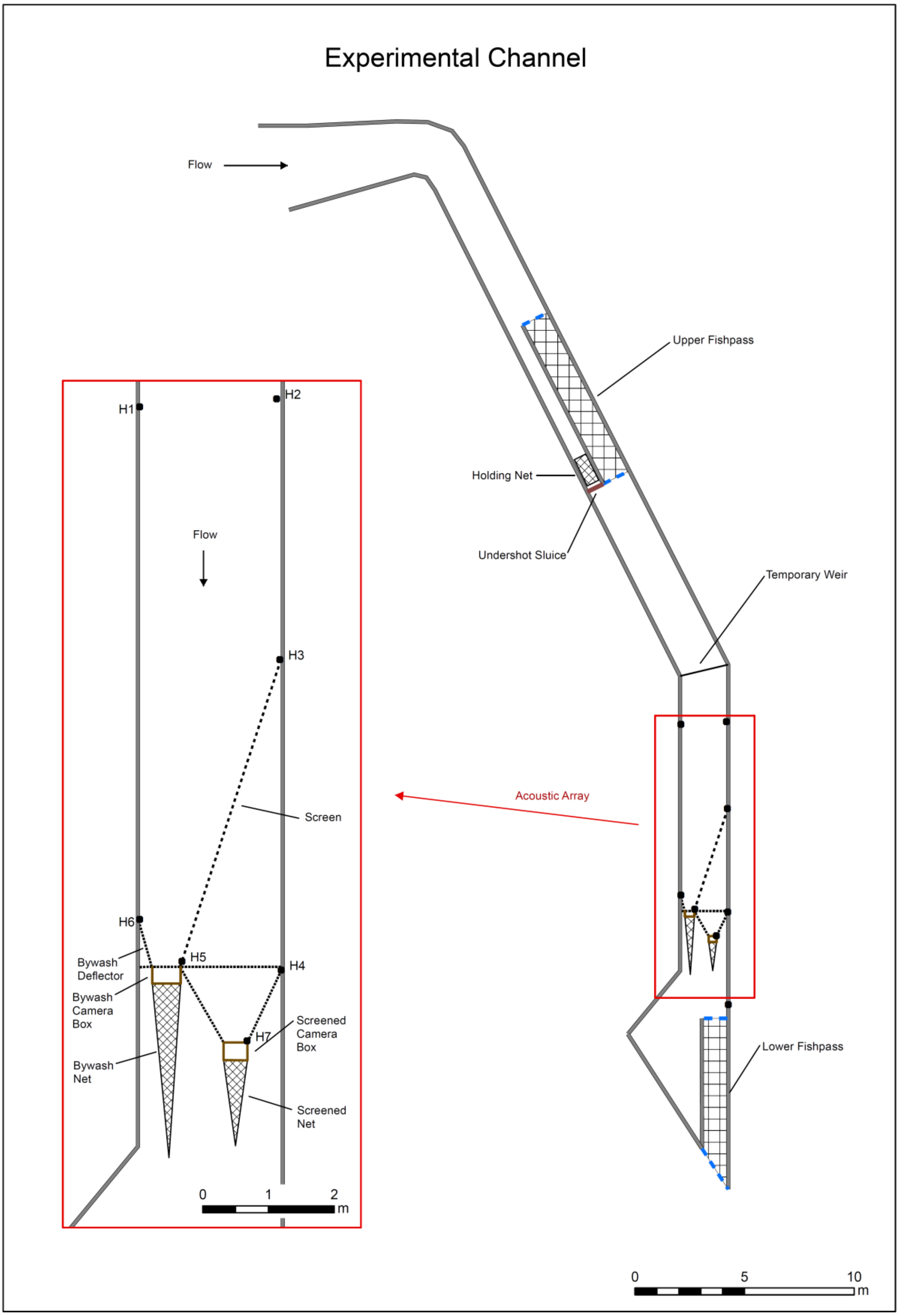

Figure 3.1 Schematic illustrating the location and arrangement of the screen and bypass installation and the approximate position of the hydrophones for acoustic tracking (black dots)

Figure 3.2 Photograph of the screen installation and bypass (to left and downstream of the screen) along with hydrophones in place (flow direction is going away from the camera). Note the screens are not in place in this photograph and the flume has been de-watered. Experimental water levels are indicated by the high water line on the bypass deflector. White arrows indicate approximate location of hydrophones

Figure 3.3 Photograph with screens in place. Note the flume has been de-watered in the photograph

3.2 Proposed experimental design

The initial experimental design proposed employs 10 fish per condition replicate, with 11 replicates as the ideal level of repetition to be most confident of gaining statistically robust results. The 11 replicates with 10 fish apply to the 10mm screen condition, the 12.5mm screen condition and a control condition, leading to a total (maximum) of 330 salmon smolts and 330 silver eels to be tested.

Data derived from previous studies at the River Test installation was used to estimate any variability inherent in the proposed screen testing study and to determine the number of replicates required for the screen comparisons. Power analysis showed that sample sizes of n=3 were sufficient if relatively liberal criteria were accepted: 80% chance of detecting a 20% difference in means with a type I error rate of 0.1. Sample sizes of n=11 were found sufficient if much more conservative criteria were adopted: 90% chance of detecting a 20% difference in means with a type I error rate of 0.05. Hence, it was proposed to begin experiments with n=11 replicates.

Replicate numbers in the subsequent trials were fine-tuned as the experiment progressed and fish numbers outlined in the initial design allow for redundancy through fish losses and tag failure or losses while still retaining good statistical resolution.

3.3 Fish supply and containment

3.3.1 Atlantic salmon smolt

The use of local wild salmon smolt was considered due to the suitability of fish in the catchment and as a result of their active and natural migration behaviour. However, this was precluded due to the sensitivities of extracting fish from a vulnerable population and due to concerns over being able to gather sufficient fish to give meaningful results within a suitable timescale. As a result, other sources were investigated.

Salmon smolts were obtained from the burns upstream of Kielder Reservoir in Northumberland. Eggs are stripped from wild salmon broodstock and the fry are grown on in the Environment Agency's Kielder hatchery. Fed fry are then released upstream of the Kielder reservoir as part of a mitigation programme in the Tyne Catchment. The fry then grow and are trapped as descending smolts, and in 2014 some of these were kept aside for use in this study. The remainder of the trapped smolts are transported below the reservoir to allow for their continued migration past the obstruction. In spring 2014 some of these fish were trapped

The River Tyne population was considered healthy in comparison to the River Test population, and was thus an appropriate source of salmon smolts for use in this study. Discussions were held with fisheries officers in both donor and recipient catchments to ensure minimal risks to either fish populations or local reputation with stakeholders.

Section 30 consents under the Salmon and Freshwater Fisheries Act 1975, for fish movement, were secured prior to transportation. The hatchery fish received a health test certificate prior to stocking, which assisted with ensuring confidence in the health status of the collected smolts. To be certain, 30 fish, representing the size range to be used, were sampled from early smolt collections to undergo a health check in the Brampton laboratory of the Environment Agency. Overall, 294 salmon smolts were used during the trials, close to the number proposed in the original experimental design.

The smolts were transported by a commercial fish transporter in water of a temperature between that of their source (River Tyne/Kielder Reservoir) and destination (River Test) and were acclimatised in River Test water for a few days prior to experimentation.

Two micromesh containment nets were placed in the side channel alongside the upstream fish pass. The two micromesh nets were placed within a larger cuboid micromesh net to prevent the fish escaping and to give suitable protection from predators. Lids with secure closures gave additional protection from above. The site was located on private land and was therefore secure from public access. Fish were left for three full days to acclimatise to their new environment. They were fed to keep them in as good a condition as possible. Regular checks were made to monitor water quality and fish health during that period.

Two further keep nets were placed in the channel in which each set of 10 fish were placed for recovery from tagging and from which they were released into the experimental channel for each trial.

3.3.2 Silver eel

The use of local wild silver eels for the experiment was preferred as they were most likely to display natural migration behaviour in the test environment. However, this was precluded due to insufficient fish of an appropriately small size being available from the suppliers on the River Test. As a result, other sources were investigated.

Silver eels were sourced from the River Avon located near Christchurch, Dorset. Discussions were held with Environment Agency fisheries officers in both donor and recipient catchments to ensure minimal risks to either fish populations or local reputation with stakeholders. The silver eels were captured by a licensed eel netsman using fyke nets. Those showing typical migration characteristics (silver eels) were retained, while all yellow eels (non-migratory) were released back into the river. Eels were captured during November and December 2014 and were held in in-river tanks in the River Avon until being transported to the River Test.

The silver eels were transferred to the River Test in early December using a transport tank with hessian sacking. The fish were stored in in-stream holding tanks to acclimatise to River Test water for a few days prior to experimentation.

Section 30 consents under the Salmon and Freshwater Fisheries Act 1975, for fish movement, were secured prior to transportation. A sample batch of fish representing the size range to be used underwent a health check at the Environment Agency Brampton laboratory prior to transfer to the River Test. A total of 42 silver eels were used in the trials. The total number of silver eels captured was significantly less than that proposed in the original experimental design due to less eels present. As a result, during the trials, silver eels were generally used in two trials a night, thus increasing the number of releases to a total of 67 silver eels.

Silver eels were stored in an in-river holding tank in the River Test which allowed a flow of water through the unit via small holes. Eels were held in the same location on site as the smolts outlined above. The holding area and the in-stream holding tank were sealed to prevent fish escaping and to provide suitable protection from aquatic predators. Lids with secure closures gave additional protection from above. Regular checks were made to monitor water quality and fish health during the trial period.

A further smaller container was placed in the channel within the fish pass. Each set of six silver eels were placed here for recovery from tagging and then released into the experimental channel for each trial.

3.4 Size distribution

3.4.1 Atlantic salmon smolt

It was important to use fish in a size range for which the screen aperture is designed and intended to deflect. The size of Atlantic salmon smolts around the UK varies and the guidance accommodates this variation through different screen aperture requirements.

The guidance for run-of-river hydropower development suggests that 12.5mm aperture screens are suitable to protect the majority of salmon smolts (Environment Agency 2013). This aperture dimension was determined by the fineness ratio for salmon of 4.65, which indicates the likelihood of fish of a certain width, depth and length combination being drawn through certain screen apertures (Turnpenny and O’Keeffe 2005). Atlantic salmon smolts in the UK are generally around 100mm or more in length, with a few smaller exceptions in the colder waters of northern regions. A 12.5mm aperture screen is estimated by the fineness ratio to exclude salmon with lengths ≥105mm. Similarly, in those colder areas where smolts are a smaller size and where parr are also to be protected, a 10mm aperture screen should exclude salmon with lengths ≥79mm.

Smolt collections at the Kielder reservoir use a smolt trap with a 10mm aperture screen which retained fish as small as 100mm fork length in 2013, and in 2012 as small as 78mm. Using the published fineness ratio of 4.65 for smolts, this size aperture should retain salmon with lengths ≥79mm, which would be expected to include all smolts and a few larger parr. Hence the smolts collected using the 10mm screen at Kielder reservoir were considered to be representative of the full range of sizes of smolts likely to be encountered in English rivers and so were appropriate for testing the effectiveness of a 10mm screen for deflecting salmon smolts.

Further details on the size ranges of smolts used in the study are provided in section 4.1.2.

3.4.2 Silver eel

It was important to use fish in a size range for which the screen aperture is designed and intended to deflect. The guidance for run-of-river hydropower development suggests that a 12.5mm aperture screen is suitable to protect the majority of silver eels. This aperture dimension was determined by the fineness ratio for silver eels of 16, which indicates the likelihood of fish of a certain width, depth and length combination being drawn through certain screen apertures (Turnpenny and O'Keeffe 2005).

The total size distribution of silver eels used for the trial ranged between 335mm and 555mm in length. Using the published fineness ratio of 16 for eels, this size range is appropriate for testing the efficiency of a 12.5mm screen for deflecting silver eels. Using a fineness ratio of 16 as outlined above, the 12.5mm aperture is predicted to be effective at protecting silver eels greater than 335mm.

Further details on the size ranges of silver eels used in the study are provided in section 4.1.2.

3.5 Acoustic tags

Acoustic tagging would provide real-time and recorded positions of fish in relation to the screen and bywash, and enable illustration, analysis and playback through ArcGIS. The suitability of using this technique in the relatively narrow concrete channel at Romsey was queried because of concerns regarding required positional resolution and interfering signal reflections. As a result, fixed location and tag-drag tests were conducted in mid-November 2013 to test its applicability. Further tests were conducted at the outset of the smolt trial period with multiple test tags and an additional review of fixed tag locations was carried out prior to the silver eel trial. Subsequent data processing showed interference to the acoustic signals from the channel and screen structure was significant but manageable through data processing. It was therefore determined that the HTI acoustic tracking equipment would be suitable to operate in the study channel.

HTI model 900-LD tags were used (tags supplied by Hydroacoustic Technology Inc., 711 NE Northlake Way Seattle, WA 98105, USA). The pulse rate interval was set at approximately 0.5 seconds to enable the plotting of fish that rapidly transit the 20m length channel, and a pulse duration (PD) or pulse width (PW) of around 3ms to enhance position resolution and maintain suitable signal strength (shorter PWs were tested in November 2013, but appeared to lack the power to provide reliable direct-path signals on all hydrophones). The model 900-LD tags were approximately 9mm in diameter and 20mm in length and weighed about 0.96g in air (HTI 2015), which is significantly lower than the recommended maximum of 5% of body weight (actually around 1% or less). There was no specific programming required up front on each tag as this is achieved using a tag programmer during the site and equipment setup period. Tags were programmed with a unique pulse rate interval for that trial, ranging from 500ms to 780ms with intervals of 14ms to ensure a clear separation between individual tag signals.

3.6 Hydrophone array

The hydrophone array involved the setting of eight hydrophones at strategic places within the experimental arena to best record fish position throughout while minimising multipath signals from walls, screen and floor (Figure 3.1). Hydrophones were positioned to ensure the entire experimental arena was covered by a minimum of three hydrophones and to indicate when fish had passed downstream of the trial area.

Real-time observation of echoes from each tag in the channel was possible for each replicate during the trial. This meant we could observe which combinations of hydrophones were giving the strongest signals and estimate the approximate position of fish in the channel. In turn this meant it was possible to determine whether or not fish had reached the bywash and entered the capture net.

Tag positions calculated from the hydroacoustic array are subject to errors. To quantify the positional error (jitter) about the tag position, tests were carried out in November 2013 and December 2014 using tags in fixed positions in the channel confirmed by actual physical measurements. Hydroacoustic recordings were taken and the resultant positions were plotted. Jitter from tags positioned on the upstream side of the screens in three locations was roughly circular with approximately 90% of recorded tag positions within 10cm of the true tag position.

Note that the positional fixes recorded when a tag was near a hydrophone or a wall were prone to greater errors. This was due to a combination of poorer triangulation near the boundaries of the hydrophone array and positional ambiguity due to multipath echoes from solid surfaces.

Acoustic tag position raw data was processed by the Environment Agency to extract valid tracking signals from background noise and to provide a spreadsheet of time–position data for further analysis.

3.7 Anaesthetic and tag insertion

Tags were surgically inserted into the fish following anaesthesia under a Home Office licensed procedure prior to their trial night, and the fish were carefully sutured before placement in a recovery vessel for eight hours. While under the influence of anaesthesia, the current state of migration condition, body length, width, depth and weight of each fish was measured and recorded alongside the unique pulse rate interval. The condition of the eels was checked prior to each trial for the distinctive migration characteristics (silver condition). Any eels not in silver condition would not be used in the trial but all were found to be in silver condition.

3.8 Release

Hydrophones and recording equipment (acoustic and video) were turned on and a series of checks were carried out to ensure that data was being collected from all hydrophones. This helped to show that suitable signals were being received from all of the hydrophones. A checklist is commonly used to confirm suitable operation and an adapted version of this was used here (Appendix B).

The first batch of fish was released at dusk into the channel at the start of each trial. The release point was just upstream of the uppermost hydrophones (H1 and H2 – Figure 3.1). Dusk was assumed to begin at around one hour before sunset.

Once fish were released into the experimental area, they were tracked in real time by the hydrophones, passing the screen and appearing downstream, where it was expected that they would swim into one of the two downstream nets for post-trial capture (one behind the screen and one downstream of the bywash). The number of fish supplied allowed for a total of ten salmon smolt to be released during each trial and a total of six silver eels. The first two trials were used to identify and address any aspects of the experimental design that required fine tuning. These included aspects such as the length of time required to permit the transit of experimental fish through the trial arena, the number of boards required to be withdrawn from the penstock to regulate flow and to identify any vibrations (e.g. screen movement) or possible barriers to passage.

The second trial of the night commenced following the recapture of all fish from the first trial. For the smolt trials, a new set of 10 fish were used in the second trial. Due to a lower number of silver eels being available for the study, the six eels were recaptured (where possible) following the first trial and released again in the second trial. On a number of occasions not all silver eels were recaptured after the first trial (due to fish escaping from the arena), and thus the number of silver eels available for the second trial was reduced.

Table 3.1 outlines the dates on which trials were undertaken along with the species released, number of fish released and what trial condition was carried out on each occasion. Further details for each species are provided in sections 3.8.1 and 3.8.2.

Table 3.1 Trial release dates, species, number of fish trialled and trial condition

Trial date	Trial	Species	Number of fish trialled	Trial condition
01/05/2014	1	Atlantic salmon smolt	10	Screen 10mm
06/05/2014	2	Atlantic salmon smolt	10	Screen 10mm
07/05/2014	3	Atlantic salmon smolt	10	Screen 10mm
07/05/2014	4	Atlantic salmon smolt	10	Screen 10mm
08/05/2014	5	Atlantic salmon smolt	10	Screen 10mm
08/05/2014	6	Atlantic salmon smolt	10	Screen 10mm
09/05/2014	7	Atlantic salmon smolt	10	Screen 10mm
09/05/2014	8	Atlantic salmon smolt	10	Screen 10mm
12/05/2014	9	Atlantic salmon smolt	9	Screen 10mm
12/05/2014	10	Atlantic salmon smolt	10	Screen 10mm
13/05/2014	11	Atlantic salmon smolt	10	Screen 10mm
13/05/2014	1	Atlantic salmon smolt	10	Screen 12.5mm
14/05/2014	2	Atlantic salmon smolt	10	Screen 12.5mm

Trial date	Trial	Species	Number of fish trialled	Trial condition
14/05/2014	3	Atlantic salmon smolt	10	Screen 12.5mm
15/05/2014	4	Atlantic salmon smolt	10	Screen 12.5mm
15/05/2014	5	Atlantic salmon smolt	10	Screen 12.5mm
16/05/2014	6	Atlantic salmon smolt	10	Screen 12.5mm
16/05/2014	7	Atlantic salmon smolt	10	Screen 12.5mm
19/05/2014	8	Atlantic salmon smolt	10	Screen 12.5mm
19/05/2014	9	Atlantic salmon smolt	10	Screen 12.5mm
20/05/2014	10	Atlantic salmon smolt	10	Screen 12.5mm
20/05/2014	11	Atlantic salmon smolt	10	Screen 12.5mm
21/05/2014	12	Atlantic salmon smolt	10	Screen 12.5mm
21/05/2014	1	Atlantic salmon smolt	7	Control
22/05/2014	2	Atlantic salmon smolt	7	Control
22/05/2014	3	Atlantic salmon smolt	7	Control
23/05/2014	4	Atlantic salmon smolt	7	Control
23/05/2014	5	Atlantic salmon smolt	0	Control (trial not run)
27/05/2014	6	Atlantic salmon smolt	7	Control
27/05/2014	7	Atlantic salmon smolt	7	Control
28/05/2014	8	Atlantic salmon smolt	6	Control
28/05/2014	9	Atlantic salmon smolt	5	Control
29/05/2014	10	Atlantic salmon smolt	6	Control
29/05/2014	11	Atlantic salmon smolt	6	Control
01/12/2014	1	Silver eels	6	Screen 12.5mm
01/12/2014	1	Silver eels	6	Control
17/12/2014	2	Silver eels	12	Screen 12.5mm
19/12/2014	3	Silver eels	6	Screen 12.5mm
19/12/2014	4	Silver eels	3	Screen 12.5mm
21/12/2014	5	Silver eels	6	Screen 12.5mm
21/12/2014	6	Silver eels	5	Screen 12.5mm
22/12/2014	2	Silver eels	6	Control
22/12/2014	3	Silver eels	5	Control
23/12/2014	4	Silver eels	6	Control
23/12/2014	5	Silver eels	6	Control

3.8.1 Atlantic salmon smolt

Fish were received on 16 April 2014 and held in containment nets for a few days prior to the first trial to allow acclimatisation and provide confirmation that smolts remained healthy prior to the trials. Trials were run between 1 and 29 May 2014 with tagging occurring during the morning and generally two replicates being run per night.

The 10mm aperture screen was trialled first and was therefore used to identify and address any aspects of experimental design that were unpredictable prior to running the trials. One such aspect was the length of time required to allow fish to move through the trial arena. The first and second night of trials each ran a single replicate (of ten fish) to give the best chance of all fish transiting the experimental arena in the available time and to allow time for site adjustment once operational. Following these first two days, two trial replicates were run each night providing a total of 11 replicates for the 10mm screen with 109 fish being released.

The 12.5mm screen was then employed, carrying out two trial replicates per night, achieving a total of 12 replicates with 120 fish being released. Control trials were then run without the screen in place and used 10 replicates with a total of 65 fish released. The lower number for fish releases during the control trial was the result of a reduction of operating tags largely due to battery failures. Overall, 294 salmon smolts were released throughout the trials.

3.8.2 Silver eels

Silver eels were collected between November and December 2014 and trials were run between 1 and 23 December 2014. A total of 42 silver eels were used in the trials. Eels were generally used in two trials a night, equating to a total of 67 silver eel releases. Of the 67 silver eel releases, 38 releases were trialled with the 12.5mm screen in place and 29 releases during control trials (no screen in place). It was intended that each eel would be trialled in one screen trial and one control trial.

Following the first night of trials, health and safety concerns in removing the screen in the dark meant that the screen would need to be left in place over the course of the night during the screen trials. As a result, during the first night trial fish were trialled under the screen and control conditions whereas the remaining trials were carried out as screen only or control only nights.

The first two trials were used to identify and address any aspects of the experimental design that required fine tuning. These included aspects such as the length of time required to permit the transit of experimental fish through the trial arena, the number of boards required to be withdrawn from the upstream penstock to regulate flow, and possible barriers to passage.

3.9 Trial period

3.9.1 Atlantic salmon smolt

The length of the trial period for each replicate of ten fish was determined over the course of the first two nights of trials. The majority of fish appeared to move through the arena within a 1.5 hour time period and this became the defined trial period to maintain consistency in terms of trial effort.

3.9.2 Silver eel

The length of the trial period for each replicate of six fish was determined over the course of the first two nights of trials. The maximum study period was set at 2.5 hours for each trial to maintain consistency in terms of trial effort. The time taken for eels to move through the study area varied between study groups. If all fish had moved through the study area and into the bywash or screen nets (i.e. appearing as a strong signal on H8 (Figure 3.1)) after less than the defined 2.5 hour period, then the trial was stopped.

3.10 Fish recapture and tag recovery

Water levels were lowered in the channel after each trial to permit access and to ease the capture of any fish remaining in the channel upstream of the bywash, screen and nets. Fish that had not passed the screen and remained hidden in the channel above the bywash were encouraged to descend towards the screen trial area using a net for salmon smolt and the light from a torch for eels. Afterwards, water levels were raised temporarily to use the hydrophones to confirm all captures or to locate any elusive fish.

On completion of trials, the tags were removed from the recaptured fish, deactivated using a tag programmer to save battery power and disinfected for further use. Subject to Home Office criteria, these fish were humanely destroyed to avoid the release of fish from a foreign catchment into the River Test and prevent fish health and welfare deterioration while no longer under observation.

During each trial capture nets covered the whole width and depth of the experimental channel; one attached to the bywash exit and one to the funnel exit behind the screen (Figure 3.1). There was no free gap for upstream-migrating fish ascending the lower fish pass during each trial period. However, there was a pool in the channel between the lower fish pass and the experimental setup where any such fish could gather and remain until the bywash capture net was removed after each trial, allowing these fish safely past. A free gap through the bywash was also maintained during periods when no trials were being run.

3.11 Channel and escape velocities

The weather and natural changes in river flow conditions were an unpredictable constraint to the trials. A sustained period of high flows prior to the start of the smolt trials resulted in excessive debris being caught against the screen (screen blinding) and also increased river level downstream of the experimental channel, reducing the ability to adjust the flow in the channel. This would reduce the effectiveness of the trial and therefore the start of the trial was delayed until the river returned to a level that would permit controllable trials. There were no further issues with flow conditions over the course of the smolts or eel trials.

Velocities in the channel were measured prior to most trial events, covering an area along the screen edge and across the channel to the opposite bank at a depth equivalent to 60% of the depth from the substrate to the surface (Figure 3.4).

Screen escape velocity (often also referred to as ‘approach velocity’) is defined as the velocity 10cm upstream of the screen, at right angles to the screen face (Environment Agency 2013). It was calculated using the methods outlined in *Screening for intake and outfalls: a best practice guide* (Turnpenny and O’Keeffe 2005). All velocities were measured using a Valeport flow meter and recorded as a one-minute average.

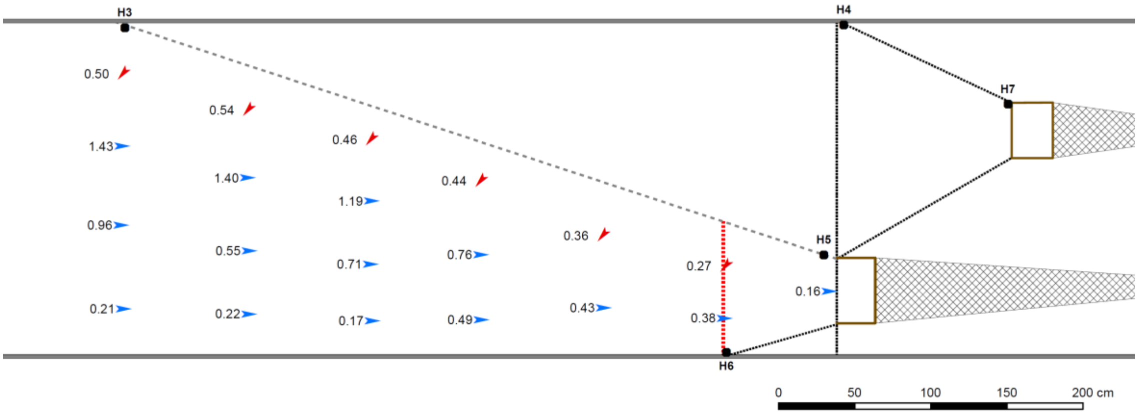

Figure 3.4 Velocity measuring locations – channel velocities (ms^{-1}, blue arrows) and escape velocities (ms^{-1}, red arrows, measured 10cm from screen face). Example velocity measurements shown mean measurements for the 10mm screened salmon smolt trail. Red line = line of deflection; once tracks reached this line fish were considered to have been deflected

3.12 Video

Video cameras in dry chambers positioned within each bywash started recording footage at the beginning of each trial and were turned off once the trial was complete. This footage was available as a back-up dataset in the event of hydroacoustic equipment failure and would be available for analysis where specific events needed to be examined.

3.13 Data analysis

Data was analysed by identifying incidents of potential impingement or entrainment and determining the deflection efficiency of each screen aperture condition tested. Spatial analysis, interrogation and presentation of tracks and data was undertaken using the GIS packages ArcView 9.3 and 10.1.

The results are compared to fineness ratios derived from theoretical values for the sizes of fish released and actual fineness ratios calculated for each fish.

4 Results

4.1 Results for Atlantic salmon smolts

4.1.1 Study limitations

The smolt trials were delayed as a result of very high flows that were being experienced on the Test. The flows required that the bypass channel was fully open to help reduce upstream water levels. Hence, regulation of the flows to facilitate trials was not possible.

When flows were at a level to permit trials, excessive levels of debris were experienced. This was unusual for the season and was attributed to the flooding events washing out debris from the river and flood plain. The debris caused issues with the upstream and downstream containment nets, and also caused blockage of the capture nets. Without constant management, the debris loading risked the robustness of the test arena and on a number of occasions led to the escape of fish due to failures in containment.

In addition, the build-up of debris in the capture nets led to increased water pressure and the creation of a pressure wave ahead of the nets, which may have influenced the behaviour of the smolts, discouraging them from continuing downstream into the net.

The total number of fish released during the smolt control trials was lower than that intended. This was due to a reduction in the number of operational tags, largely as a consequence of battery failures.

4.1.2 Fish size range

Fish used in the trials ranged from 105mm to 170mm in fork length with an average length of 129mm. Table 4.1 shows the range of sizes within each trial condition. Fish were picked from the supply net regardless of size in order to ensure that the size range used across trial conditions was effectively random and varied.

Table 4.1 Lengths (fork length) of fish (mm) used across trial conditions – smolts

Fish fork lengths	10mm	12.5mm	Control
Max size	147	158	170
Min size	105	111	108
Average size	125	130	131

4.1.3 Fish interaction with the screen

Fish moving downstream of hydrophone H3 (Figure 3.1) were considered to have interacted with the screen. In total, 294 smolts were released across all trials, and of these 279 provided active tracking data. One fish during the 10mm trial could be seen from analysis of its track in GIS to completely avoid any interaction with the screen area of the channel. In this instance, the fish remained in the upstream section of the experimental arena (upstream of H3). As a result, its data was not considered in further analysis. All data analysis included fish that have encountered and responded to the screen and experimental arena. A summary of figures (six tracks for 10mm trial, six tracks for 12.5mm trial and six tracks for control trial) are presented in Appendix C (C1–C18). The tracks presented represent typical salmon smolt behaviour seen during the experiment including any potential impingement and entrainment.

Table 4.2 illustrates the number and percentage of fish interacting with the screen and therefore the number of fish which provided experimental data.

Table 4.2 Number of fish providing active tracking data during the trials – smolts

Screen aperture	No. of fish released with active tag	No. of fish interacting with the screen	% fish interacting with the screen
10mm	101	100	99%
12.5mm	114	114	100%
Control	64	64	100%

4.1.4 Impinged fish

Impingement occurs when fish are held on the screen face or partially through the screen by virtue of water pressure and/or escape velocities in excess of the fish swimming speed. To distinguish between an impinged fish and the acoustic noise surrounding a tag position, the description requires greater definition. An impinged fish is **likely** to be one whose acoustic position remains in one place, within a radius of 10cm either side of the screen (which accounts for tag jitter), for a period of at least five seconds (determined through GIS position and time signatures). This behaviour is unlikely to be seen naturally and would indicate enforced restriction to fish movement. Figure 4.1 illustrates two examples of how this criterion can be seen in the dataset and allows for the influence of tag position error or jitter, represented by the red buffer lines parallel to the screen.

The definition for impingement uses the word 'likely' as each occasion of impingement must also be interrogated for other explanations. Other possible explanations could include incorporating multipath signals in the track, a period of inactivity or a discarded tag. Table 4.3 summarises the number of fish potentially impinged.

Where fish are impinged for a period of time, it is possible that they get free and continue to descend the channel and will be inadvertently counted as deflected fish. Deflection is achieved once fish reach a predefined line drawn across the channel near the bywash referred to here as the 'line of deflection'. By reaching this point, fish have swum past nearly the whole length of screen.

Figure 4.1 shows that the two fish that were potentially impinged both descended to the line of deflection. Any impinged fish may suffer physical damage that will hinder their continued migration and health. The implications that even temporarily impinged fish can then be considered deflected was therefore avoided and for simplicity, and as a worst case approach, fish identified as potentially impinged were removed from the count of deflected fish.

Table 4.3 Potentially impinged fish for each screen aperture with example plots shown in Figure 4.1 – smolts

Screen aperture	No. of fish interacting with the screen	No. of fish suggesting potential impingement	No. of those potentially impinged fish also reaching line of deflection in trial period
10mm	**100**	**1**	**1**
12.5mm	**114**	**1**	**1**

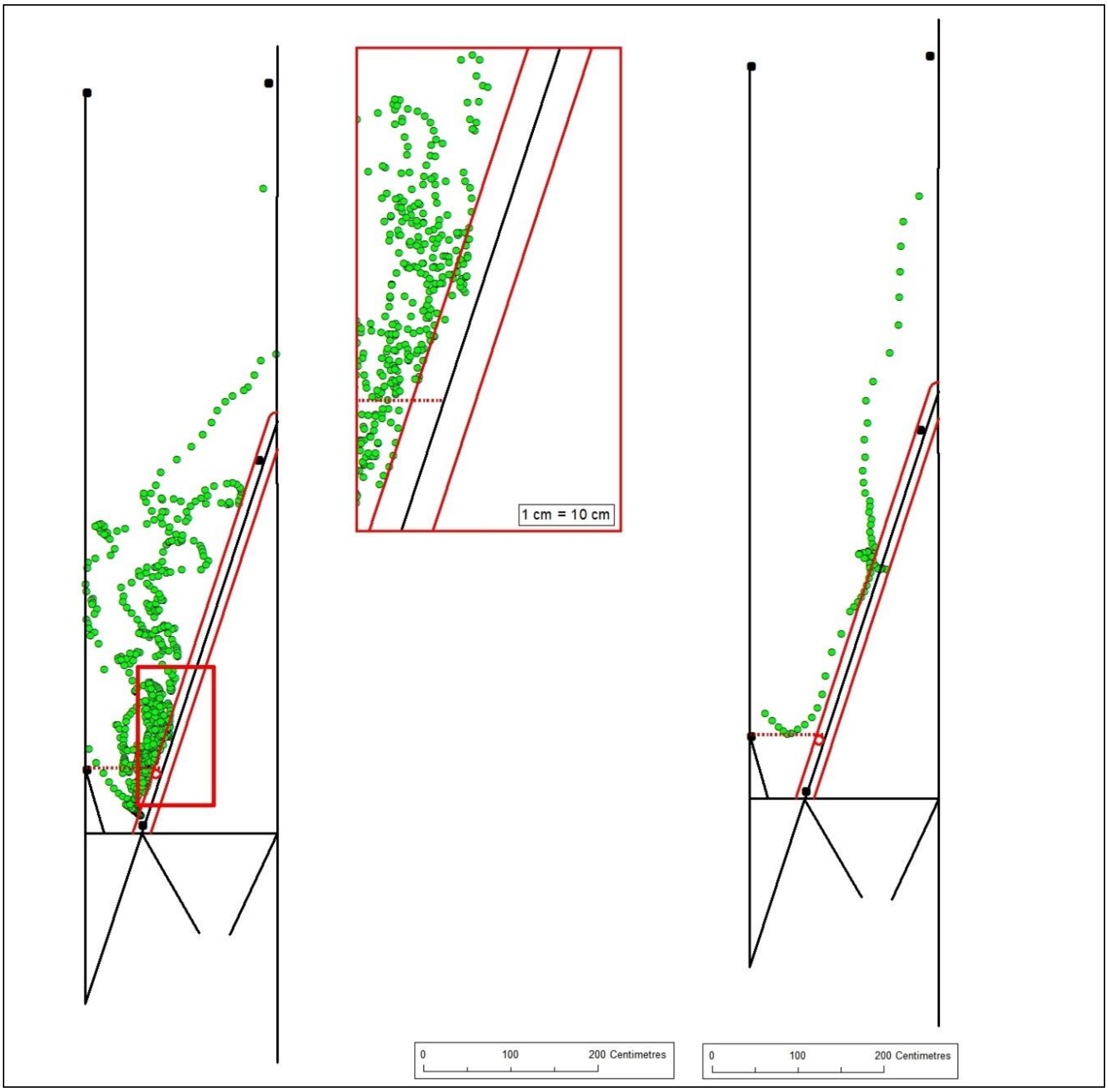

Figure 4.1 Left T10-R4-F668 and right T125-R7-F752: Fish tracks which suggest potential impingement, requiring further examination (accounting for tag position error/jitter through presence in red buffer zone on upstream side of screen)

4.1.5 Entrained fish

Entrainment occurs when fish travel through the screen by virtue of water pressure, choice and/or escape velocities in excess of the fish swimming speed. An entrained fish would be expected, having passed through the screen, to continue downstream into the recapture net. It is generally assumed that this is a one-way passage. However, the fish may not always continue to the net and may instead linger in the area behind the screen, or may pass back through it.

To distinguish between an entrained fish and the error surrounding an acoustic position, the description requires greater definition. An entrained fish is likely to be one whose acoustic position is consistently present, following passage through the screen, at least 10cm from the downstream side of the screen (the buffer due to acoustic position jitter). This situation is unlikely to have occurred without an enforced restriction to fish movement arising from escape velocities in excess of fish swimming speed and/or a screen aperture large enough to allow fish passage.

This definition states that an entrained fish is 'likely' to be one fulfilling these criteria because each such occasion must also be interrogated for other explanations, such as acoustic positional error or consideration of the realities of fish behaviour. Table 4.4 summarises the number of fish potentially entrained. Potential entrainment events during the 10mm screen aperture trials are illustrated in Figure 4.2 and those during 12.5mm aperture trials in Figure 4.3.

Table 4.4 Potentially entrained fish for each screen aperture – smolts

Screen aperture	No. of fish interacting with the screen	No. of fish suggesting potential temporary entrainment	No. of those potentially entrained fish also reaching line of deflection
10mm	100	2	1
12.5mm	114	2	2

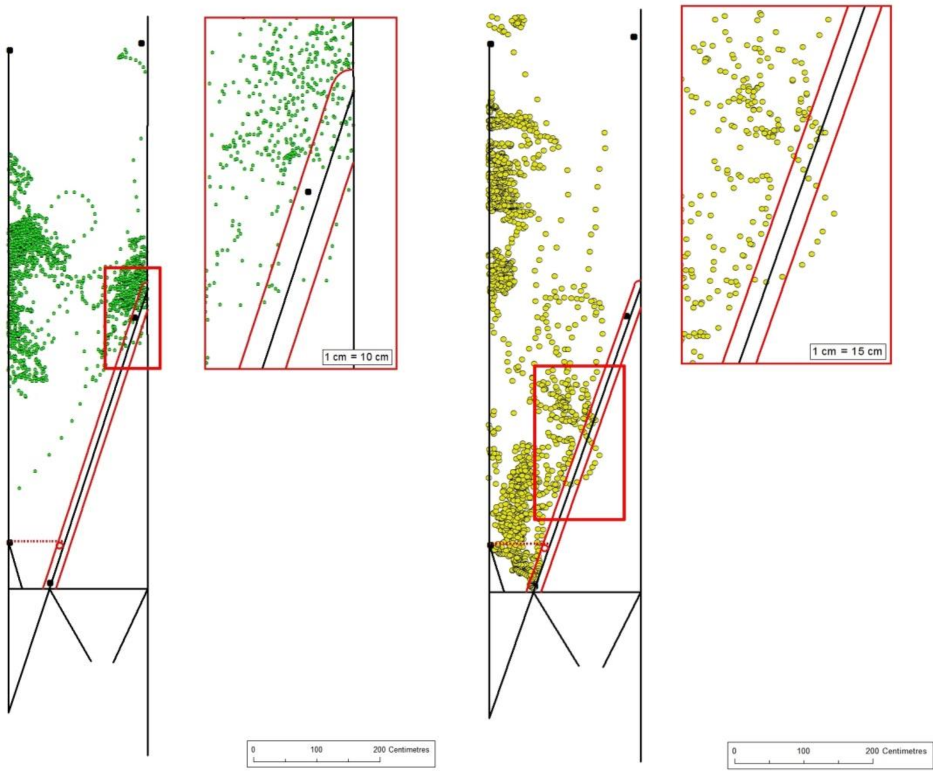

Figure 4.2 Left T10-R3-F514 and right T10-R6-F656: Fish tracks during 10mm screen aperture trials suggesting potential entrainment, requiring further examination (accounting for tag position error/jitter through presence downstream of red buffer)

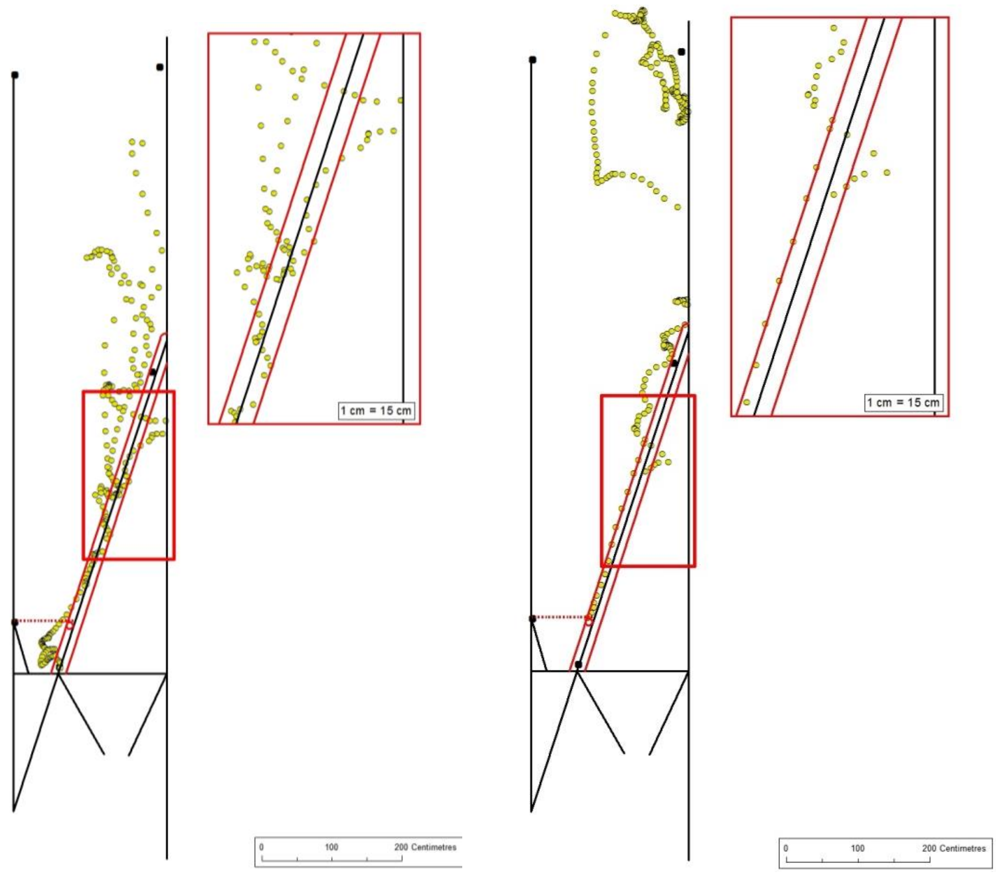

Figure 4.3 Left T125-R1-F752 and right T125-R11-F682: Fish tracks during 12.5mm screen aperture trials suggesting potential entrainment, requiring further examination (accounting for tag position error/jitter through presence downstream of lower red buffer line)

4.1.6 Channel flow and escape velocities

Our ability to control channel velocities was compromised at first by elevated river levels and flows. This was because the minimal difference in river level from upstream to downstream of the trial arena reduced head drop and thus water velocities.

Tables 4.5 and 4.6 illustrate the maximum, minimum and average velocities within the main channel. Channel velocity is defined as the velocity across the channel. Escape velocity (also known as 'approach velocity') is defined as the velocity 10cm upstream of the screen, at right angles to the screen face. Overall, in-channel velocities ranged from 0.06ms^{-1} recorded on the true right back opposite the screen to 2.02ms^{-1} recorded on the true left bank near the screen, with an average channel velocity of 0.93ms^{-1}.

Along the screen face, flow was drawn through the screen resulting in a localised head drop and acceleration. Overall, along the screen face, escape velocities ranged from 0.04ms^{-1} to 0.63ms^{-1} with an average of 0.44ms^{-1}. This is close to the maximum escape velocity of 0.6ms^{-1} specified for salmonids within the guidance for run-of-river hydropower development (Environment Agency 2013). The minimum and maximum velocities were measured between the middle and upstream end of the screen indicating variability in the hydrodynamics of the site possibly caused by flow pulses, screen structure and/or boundary layer effects. Figures 4.4, 4.5 and 4.6 show a mean escape and channel value for each monitoring point associated with the 10mm, 12.5mm and control trial conditions.

Table 4.5 Channel flow velocities in ms⁻¹ measured across trial arena – smolts

Channel velocities	10mm	12.5mm	Control
Max ms^{-1}	1.63	1.84	2.02
Min ms^{-1}	0.06	0.09	0.11
Average ms^{-1}	0.92	0.94	0.97

Table 4.6 Escape flow velocities in ms^{-1} measured in front and perpendicular to the screen and along the screen face approximately 10cm from the screen – smolts

Escape velocities	10mm	12.5mm
Max ms^{-1}	0.58	0.63
Min ms^{-1}	0.04	0.12
Average ms^{-1}	0.43	0.45

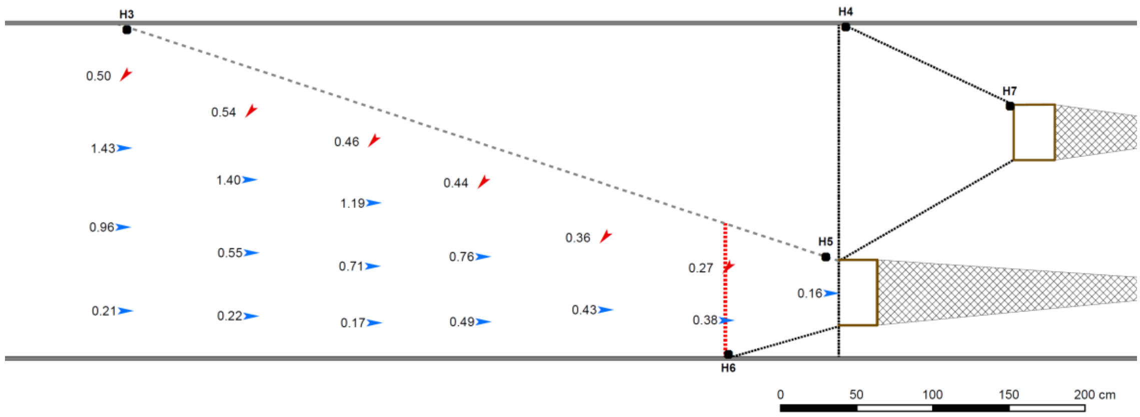

Figure 4.4 Smolt 10mm screen trial mean escape and channel flow velocities. Channel velocities (ms^{-1}, blue arrows) and escape velocities (ms^{-1}, red arrows, measured 10cm from screen face). Red line = line of deflection; once tracks reached this line fish were considered to have been deflected

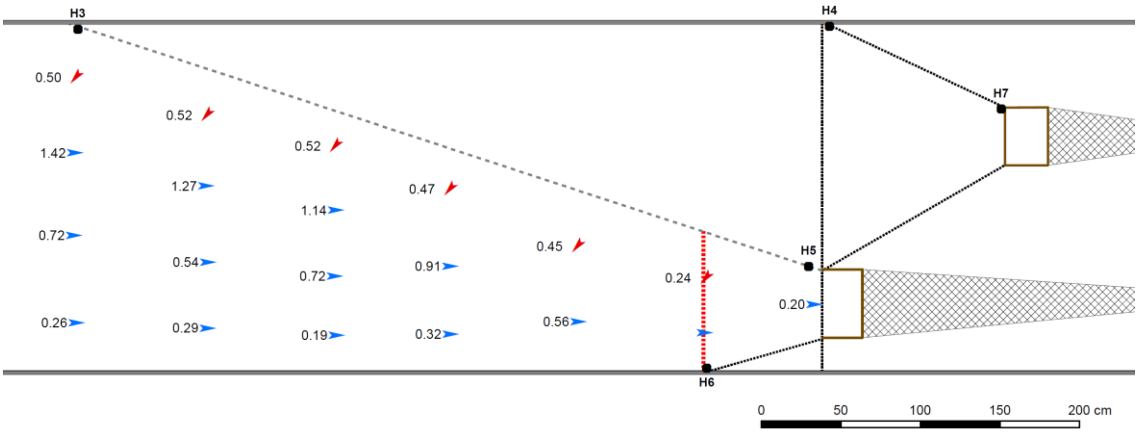

Figure 4.5 Smolt 12.5mm screen trial mean escape and channel flow velocities. Channel velocities (ms^{-1}, blue arrows) and escape velocities (ms^{-1}, red arrows, measured 10cm from screen face). Red line = line of deflection; once tracks reached this line fish were considered to have been deflected

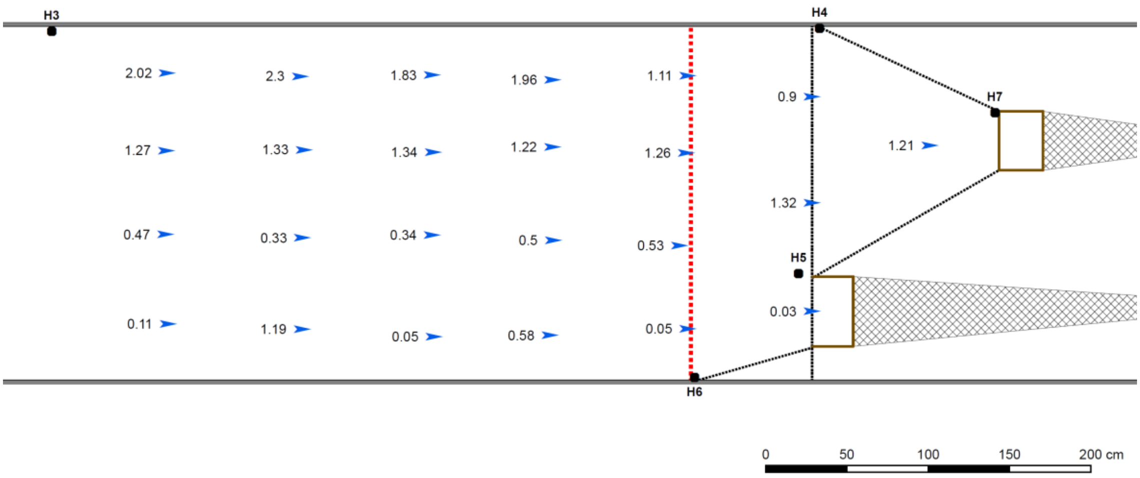

Figure 4.6 Smolt control screen trial mean escape and channel flow velocities. Channel velocities (ms^{-1}, blue arrows) and escape velocities (ms^{-1}, red arrows, measured 10cm from screen face). Red line = line of deflection; once tracks reached this line fish were considered to have been deflected

4.2 Interpretive analysis for Atlantic salmon smolts

4.2.1 Deflection efficiency

Deflection is achieved once fish reach a predefined line drawn across the channel near the bywash referred to here as the 'line of deflection'. By reaching this point, fish have swum past nearly the whole length of the screen and remained on the upstream side of the screen. Once passing the line of deflection the fish has successfully avoided complete entrainment or long-term impingement. These fish are then described as having been deflected by the screen.

$$\text{Deflection efficiency (\%)} = \frac{\text{No. of fish reaching line of deflection}}{\text{No. of fish interacting with the screen}} \times 100$$

Of the 229 smolts released into the channel over the course of the trials for both 10mm and 12.5mm screen apertures, 215 fish provided usable acoustic signals, and of these only one fish did not interact with the screen instead remaining upstream. The 14 fish without acoustic data were the result of tag failures prior to release and/or during the trial. This level of tag failure was less than the 10% anticipated (HTI, personal communication). In total, 209 fish successfully reached the line of deflection within the defined trial period. This gives an overall minimum deflection efficiency of 97% for 10mm aperture and 93% for 12.5mm aperture. Table 4.7 shows results for each trial condition.

Table 4.7 Deflection efficiency of each screen aperture* – smolts

Screen aperture	No. of fish interacting with the screen	No. of signals suggesting impingement	No. of signals suggesting entrainment	No. of fish that were not impinged or entrained that did not reach the line of deflection	Remaining fish reaching line of detection	Deflection efficiency
10mm	100	1	2	0	97	97%
12.5mm	114	1	2	5	106	93%

*Control data has not been provided for the acoustic tag data as during the control fish did not interact with the screen or get impinged/ entrained. Providing control data of impingement/entrainment would potentially be misleading. Control data was, however, provided for the netting data.

4.2.2 Recapture net data versus hydroacoustic data

Using only recapture net data, and in the absence of GIS analysis, deflection efficiencies were calculated and are provided in Table 4.8. Deflection efficiency using this method was calculated by the simple formula below and uses only net recapture data.

$$\text{Estimated deflection efficiency (\%)} = \frac{\text{No. of fish captured in bywash net}}{\text{No. of fish challenging the screen}} \times 100$$

Table 4.8 Deflection efficiency of each screen aperture using only recapture net data – smolts

Aperture	Estimated no. of fish challenging screen*	No. fish passing behind screen	No. fish in bywash net	Estimated mean deflection efficiency
10mm	68	0	68	100%
12.5mm	81	0	81	100%
Control	41	39**	2	5%

* The assumption is that the number of fish challenging the screen is equivalent to the number of fish captured in the downstream nets.

** For the control data, the ‘passing behind screen’ is the left hand bank net behind where the screen had been. The result for deflection efficiency for the control trials provides an illustration of the relative direction taken by control fish, in the absence of a deflecting screen, and is for illustration only.

The remaining fish that were released but had not been captured in the nets at the end of each trial period are represented by tag failures, fish losses or, were predominantly, those fish remaining in the trial channel without descending fully into the nets. Fish that were lost and those remaining in the trial channel are recorded by the acoustic tracking data.

4.2.3 Confidence in deflection efficiency

Statistical confidence in the trials' ability to prove the hypothesis is best demonstrated by binomial probability calculations. To prove a minimum of 90% deflection efficiency with 95% confidence, we would need to achieve at least 95.2 successes out of an arbitrary 100 fish challenging the screen (at first glance a deflection efficiency of 95.2%). Similarly, to prove a minimum of 90% deflection efficiency with a higher confidence of 99%, we would need 96.8 successes out of 100 fish (at first glance a deflection efficiency of 96.8%). If every fish that challenged the screen succeeded in reaching the bywash (i.e. 100 successes from 100 fish) we could be 99.9973% confident that the trial has proven better than 90% deflection efficiency. The higher the sample size, the closer this confidence level will tend to 100%.

Using data from Table 4.7, binomial probability calculations show that trials have proved with 95% confidence (n=100 fish) that salmon smolt deflection efficiencies greater than 92.4% are achieved with the 10mm aperture screen. Similarly, trials have proved with 95% confidence (n=114 fish) that salmon smolt deflection efficiencies greater than 87.7% are achieved with the 12.5mm aperture screen.

4.2.4 Fineness ratio and influence of fish size

The guidance for run-of-river hydropower development requires particular mesh aperture sizes in waters where salmonids are to be protected (Environment Agency 2013). These aperture sizes were derived by considering how the fish fineness ratio affects the chances of fish of certain sizes of passing through particular apertures in the screen.

The fineness ratio was used to determine the mesh aperture size expected to prevent entrainment of the specific fish sizes used in this trial. Calculated mesh aperture size estimates for each fish used in this trial are shown in Appendix D. All fish used in the 10mm screen trial might be expected to be deflected based on using a fineness ratio of 4.65 for smolt (Turnpenny and O'Keeffe 2005). Under the 12.5mm screen condition, 5 of the 120 fish had a predicted mesh aperture size less than 12.5mm. The smallest mesh aperture size identified was 11.8mm for the fish with a fork length of 105mm and standard length of 98mm.

If individual fineness ratios are calculated for each fish using fish-specific measurements recorded during the trials, the smallest mesh aperture size required throughout the trial was identified as being 10.45mm. This was calculated for a smolt 106mm in standard length and 17.5mm in body depth. The individual fineness ratio for each of the released fish indicates the 10mm mesh aperture size was predicted to exclude all fish released in the 10mm trial. Under the 12.5mm trial 80 of the 120 fish released had a predicted mesh aperture size less than 12.5mm.

It should be noted though that the fineness ratio of a fish is only one of the factors influencing whether a fish will be entrained or impinged and that escape velocity and fish behaviour are also important.

4.3 Summary for Atlantic salmon smolts

4.3.1 Deflection efficiency

Of the 229 fish released into the channel over the course of the trials for both 10mm and 12.5mm screen apertures, 215 fish provided usable acoustic signals and of these only one fish did not interact with the screen in any way. In total, 209 fish successfully reached the line of deflection within the defined trial period.

This allows us to prove with 95% confidence that an overall deflection efficiency (allowing for errors associated with sample size) of at least 92.4% for the 10mm aperture screen and at least 87.7% for the 12.5mm aperture can be achieved.

4.3.2 Fineness ratio

Using the published fineness ratio of 4.65 (Turnpenny and O'Keeffe 2005) to estimate whether the fish sizes used in this trial are likely to be entrained, we can show that none of the fish would be expected to be entrained under the 10mm trial condition and five fish under the 12.5mm trial condition. Similarly the calculated individual fineness ratios for each fish released during the trial indicated that with a mesh aperture of 10mm all fish would be expected to be deflected. This does not exclude the potential for impingement, which is also influenced by escape velocity and fish swimming speed. Under the 12.5mm trial, fish-specific (calculated) fineness ratios predicted that 33% of the fish would be deflected with a 12.5mm mesh aperture.

4.3.3 Escape velocity

Velocity conditions at the screen face were sufficient to test the capacity for impingement or entrainment of salmon smolts of the size under study. Mean escape velocity (0.44ms^{-1}) recorded along the screen was less than the maximum of 0.6ms^{-1} recommended in the guidance for run-of-river hydropower development for salmonids (Environment Agency 2013).

4.4 Results for silver eel

4.4.1 Study limitations

Prior to the eel trials the experimental arena was thoroughly checked for gaps that would permit escape of the eels. The inquisitive behaviour of eel and their tendency to 'feel' their way around the structures, required that every possible escape route was filled/blocked. However, during the initial trials a number of fish were lost through apparent gaps around the experimental structure. Subsequent checks were made and a number of small gaps around the framework supporting the screens and nets were found which were subsequently blocked. Additional fixings were also added to the structure to ensure that the water pressure was not lifting the structure when the channel was filled with water.

A number of fish were also lost through small holes that developed in the bywash capture net. The nets were checked prior to and between trials, and it is believed that the action of water pressure on larger debris in the net led to the formation of the holes in both the outer and inner meshes. To counter this, site staff made efforts to ensure that no large debris was in the experimental arena prior to flooding.

4.4.2 Fish size range

Fish used in the trials ranged from 335mm to 555mm in length with an average length of 437mm. Table 4.9 shows the range of sizes within each trial condition. Fish were picked from the supply net regardless of size in order to ensure that the size range used across trial conditions was effectively random and varied.

Table 4.9 Standard length of fish (mm) used across trial conditions – eels

Fish standard lengths	12.5mm	Control
Max size	555	531
Min size	335	338
Average size	434	440

4.4.3 Fish interaction with the screen

A review of eel behaviour while the screen was in place compared to the control illustrated that eels were generally tactile and exploratory in nature, often moving along the channel walls or in-stream structures. Eels showed a similar behaviour in both the screen trials and the control trials; often moving around the experimental arena in an upstream and downstream direction. Of the 67 releases only one fish (during the control trial) could be seen to completely avoid any interaction with the screen and remained in the upstream section of the experimental arena (upstream of H3, see Figure 3.1). As a result, data from this fish was not considered in further analysis. Data analysis only included fish that encountered and responded to the screen and experimental arena. A summary of figures (six tracks for 12.5mm trial and six tracks for control trial) are presented in Appendix E (E1–E12). Tracks presented represent typical eel behaviour seen during the experiment.

Table 4.10 illustrates the number and percentage of fish with acoustic data that interacted with the screen and therefore the number of fish which provided active experimental tracking data. Of the 67 fish releases, 51 had active signals. The remaining 16 releases experienced tag failures or were lost from the experimental arena. Further detail on project limitations is provided in Section 4.4.1.

Deflection from the screen was deemed as being achieved once fish reached a predefined line drawn across the channel near the bywash referred to here as the ‘line of deflection’. By reaching this point, fish have swum past nearly the whole length of the screen. Once a fish reached the line of deflection no further data for that fish has been analysed.

Table 4.10 Number of fish providing active tracking data during the trials – eels

Screen aperture	No. of fish released with active tag	No. of fish interacting with the screen	% fish interacting with the screen
12.5mm	27	27	100%
Control	24	23	96%

4.4.4 Impinged fish

Impingement occurs when fish are held on the screen face or partially through the screen by virtue of water pressure and/or escape velocities in excess of the fish swimming speed. To distinguish between an impinged fish and the acoustic noise surrounding a tag position, the description requires greater definition. A review of control run tracks indicated silver eels on occasion would remain in a stationary position for up to approximately 25 seconds. During one of the control runs (when there was no structure to be impinged against), a single eel track remained in a similar position for more than 5 minutes; however, for the purposes of this study this has been considered as an outlier.

A potentially impinged fish has therefore been defined as a fish **likely** to be one whose acoustic position remains in one place, within a radius of 10cm either side of the screen (which accounts for tag jitter), for a period of at least 25 seconds (determined through GIS position and time signatures) upstream of the line of deflection. Where fish are impinged for a period of time, it is possible that they become freed and continue to descend to the line of deflection and will be inadvertently counted as deflected fish. A review of the dataset indicated no impingement for a period of at least 25 seconds.

Four eels were seen from their tracks to move straight in to the buffer zone close to the screen (within 10cm of the screen); however, they did not remain there for longer than 25 seconds and therefore have not been considered impinged. These figures can be found in Appendix E. Table 4.11 summarises the number of fish potentially impinged.

Table 4.11 Potentially impinged fish at 12.5mm screen aperture – eels

Screen aperture	No. of fish interacting with the screen	No. of fish suggesting potential impingement	No. of those potentially impinged fish also reaching line of deflection in trial period
12.5mm	27	0	0

4.4.5 Entrained fish

Entrainment occurs when fish travel through the screen by virtue of water pressure, choice and/or escape velocities in excess of the fish swimming speed. An entrained fish would be expected, having passed through the screen, to continue downstream into the recapture net. It is generally assumed that this is a one-way passage. However, the fish may not always continue to the net and may instead linger in the area behind the screen, or may pass back through it.

To distinguish between an entrained fish and the error surrounding an acoustic position, the description requires greater definition. An entrained fish is **likely** to be one whose acoustic position is consistently present, following passage through the screen, at least 10cm from the downstream side of the screen (the buffer due to acoustic position jitter). This situation is unlikely to have occurred without an enforced restriction to fish movement arising from escape velocities in excess of fish swimming speed and/or a screen aperture large enough to allow fish passage. This definition states that an entrained fish is 'likely' to be one fulfilling these criteria because each such occasion must also be interrogated for other explanations, such as acoustic position error or consideration of the realities of fish behaviour. There were no potential entrainment events during the 12.5mm screen aperture trial for silver eels. Table 4.12 summarises the number of fish potentially entrained.

Table 4.12 Potentially entrained fish for 12.5mm screen aperture – eels

Aperture	No. of fish interacting with the screen	No. of fish suggesting potential entrainment	No. of those potentially entrained fish also reaching line of deflection
12.5mm	27	0	0

4.4.6 Channel flow and escape velocities

Tables 4.13 and 4.14 illustrate the maximum, minimum and average velocities measured throughout the experimental arena. Channel velocity is defined as the velocity down the main channel. Overall, in-channel velocities ranged from 0.06ms^{-1} on the true right bank on the other side to the screen to 1.69ms^{-1} near the mid-channel, with an average channel velocity of 0.91ms^{-1}.

Table 4.13 Channel flow velocities in ms^{-1} measured across trial arena – eels

Channel velocities	12.5mm	Control
Max ms^{-1}	1.69	1.60
Min ms^{-1}	0.09	0.06
Average ms^{-1}	0.97	0.81

Table 4.14 Escape flow velocities in ms^{-1} measured in front and perpendicular to the screen and along the screen face approximately 10cm from the screen – eels

Escape velocities	12.5mm
Max ms^{-1}	0.56
Min ms^{-1}	0.05
Average ms^{-1}	0.39

Escape velocity is defined as the velocity 10cm upstream of the screen, at right angles to the screen face. Along the screen face, flow is drawn through the screen resulting in a localised head drop and acceleration. Overall, along the screen face, escape velocities ranged from 0.05ms^{-1} to 0.56ms^{-1} with an average of 0.39ms^{-1}. This is close to the maximum escape velocity of 0.5ms^{-1} specified for eels within the guidance for run-of-river hydropower development (Environment Agency 2013). The minimum and maximum velocities were measured near the upstream end of the screen indicating variability in the hydrodynamics of the site possibly caused by flow pulses, the screen structure and/or boundary layer effects. Figures 4.7 and 4.8 show a mean escape and channel value for each monitoring point associated with the 12.5mm and control trial conditions.

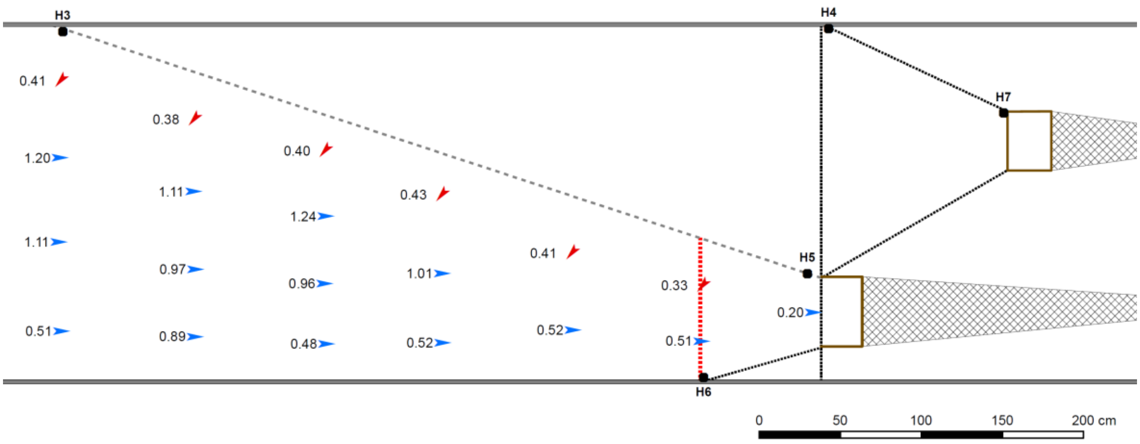

Figure 4.7 Silver eel 12.5mm screen trial mean escape and channel flow velocities. Channel velocities (ms^{-1}, blue arrows) and escape velocities (ms^{-1}, red arrows, measured 10cm from screen face). Red line = line of deflection; once tracks reached this line fish were considered to have been deflected

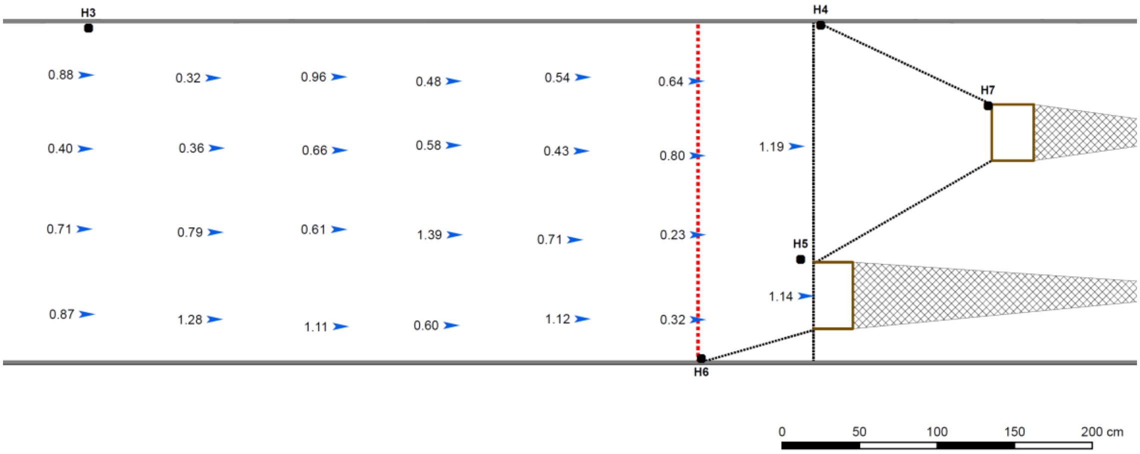

Figure 4.8 Silver eel control screen trial mean escape and channel flow velocities. Channel velocities (ms^{-1}, blue arrows) and escape velocities (ms^{-1}, red arrows, measured 10cm from screen face). Red line = line of deflection; once tracks reached this line fish were considered to have been deflected

4.5 Interpretive analysis for silver eel

4.5.1 Deflection efficiency

Deflection is achieved once fish reach a predefined line drawn across the channel near the bywash referred to here as the 'line of deflection'. By reaching this point, fish have swum past nearly the whole length of the screen panel and remained on the upstream side of the screen. Once passing the line of deflection the fish has successfully avoided entrainment or long-term impingement. These fish have therefore been deflected by the screen.

$$\text{Deflection efficiency (\%)} = \frac{\text{No. of fish reaching line of deflection}}{\text{No. of fish interacting with the screen}} \times 100$$

Of the 38 fish released into the channel over the course of the trial for the 12.5mm screen, 27 fish provided usable acoustic signals. The 11 fish without acoustic data were the result of tag failures prior to release and/or during the trial. This level of tag failure was higher than the 10% anticipated (HTI, personal communication). In total, 27 fish successfully reached the line of deflection within the defined trial period. This gives an overall deflection efficiency of 100% for the 12.5mm aperture (Table 4.15).

Table 4.15 Deflection efficiency of the 12.5mm screen aperture – eels

Aperture	No. of fish interacting with the screen	No. of signals suggesting impingement	No. of signals suggesting entrainment	Remaining fish reaching line of detection	Deflection efficiency
12.5mm	27	0	0	27	100%

4.5.2 Recapture net data versus hydroacoustic data

Using only recapture net data, and in the absence of GIS analysis, deflection efficiencies were calculated and are provided in Table 4.16. Deflection efficiency using this method is calculated by the simple formula below and uses only net recapture data.

$$\text{Estimated deflection efficiency (\%)} = \frac{\text{No. of fish captured in bywash net}}{\text{No. of fish challenging the screen}} \times 100$$

Table 4.16 Deflection efficiency of each screen aperture using only recapture net data – eels

Aperture	Estimated no. of fish challenging the screen*	No. fish passing behind screen	No. fish in bywash net	Estimated mean deflection efficiency
12.5mm	20	0	20	100
Control	15	10**	5	33.3%

* The assumption is that the number of fish challenging the screen is equivalent to the number of fish captured in the downstream nets.

** For the control data, the 'passing behind screen' is the left hand bank net behind where the screen had been. The result for deflection efficiency for the control trials provides an illustration of the relative direction taken by control fish, in the absence of a deflecting screen, and is for illustration only.

The remaining fish that were released but had not been captured in the nets at the end of each trial period are represented by either tag failures or fish losses or were predominantly those fish remaining in the trial channel without descending fully into the nets. Fish that were lost and those remaining in the trial channel are recorded by the acoustic tracking data.

4.5.3 Confidence in deflection efficiency

Statistical confidence in the trials' ability to prove the study hypothesis is best demonstrated by binomial probability calculations.

Due to a low supply of silver eels only 38 eels were trialled with the 12.5mm screen. To prove a minimum of 90% deflection efficiency with 95% confidence, we would need to achieve at least 37 successes out of 38 fish challenging the 12.5mm screen. If all fish successfully provided tracking data and reached the line of deflection without any suggestion of impingement or entrainment (as shown in Table 4.15), the trial could meet a 94.1% deflection efficiency with 90% confidence (n=38) and 92.4% deflection efficiency with 95% confidence. The higher the sample size, the closer this confidence level will tend to 100%.

Using data from Table 4.15, 27 fish provided usable acoustic signals. Binomial probability calculations therefore show that trials have proved with 95% confidence (n=27 fish) that silver eel deflection efficiencies greater than 89.5% are achieved with the 12.5mm aperture screen.

4.5.4 Fineness ratio and influence of fish size

The Environment Agency guidance for run-of-river hydropower development requires use of screens with particular mesh aperture sizes in waters where eels are to be protected. The mesh aperture sizes were derived by considering how the fish fineness ratio affects the chances of fish of certain sizes passing through particular apertures in the screen.

The fineness ratio was used to determine the mesh aperture size expected to prevent entrainment of the specific fish sizes used in this trial. Calculated mesh aperture size estimates for each fish whose data was used in this trial are shown in Appendix F. All fish used in the trial might be expected to be deflected based on using a fineness ratio of 16 for eels (Turnpenny and O'Keeffe 2005).

If individual fineness ratios are calculated for each fish using fish-specific measurements recorded during the trials, the smallest mesh aperture size required was identified as being 11mm. This was calculated for a silver eel 345mm in length and 17mm in width. The individual fineness ratio for each of the released fish indicates the mesh aperture size predicted for the fish to be excluded was less than 12.5mm for 26 of the 67 eel releases (15 in the 12.5mm trials and 11 in the control trials).

Note though that the fineness ratio of a fish is only one of the factors influencing whether a fish will be entrained or impinged and that escape velocity and fish behaviour are also important.

4.6 Summary for silver eel

4.6.1 Deflection efficiency

Of the 38 fish released into the channel over the course of the trial for the 12.5mm screen, 27 fish provided usable acoustic signals. In total, 27 fish successfully reached the line of deflection within the defined trial period. This gives an overall deflection efficiency of 100% for 12.5mm aperture.

This allows us to prove with 95% confidence that an overall deflection efficiency (allowing for errors associated with sample size) of at least 89.5% for the 12.5mm aperture screen can be achieved.

4.6.2 Fineness ratio

Using the published fineness ratio of 16 (Turnpenny and O'Keeffe 2005) to estimate whether the fish sizes used in this trial are likely to be entrained, we can show that none of the fish would be expected to be entrained. The calculated individual fineness ratios for each eel released, however, indicates that the mesh aperture size predicted for the fish to be excluded was less than 12.5mm for 39% of the fish released although none of these fish were impinged or entrained during this trial.

4.6.3 Escape velocity

Water velocity conditions at the screen face were sufficient to test the capacity for impingement or entrainment of silver eels of the size under study. Mean escape velocity (0.39ms^{-1}) recorded along the screen was within the maximum escape velocity of 0.5ms^{-1} outlined in the guidance for run-of-river hydropower development for eels (Environment Agency 2013).

5 Discussion

The primary aim of this study was to quantify the level of protection provided to fish by the screen designs recommended in the Environment Agency guidance for run-of-river hydropower development (Environment Agency 2013). This work has been conducted through a literature review and field-based experimental evaluation. The focus of the study has been on two species known to be at risk of being entrained into hydropower turbines used to generate electricity. Atlantic salmon and European eel are listed as UK BAP priority species and under Annex II of the Habitats Directive.

One specific area of the Environment Agency guidance covers the need to provide appropriate screening to prevent fish injury or mortality by restricting access to HEP turbines where this is considered to be a risk.

This project provides supporting evidence of the deflection efficiencies of salmon smolts and silver eels in response to the screen dimensions recommended in the guidance for run-of-river hydropower development. The following discussion has focused on two aspects:

- Validation and appropriateness of the experimental methodology to quantify the level of protection provided to fish species by the screen designs recommended in the Environment Agency guidance for run-of-river hydropower development (section 5.1).
- Discussion around the experimental outcomes (section 5.2).

5.1 The field trial

This project established an experimental arena that mimics the general conditions experienced by a fish passing a hydropower screen system, as designed following the requirements outlined in the guidance for run-of-river hydropower development (Environment Agency 2013). It is accepted that this arena would be unable to directly mimic a real hydropower setup, not least because no single mimic can address all possible site format/arrangement scenarios, flows and conditions experienced by real hydropower sites.

The review of literature identified that few studies have experimented with the effect of bar spacing on fish deflection efficiencies, particularly in relation to the bar spacing guidance for silver eels and salmon smolts in the UK. Current guidance is based on a combination of the likelihood of entrainment based on the fish fineness ratio and the few experimental studies that have been undertaken. The following sections discuss aspects of the experimental trials and the appropriateness of the methods used.

5.1.1 Field experiment constraints

The site selected for the trials offered a number of advantages over the use of an artificial flume setup. However, as an on-line river channel, the site also provided a number of challenges to effectively carrying out controlled, repeatable experimental trials.

Although the site offered some control over flows through the experimental arena, fine-tuning the flows was difficult, especially during the high flow conditions experienced during the smolt trials. The high flows effectively reduced the head drop, which required more water to be released down the experimental channel to achieve the desired flow velocities. However, this was constrained by the freeboard on the camera boxes and main screening frame.

In addition, the on-line nature of the channel resulted in the trials being subject to debris being carried in the river. During the high flows, debris levels made running the trials impossible, and threatened the viability of using the smolts due to the delays encountered. In addition, the debris also proved to be an issue during the eel trials, whereby larger debris and water pressure was believed to have resulted in a number of holes forming in the bywash capture net.

A number of fish losses were encountered during both the smolt and eel trials. Proportionally fewer losses were encountered during the smolt trials, probably as a result of the behavioural differences between the two species. During the trials, smolts tended to migrate mid-channel, avoiding contact with the channel bed and walls. Eels on the other hand tended to explore and make contact with structures during passage. As a result, it is considered that the eels were more able to discover weakness or gaps in the experimental arena. Completely eel-proofing the arena proved to be difficult.

5.1.2 Acoustic tags

The literature review identified a number of advantages of using acoustic tags over other tagging methods to determine if fish have been entrained or impinged. Advantages of using acoustic tags include the ability to record continuous tracks of fish movements and the ability to record either 2D or 3D positioning. During the smolt and eel trials it was clear that without the more detailed data from acoustic tracking, the sole use of recapture net data would likely underestimate the deflection efficiency. This is due to fish avoiding recapture by remaining in the channel or being lost from the arena. Similarly, without the acoustic tracking data it would not have been possible to determine when the fish were in the net or if they had passed the screen. There would also be no understanding of whether any fish were temporarily impinged, went through and returned through the screen, or indeed ever challenged the screen during the trial period.

The suitability of using acoustic tags in the relatively narrow concrete channel at Romsey was queried because of concerns regarding required positional resolution and interfering signal reflections. In order to assess the appropriateness of the methodology, testing of acoustic tags in fixed locations and tag-drag trials were conducted in mid-November 2013 to test its applicability. Further trials were run at the outset of the smolt study period with multiple test tags and an additional review of fixed tag locations was carried out prior to the silver eel trial. Subsequent data processing showed interference to the acoustic signals from the channel and screen structure was significant but manageable. Following data processing to remove noise and outliers, it was determined that the HTI acoustic tracking equipment would be suitable to operate in the study channel.

It was identified that tag positions calculated from the hydroacoustic array were subject to errors. Hydrophones were positioned to ensure the entire experimental volume was covered by a minimum of three hydrophones and to indicate when fish had passed downstream of the trial area. To quantify the positional error (jitter) about the tag positions, tests were carried out in November 2013 and December 2014. Hydroacoustic recordings were taken of tags in fixed positions in the channel and the resultant positions plotted. Jitter from tags positioned on the upstream side of the screens in three locations was roughly circular with approximately 90% of recorded tag positions within 10cm of the true tag position.

In order to take this jitter into account a 10cm screen buffer was established on either side of the screen. If a tag (and therefore the corresponding fish) was found within this screen buffer then it could be an indication of potential impingement and would require further investigation. In order to take the level of jitter into consideration regarding entrainment, a potentially entrained fish was identified if the tag was found beyond the 10cm screen buffer zone on the downstream side of the screen.

5.1.3 Fish supply

The use of local wild Atlantic salmon smolts was considered due to the suitability of fish in the catchment and as a result of their active and natural migration behaviour. However, this was precluded due to the sensitivities of extracting fish from a vulnerable population and due to concerns over being able to gather sufficient fish to give meaningful results within a suitable timescale. It was also identified that there were insufficient silver eels of an appropriately small size available from the River Test.

The literature review identified a preference for the use of wild fish as opposed to farmed fish. The behavioural characteristics of wild fish populations are likely to better reflect migratory fish behaviours than farmed fish. Although it was not possible to source local wild fish, both the salmon smolts and silver eels sourced for the trials were wild fish. During the trials the fish tested did show a migrating tendency to move downstream and both the smolts and the eels exhibited migratory conditioning. The fish tested were therefore considered suitable for the trials.

5.1.4 Fish behaviour

As part of the literature review behavioural differences were identified between salmon smolts and silver eels when approaching and encountering screens. Unlike salmon smolts, eels have a tendency to make contact with obstructions before moving past them (Russon et al. 2010). These behavioural differences were supported by the results of the trial, with smolt often observed shoaling mid-channel or at the downstream end of the study arena near the line of deflection (just upstream of the bywash camera box). Silver eels on the other hand were observed to be more tactile and exploratory in nature often moving along the channel walls or in-stream screening structures. Silver eels were also noted to move in both an upstream and downstream direction, on occasion multiple times, compared to the salmon smolts which generally moved in a downstream direction. These behavioural characteristics and the acoustic tag positioning were used to aid the definition of an impingement event during the trials. The definitions around potential impingement events are discussed further for each species in sections 5.2 and 5.3.

5.1.5 Flow velocities

One consequence of not being able to test the efficiency of screens on a fully operational hydropower site is the lack of draw through the screen as a result of a water abstraction behind the screens. Instead the experiment was subject to velocities drawn through the screen under the existing flow conditions. Environment Agency guidance recommends a maximum acceptable escape velocity towards any part of the screen of 0.6ms^{-1} for salmon smolt and 0.5ms^{-1} for eel.

The mean escape velocities during both trials were below these maximum levels: 0.44ms^{-1} during the smolt trials and 0.39ms^{-1} during the eel trials. The maximum escape velocity recorded during the smolt trials reached 0.63ms^{-1} on one occasion, while the maximum escape velocity recorded during the eel trials reached $0.56ms^{-1}$. Both these measurements were slightly above the maximum criteria outlined in the guidance for run-of-river hydropower development (Environment Agency 2013). The minimum and maximum velocities measurements recorded during the trials were generally both near the upstream end of the screen. This indicates that there was variability in the hydrodynamics at the site, possibly caused by flow pulses, the screen structure and/or boundary layer effects. Velocity conditions at the screen face were considered sufficient to test the capacity for impingement or entrainment of salmon smolts and silver eels of the size used in the study.

5.1.6 Fineness ratio

The Environment Agency guidance for run-of-river hydropower development requires the use of screens with particular mesh aperture sizes in waters where smolts and/or eel are to be protected. The mesh aperture sizes used in the guidance are derived from aspects such as screen angle, escape and sweep velocities and by considering how the fish fineness ratio affects the chances of fish of certain sizes physically passing through particular size apertures in the screen. Fish fineness ratio is a measure of how elongate a fish is relative to its transverse sectional diameter. This is defined as the length divided by the maximum depth of the fish (Turnpenny and O'Keeffe 2005).

The screening for intake and outfalls: a best practice guide provides observed fineness ratios for 24 marine and freshwater fish species including 4.65 for salmon and 16 for eel (Turnpenny and O'Keeffe 2005). These observations were sourced from Turnpenny 1981, with additional data supplied for cyprinids. For the purpose of this study it was deemed appropriate to assess not only the published fineness ratios but also to calculate a fineness ratio for each individual fish in the experiment. The published fineness ratios were based on a sample size of two for eels and 50 for salmon smolt. For the smolts used in the current study, the maximum calculated fineness ratio was recorded as 6.3, the minimum as 4.3 and the average as 5.6. For the eels used in the current study the maximum calculated fineness ratio was recorded as 24.6, the minimum as 14.9 and the average as 18.6. The individual fineness ratios for the test fish therefore indicate a range similar those published in the best practice guide (Turnpenny and O'Keeffe 2005).

All smolts used in the 10mm screen trial might be expected to be deflected based on using a fineness ratio of 4.65. Under the 12.5mm screen condition, 5 of the 120 smolt had a predicted mesh aperture size less than 12.5mm. All silver eels used in the study might be expected to be deflected based on using a fineness ratio of 16 (Turnpenny and O'Keeffe 2005). Individually calculated fineness ratios, however, indicated that a greater number of both smolts and silver eels may not be excluded from the respective mesh apertures tested. Further detail on entrainment and impingement for individual species are provided in sections 5.2 and 5.3.

5.2 Atlantic salmon smolts

5.2.1 Interactions

Of the 294 salmon smolt released during the trial, 279 provided active hydroacoustic tracking data. Of these 279 fish, only one fish was identified to completely avoid any form of interaction with the screen (remaining upstream of hydrophone H3). This fish remained upstream of the experimental area not moving near the screen on any occasion and was therefore removed from the dataset. A review of fish behaviour and the acoustic tag positioning data indicated that while the screens were in place two fish moved down the channel close to the right bank and therefore did not directly interact with the screen. For the purpose of this study it was decided to keep these fish in the dataset as although they did not directly challenge the screen they may have been indirectly interacting with the screen by showing possible avoidance of the screen.

5.2.2 Impingement

For the purposes of this study, an impinged fish was defined as a fish **likely** to be one whose acoustic position remained in one place, within a radius of 10cm either side of the screen (which accounts for acoustic position jitter), for a period of at least five seconds (determined through GIS position and time signatures).

The five-second period was determined through a review of smolt behaviour during the trials. Smolts were found to be very active and therefore did not remain in a single position for greater than five seconds. A fish remaining in a single position for greater than five seconds is potentially displaying a behaviour that is unlikely to be seen naturally and would instead indicate enforced restriction to fish movement. Any fish remaining within the 10cm buffer for more than five seconds were therefore deemed to have been potentially impinged. Two fish (one for the 10mm screen and one for the 12.5mm screen) during the trials showed potential impingement. One potential impingement occurred mid-screen and the second on the downstream portion of the screen near the line of deflection. On both occasions the fish moved away from the screen just after the defined five-second time period.

Where fish are impinged for a period of time, it is possible that they become freed and continue to descend to the line of deflection and will be inadvertently counted as deflected fish. The two fish that were potentially impinged both descended to the line of deflection. Impinged fish may suffer physical damage that will hinder their continued migration and health. Therefore in order to take into account a worst case approach, fish identified as potentially impinged were not recorded as deflected fish as part of the deflection efficiency calculations.

5.2.3 Entrainment

To distinguish between an entrained fish and the jitter surrounding an acoustic tag position, the following definition was used. An entrained fish was defined as a fish **likely** to be one whose acoustic position is consistently present, following passage through the screen, at least 10cm from the downstream side of the screen (the buffer due to acoustic position jitter). This situation is unlikely to have occurred without an enforced restriction to fish movement arising from escape velocities in excess of fish swimming speed and/or a screen aperture large enough to allow fish passage.

Four smolts were identified to pass the 10cm buffer zone on the downstream side of the screen therefore indicating potential entrainment; two fish during the 10mm screen trial and two fish during the 12.5mm screen trial. Further analysis of the acoustic positions indicated that the fish moved through the screen for a short period of time before returning to the main channel. In a typical entrainment event a fish would be expected to move through or be forced through a screen and then remain on the downstream side of the screen. In a hydropower intake scenario this fish may then be drawn into the intake/turbines.

All four fish indicating potential entrainment during this trial returned to the main channel within four seconds, with no smolts being captured in the screen net while the screen was in place. The individual and published fineness ratios for the two fish indicating potential entrainment during the 10mm screen trial had required mesh sizes larger than 10mm. The two fish potentially entrained during the 12.5mm trials had calculated mesh sizes less than 12.5mm for both fish although when using the published derived fineness ratios required mesh sizes were above 12.5mm. As discussed each tag is subject to a degree of error as a result of tag jitter. It is possible that on these four occasions positional error may explain the apparent movement of the fish through the screen and then back into the main channel. For each potential entrainment event a conservative (worst case) approach has been taken thereby recording each fish as a potential entrainment event.

5.2.4 Deflection efficiency

In order to provide statistical confidence in the trials' ability to prove the hypothesis, binomial probability calculations were carried out on the dataset. The salmon smolt trial has allowed us to prove with 95% confidence that an overall deflection efficiency (allowing for errors associated with sample size) of at least 92.4% can be achieved for salmon smolts with a 10mm aperture screen and an overall deflection efficiency of at least 87.7% can be achieved for a 12.5mm aperture.

The reason why the deflection efficiency was slightly lower for the 12.5mm screen aperture is that five of the 114 fish released did not reach the line of deflection and were therefore not counted as deflected fish. It should be noted that of these five fish none were identified as being impinged or entrained following review of the acoustic positions. It is possible that conditions at the mouth of the bywash were not conducive to the fish continuing their descent into the recapture net. Under natural conditions these five fish may have moved down past the line of deflection at a later time and would have therefore been counted as defected fish. As a result, the 87.7% deflection efficiency with 95% confidence for the 12.5mm trial is a worst case estimate. This demonstrates that under the conditions pertaining during the test period, both 10mm and 12.5mm screens provided deflection efficiencies for salmon smolt consistent with the aim of achieving 100% passage of downstream migrants.

5.2.5 Impingement

The same approach was used in defining impingement for silver eels as that used for smolts. However, in reviewing track data the behavioural differences between salmon smolts and silver eels when approaching and encountering screens were noted. Unlike salmon smolts, eels were more exploratory in nature and were also observed to remain in a single location for a greater period of time.

A review of control run tracks indicated that silver eels on occasion would remain in a stationary position for up to approximately 25 seconds. A single eel track remained in a similar position for more than five minutes; however, for the purposes of this study this was considered as an outlier. As a result an impinged eel was defined as a fish **likely** to be one whose acoustic position remained in one place, within a radius of 10cm either side of the screen (which accounts for tag jitter), for a period of at least 25 seconds (determined through GIS position and time signatures) upstream of the line of deflection. A review of the dataset indicated no impingement upstream of the deflection area for a period of at least 25 seconds. In fact, no fish were observed within the 10cm buffer zone of the screen for a period greater than five seconds.

5.2.6 Entrainment

The definition for an entrained fish remained the same between the smolt and silver eel trials (section 5.2.3). During the 12.5mm screen trial no fish were found to move beyond the 10cm buffer zone downstream of the screen.

5.2.7 Deflection efficiency

In order to provide statistical confidence in the trials' ability to prove the hypothesis binomial probability calculations were carried out on the dataset. The silver eel trial has allowed us to prove with 95% confidence that an overall deflection efficiency (allowing for errors associated with sample size) of at least 89.5% for a 12.5mm aperture screen can be achieved for silver eels. During the trial no silver eels were found to be entrained or impinged thus indicating 100% deflection efficiency. However, due to the low sample size (n=27 fish) the deflection efficiency is reduced to 89.5% with 95% confidence. The fish released in the trials ranged in size between 335mm and 555mm. Fish larger than 500mm were deliberately not targeted as Environment Agency guidance recommends a screen aperture of 20mm (screen angle ≤20º) for larger eels (Environment Agency 2013) and we did not have access to a 20mm screen during this experiment.

Under the test conditions experienced, the 12.5mm screen provides protection for silver eels of a size range between 335mm and 555mm.

5.3 Run-of-river hydropower guidance

The current guidance provided by the Environment Agency (Environment Agency 2013) specifies the bar spacing for screens based on the species to be protected, the geographical location (which affects fish size) and site turbine characteristics. For all cross-flow turbines and other turbines with a maximum turbine flow <1.5m^3 per second and for any other turbine with a maximum turbine flow ≥1.5 m^3 per second (excluding cross-flow turbines) a screen aperture of ≤10.0mm and ≤12.5mm is required for migratory salmonids depending on the region. For all other species including eel (smaller than 500mm), ≤12.5mm is required. For larger eels (>500mm in length) a 20mm mesh size is recommended (screen angle ≤20º).

This study has allowed us to show in an experimental setting:

- that an overall deflection efficiency (allowing for errors associated with sample size) of at least 92.4% (with 95% confidence) can been achieved for salmon smolts with a 10mm aperture screen and an overall deflection efficiency of at least 87.7% (with 95% confidence) can be achieved for a 12.5mm aperture
- that an overall deflection efficiency (allowing for errors associated with sample size) of at least 89.5% (with 95% confidence) for a 12.5mm aperture screen can be achieved for silver eels between 335mm and 555mm in length.

6 Conclusions

The primary aim of this study was to test and quantify the level of protection provided to fish species by the screen designs recommended in the Environment Agency guidance for run-of-river hydropower development (Environment Agency 2013). This was carried out by testing the recommended screen apertures for salmon of 10mm and 12.5mm and the screen aperture recommended for eels of 12.5mm. The literature review and field study elements have drawn the following conclusions:

- Behavioural differences were identified between salmon smolts and silver eels when approaching and encountering screens. Salmon smolts were often observed shoaling mid-channel or at the downstream end of the study arena near the line of deflection. Their behaviour appeared to be influenced by the hydrodynamic patterns within the channel, especially those related to the screening structure. Silver eels were observed to be more tactile and exploratory in nature often moving along the channel walls or in-stream structures.

- During the field trials it was clear that without the more detailed data from the hydroacoustic tracking, the sole use of recapture net data widely used in other studies, would likely underestimate the deflection efficiency.

- A single fish fineness ratio to determine the screen apertures is a useful tool to provide generic protection from entrainment to an identifiable range of fish species of defined lengths. However, this study has shown that there can be great variation in individual calculated fineness ratios of fish and the corresponding predicted mesh aperture size compared to the published ratios. A number of other factors play a key role in fish deflection, such as variation in fish sizes, fish behaviour, escape velocities and sweep velocities.

- Environment Agency guidance recommends a maximum acceptable escape velocity towards any part of the screen of $0.6ms^{-1}$ for salmonid and $0.5ms^{-1}$ for eel. The mean escape velocities during both trials were below these maximum levels: $0.44ms^{-1}$ during the smolt trials and $0.39ms^{-1}$ during the silver eel trials. The maximum escape velocity during the smolt trials reached $0.63ms^{-1}$ while the maximum escape velocity during the eel trials reached $0.56ms^{-1}$, both slightly in excess of the maximum criteria outlined in the guidance for run-of-river hydropower development (Environment Agency 2013). There was variability in the hydrodynamics at the site possibly caused by flow pulses, the screen structure and/or boundary layer effects. Flow velocity conditions at the screen face were considered sufficient to test the capacity for impingement or entrainment of salmon smolts and eels of the size used in the study.

- This study has shown in an experimental setting that an overall deflection efficiency (allowing for errors associated with sample size) of at least 92.4% (with 95% confidence) can been achieved for salmon smolts with a 10mm aperture wedge-wire screen, and an overall deflection efficiency of at least 87.7% (with 95% confidence) can be achieved for a 12.5mm aperture wedge-wire screen.

  - Two salmon smolts indicated **potential** temporary impingement; one of the 100 fish in the 10mm screen trial and one of the 114 fish in the 12.5mm screen trial.

  - Four salmon smolts passed through the screen and the 10cm buffer zone on the downstream side of the screen indicating **potential** entrainment: two of the 100 fish in the 10mm screen trial and two of the 114 fish in the 12.5mm screen trial. However, as all four fish were subsequently tracked back through the screens, it is probable these events were actually due to positional uncertainty.

- This study has shown in an experimental setting that an overall deflection efficiency (allowing for errors associated with sample size) of at least 89.5% (with 95% confidence) for a 12.5mm aperture wedge-wire screen can be achieved for silver eels between 335mm and 555mm in length.

  - None of the 27 silver eels were impinged by the 12.5mm aperture screen.

  - None of the 27 silver eels were entrained by the 12.5mm aperture screen.

The results of this study support the screen design recommendations outlined in the Environment Agency guidance for run-of-river hydropower development (Environment Agency 2013).

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List of abbreviations

FDE	Fish deflection efficiency
HEP	Hydroelectric power
HTI	Hydroacoustic Technology Inc.
PIT	Passive inductive transponders

Glossary

Angled screens	Fish screens can be placed perpendicular to the flow (90°) or be angled (<90°). Screens are often angled to help guide fish towards a bypass at the downstream end, to reduce escape velocities and reduce impingement and entrainment.
Aperture	The size of the gaps in the screen, also known as bar spacing or mesh size.
Approach velocity	See Escape velocity.
Bar rack screen	A screen made up of bars (rather than a mesh).
Bar spacing	The distance between bars on a trashrack (also known as slot width).
Bar width	The thickness of the bars on a bar or trash rack.
Bywash	The arrangement of flow that is needed to prevent fish becoming impinged on the screen or entrained. This is located at the downstream end of an angled screen.
Channel velocity	The main channel velocity.
Entrainment	When fish pass through the screen they are drawn into the turbine.
Escape velocity (also known as 'approach velocity')	The velocity 10cm upstream of the screen, at right angles to the screen face: this velocity must be low enough for the fish to be able to escape to avoid impingement or entrapment. It is calculated using methods outlined in Turnpenny and O'Keeffe (2005).
Fish fineness ratio	A measure of how elongate a fish is relative to its transverse sectional diameter. This is defined here as the standard length divided by the maximum depth of the fish. The fineness ratio formula is presented in Turnpenny and O'Keeffe (2005).
Fish deflection efficiency (FDE) (also known as guidance efficiency)	The percentage of fish deflected by the screen (i.e. not impinged or entrained).
Fork length	The length of a fish measured from the tip of the snout to the end of the middle caudal fin rays. Used in fishes in which it is difficult to tell where the vertebral column ends
Guidance efficiency	See fish deflection efficiency.
Headloss	A reduction in water depth. The efficiency of the turbine is affected by the difference in the water level (head) between the upstream and downstream end of the turbine; therefore a reduction in the upstream water level as a result of a fish screen (or trashrack)

	will impact on the turbine efficiency.
HTI tag	A brand of acoustic tag used for tracking fish.
Hydrophone	A device which receives signals from acoustic tags. A microphone designed to record or listen to underwater sound.
Impingement	When fish become stuck against the screen as a result of the flow conditions (if the escape velocity is too high).
Inclined screens	Fish screens can be placed vertically within the channel or inclined relative to the river bed. Inclined screens are used to guide fish towards a bypass usually near the water surface and to reduce escape velocities and reduce impingement and entrainment.
Jitters	Slight irregular movement, variation, or unsteadiness, in the electrical signal
Line of deflection	Deflection is achieved once fish reach a predefined line drawn across the channel near the bywash referred to here as the 'line of deflection'. By reaching this point, fish have swum past nearly the whole length of screen panel and remained on the upstream side of the screen. Once past the line of deflection the fish has successfully avoided entrainment or long-term impingement.
Parr	A young salmon (or trout) between the stages of fry and smolt, distinguished by dark rounded patches evenly spaced along its sides.
Passive inductive transponder (PIT) tag	A type of tag used to track fish that emits a signal when activated by passing through an electrical field
Silver eel	When eels mature they change to a silvery colour and migrate seawards; in this life stage they are known as silver eels.
Smolt	A juvenile salmonid that has undergone physiological and physical changes in preparation for the downstream migration to the sea.
Standard length	The length of a fish measured from the tip of the snout to the posterior end of the last vertebra or to the posterior end of the midlateral portion of the hypural plate. This measurement excludes the length of the caudal fin.
Sweep velocity	Sweep velocity is the velocity component parallel to the screen face. This is used to calculate the time taken for the fish to traverse the screen from any given point.
Trashrack	A bar rack which is used to stop debris (trash) entering an intake (e.g. for a hydropower turbine). These may also act as a physical or behavioural

	barrier to fish migrating downstream.

Appendix A: Literature review summary tables

Summary of screen properties and key findings for studies reviewed

Study	Species	Location	Bar spacing and type	Screen angle (to axis of river)	Screen inclination	Escape velocity	Fish deflection efficiency (FDE)	Key findings
Turnpenny 2010	Rainbow trout (*Oncorhynchus mykiss*)	River Test, Hampshire, UK	10 and 15mm bar spacing, bar width 6mm. Vertical bar screens	18°, 45° and 90°	Vertical	<0.75ms^{-1}	FDE for 10mm screens 88.3–100% (96.52, ± 1.09 SE, n=11). FDE for 15mm screens 90.6–95.4% (95.97, ± 0.66 SE, n=12). No impingement or entrainment	Highest fish deflection efficiencies with the smaller bar width. No significant difference between angles: attributed to low escape velocity.
Russon et al. 2010	European silver eels (*Anguilla anguilla*)	Laboratory flume, UK	12mm Vertical bar rack	15°, 30°, 45° and 90°	Vertical and 30° relative to channel floor	Up to 0.9ms^{-1}	Angled screens (15°, 30° 45°), vertical to the channel floor: 98.3% FDE, no impingement or entrainment. Perpendicular screen (vertical and 30° to channel floor): 46.8% impinged for >5 seconds, 25% entrained	Angled/inclined racks rather than those placed vertically or perpendicular to the flow were shown to be more efficient for guiding eels and avoiding impingement with angles <45° on the vertical or horizontal planes most effective.
Calles et al. 2013	European silver eels (*Anguilla anguilla*)	HEP, River Ätran, Sweden	20mm and 18mm. Bar rack (direct of bars not specified)	Not reported. Appears to be perpendicular to the flow in diagram.	63.4° and 35° relative to the channel floor	0.11 to 0.90ms^{-1}	Mortality reduced from >70% at the old 20mm bar rack inclined at 63.4° to <10% at the new 18mm bar rack inclined at 35°. No tagged eels were impinged and killed on the racks, and 80% entered the collection facility	

Study	Species	Location	Bar spacing and type	Screen angle (to axis of river)	Screen inclination	Escape velocity	Fish deflection efficiency (FDE)	Key findings
Croze 2008	Atlantic salmon smolts (*Salmo salar*)	4 HEP schemes on the River Ariège, France	Uneven 30-60mm Vertical bar trash racks	Not reported	Not reported	$1.2ms^{-1}$ and $0.9ms^{-1}$	Mean downstream bypass efficiencies: Guilhot: 70.9% (SD = 1.4%) Las Mijanes: 32.3% (SD = 1.7%) Las Rives: 39.5% (SD = 1.6%) Crampagna:65.6% (SD = 1.9%)	The behaviour deterrent effect of a trashrack with 30mm bar spacing was shown; however, the effect was affected by the escape velocity. Smaller smolts (<175mm) only showed a behavioural deterrent effect at lower velocities (<$0.9ms^{-1}$).
Travade et al. 2010	European silver eel (*Anguilla anguilla*)	HEP, France	30mm Vertical bar trash racks	30°	Not reported	Up to $0.35ms^{-1}$	No impingement Entrapment varied between years from 8.1% to 60% (mean 41.4%).	The trashrack did not impede the migration of small eels; they were not physically blocked by the trashrack and migrated through the turbines. Intermediate size eels (which were not physically blocked) appeared to be influenced by the racks and generally passed less quickly. No eels were found to be impinged on the racks
Turnpenny et al. 2004	Atlantic salmon smolt (*Salmo salar*)	HEP, Stanley Mill on Lower River Tay, Scotland	10mm Vertical bar screens	15°	10° to vertical	≤$0.05ms^{-1}$ approx.	31.3% smolts recaptured downstream (attributed to low electrofishing efficiency). With the exception of one undersized hatchery smolt (100mm), no impingement was recorded and no fish passed through the screen in typically sized smolt ≤120mm or other smaller fish	

Study	Species	Location	Bar spacing and type	Screen angle (to axis of river)	Screen inclination	Escape velocity	Fish deflection efficiency (FDE)	Key findings
EPRI 2001	Smallmouth (*Micropterus dolomieu*) and largemouth (*Micropterus salmoides*) bass, golden shiners (*Notemigonus crysoleucas*), walleye (*Stizostedion vitreum*), channel catfish (*Ictalurus punctatus*), shortnose (*Acipenser brevirostrum*) and lake sturgeon (*Acipenser fulvescens*) and silver phase American eel (*Anguilla rostrata*)	Laboratory study (USA)	25mm and 50mm spacing bar rack and 50mm louvres spacing. Bar and louvre width 12.5mm. Vertical bars and louvres	90°, 45° and 15°	Not reported	Up to $0.9ms^{-1}$	Large number of guidance efficiencies reported due to no. of species and setups. Guidance efficiency was often <50% for the 45° bar racks and louvre array. American eel demonstrated the highest guidance efficiencies, up to 73%. With the exception of lake sturgeon, guidance efficiency was often >70% for the 15° bar rack and louvre	Guidance efficiency was low for screens angled at 45° for all species. Efficiency was increased when the screen angle was reduced to 15°.
EPRI 1996	Juvenile blueback herring (*Alosa aestivalis*), juvenile golden shiners (*Notemigonus crysoleucas*) and rainbow trout (*Oncorhynchus mykiss*)	HEP site (USA)	2mm spacing 2mm diameter horizontal bars modular inclined screen	Not reported	Angled upwards at 15°	Up to $1.22ms^{-1}$	Golden shiners and rainbow trout showed diversion and survival rates approaching 100% under most test conditions Diversion efficiency averaged 96 to 97% for most of the tests with blueback herring	In general the field tests showed high diversion efficiencies with all three species at velocities up to $1.22ms^{-1}$

Study	Species	Location	Bar spacing and type	Screen angle (to axis of river)	Screen inclination	Escape velocity	Fish deflection efficiency (FDE)	Key findings
Clough et al. 2000	Atlantic salmon smolt (*Salmo salar*)	Field flume tests, River Guar, Scotland	10mm and 12mm vertical bar screens (7mm bar width) and 12mm (vertical) x 25mm (horizontal) mesh screens	0°, 75° and 90°	Vertical (75° angled screen) and 10° to the vertical (0 and 90° angled screens)	$0.3ms^{-1}$ except in one test with $0.4ms^{-1}$	No Impingement No entrainment Diversion efficiency (in the time allowed) varied from 7.7% to 87.7% with a large variability between replicates under each setup.	The behaviour of fish was similar between screen types and positions. The orientation of fish varied between screen positions, but not types; this was attributed to the flow patterns created by the angle of the screen. Increasing the velocity from 0.3 to $0.4ms^{-1}$ did not result in impingement.
Boubée and Williams 2006	Silver eels, 3 species: shortfin eel (*Anguilla australis*), longfin eel (*Anguilla dieffenbachia*) and the Australian longfin eel or spotted eel (*Anguilla reinhardtii*)	HEP site, Mokau River New Zealand	30mm	Not reported. Situated on dam face	Vertical	$0.3–1.2ms^{-1}$	Impingement and entrainment rates not reported. 544 and 744 eels recorded migrant eels recorded using the bypass in 2002 and 2003 respectively. Approximately 10% of tagged eels used the bypass. (also able to migrate using the spillway and tag detection rates were low)	The 30mm gaps between bars did not prevent all eels from entrainment. The racks were shown to exclude mostly eels longer than 1,000mm and would therefore protect only part of the migrant stock.
Pedersen et al. 2011	European silver eel (*Anguilla anguilla*)	Tange HEP station, River Gudenna, Denmark	10mm spacing Vertical bar screen	90°	Not reported	0.26–$0.45ms^{-1}$ in low to moderate flows, up to $1ms^{-1}$ in high flows	23% of the tagged eels reached the tidal limit, mainly due to difficulties in passing the hydropower dam. Impingement and entrapment not directly measured	Eels are known to become impinged on the racks and are removed by the automatic debris cleaner, often dead or severely damaged.

Study	Species	Location	Bar spacing and type	Screen angle (to axis of river)	Screen inclination	Escape velocity	Fish deflection efficiency (FDE)	Key findings
Gosset et al. 2005	European silver eel (*Anguilla anguilla*)	Halsou HEP, River Nive, France	30mm spacings, vertical bars. Bar width 8mm	15°	25° to the vertical	$0.5ms^{-1}$	Bypass efficiency ranged from 40% to 80% Entrainment peaked at 40–45%	Study confirmed the behavioural effect of the trashrack on the eel, eels were seen to approach several times without going through even though the 30mm spacings were large enough for 80% of the eels monitored to fit between. The repulsive effect of the rack increased with turbine flow (and therefore velocity).
Haro et al. 2000	American silver eel (*Anguilla rostrata*)	HEP, Connecticut River, USA	32mm from the surface down to 3.5m, and 102mm below 3.5m.	Not reported	Not reported	$0.3–1.2ms^{-1}$	76.9% of the actively migrating tagged eels were entrained	Results indicated that eels may be reluctant to pass through the racks or into the bypass on first encounter and high escape velocities make it harder for eels to swim back upstream or avoid entrainment.
Travade et al. 2006	European silver eel (*Anguilla anguilla*)	Two HEP sites, SW France	30mm bar spacing, vertical bars	Halsou – 15° Baigts – 18°	Halsou and Baigts – 25° to the vertical	Halsou – $0.5ms^{-1}$ Baigts – $0.45ms^{-1}$	Halsou – 28–36% entrainment Baigts – 50–64% entrainment	The deterrent effect of the 30mm bar spacing was evident at both sites as very few eel passed straight through the racks but was not sufficient to prevent entrainment.

Summary of monitoring methods studies reviewed

Study	Tagging	Camera/video	Velocity readings	Comments
Turnpenny 2010 River Test, Hampshire, UK Salmonids	Fish not tagged	Underwater Perspex camera boxes (800mm height × 450mm width × 400mm depth). 3 submersible concept monochrome CCTV cameras mounted within each of the boxes. Infra-red lamps mounted above each camera box for illumination at night and low light conditions.	Streamflo™ 442 velocity meter fitted with a high velocity propeller probe	The study was designed to intercept the natural run of Atlantic salmon smolts within the River Test but due to the late delivery of the screen this was not possible. In the absence of wild salmon smolts and no suitably sized brown trout available on the River Test, the Environment Agency approved use of rainbow trout as a suitable replacement. Size equivalent to parr rather than smolt.
Russon et al. 2010 Laboratory flume, UK European silver eels	Fish not tagged	Overhead and side-mounted cameras along a glass-sided flume capable of recording fish movement under low light with infra-red illumination. Four 15.0W infra-red illumination units emitting light at 850nm wavelength were used to illuminate the flume.	Acoustic Doppler Velocimeter	
Calles et al. 2013 HEP, River Ätran, Sweden European silver eels	The eels were either surgically radio-tagged (n=40, model F1540, 2.0g; Advanced Telemetry Systems (ATS), Isanti, MN, USA) or externally tagged using streamer tags (n=45, model PST transparent polyethylene streamer tag 13s, Hallprint, Australia). Prior to tagging, the eels were anaesthetised using benzocaine (2g in 10L water, median time until anaesthetised was 18 min, range 10–39 min).	None	Acoustic Doppler Current Profiler (ADCP, Sontek M9 River Surveyor)	After tagging, recovery of all eels was monitored prior to release c. 1–5h later. No eels showed any signs of injury or died during this period of recovery.

Study	Tagging	Camera/video	Velocity readings	Comments
Croze 2008 4 HEP schemes on the River Ariège, France Atlantic salmon smolts	Tagged with a passive integrated transponder (PIT) tag (Trovan Ltd), 2.1mm in diameter and 12.0mm in length. Inserted into the body cavity of each fish using a 12-gauge needle mounted on a spring-loaded syringe. Fish placed in an aesthetic bath of clove oil diluted at a concentration of 0.035mL per litre of water prior to tagging.	None	Instrument not specified.	Successfully used PIT tag technology to evaluate juvenile bypass efficiency at four HEP sites. Major disadvantage of PIT tag systems is the inability to continuously follow tagged fish. This study provides strong evidence that the efficiency of downstream bypasses may be assessed successfully using a low cost technology such as PIT tagging; most of the drawbacks of the technique can be circumvented.
Travade et al. 2010 HEP Baigts, France European silver eel	Fish were anaesthetised by electronarcosis. An ATS (Advanced Telemetry System) radio transmitter (frequency 48−49MHz, length 45mm, diameter 11mm, weight 8g, life 4 months) was implanted in the body cavity by surgical incision. At the same time the fish were PIT-tagged with a glass encapsulated transponder (TIRIS RI-TRP-RR2B, length 32mm, diameter 3mm, weight 0.8g), inserted in the body cavity next to the radio transmitter.	None	Instrument not specified.	The radio telemetry methodology could not provide a sufficiently high resolution description of the eels' behaviour. No information on the depth at which eels migrated or passed through the intake trashracks, as could have been achieved using 3D acoustic telemetry.
Turnpenny et al. 2004 HEP, Stanley Mill on Lower River Tay, Scotland Atlantic salmon smolt	The test smolts were fitted with float tags, allowing their positions to be seen from above. The float tags were made from 10mm diameter polystyrene balls which were attached to the root of the dorsal fin with monofilament line. The floats were first sprayed with a fluorescent paint to aid visibility. For tests conducted during darkness, the float tags were fitted with small chemical lights.	4 CCTV cameras (Aquacam™) were positioned along a pair of high-tensile wires running parallel to and above the front of the screen the screen. Two infra-red security floodlights were positioned on the overhead raking machine directly above the cameras to enable night-time recording.	Velocity measurements were made using a 70mm diameter propeller-type flow meter (Geopacks 'MJP Flometer 1') mounted on a Dexion™ support frame.	The method of tagging the smolts proved very successful, allowing the positions of smolts to be clearly visible in both daylight and darkness. The swimming ability of the smolts did not appear to be markedly affected by the attachment of the tags, and tagged fish were able to dive to the bottom of the channel when they chose to. The method allowed detailed real-time monitoring of smolt behaviour in the headrace and as they encountered the screen.
EPRI 2001 Laboratory flume study (USA) 7 species including silver phase American eel.	Fish were marked with coloured photonic marking solutions that were injected at the base of a fin. Five dye coloured and three fin locations provided 15 distinct marks for each species evaluated. Fish were anaesthetised/ sedated with ms-222 or clove oil.	Video used, no details on equipment.	Instrument not specified.	

Study	Tagging	Camera/video	Velocity readings	Comments
EPRI 1996 HEP site (USA) 3 species including rainbow trout.	No tagging.	Low light video cameras and incandescent lights mounted flush to the walls and roof of the modular inclined screen facility at several locations to observe fish passage and to evaluate impingement of fish or debris on the screen.	Instrument not specified	Natural entrapment and injector tests. Fish migration activity was monitored using two WESMAR Model HD600 scanning sonar units.
Clough et al. 2000 Field flume tests, River Guar, Scotland Atlantic salmon Smolt	No tagging	Infra-red sensitive monochrome CCD with auto iris linked to a time lapse video recorder with overhead shading to reduce glare, a float board to reduce surface turbulence and reflective scotchlight material on the base of the flume. Deep red light used for tests undertaken in the dark.	Valeport Braystoke (BFM002) Propeller flow meter	
Boubée and Williams 2006 HEP site, Mokau River New Zealand Silver eels (3 species)	Eels were sedated with clove oil. Small, 32mm PITs (Texas Instruments RI-TRPWR2B) were inserted into the body cavity of the sedated eels through a 3mm ventral incision. Larger PITs (>32mm) were inserted through a 10 to 15mm incision that was then closed with three absorbable sutures (VPS 30084)	None	Not measured	
Pedersen et al. 2011 Tange HEP station, River Gudenna, Denmark. European silver eel	Tagged by surgical implanting with THELMA Ltd., Norway, LP-9 acoustic transmitters (9 x 34mm, weight in air of 5.3g, weight in water of 3.3g). Twelve hydrophone buoys (ALS, VR2; VEMCO Ltd., Canada) were placed in pairs at six locations in the river.	None	Instrument not specified	Two of the 45 tagged eels were not detected after release at any of the detection stations. Their fate is unknown and they were omitted from further analyses. It cannot be ruled out that the adverse effects of capture, handling and tagging or transmitter malfunction could be reasons for the loss of some eels.

Study	Tagging	Camera/video	Velocity readings	Comments
Gosset et al. 2005 Halsou HEP, River Nive, France European silver eel	Trailing antenna transmitters (uncoded ATS 10/28 model, frequency 48 to 49MHz, length 45mm, diameter 1mm, weight 8g, with mortality switches) surgically implanted in the abdominal cavity of eels anaesthetised with clove oil. The ratio of transmitter weight to eel weight was ≤2% (except for 3 cases). An exit hole was made for the antenna with a hollow needle through the body wall 2cm behind the incision stitched with nylon thread. Monitored by both manual and automated radiotracking.	None	Instrument not specified	Unfavourable hydrological conditions (numerous spates) limited monitoring precision, and uncertainties remain with respect to the path taken by some individuals during this time.
Haro et al. 2000 HEP, Connecticut River, USA American silver eel	Eels were either restrained in a wooden foam-lined trough (no anaesthetic used), or anaesthetised using buffered ms-222 (methane tricanesulfonate, 100mg per litre in ambient river water), or crushed-ice. Radio-tagged and some also acoustically tagged. To minimise stress from handling and surgery, transmitters externally attached using 2-0 polyamide suture material or 30Ib. test Dacron line and a size 12,3/-circle cutting needle. Each transmitter was attached with two sutures (one at each end of the transmitter) through the skin on the dorsal surface approximately 30–50mm anterior to the origin of the dorsal fin. Potable and fixed receivers used.	None	Not specified	Sought to minimise any deleterious effects on downstream migratory motivation by externally attaching tags. The method introduced problems of premature tag loss, irritation, and potential for entanglement of tags in vegetation or substrates. Many of the tags that had become stationary soon after release were probably shed.
Travade et al. 2006 Two HEP sites, SW France European silver eel	As for Gosset et al. 2005, which reports the Halsou study. At Baigts the same method except anaesthesia was by electricity (galvanonarcosis) at this site. Automatic and manual radiotracking at both sites.	None	Instrument not specified	See Gosset et al. 2005

Summary of information relating to fish used in screen testing for studies reviewed

Study	Species	Experimental setup	Fish source	Released in groups?	Individual fish reused?	No. of test fish	Size range
Turnpenny 2010	Rainbow trout (*Oncorhynchus mykiss*)	River Test, Hampshire, UK	Rainbow trout (hatchery)	25–75 fish	No	>1,600	60.9 to 121.8mm (mean 90.83 ± 2.08 SE as fork length)
Russon et al. 2010	European silver eels (*Anguilla anguilla*)	Laboratory flume, UK	Actively migrating adult European eel locally sourced from a commercial trapper on the River Test (Hampshire, UK)	Single eels	No	80	mean total length: 660 ± 47mm, min–max = 583–806mm
Calles et al. 2013	European silver eels (*Anguilla anguilla*)	HEP, River Ätran, Sweden	Migrating eels caught in the collection facility at the HEP station	Released on five occasions	No	196	average size (±SE) of 776 ± 13mm (range 510–1060mm)
Croze 2008	Atlantic salmon smolts (*Salmo salar*)	4 HEP schemes on the River Ariège, France	Smolts were acquired from the same fish hatchery as the one producing fry and parr for stocking in the river	Batches of ~50 smolt	No	~3500	140 to 230mm (mean length 170mm)
Travade et al. 2010	European silver eel (*Anguilla anguilla*)	HEP Baigts, France	Eels came from professional silver eel fisheries on the Loire River and on a small river 50km from Baigts	Small batches (2–6 eels)	No	116 (~40 in each year)	2004: 40 eels, mean body length 610mm. 2005: 39 eels, mean length 646mm 2006: 37 eels, mean body length 840mm
Turnpenny et al. 2004	Atlantic salmon smolt (*Salmo salar*)	HEP, Stanley Mill on Lower River Tay, Scotland	25 wild salmon smolts were captured in a trap in the lake of a nearby hydroelectric plant and 300 hatchery reared smolts (from wild broodstock) were acquired	6–19	No	325 (63 all used in screen test)	Tagged smolt ranged from 95–145mm (mean 117mm)

Study	Species	Experimental setup	Fish source	Released in groups?	Individual fish reused?	No. of test fish	Size range
EPRI 2001	Smallmouth (*Micropterus dolomieu*) and largemouth (*Micropterus salmoides*) bass, golden shiners (*Notemigonus crysoleucas*), walleye (*Stizostedion vitreum*), channel catfish (*Ictalurus punctatus*), shortnose (*Acipenser brevirostrum*) and lake sturgeon (*Acipenser fulvescens*) and silver phase American eel (*Anguilla rostrata*)	Laboratory study (USA)	Mixture of hatchery and trapped fish	The number of fish released per trial varied depending on the availability of each species. Varied from 10 to 50	Reused for through control and for shortnose sturgeon		smallmouth bass (small): year 1 (1999)- mean (±SD) 59mm ± 5mm (range 49–86mm), year 2 (2000)- 75 ± 8mm (range 31–108) smallmouth bass (large): year 1, 85 ± 11mm (range 63–132mm), year 2- 117 ± 13mm (range 90–197mm) largemouth bass: year 2, 73 ± 4mm (range 55–88) walleye: year 2, 75 ± 5mm (range 28–95mm) channel catfish: year 2, 109 ± 13mm (range 81–145mm) golden shiner: year 1, 79 ± 6mm (range 50–96mm) lake sturgeon: year 1, 153 ± 17mm (range 82–194mm), year 2, 132 ± 12mm (range 91–161mm). shortnose sturgeon: year 2, 319 ± 31mm (range 243–389mm) American eel: year 1, 558 ± 46mm (range 151–697mm). Year 2, 569 ± 76mm (range 410–781mm)

Study	Species	Experimental setup	Fish source	Released in groups?	Individual fish reused?	No. of test fish	Size range
EPRI 1996	Juvenile blueback herring (*Alosa aestivalis*), juvenile golden shiners (*Notemigonus crysoleucas*) and rainbow trout (*Oncorhynchus mykiss*)	HEP site (USA)	Hatchery and naturally migrating fish	Batches of 25–100	No	20739	golden shiners average length 71mm rainbow trout average length 95mm blueback herring average length 61mm
Clough et al. 2000	Atlantic salmon smolt (*Salmo salar*)	Field flume tests, River Gaur, Scotland	Hatchery	Groups of 30	No	900	Mean length 162mm ± 0.6mm, standard length range 135–190mm
Boubée and Williams 2006	Silver eels, 3 species: shortfin eel (*Anguilla australis*), longfin eel (*Anguilla dieffenbachia*) and the Australian longfin eel or spotted eel, (*Anguilla reinhardtii*)	HEP site, Mokau River New Zealand	Trapped on site	Unknown	No	Unknown	Shortfin eels: size range 630–1210, average ± 101mm (SD) Longfin eels: size 640–1,300mm, average 1,078 ± 177mm (SD)
Pedersen et al. 2011	European silver eel (*Anguilla anguilla*)	Tange HEP station, River Gudenna, Denmark	Downstream migrating silver eel captured in a permanent eel tap	All released on the same day	No	45	Mean body length of the tagged fish was 663 ± 72mm (SD) (range 560–860mm)

Study	Species	Experimental setup	Fish source	Released in groups?	Individual fish reused?	No. of test fish	Size range
Gosset et al. 2005	European silver eel (*Anguilla anguilla*)	Halsou HEP, River Nive, France	Trapped on site	5–10	No	637	Not specified
Haro et al. 2000	American silver eel (*Anguilla rostrata*)	HEP, Connecticut River, USA	Collected from a downstream migrant fish bypass sampler	Not specified	No	Unknown	Not specified
Travade et al. 2006	European silver eel (*Anguilla anguilla*)	Two HEP sites, SW France	Trapped on site	1–8	No	716	Halsou 1999: 570–930mm (mean 725mm) 2000: 550–950mm (mean 699mm) 2001: 560–740mm (mean 699mm) Baigts 2004: 450–750mm (mean 750mm) 2005: 500–990 (mean 646)

Appendix B: HTI acoustic tag system

Turning on, connecting and logging data:

- Plug all the hydrophone cables into the back panel of the Acoustic Tag Receiver (ATR). They MUST be in the correct order to match the Project File Hydro positions.
- Plug power lead into ATR and surge protector. Also power lead for laptop.
- Connect network cable between ATR front panel and laptop.
- Power up the ATR with on/off switch on lower right of front panel.
- After it has 'warbled', start the laptop.
- Double-click on the 'AcousticTag' icon.
- Make sure the correct Project File is loaded up on the blue strip at the very top.
- To store all data in a new folder, create a new folder in Windows Explorer and then select it by; Setup > Output Files > Folder Selection.
- Command > Connect to Receiver. In Status Window should say; 'Connected: Yes' in red.
- Command > Enable Receiver. In Status Window should say; 'Processing: Yes' and 'Saving Data: Yes' in red.
- Gear should now be logging data as hourly files.

Check:

- All the lights on the front panel Receiver Boards are GREEN.
- In the Status Window: 'Connected, Processing and Saving Data' are all 'Yes'.
- In the Status Window: Delta Time does not exceed 5.
- In the Status Window: The number next to 'PeakLoc' is increasing.

Turning off:

- Command > Disable Receiver. In Status Window should say; 'Processing: No' and 'Saving Data: No' in black.
- Close Acoustic Tag programme.
- Switch off ATR with on/off switch on lower right of front panel.
- Shut down laptop.

Changing screen views:

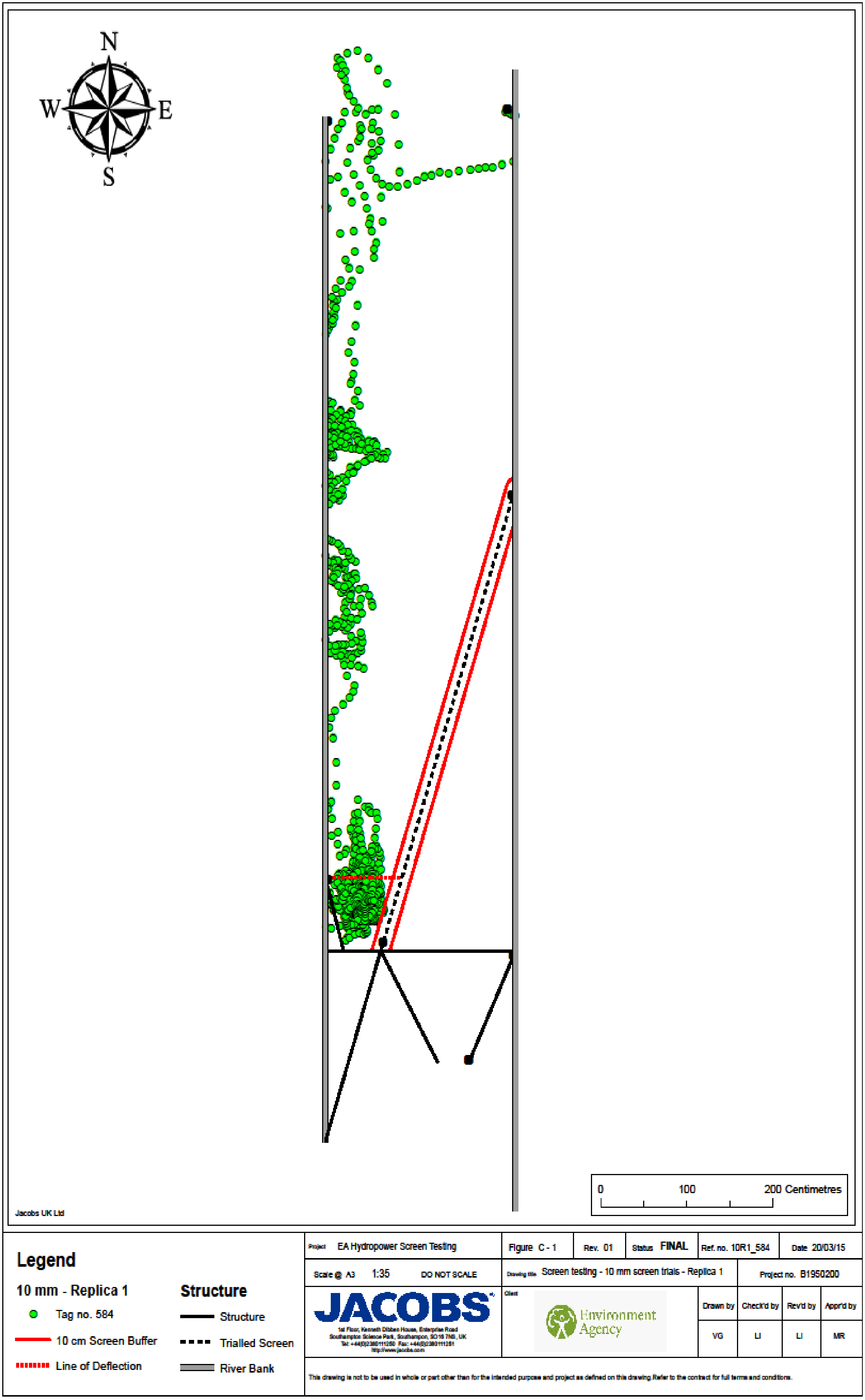
- To activate a window, click on it. Click on the appropriate button ('Top', Realtime Echogram' etc).
- To change the display, right click within the graph to get 'Display Options'. You can now fiddle around with which hydrophones you want to look at etc. Highlight the hydrophone in blue with a single mouse-click.
- To view realtime tracking (i.e. watching a tag moving through the array), it is best to select a single window ('View one graph' button), select 'Top View' and zoom into the array with the Magnifying Glass button.

Realtime tracking:
It can be very useful to see a tag moving through the array in realtime (e.g. for tag-drag tests or – perhaps optimistically – demonstrating live fish behaviour).

- Ensure the Project File is currently set up to enable Realtime Tracking. Setup > Realtime Tag Positioning > Update Histogram is ticked.
- Check; Setup > Realtime Tag Positioning > Tag Positioning Options > Enable Realtime Tag Positioning is ticked.
- Choose which tag to review. If you are tag-dragging, select the correct Period from the right-hand dropdown box, located below 'Scene' and 'Position'.
- To view fish, look at the histogram window at the bottom right and identify a period with lots of echoes. Then select that period from the dropdown as above. After a pause, you

should see yellow figures moving through the ‘Top’ window, leaving red figures behind in a trail.

Appendix C: Example Atlantic salmon smolt acoustic track figures


N
W
E
S
0
100
200 Centimetres
Jacobs UK Ltd
Legend
10 mm - Replica 1
Tag no. 584
10 cm Screen Buffer
Line of Deflection
Structure
Structure
Trialled Screen
River Bank
Project EA Hydropower Screen Testing
Figure C - 1
Rev. 01
Status FINAL
Ref. no. 10R1_584
Date 20/03/15
Scale @ A3 1:35
DO NOT SCALE
Drawing title Screen testing - 10 mm screen trials - Replica 1
Project no. B1950200
JACOBS
1st Floor, Kenneth Dibben House, Enterprise Road
Southampton Science Park, Southampton, SO16 7NS, UK
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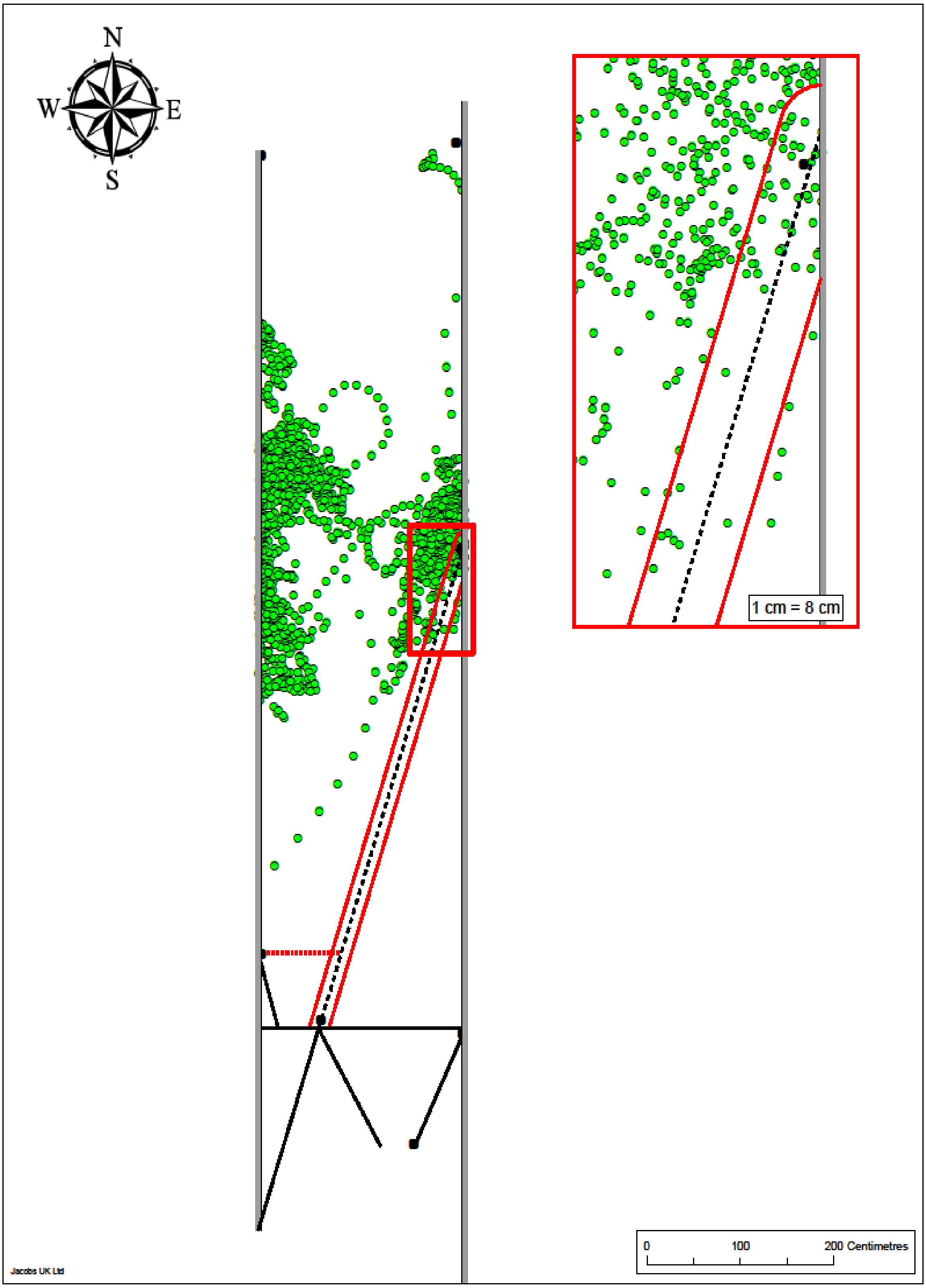

Legend

10 mm - Replica 3

- Tag no. 514
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project: EA Hydropower Screen Testing	Figure C - 2	Rev. 01	Status FINAL	Ref. no. 10R3_514	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title: Screen testing - 10 mm screen trials - Replica 3			Project no. B1950200	
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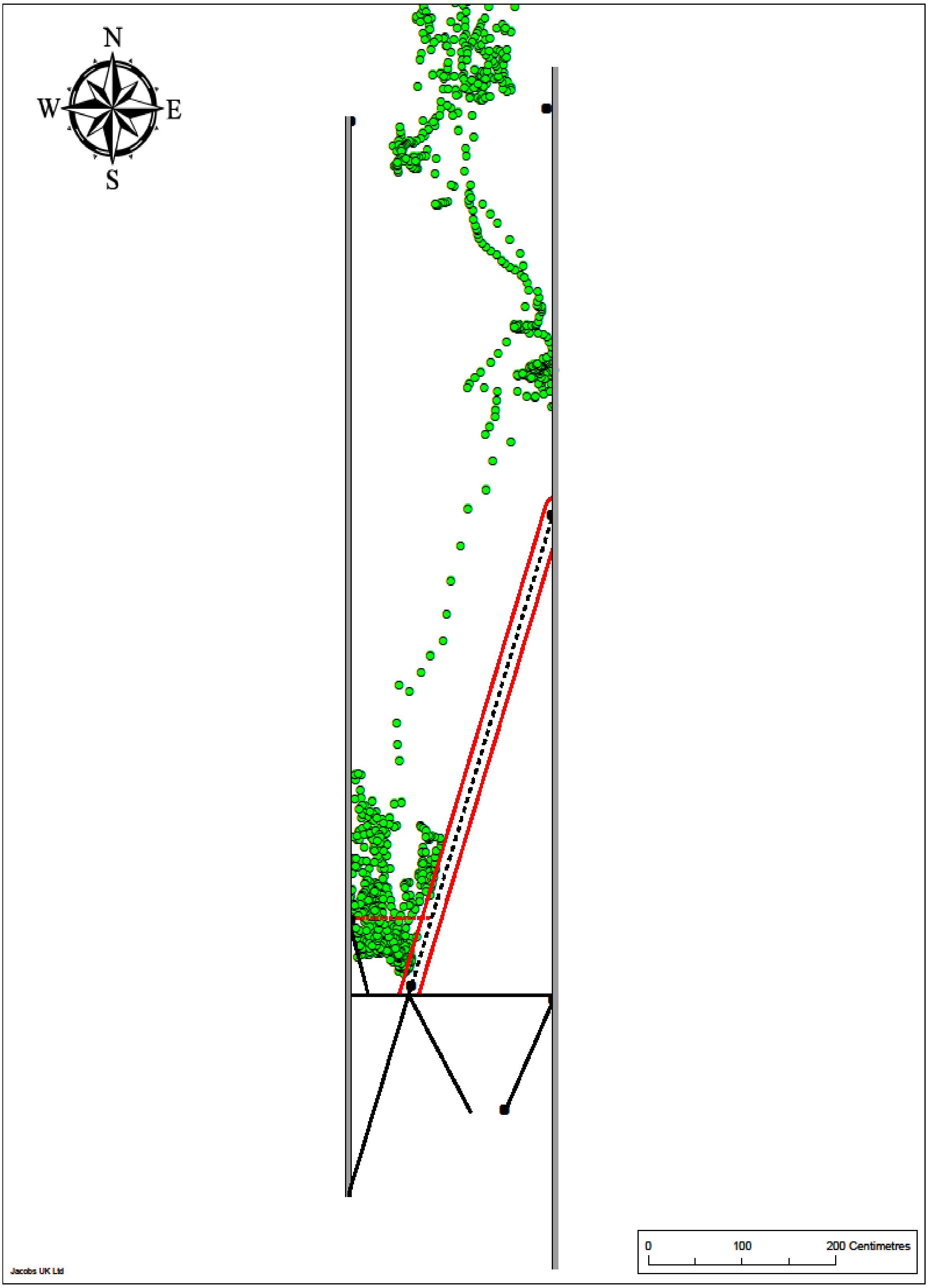

Legend

10 mm - Replica 4

- Tag no. 654
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project EA Hydropower Screen Testing	Figure C - 3	Rev. 01	Status FINAL	Ref. no. 10R4_654	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - 10 mm screen trials - Replica 4			Project no. B1950200	

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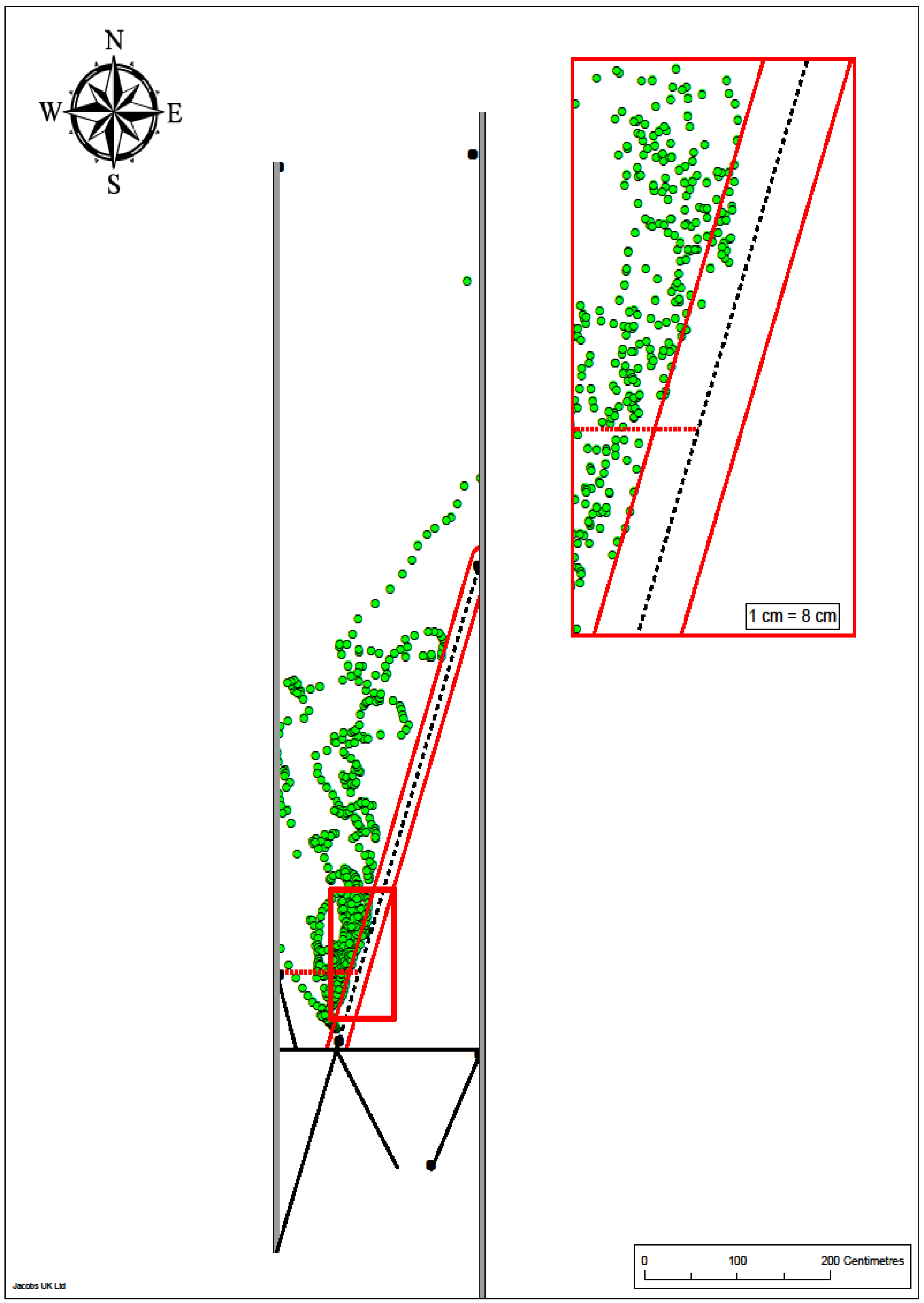

Legend

10 mm - Replica 4

- Tag no. 668
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project: EA Hydropower Screen Testing	Figure C - 4	Rev. 01	Status FINAL	Ref. no. 10R4_668	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title: Screen testing - 10 mm screen trials - Replica 4			Project no. B1950200	
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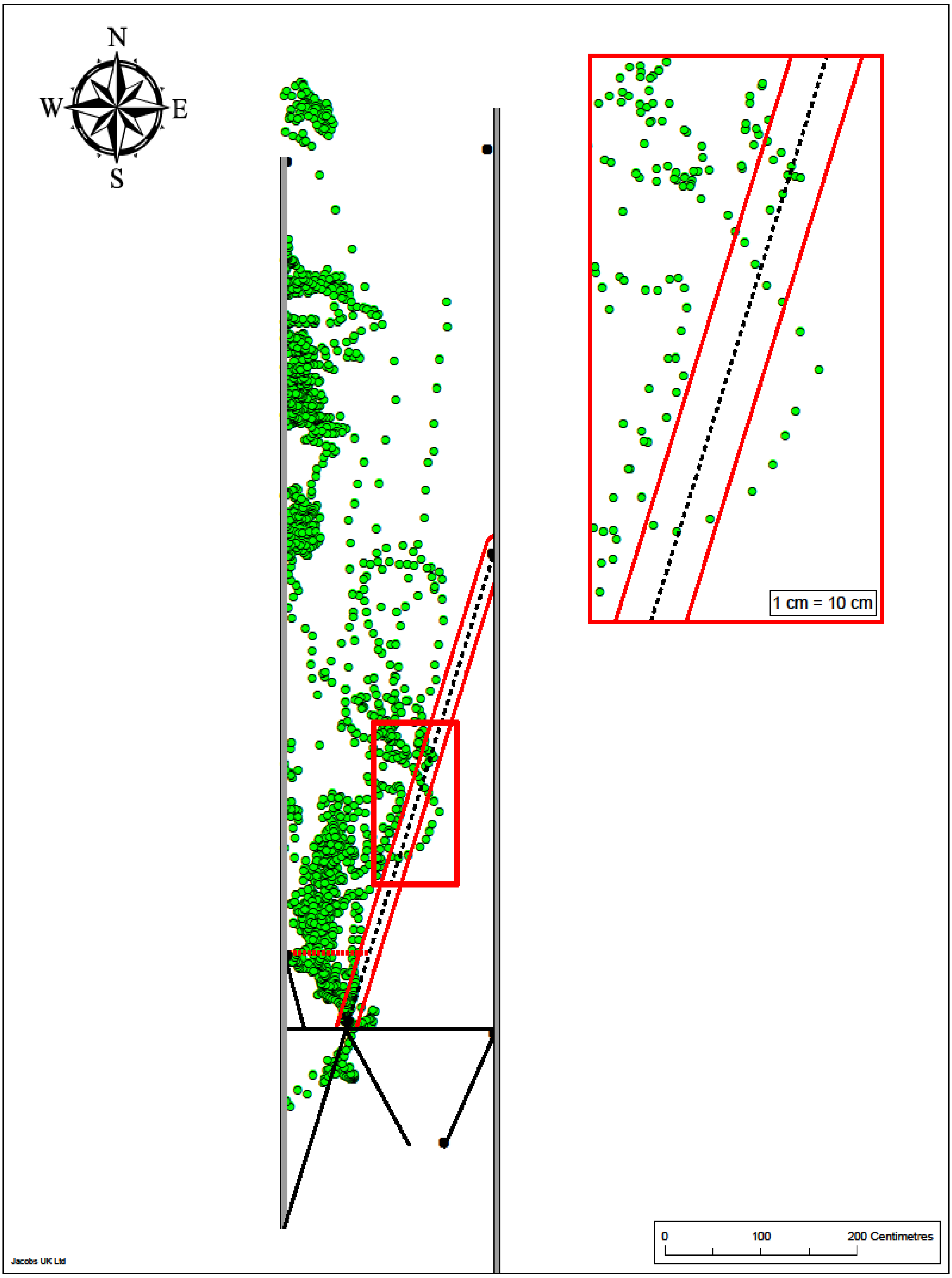

Legend

10 mm - Replica 6

- Tag no. 656
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project: EA Hydropower Screen Testing	Figure C - 5	Rev. 01	Status FINAL	Ref. no. 10R6_656	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title: Screen testing - 10 mm screen trials - Replica 6			Project no. B1950200	

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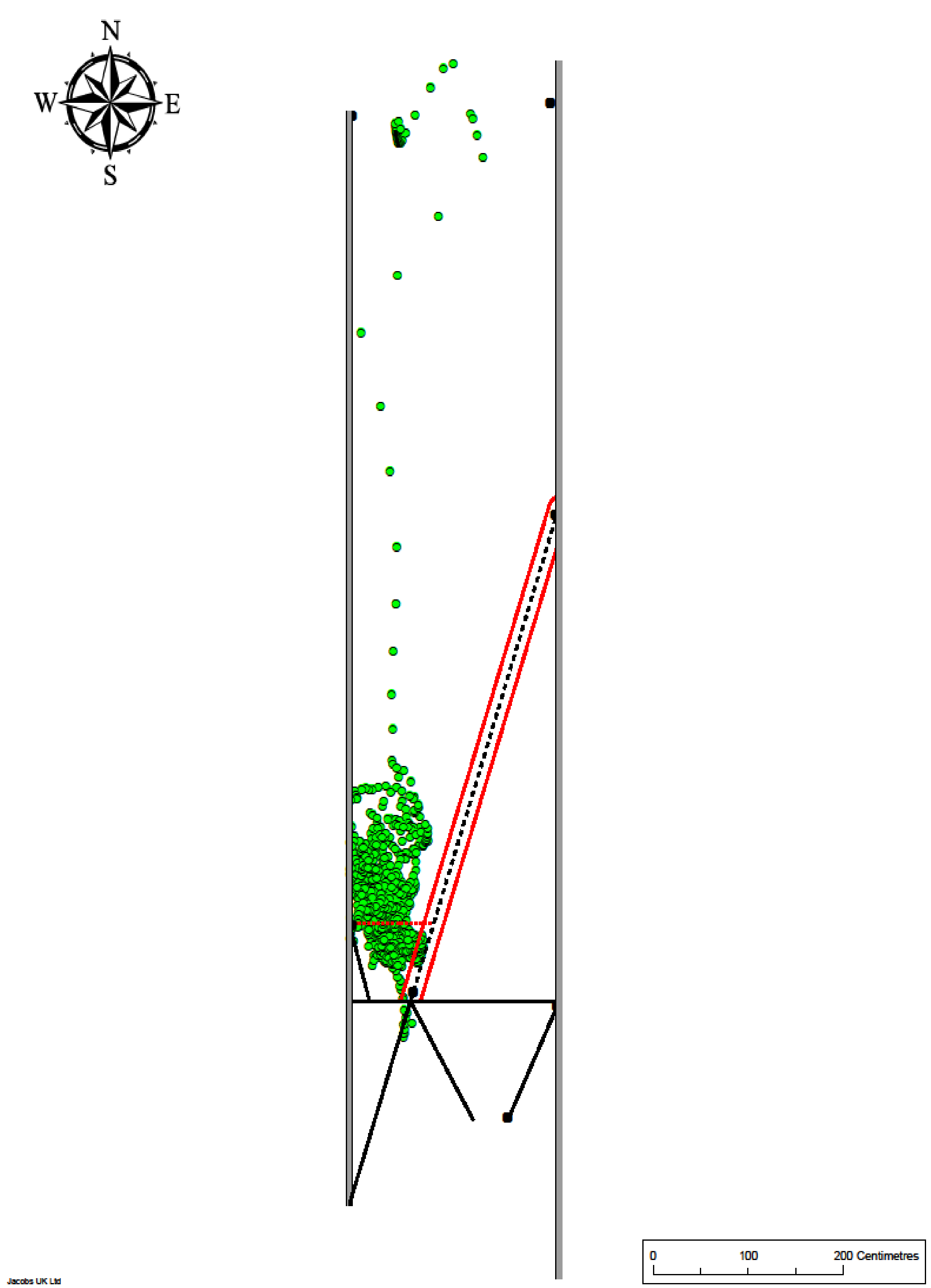

Legend

10 mm - Replica 9

- Tag no. 612
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project: EA Hydropower Screen Testing	Figure C - 6	Rev. 01	Status FINAL	Ref. no. 10R9_612	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title: Screen testing - 10 mm screen trials - Replica 9			Project no. B1950200	

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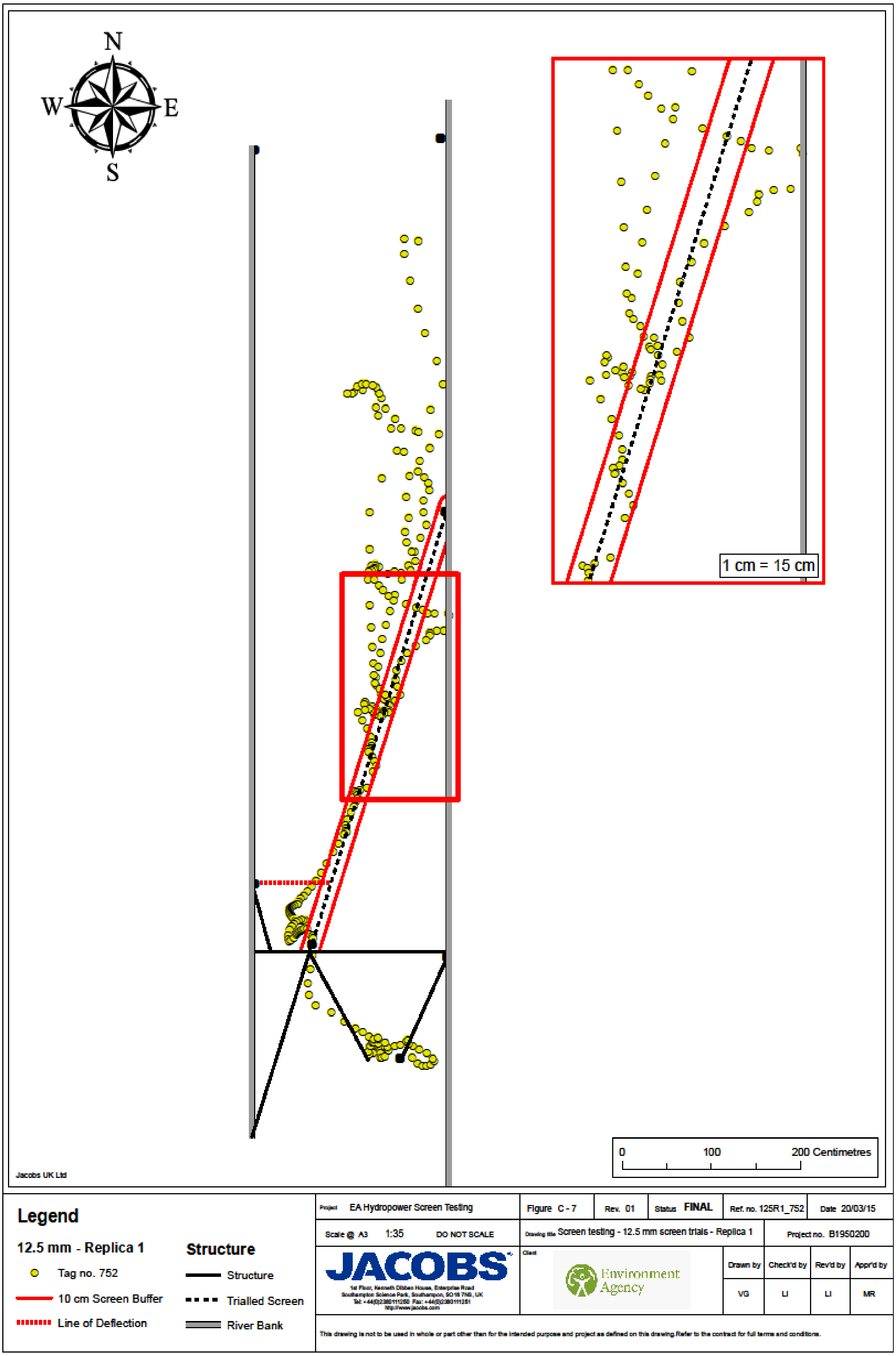
N
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S
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1 cm = 15 cm
0
100
200 Centimetres
Jacobs UK Ltd
Legend
12.5 mm - Replica 1
Tag no. 752
10 cm Screen Buffer
Line of Deflection
Structure
Structure
Trialled Screen
River Bank
Project EA Hydropower Screen Testing
Figure C - 7
Rev. 01
Status FINAL
Ref. no. 125R1_752
Date 20/03/15
Scale @ A3 1:35
DO NOT SCALE
Drawing title Screen testing - 12.5 mm screen trials - Replica 1
Project no. B1950200
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Client
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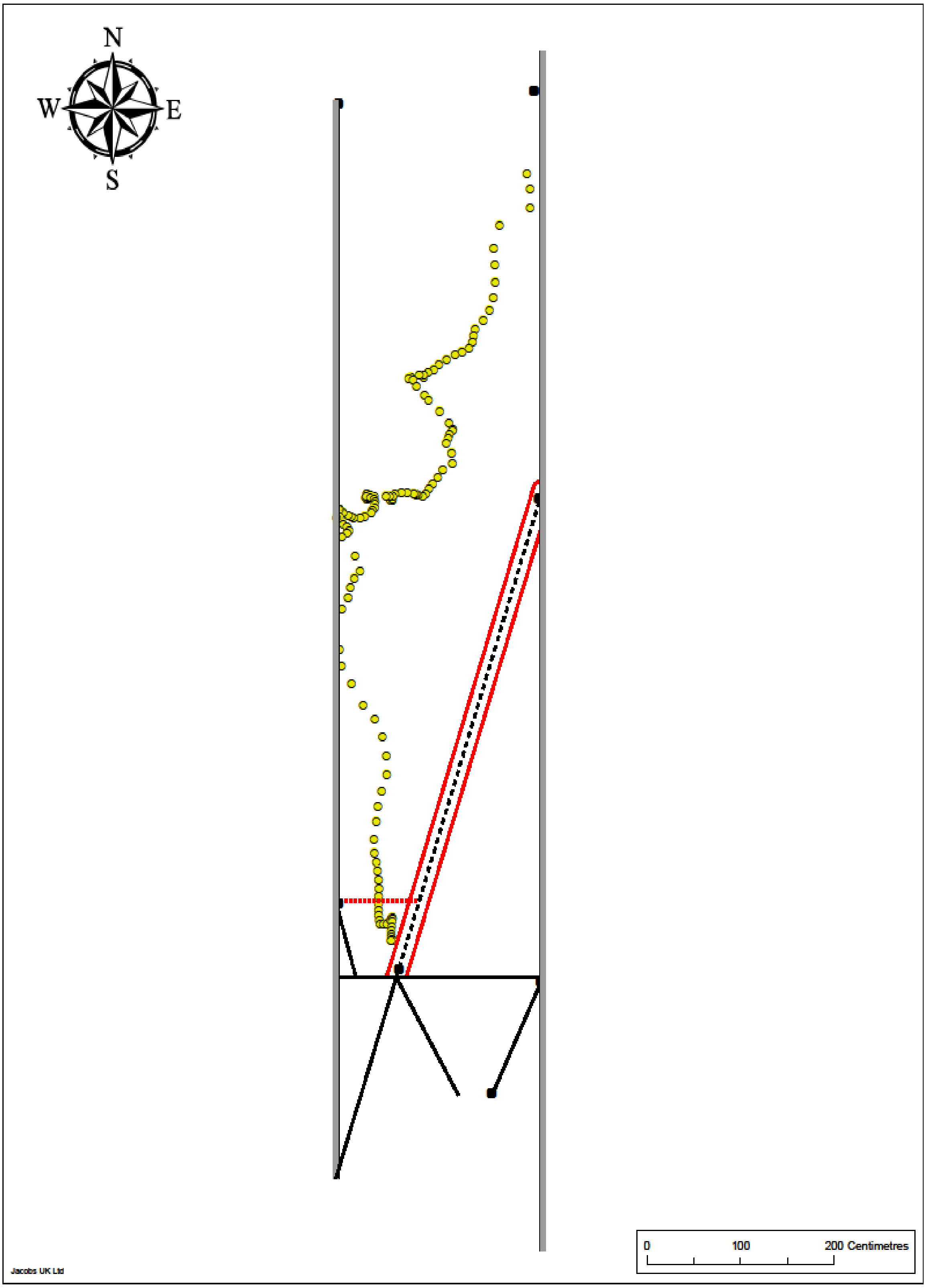

Legend

12.5 mm - Replica 6

- Tag no. 528
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project: EA Hydropower Screen Testing	Figure C - 8	Rev. 01	Status FINAL	Ref. no. 125R6_528	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title: Screen testing - 12.5 mm screen trials - Replica 6			Project no. B1950200	

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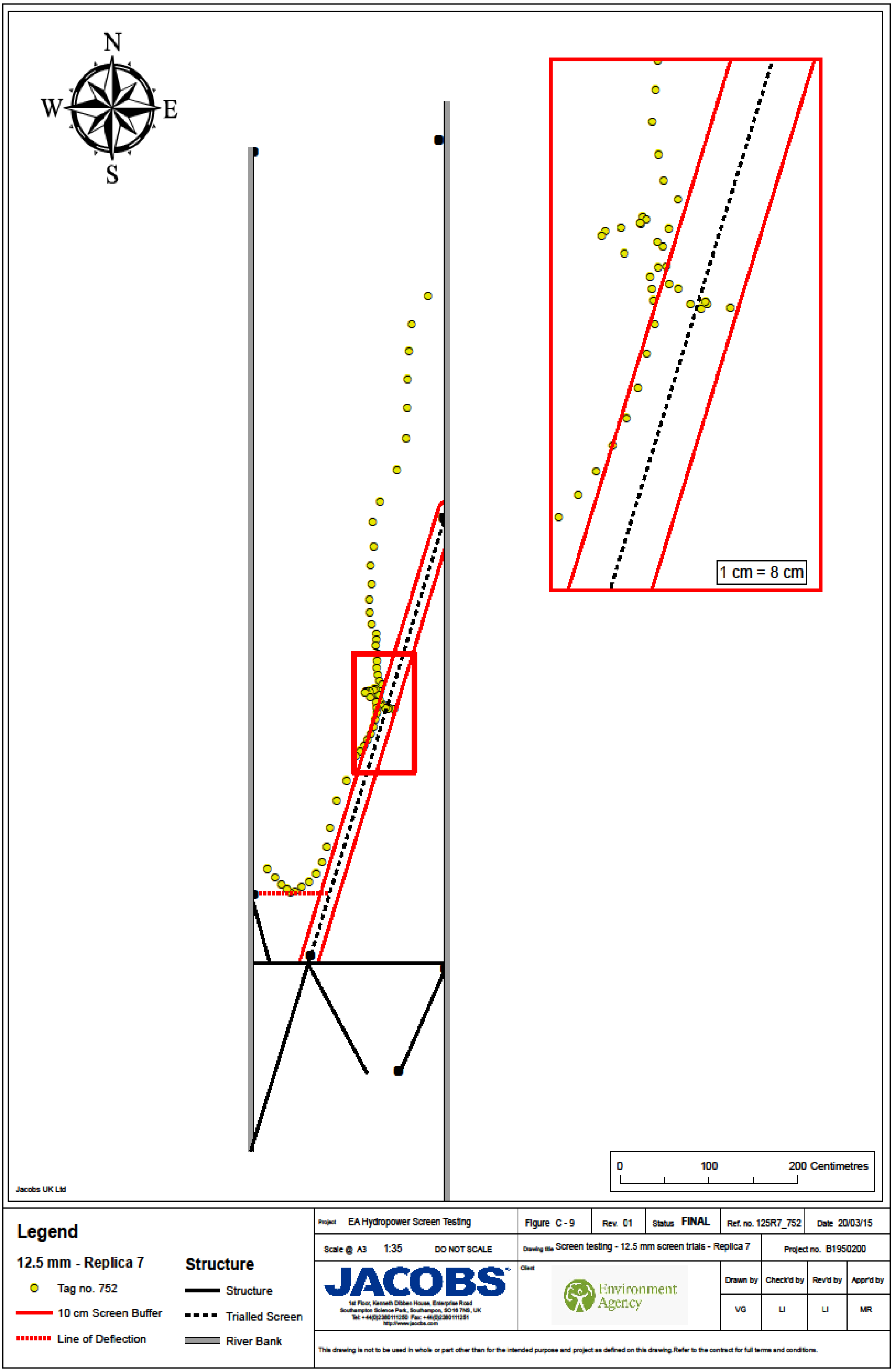
N
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1 cm = 8 cm
0
100
200 Centimetres
Jacobs UK Ltd
Legend
12.5 mm - Replica 7
Tag no. 752
10 cm Screen Buffer
Line of Deflection
Structure
Structure
Trialled Screen
River Bank
Project EA Hydropower Screen Testing
Figure C - 9
Rev. 01
Status FINAL
Ref. no. 125R7_752
Date 20/03/15
Scale @ A3 1:35
DO NOT SCALE
Drawing title Screen testing - 12.5 mm screen trials - Replica 7
Project no. B1950200
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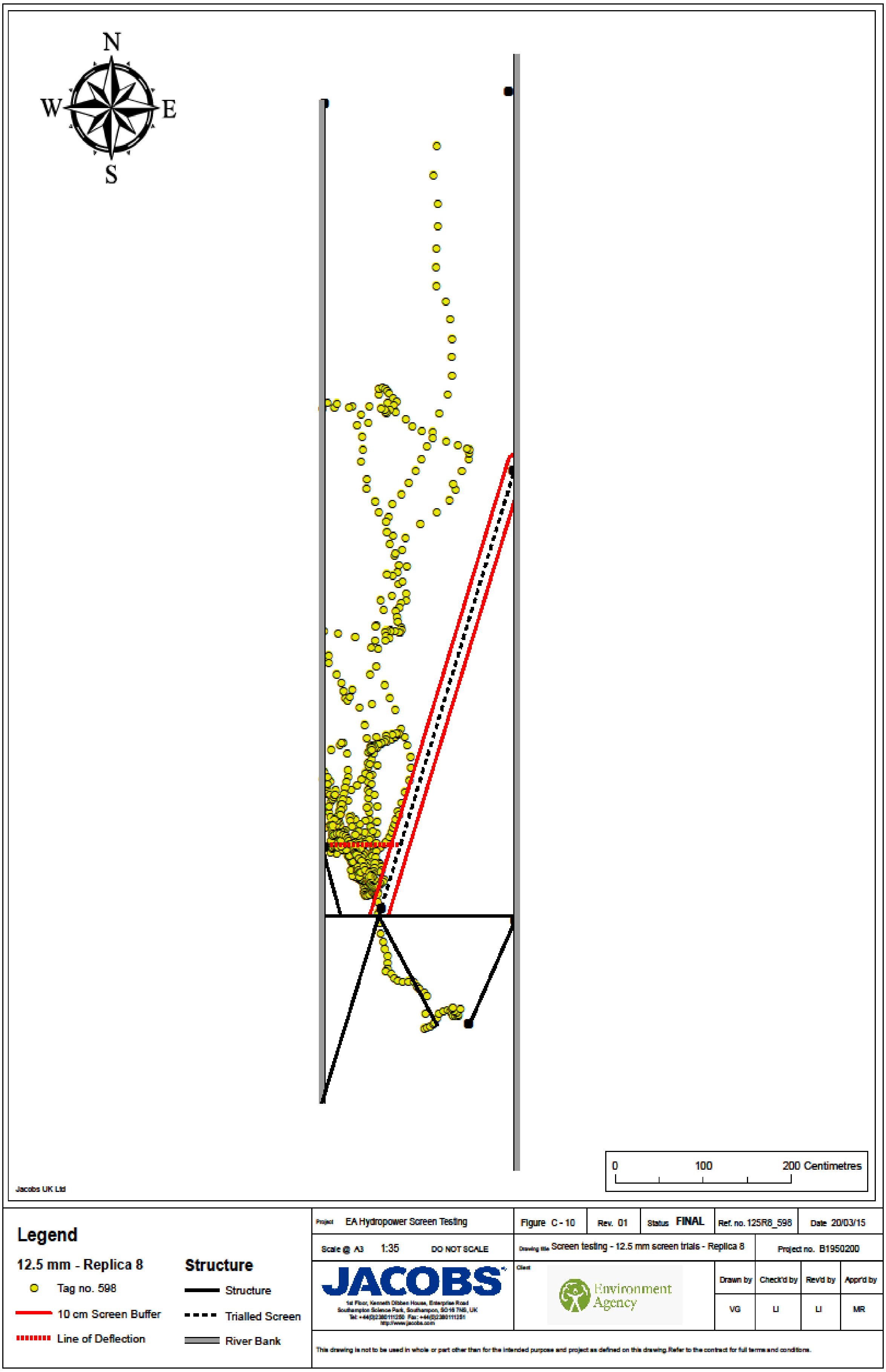
N
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W
E
0
100
200 Centimetres
Jacobs UK Ltd
Legend
12.5 mm - Replica 8
Tag no. 598
10 cm Screen Buffer
Line of Deflection
Structure
Structure
Trialled Screen
River Bank
Project EA Hydropower Screen Testing
Figure C - 10
Rev. 01
Status FINAL
Ref. no. 125R8_598
Date 20/03/15
Scale @ A3 1:35
DO NOT SCALE
Drawing title Screen testing - 12.5 mm screen trials - Replica 8
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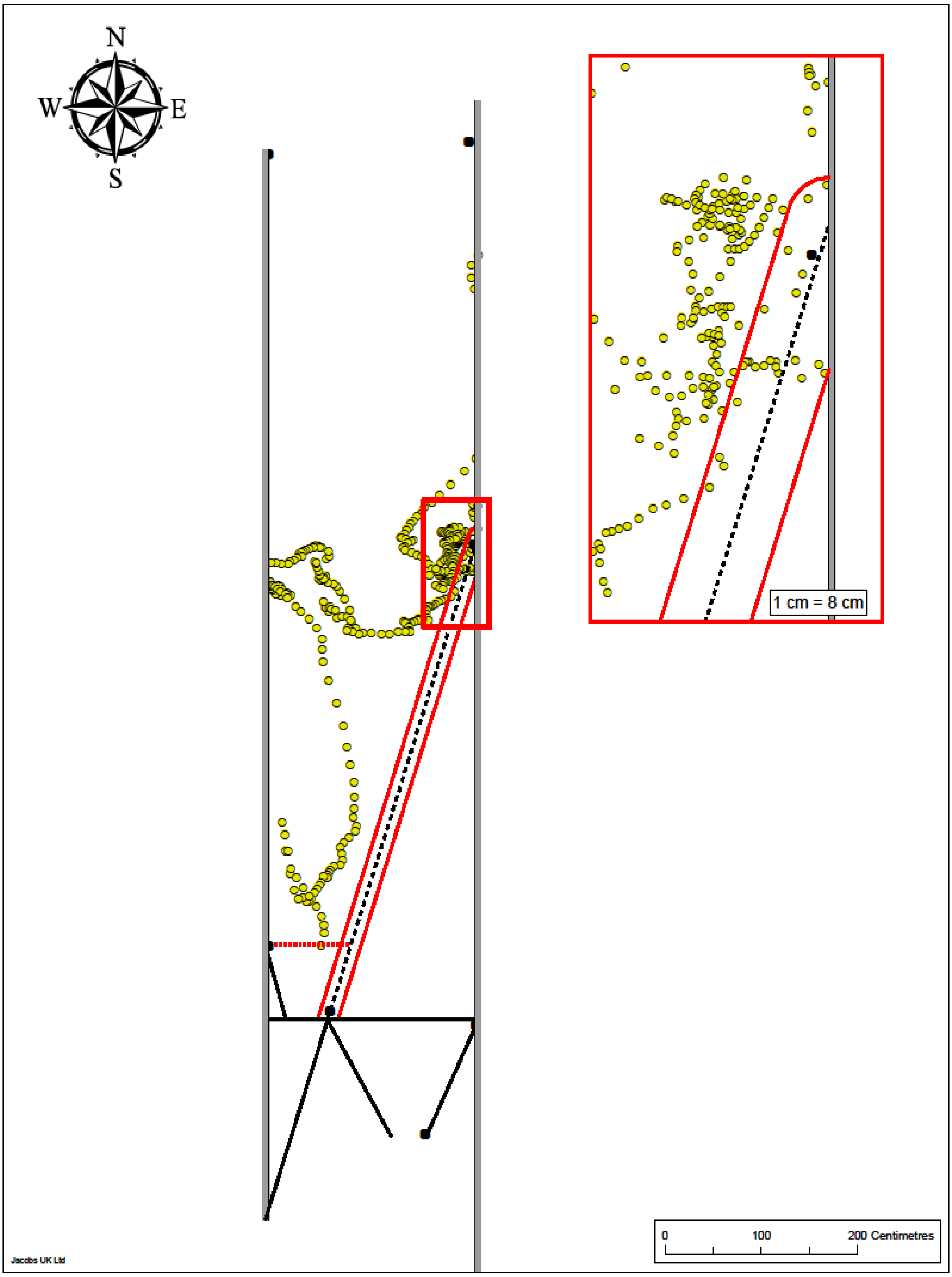

Legend

12.5 mm - Replica 10

- Tag no. 514
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project: EA Hydropower Screen Testing	Figure C - 11	Rev. 01	Status FINAL	Ref. no. 125R10_514	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title: Screen testing - 12.5 mm screen trials - Replica10			Project no. B1950200	

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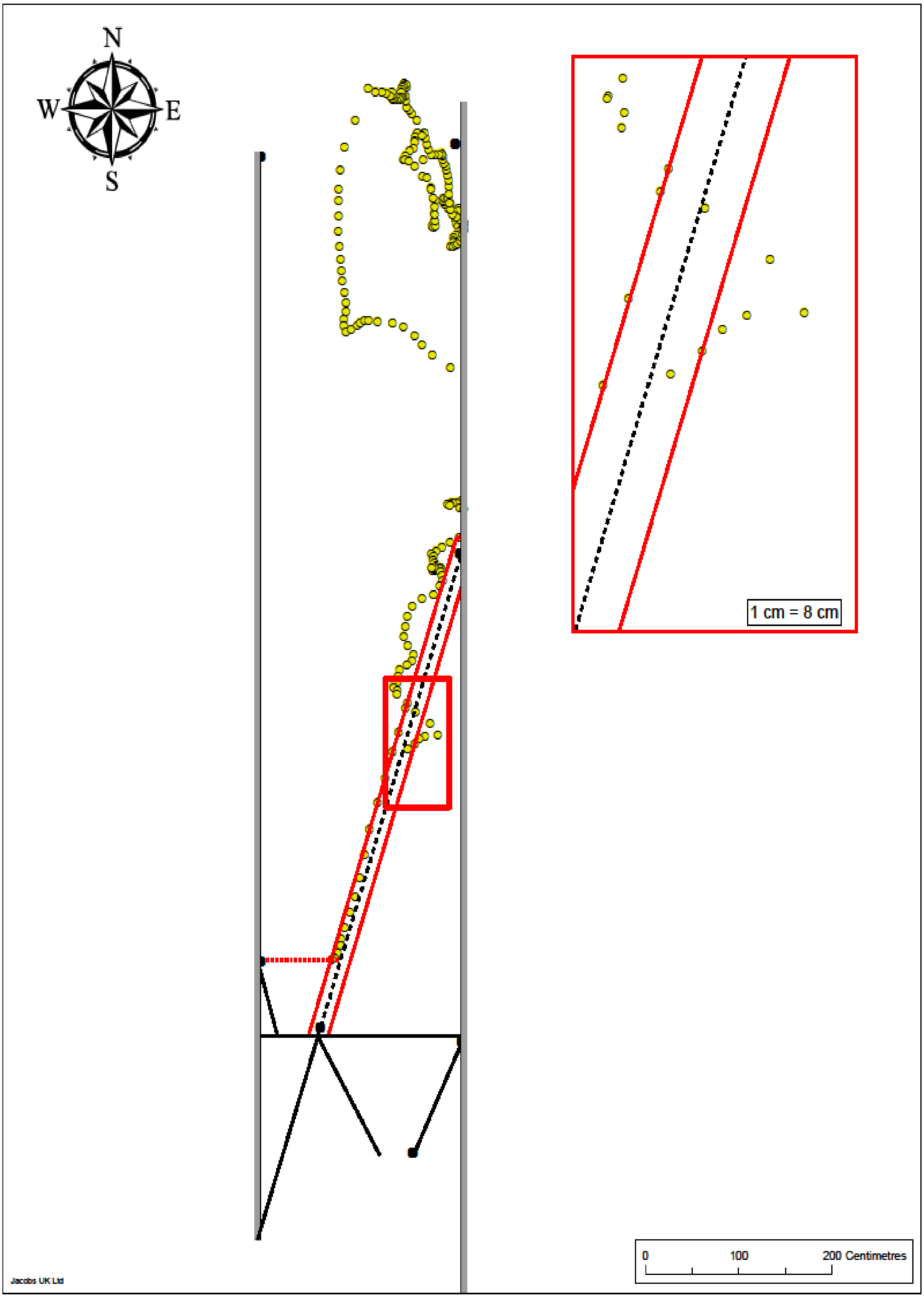

Legend

12.5 mm - Replica 11

- Tag no. 682
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project: EA Hydropower Screen Testing
Figure C - 12 | Rev. 01 | Status FINAL | Ref. no. 125R11_682 | Date 20/03/15

Scale @ A3 1:35 DO NOT SCALE
Drawing title: Screen testing - 12.5 mm screen trials - Replica 11
Project no. B1950200

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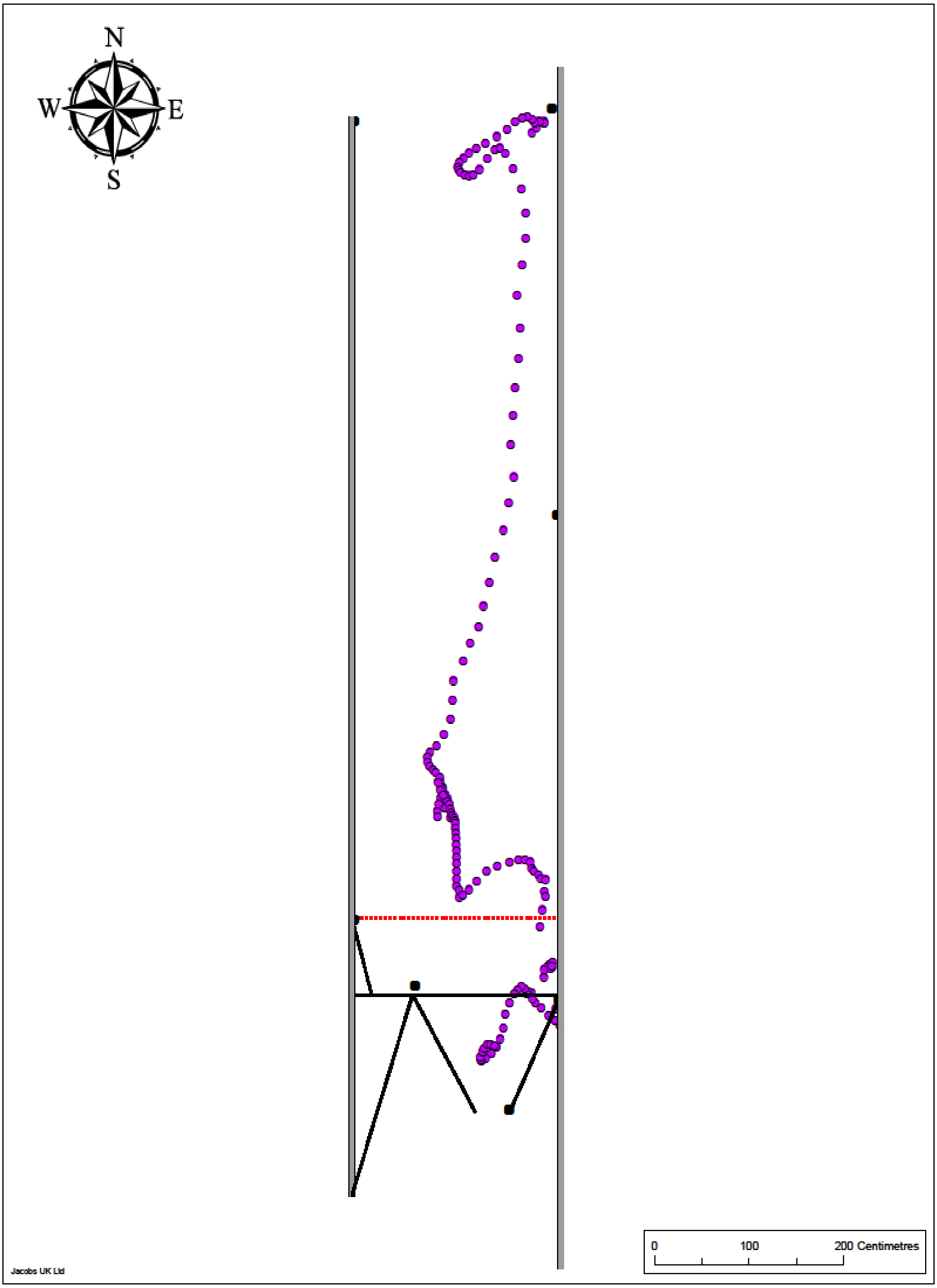

Legend

Control - Replica 1

Tag no. 654

Line of Deflection

Structure

Structure

River Bank

Project EA Hydropower Screen Testing	Figure C - 13	Rev. 01	Status FINAL	Ref. no. C_R1_654	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - Control trials - Replica 1			Project no. B1950200	
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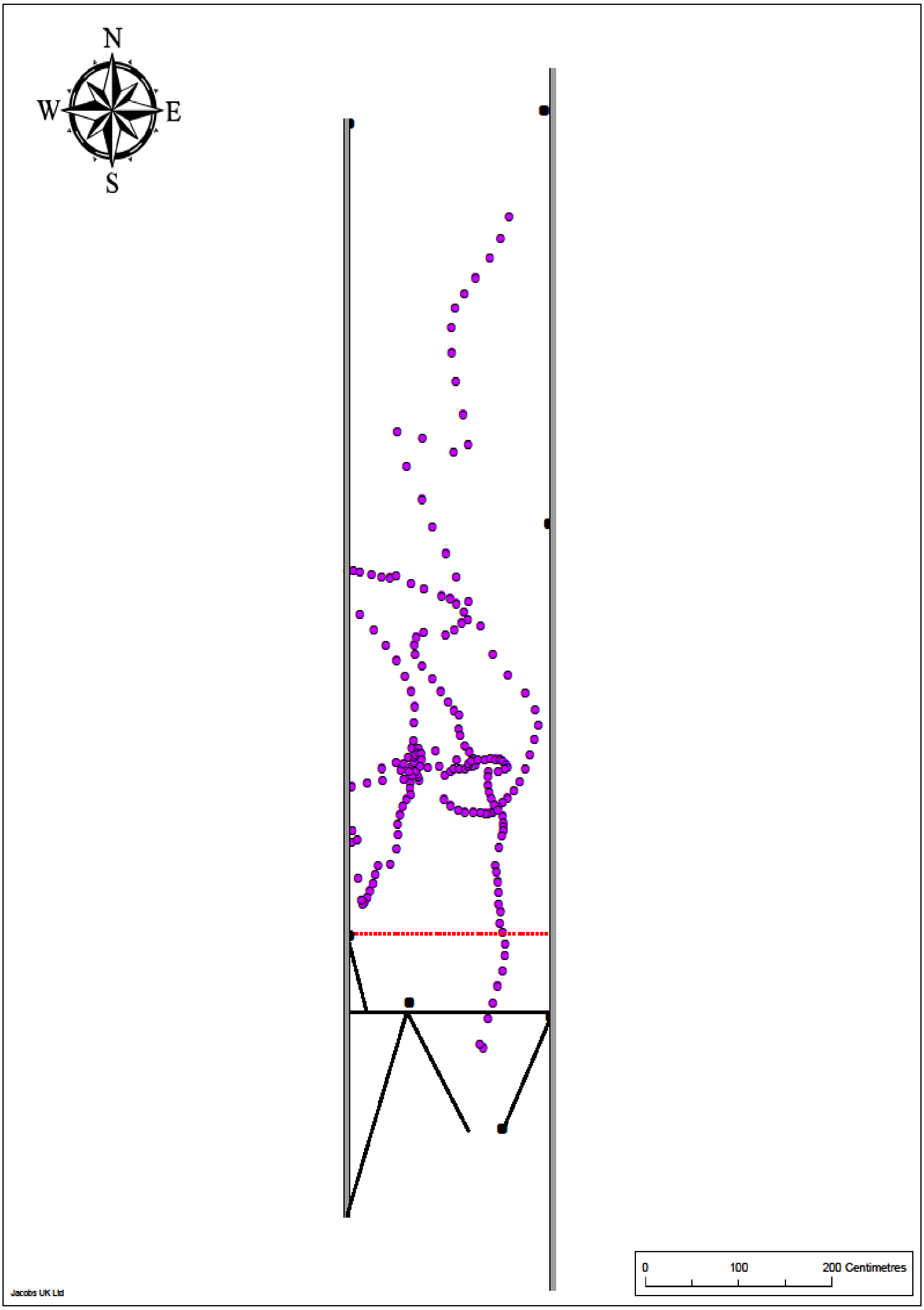

Legend

Control - Replica 3

- Tag no. 612
- Line of Deflection

Structure

- Structure
- River Bank

Project EA Hydropower Screen Testing	Figure C - 14	Rev. 01	Status FINAL	Ref. no. C_R3_612	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - Control trials - Replica 3			Project no. B1950200	
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Appendix D: Atlantic salmon smolt chronological results, fish body lengths and predictions from fineness ratio

Results for smolt trials of 10mm, 12.5mm and control screens

E = Possibly entrained, I = Possibly impinged, NI = Did not interact, D = Deflected, U = Unknown, DL=Did not reach line of deflection. FL= Fork Length (mm), SL = Standard length (mm). Deflection prediction based on fineness ratio (Def = deflected expected, Not = not deflected)

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
01/05/2014	10mm	1	542	Yes	112	104	4.65	12.4	Def	5.3	11.3	Def	D
01/05/2014	10mm	1	556	Yes	128	120	4.65	13.7	Def	4.8	13.4	Def	D
01/05/2014	10mm	1	500	Yes	128	117	4.65	13.5	Def	5.1	12.6	Def	D
01/05/2014	10mm	1	514	No	128	120	4.65	13.7	Def	5.3	12.6	Def	U
01/05/2014	10mm	1	528	Yes	123	115	4.65	13.3	Def	5.2	12.4	Def	D
01/05/2014	10mm	1	570	Yes	118	111	4.65	13.0	Def	5.2	12.1	Def	D
01/05/2014	10mm	1	584	Yes	122	114	4.65	13.2	Def	5.2	12.2	Def	D
01/05/2014	10mm	1	598	Yes	129	121	4.65	13.8	Def	5.8	12.0	Def	D
01/05/2014	10mm	1	612	Yes	119	113	4.65	13.1	Def	4.9	12.7	Def	D
01/05/2014	10mm	1	626	Yes	115	107	4.65	12.6	Def	5.1	11.9	Def	D
06/05/2014	10mm	2	556	Yes	123	115	4.65	13.3	Def	5.1	12.5	Def	D
06/05/2014	10mm	2	500	Yes	132	124	4.65	14.0	Def	5.4	12.7	Def	D
06/05/2014	10mm	2	626	Yes	108	100	4.65	12.0	Def	5.2	11.1	Def	D
06/05/2014	10mm	2	584	Yes	134	125	4.65	14.1	Def	5.3	12.9	Def	D
06/05/2014	10mm	2	514	Yes	108	101	4.65	12.1	Def	5.5	10.8	Def	D

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
06/05/2014	10mm	2	598	Yes	114	106	4.65	12.5	Def	5.4	11.3	Def	D
06/05/2014	10mm	2	612	No	115	107	4.65	12.6	Def	5.3	11.6	Def	U
06/05/2014	10mm	2	528	Yes	114	105	4.65	12.5	Def	5.7	10.9	Def	D
06/05/2014	10mm	2	570	Yes	116	109	4.65	12.8	Def	5.9	10.8	Def	D
06/05/2014	10mm	2	640	Yes	119	110	4.65	12.9	Def	5.4	11.7	Def	D
07/05/2014	10mm	3	570	Yes	140	132	4.65	14.7	Def	4.3	15.4	Def	D
07/05/2014	10mm	3	556	Yes	125	118	4.65	13.6	Def	5.3	12.4	Def	D
07/05/2014	10mm	3	626	Yes	123	115	4.65	13.3	Def	5.7	11.7	Def	D
07/05/2014	10mm	3	514	Yes	123	115	4.65	13.3	Def	5.2	12.4	Def	E/DL
07/05/2014	10mm	3	612	Yes	133	127	4.65	14.3	Def	5.3	13.2	Def	D
07/05/2014	10mm	3	542	Yes	123	115	4.65	13.3	Def	5.7	11.6	Def	DL/NI
07/05/2014	10mm	3	640	Yes	116	106	4.65	12.5	Def	6.1	10.5	Def	D
07/05/2014	10mm	3	528	Yes	124	116	4.65	13.4	Def	5.6	11.8	Def	D
07/05/2014	10mm	3	500	Yes	126	119	4.65	13.6	Def	5.7	12.0	Def	D
07/05/2014	10mm	3	598	Yes	125	117	4.65	13.5	Def	5.5	12.0	Def	D
07/05/2014	10mm	4	654	Yes	125	118	4.65	13.6	Def	5.5	12.1	Def	D
07/05/2014	10mm	4	668	Yes	119	112	4.65	13.1	Def	5.7	11.4	Def	I
07/05/2014	10mm	4	682	Yes	115	107	4.65	12.6	Def	5.1	11.8	Def	D
07/05/2014	10mm	4	710	Yes	133	127	4.65	14.3	Def	5.8	12.3	Def	D
07/05/2014	10mm	4	724	Yes	109	104	4.65	12.4	Def	5.3	11.3	Def	D
07/05/2014	10mm	4	738	Yes	115	106	4.65	12.5	Def	5.2	11.6	Def	D
07/05/2014	10mm	4	752	Yes	116	107	4.65	12.6	Def	5.3	11.6	Def	D
07/05/2014	10mm	4	696	Yes	135	125	4.65	14.1	Def	5.4	12.8	Def	D

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
07/05/2014	10mm	4	766	Yes	137	126	4.65	14.2	Def	5.7	12.5	Def	D
07/05/2014	10mm	4	780	Yes	126	109	4.65	12.8	Def	4.9	12.4	Def	D
08/05/2014	10mm	5	500	Yes	134	127	4.65	14.3	Def	5.7	12.5	Def	D
08/05/2014	10mm	5	514	Yes	114	106	4.65	12.5	Def	5.1	11.8	Def	D
08/05/2014	10mm	5	528	Yes	116	109	4.65	12.8	Def	5.2	11.8	Def	D
08/05/2014	10mm	5	542	Yes	140	132	4.65	14.7	Def	6.1	12.3	Def	D
08/05/2014	10mm	5	556	Yes	129	121	4.65	13.8	Def	5.6	12.2	Def	D
08/05/2014	10mm	5	570	Yes	134	125	4.65	14.1	Def	5.4	12.9	Def	D
08/05/2014	10mm	5	584	Yes	119	112	4.65	13.1	Def	5.3	11.9	Def	D
08/05/2014	10mm	5	598	Yes	115	106	4.65	12.5	Def	5.3	11.5	Def	D
08/05/2014	10mm	5	612	Yes	124	116	4.65	13.4	Def	5.8	11.6	Def	D
08/05/2014	10mm	5	624	Yes	121	114	4.65	13.2	Def	5.7	11.6	Def	D
08/05/2014	10mm	6	656	Yes	114	106	4.65	12.5	Def	5.0	11.9	Def	E
08/05/2014	10mm	6	670	Yes	122	114	4.65	13.2	Def	5.1	12.4	Def	D
08/05/2014	10mm	6	684	Yes	119	111	4.65	13.0	Def	5.6	11.4	Def	D
08/05/2014	10mm	6	698	Yes	131	122	4.65	13.9	Def	5.8	12.0	Def	D
08/05/2014	10mm	6	712	Yes	124	117	4.65	13.5	Def	5.6	11.9	Def	D
08/05/2014	10mm	6	724	Yes	119	112	4.65	13.1	Def	5.5	11.7	Def	D
08/05/2014	10mm	6	738	Yes	132	123	4.65	14.0	Def	5.3	12.8	Def	D
08/05/2014	10mm	6	742	Yes	137	128	4.65	14.4	Def	5.8	12.4	Def	D
08/05/2014	10mm	6	756	Yes	128	120	4.65	13.7	Def	5.5	12.3	Def	D
08/05/2014	10mm	6	770	Yes	131	123	4.65	14.0	Def	5.2	13.0	Def	D
09/05/2014	10mm	7	500	Yes	124	115	4.65	13.3	Def	5.6	11.8	Def	D

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
09/05/2014	10mm	7	514	Yes	127	120	4.65	13.7	Def	5.2	12.8	Def	D
09/05/2014	10mm	7	528	Yes	124	121	4.65	13.8	Def	6.0	11.7	Def	D
09/05/2014	10mm	7	542	Yes	136	130	4.65	14.5	Def	5.4	13.1	Def	D
09/05/2014	10mm	7	556	Yes	131	122	4.65	13.9	Def	5.6	12.3	Def	D
09/05/2014	10mm	7	570	Yes	122	114	4.65	13.2	Def	5.2	12.2	Def	D
09/05/2014	10mm	7	584	Yes	124	116	4.65	13.4	Def	5.3	12.2	Def	D
09/05/2014	10mm	7	598	No	137	128	4.65	14.4	Def	5.6	12.8	Def	U
09/05/2014	10mm	7	612	Yes	111	105	4.65	12.5	Def	5.6	11.0	Def	D
09/05/2014	10mm	7	624	Yes	124	116	4.65	13.4	Def	5.6	11.8	Def	D
09/05/2014	10mm	8	638	Yes	132	124	4.65	14.0	Def	5.6	12.5	Def	D
09/05/2014	10mm	8	652	Yes	113	104	4.65	12.4	Def	5.3	11.4	Def	D
09/05/2014	10mm	8	666	Yes	125	115	4.65	13.3	Def	5.5	11.9	Def	D
09/05/2014	10mm	8	680	Yes	114	107	4.65	12.6	Def	5.4	11.4	Def	D
09/05/2014	10mm	8	694	Yes	128	121	4.65	13.8	Def	5.6	12.2	Def	D
09/05/2014	10mm	8	708	Yes	113	107	4.65	12.6	Def	5.2	11.7	Def	D
09/05/2014	10mm	8	722	Yes	142	133	4.65	14.8	Def	5.9	12.7	Def	D
09/05/2014	10mm	8	736	Yes	129	120	4.65	13.7	Def	5.7	12.0	Def	D
09/05/2014	10mm	8	750	No	128	120	4.65	13.7	Def	5.1	12.9	Def	U
09/05/2014	10mm	8	764	Yes	109	102	4.65	12.2	Def	5.5	10.8	Def	D
12/05/2014	10mm	9	500	Yes	138	130	4.65	14.5	Def	5.7	12.7	Def	D
12/05/2014	10mm	9	514	No	147	140	4.65	15.3	Def	5.8	13.3	Def	U
12/05/2014	10mm	9	542	Yes	118	110	4.65	12.9	Def	5.1	12.1	Def	D
12/05/2014	10mm	9	556	Yes	132	123	4.65	14.0	Def	5.9	12.0	Def	D

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
12/05/2014	10mm	9	570	Yes	138	129	4.65	14.4	Def	6.1	12.1	Def	D
12/05/2014	10mm	9	584	No	131	122	4.65	13.9	Def	5.7	12.1	Def	U
12/05/2014	10mm	9	598	Yes	121	114	4.65	13.2	Def	5.4	12.0	Def	D
12/05/2014	10mm	9	612	Yes	111	104	4.65	12.4	Def	5.9	10.6	Def	D
12/05/2014	10mm	9	626	No	132	122	4.65	13.9	Def	5.9	11.9	Def	U
12/05/2014	10mm	10	640	Yes	121	113	4.65	13.1	Def	5.4	11.9	Def	D
12/05/2014	10mm	10	654	Yes	111	104	4.65	12.4	Def	5.3	11.3	Def	D
12/05/2014	10mm	10	668	Yes	141	132	4.65	14.7	Def	6.0	12.4	Def	D
12/05/2014	10mm	10	682	Yes	128	120	4.65	13.7	Def	5.9	11.7	Def	D
12/05/2014	10mm	10	696	No	144	137	4.65	15.1	Def	6.1	12.6	Def	U
12/05/2014	10mm	10	710	Yes	134	125	4.65	14.1	Def	5.3	13.0	Def	D
12/05/2014	10mm	10	724	Yes	136	128	4.65	14.4	Def	5.7	12.6	Def	D
12/05/2014	10mm	10	738	Yes	127	116	4.65	13.4	Def	5.4	12.1	Def	D
12/05/2014	10mm	10	752	Yes	131	124	4.65	14.0	Def	6.3	11.5	Def	D
12/05/2014	10mm	10	766	Yes	105	98	4.65	11.8	Def	5.2	10.9	Def	D
13/05/2014	10mm	11	500	Yes	138	130	4.65	14.5	Def	5.4	13.3	Def	D
13/05/2014	10mm	11	514	Yes	146	138	4.65	15.1	Def	5.6	13.5	Def	D
13/05/2014	10mm	11	528	Yes	134	125	4.65	14.1	Def	5.8	12.2	Def	D
13/05/2014	10mm	11	542	Yes	145	135	4.65	14.9	Def	5.7	13.1	Def	D
13/05/2014	10mm	11	556	Yes	129	121	4.65	13.8	Def	5.6	12.2	Def	D
13/05/2014	10mm	11	570	Yes	142	132	4.65	14.7	Def	5.7	12.8	Def	D
13/05/2014	10mm	11	584	Yes	125	117	4.65	13.5	Def	5.5	12.0	Def	D
13/05/2014	10mm	11	598	Yes	117	110	4.65	12.9	Def	5.6	11.4	Def	D

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
13/05/2014	10mm	11	612	Yes	122	114	4.65	13.2	Def	5.8	11.4	Def	D
13/05/2014	10mm	11	626	Yes	124	115	4.65	13.3	Def	5.6	11.8	Def	D
13/05/2014	12.5mm	1	640	Yes	128	120	4.65	13.7	Def	5.2	12.7	Def	D
13/05/2014	12.5mm	1	654	Yes	131	122	4.65	13.9	Def	6.0	11.7	Not	D
13/05/2014	12.5mm	1	668	No	134	125	4.65	14.1	Def	6.0	12.0	Not	U
13/05/2014	12.5mm	1	682	Yes	129	122	4.65	13.9	Def	5.4	12.6	Def	D
13/05/2014	12.5mm	1	696	Yes	119	112	4.65	13.1	Def	5.7	11.5	Not	D
13/05/2014	12.5mm	1	710	Yes	130	123	4.65	14.0	Def	5.9	12.0	Not	D
13/05/2014	12.5mm	1	724	Yes	126	118	4.65	13.6	Def	5.6	12.0	Not	D
13/05/2014	12.5mm	1	738	Yes	134	125	4.65	14.1	Def	6.3	11.5	Not	D
13/05/2014	12.5mm	1	752	Yes	118	111	4.65	13.0	Def	5.8	11.2	Not	E
13/05/2014	12.5mm	1	766	Yes	139	131	4.65	14.6	Def	5.9	12.5	Def	D
14/05/2014	12.5mm	2	500	Yes	141	133	4.65	14.8	Def	5.4	13.5	Def	D
14/05/2014	12.5mm	2	514	Yes	137	130	4.65	14.5	Def	5.9	12.4	Not	D
14/05/2014	12.5mm	2	528	Yes	136	128	4.65	14.4	Def	5.7	12.6	Def	D
14/05/2014	12.5mm	2	542	Yes	122	114	4.65	13.2	Def	5.6	11.6	Not	D
14/05/2014	12.5mm	2	556	Yes	136	127	4.65	14.3	Def	5.7	12.5	Def	D
14/05/2014	12.5mm	2	570	Yes	134	126	4.65	14.2	Def	5.5	12.7	Def	D
14/05/2014	12.5mm	2	584	Yes	135	125	4.65	14.1	Def	6.0	11.9	Not	D
14/05/2014	12.5mm	2	598	Yes	138	129	4.65	14.4	Def	5.6	12.8	Def	D
14/05/2014	12.5mm	2	612	Yes	138	130	4.65	14.5	Def	5.7	12.7	Def	D
14/05/2014	12.5mm	2	626	Yes	125	119	4.65	13.6	Def	5.6	12.0	Not	D
14/05/2014	12.5mm	3	640	Yes	111	104	4.65	12.4	Not	5.4	11.2	Not	D

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
14/05/2014	12.5mm	3	654	Yes	139	131	4.65	14.6	Def	5.7	12.9	Def	D
14/05/2014	12.5mm	3	668	Yes	118	110	4.65	12.9	Def	5.4	11.7	Not	D
14/05/2014	12.5mm	3	682	Yes	116	107	4.65	12.6	Def	5.2	11.7	Not	D
14/05/2014	12.5mm	3	696	Yes	133	127	4.65	14.3	Def	6.1	12.0	Not	D
14/05/2014	12.5mm	3	710	Yes	133	125	4.65	14.1	Def	5.6	12.6	Def	D
14/05/2014	12.5mm	3	724	Yes	116	109	4.65	12.8	Def	5.6	11.3	Not	D
14/05/2014	12.5mm	3	738	Yes	144	135	4.65	14.9	Def	5.8	13.0	Def	D
14/05/2014	12.5mm	3	752	Yes	127	119	4.65	13.6	Def	5.9	11.7	Not	D
14/05/2014	12.5mm	3	766	Yes	132	125	4.65	14.1	Def	6.1	11.8	Not	D
15/05/2014	12.5mm	4	500	Yes	124	116	4.65	13.4	Def	5.3	12.3	Not	D
15/05/2014	12.5mm	4	514	Yes	142	135	4.65	14.9	Def	5.8	13.0	Def	D
15/05/2014	12.5mm	4	528	Yes	124	116	4.65	13.4	Def	5.7	11.7	Not	D
15/05/2014	12.5mm	4	542	Yes	135	126	4.65	14.2	Def	6.0	12.1	Not	D
15/05/2014	12.5mm	4	556	Yes	120	121	4.65	13.8	Def	5.6	12.2	Not	D
15/05/2014	12.5mm	4	570	Yes	144	133	4.65	14.8	Def	5.8	12.8	Def	D
15/05/2014	12.5mm	4	584	Yes	134	127	4.65	14.3	Def	5.5	12.8	Def	D
15/05/2014	12.5mm	4	598	Yes	134	126	4.65	14.2	Def	6.1	11.9	Not	D
15/05/2014	12.5mm	4	612	Yes	136	128	4.65	14.4	Def	5.7	12.6	Def	D
15/05/2014	12.5mm	4	626	Yes	125	119	4.65	13.6	Def	5.7	12.0	Not	D
15/05/2014	12.5mm	5	640	Yes	124	117	4.65	13.5	Def	5.6	11.8	Not	D
15/05/2014	12.5mm	5	654	Yes	118	110	4.65	12.9	Def	5.2	11.9	Not	D
15/05/2014	12.5mm	5	668	Yes	136	127	4.65	14.3	Def	5.9	12.2	Not	D
15/05/2014	12.5mm	5	682	Yes	137	128	4.65	14.4	Def	5.8	12.4	Not	D

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
15/05/2014	12.5mm	5	696	Yes	125	116	4.65	13.4	Def	5.5	12.0	Not	D
15/05/2014	12.5mm	5	710	Yes	137	128	4.65	14.4	Def	5.9	12.3	Not	D
15/05/2014	12.5mm	5	724	Yes	134	125	4.65	14.1	Def	5.8	12.2	Not	D
15/05/2014	12.5mm	5	738	Yes	137	127	4.65	14.3	Def	5.9	12.3	Not	D
15/05/2014	12.5mm	5	752	No	142	133	4.65	14.8	Def	5.6	13.1	Def	U
15/05/2014	12.5mm	5	766	Yes	129	121	4.65	13.8	Def	5.8	11.9	Not	D
16/05/2014	12.5mm	6	500	Yes	126	120	4.65	13.7	Def	5.8	11.9	Not	D
16/05/2014	12.5mm	6	514	Yes	127	118	4.65	13.6	Def	5.6	12.0	Not	D
16/05/2014	12.5mm	6	528	Yes	120	114	4.65	13.2	Def	5.5	11.8	Not	D
16/05/2014	12.5mm	6	542	No	134	127	4.65	14.3	Def	5.4	12.9	Def	U
16/05/2014	12.5mm	6	556	Yes	119	111	4.65	13.0	Def	5.2	12.1	Not	D
16/05/2014	12.5mm	6	570	Yes	117	108	4.65	12.7	Def	5.2	11.8	Not	D
16/05/2014	12.5mm	6	584	No	146	139	4.65	15.2	Def	6.3	12.5	Def	U
16/05/2014	12.5mm	6	598	Yes	131	124	4.65	14.0	Def	5.8	12.1	Not	D
16/05/2014	12.5mm	6	612	No	134	123	4.65	14.0	Def	6.2	11.6	Not	D
16/05/2014	12.5mm	6	624	Yes	138	131	4.65	14.6	Def	6.3	11.9	Not	D
16/05/2014	12.5mm	7	640	Yes	127	126	4.65	14.2	Def	5.8	12.3	Not	D
16/05/2014	12.5mm	7	654	Yes	137	129	4.65	14.4	Def	6.1	12.1	Not	D
16/05/2014	12.5mm	7	668	Yes	125	117	4.65	13.5	Def	5.9	11.5	Not	D
16/05/2014	12.5mm	7	682	Yes	131	123	4.65	14.0	Def	6.2	11.5	Not	D
16/05/2014	12.5mm	7	696	Yes	149	139	4.65	15.2	Def	5.7	13.3	Def	DL
16/05/2014	12.5mm	7	710	Yes	139	130	4.65	14.5	Def	5.8	12.5	Def	DL
16/05/2014	12.5mm	7	724	Yes	131	123	4.65	14.0	Def	5.8	12.1	Not	D

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
16/05/2014	12.5mm	7	738	Yes	127	129	4.65	14.4	Def	5.8	12.4	Not	D
16/05/2014	12.5mm	7	752	Yes	122	114	4.65	13.2	Def	5.4	12.0	Not	I
16/05/2014	12.5mm	7	766	Yes	115	117	4.65	13.5	Def	6.1	11.2	Not	D
19/05/2014	12.5mm	8	500	Yes	139	130	4.65	14.5	Def	5.8	12.6	Def	D
19/05/2014	12.5mm	8	514	Yes	143	134	4.65	14.8	Def	5.9	12.7	Def	D
19/05/2014	12.5mm	8	528	Yes	118	111	4.65	13.0	Def	5.8	11.2	Not	D
19/05/2014	12.5mm	8	542	Yes	134	127	4.65	14.3	Def	6.1	12.0	Not	D
19/05/2014	12.5mm	8	556	Yes	125	117	4.65	13.5	Def	5.4	12.2	Not	D
19/05/2014	12.5mm	8	570	Yes	130	123	4.65	14.0	Def	5.9	11.9	Not	D
19/05/2014	12.5mm	8	584	Yes	121	114	4.65	13.2	Def	5.3	12.1	Not	D
19/05/2014	12.5mm	8	598	Yes	140	132	4.65	14.7	Def	5.8	12.8	Def	D
19/05/2014	12.5mm	8	612	Yes	117	110	4.65	12.9	Def	5.1	12.1	Not	D
19/05/2014	12.5mm	8	626	Yes	120	112	4.65	13.1	Def	5.7	11.3	Not	D
19/05/2014	12.5mm	9	640	Yes	119	113	4.65	13.1	Def	5.7	11.4	Not	D
19/05/2014	12.5mm	9	654	Yes	127	118	4.65	13.6	Def	5.8	11.7	Not	D
19/05/2014	12.5mm	9	668	Yes	127	118	4.65	13.6	Def	5.5	12.2	Not	D
19/05/2014	12.5mm	9	682	Yes	132	125	4.65	14.1	Def	5.7	12.4	Not	D
19/05/2014	12.5mm	9	696	Yes	124	117	4.65	13.5	Def	5.4	12.2	Not	D
19/05/2014	12.5mm	9	710	Yes	128	120	4.65	13.7	Def	6.0	11.6	Not	D
19/05/2014	12.5mm	9	724	Yes	128	120	4.65	13.7	Def	5.7	11.9	Not	D
19/05/2014	12.5mm	9	738	Yes	140	133	4.65	14.8	Def	5.7	13.0	Def	DL
19/05/2014	12.5mm	9	752	Yes	111	104	4.65	12.4	Not	5.6	10.9	Not	D
19/05/2014	12.5mm	9	766	Yes	111	104	4.65	12.4	Not	5.2	11.5	Not	D

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
20/05/2014	12.5mm	10	500	Yes	122	104	4.65	12.4	Not	5.2	11.4	Not	D
20/05/2014	12.5mm	10	514	Yes	124	116	4.65	13.4	Def	5.6	11.8	Not	D
20/05/2014	12.5mm	10	528	Yes	158	150	4.65	16.0	Def	6.3	13.2	Def	D
20/05/2014	12.5mm	10	542	Yes	140	132	4.65	14.7	Def	5.9	12.6	Def	D
20/05/2014	12.5mm	10	556	Yes	143	135	4.65	14.9	Def	5.8	12.9	Def	D
20/05/2014	12.5mm	10	570	Yes	142	134	4.65	14.8	Def	5.9	12.7	Def	D
20/05/2014	12.5mm	10	584	Yes	135	126	4.65	14.2	Def	5.9	12.1	Not	D
20/05/2014	12.5mm	10	598	Yes	119	102	4.65	12.2	Not	5.1	11.4	Not	D
20/05/2014	12.5mm	10	612	Yes	129	122	4.65	13.9	Def	5.6	12.3	Not	D
20/05/2014	12.5mm	10	626	Yes	131	124	4.65	14.0	Def	5.6	12.5	Def	D
20/05/2014	12.5mm	11	640	Yes	134	127	4.65	14.3	Def	6.0	12.0	Not	D
20/05/2014	12.5mm	11	654	Yes	137	127	4.65	14.3	Def	5.8	12.4	Not	D
20/05/2014	12.5mm	11	668	Yes	120	114	4.65	13.2	Def	5.4	11.9	Not	D
20/05/2014	12.5mm	11	682	Yes	113	107	4.65	12.6	Def	5.8	10.8	Not	E
20/05/2014	12.5mm	11	696	Yes	126	118	4.65	13.6	Def	5.2	12.5	Def	D
20/05/2014	12.5mm	11	710	Yes	121	114	4.65	13.2	Def	6.0	11.2	Not	D
20/05/2014	12.5mm	11	724	Yes	120	116	4.65	13.4	Def	5.6	11.8	Not	D
20/05/2014	12.5mm	11	738	Yes	127	119	4.65	13.6	Def	5.4	12.3	Not	DL
20/05/2014	12.5mm	11	752	No	119	110	4.65	12.9	Def	5.2	11.9	Not	U
20/05/2014	12.5mm	11	766	Yes	127	119	4.65	13.6	Def	5.3	12.5	Def	D
21/05/2014	12.5mm	12	500	Yes	134	123	4.65	14.0	Def	5.2	13.0	Def	D
21/05/2014	12.5mm	12	514	Yes	135	126	4.65	14.2	Def	5.4	12.9	Def	D
21/05/2014	12.5mm	12	528	Yes	133	128	4.65	14.4	Def	5.2	13.3	Def	D

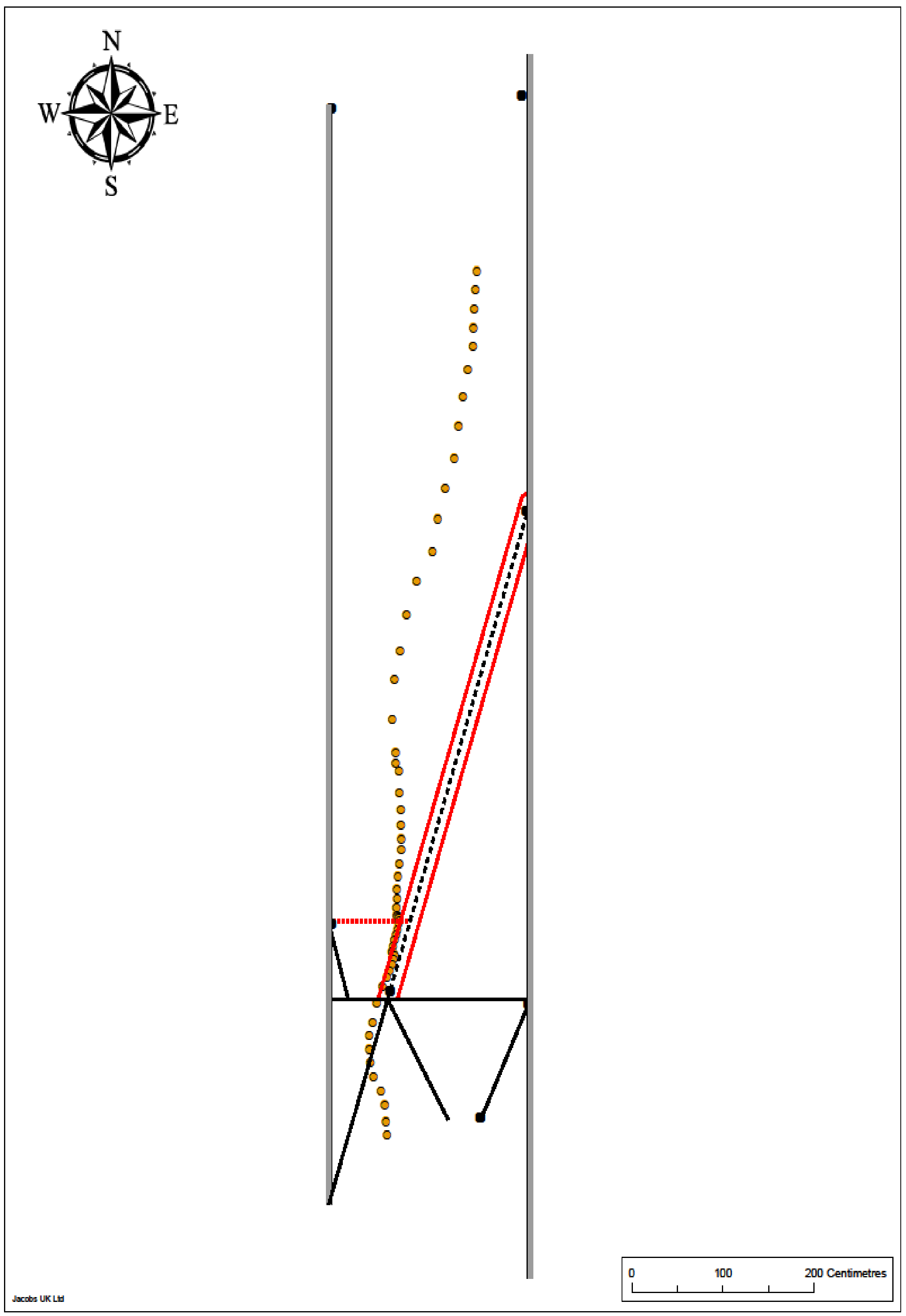
Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
21/05/2014	12.5mm	12	542	Yes	128	120	4.65	13.7	Def	5.0	13.1	Def	D
21/05/2014	12.5mm	12	556	Yes	135	122	4.65	13.9	Def	5.3	12.8	Def	D
21/05/2014	12.5mm	12	570	Yes	128	120	4.65	13.7	Def	5.1	13.0	Def	D
21/05/2014	12.5mm	12	584	Yes	141	132	4.65	14.7	Def	5.6	13.0	Def	D
21/05/2014	12.5mm	12	598	Yes	133	128	4.65	14.4	Def	6.2	11.9	Not	D
21/05/2014	12.5mm	12	612	Yes	126	118	4.65	13.6	Def	5.4	12.3	Not	D
21/05/2014	12.5mm	12	626	Yes	129	120	4.65	13.7	Def	4.9	13.3	Def	D
21/05/2014	Control	1	640	Yes	170	158	4.65	16.6		5.6	14.8		
21/05/2014	Control	1	654	Yes	143	132	4.65	14.7		5.3	13.5		
21/05/2014	Control	1	682	Yes	140	131	4.65	14.6		5.3	13.5		
21/05/2014	Control	1	696	Yes	139	130	4.65	14.5		5.6	12.9		
21/05/2014	Control	1	710	Yes	138	131	4.65	14.6		5.5	13.1		
21/05/2014	Control	1	724	Yes	129	122	4.65	13.9		5.0	13.2		
21/05/2014	Control	1	752	Yes	121	113	4.65	13.1		5.1	12.4		
22/05/2014	Control	2	500	Yes	108	102	4.65	12.2		5.5	10.9		
22/05/2014	Control	2	514	Yes	127	120	4.65	13.7		5.4	12.4		
22/05/2014	Control	2	528	Yes	115	107	4.65	12.6		5.4	11.4		
22/05/2014	Control	2	542	Yes	133	125	4.65	14.1		5.3	13.0		
22/05/2014	Control	2	556	Yes	121	115	4.65	13.3		5.7	11.6		
22/05/2014	Control	2	570	Yes	137	130	4.65	14.5		5.5	13.1		
22/05/2014	Control	2	584	Yes	135	127	4.65	14.3		5.7	12.5		
22/05/2014	Control	3	598	Yes	133	126	4.65	14.2		5.6	12.6		
22/05/2014	Control	3	612	Yes	139	130	4.65	14.5		5.8	12.5		

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
22/05/2014	Control	3	626	Yes	126	118	4.65	13.6		5.6	12.0		
22/05/2014	Control	3	640	Yes	125	120	4.65	13.7		5.7	12.0		
22/05/2014	Control	3	654	Yes	120	113	4.65	13.1		5.8	11.4		
22/05/2014	Control	3	670	Yes	117	111	4.65	13.0		5.7	11.4		
22/05/2014	Control	3	684	Yes	129	122	4.65	13.9		5.6	12.3		
23/05/2014	Control	4	500	Yes	139	131	4.65	14.6		5.8	12.7		
23/05/2014	Control	4	514	Yes	124	117	4.65	13.5		5.6	12.0		
23/05/2014	Control	4	528	Yes	121	114	4.65	13.2		5.6	11.7		
23/05/2014	Control	4	542	Yes	134	126	4.65	14.2		5.8	12.3		
23/05/2014	Control	4	556	Yes	139	131	4.65	14.6		5.7	12.8		
23/05/2014	Control	4	570	Yes	114	107	4.65	12.6		5.5	11.3		
23/05/2014	Control	4	584	Yes	113	106	4.65	12.5		5.5	11.1		
27/05/2014	Control	6	500	Yes	132	123	4.65	14.0		5.7	12.2		
27/05/2014	Control	6	514	No	134	125	4.65	14.1		5.8	12.2		
27/05/2014	Control	6	528	Yes	127	120	4.65	13.7		5.7	12.0		
27/05/2014	Control	6	542	Yes	122	114	4.65	13.2		5.7	11.5		
27/05/2014	Control	6	556	Yes	127	120	4.65	13.7		5.8	11.8		
27/05/2014	Control	6	570	Yes	131	124	4.65	14.0		5.6	12.5		
27/05/2014	Control	6	584	Yes	138	128	4.65	14.4		6.0	12.2		
27/05/2014	Control	7	598	Yes	158	149	4.65	15.9		5.6	14.2		
27/05/2014	Control	7	612	Yes	129	121	4.65	13.8		5.9	11.8		
27/05/2014	Control	7	626	Yes	122	114	4.65	13.2		5.4	11.9		
27/05/2014	Control	7	640	Yes	120	113	4.65	13.1		6.0	11.1		

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
27/05/2014	Control	7	654	Yes	129	121	4.65	13.8		5.6	12.3		
27/05/2014	Control	7	670	Yes	137	130	4.65	14.5		5.8	12.6		
27/05/2014	Control	7	684	Yes	139	132	4.65	14.7		5.9	12.6		
28/05/2014	Control	8	514	Yes	131	122	4.65	13.9		5.4	12.6		
28/05/2014	Control	8	528	Yes	132	123	4.65	14.0		5.4	12.7		
28/05/2014	Control	8	570	Yes	139	130	4.65	14.5		5.6	12.8		
28/05/2014	Control	8	584	Yes	130	122	4.65	13.9		5.5	12.5		
28/05/2014	Control	8	626	Yes	125	116	4.65	13.4		5.1	12.6		
28/05/2014	Control	8	654	Yes	133	124	4.65	14.0		5.6	12.5		
28/05/2014	Control	9	542	Yes	128	120	4.65	13.7		5.5	12.2		
28/05/2014	Control	9	556	Yes	138	129	4.65	14.4		5.5	13.0		
28/05/2014	Control	9	598	Yes	131	120	4.65	13.7		5.5	12.2		
28/05/2014	Control	9	612	Yes	124	116	4.65	13.4		5.6	11.9		
28/05/2014	Control	9	640	Yes	138	121	4.65	13.8		5.0	13.2		
29/05/2014	Control	10	500	Yes	129	118	4.65	13.6		5.6	12.0		
29/05/2014	Control	10	514	Yes	122	113	4.65	13.1		5.5	11.8		
29/05/2014	Control	10	528	Yes	138	128	4.65	14.4		5.2	13.4		
29/05/2014	Control	10	542	Yes	140	133	4.65	14.8		5.5	13.2		
29/05/2014	Control	10	556	Yes	130	122	4.65	13.9		5.9	11.9		
29/05/2014	Control	10	570	Yes	117	110	4.65	12.9		5.8	11.1		
29/05/2014	Control	11	584	Yes	126	120	4.65	13.7		5.6	12.2		
29/05/2014	Control	11	598	Yes	137	129	4.65	14.4		5.6	12.8		
29/05/2014	Control	11	612	Yes	149	141	4.65	15.4		5.6	13.6		

Date	Trial	Rep	Tag ID	Acoustic data	F L	S L	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U, DL
29/05/2014	Control	11	626	Yes	115	111	4.65	13.0		5.3	11.9		
29/05/2014	Control	11	640	Yes	132	125	4.65	14.1		5.6	12.6		
29/05/2014	Control	11	654	Yes	142	133	4.65	14.8		5.7	13.0		

Appendix E: Example silver eel acoustic track figures



Legend

12.5 mm - Replica 1

- Tag no. 542
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project EA Hydropower Screen Testing	Figure E - 1	Rev. 01	Status FINAL	Ref. no.125_R1_542	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - 12.5 mm screen trials - Replica 1			Project no. B1950200	

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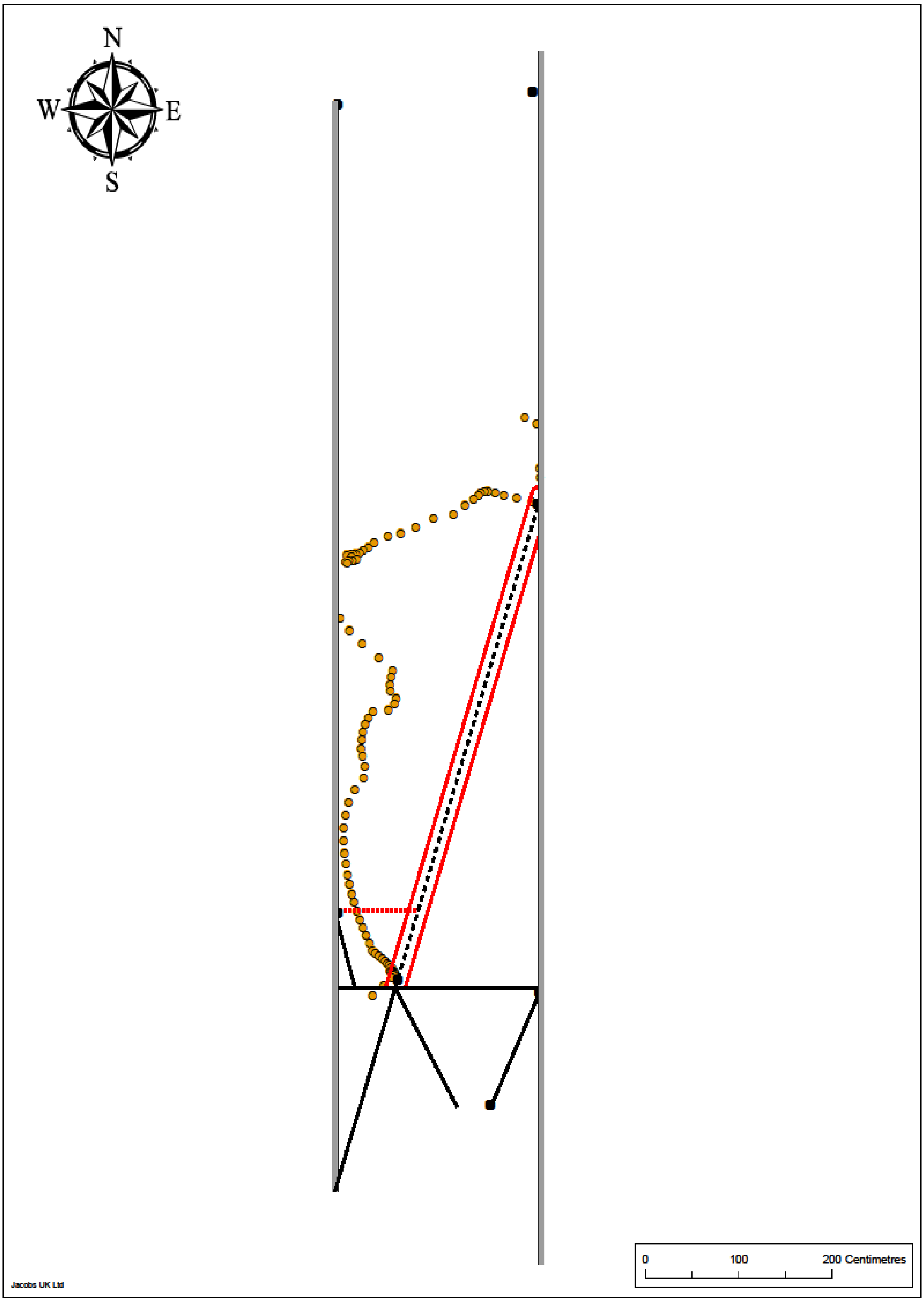

Legend

12.5 mm - Replica 2

- Tag no. 584
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project EA Hydropower Screen Testing	Figure E - 2	Rev. 01	Status FINAL	Ref. no.125_R2_584	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - 12.5 mm screen trials - Replica 2				Project no. B1950200
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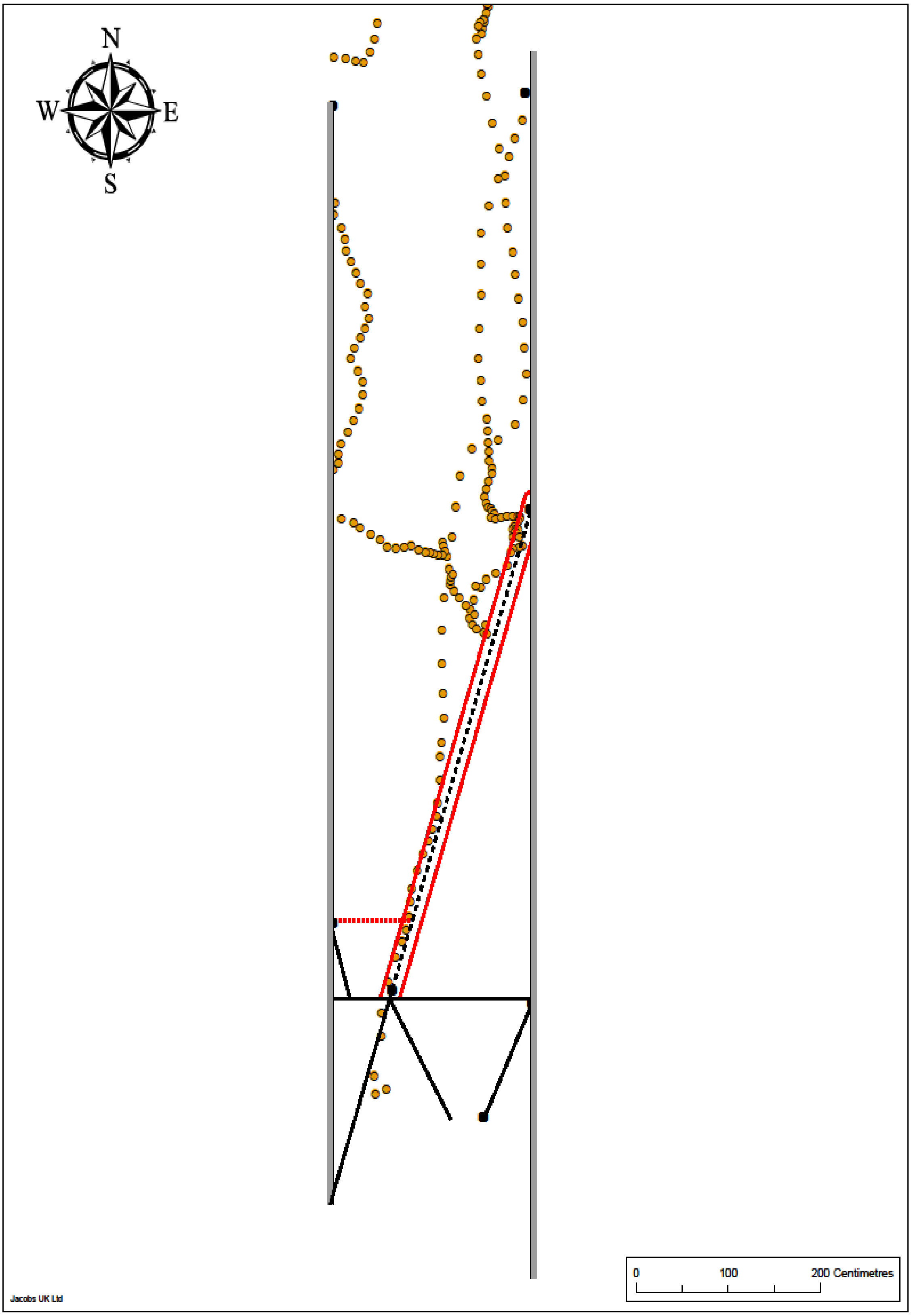

Legend

12.5 mm - Replica 3

- Tag no. 514
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project EA Hydropower Screen Testing	Figure E - 3	Rev. 01	Status FINAL	Ref. no.125_R3_514	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - 12.5 mm screen trials - Replica 3			Project no. B1950200	

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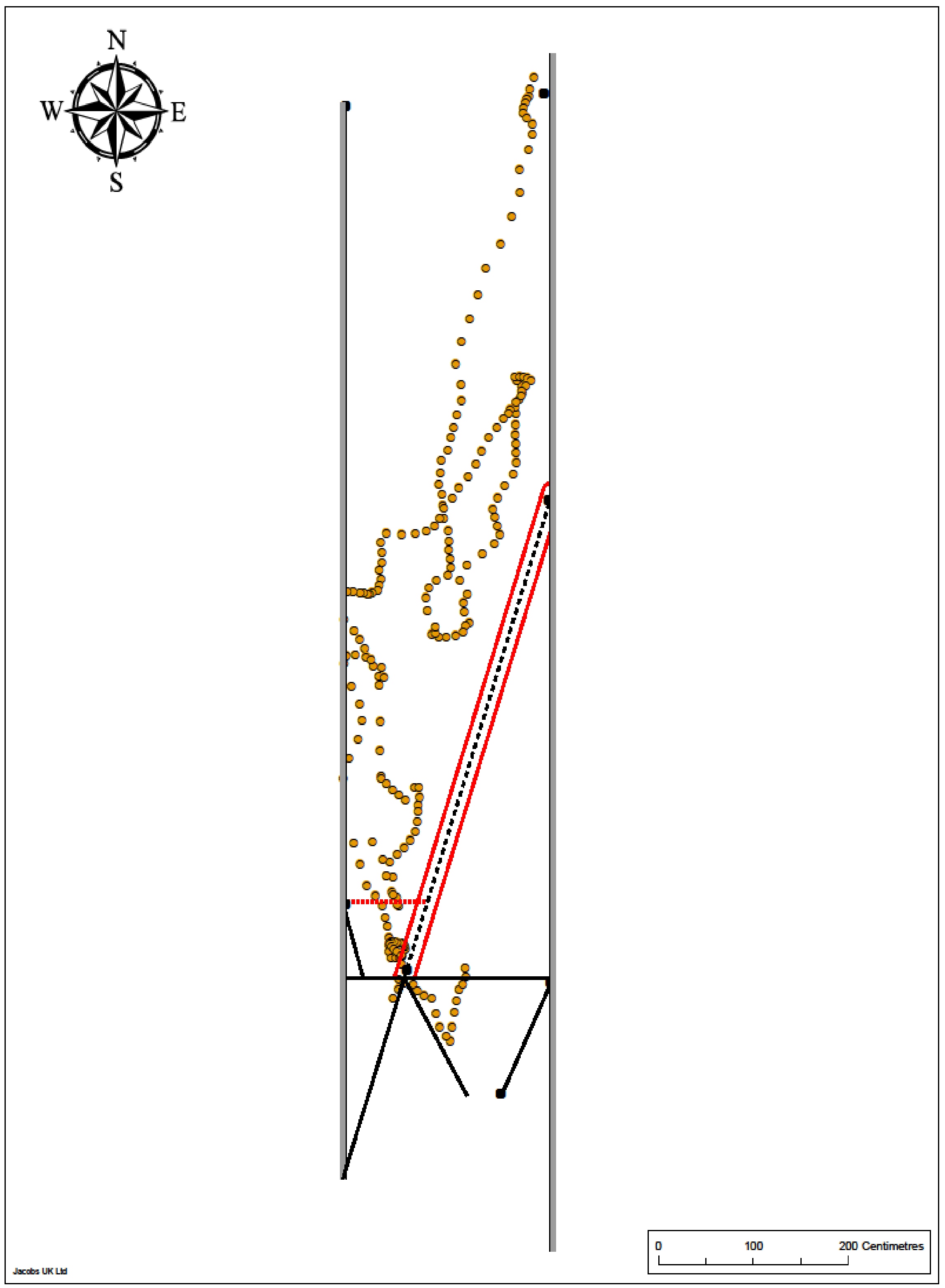

Legend

12.5 mm - Replica 4

- Tag no. 542
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project EA Hydropower Screen Testing	Figure E - 4	Rev. 01	Status FINAL	Ref. no.125_R4_542	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - 12.5 mm screen trials - Replica 4			Project no. B1950200	
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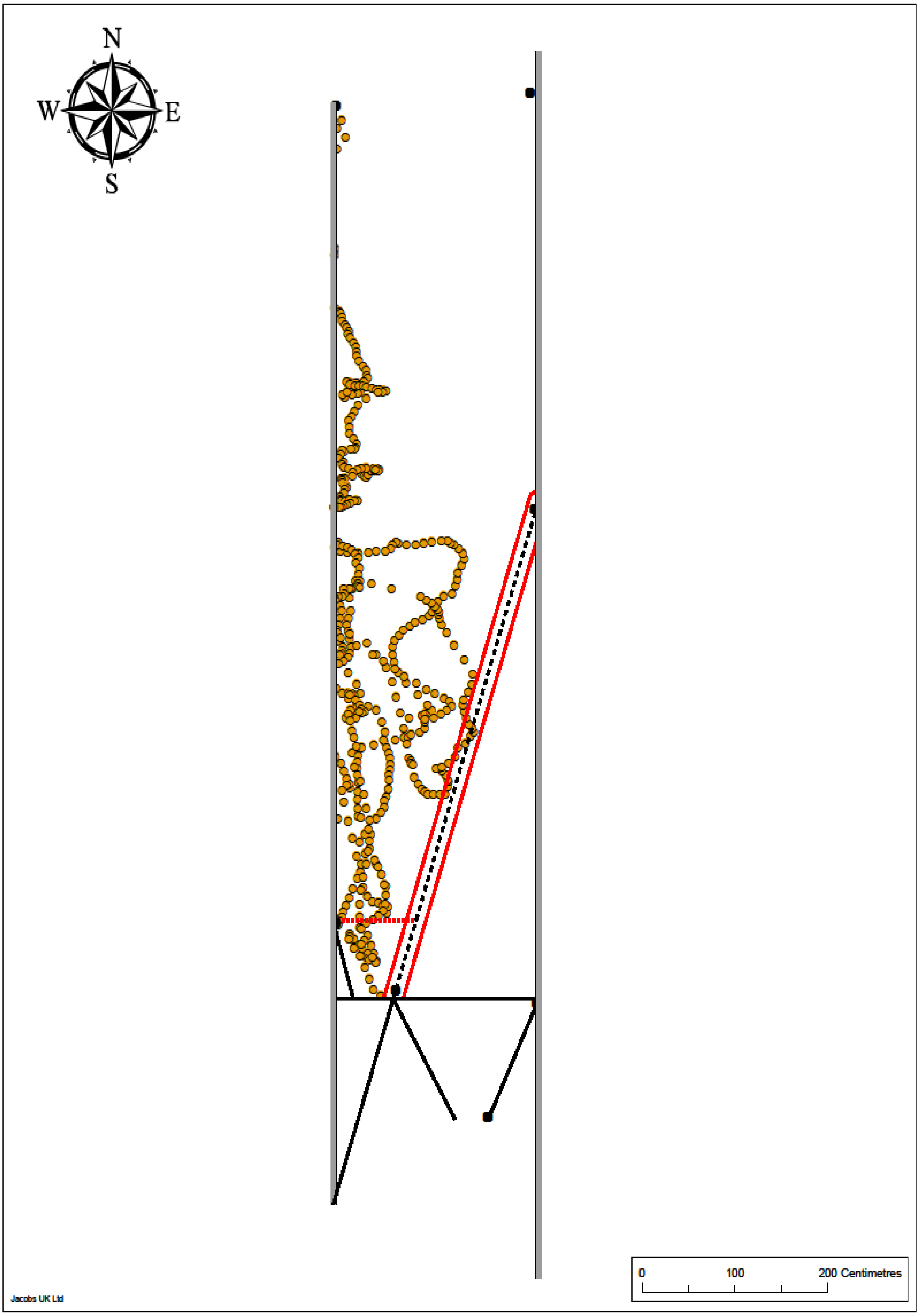

Legend

12.5 mm - Replica 5

- Tag no. 570
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project: EA Hydropower Screen Testing	Figure E - 5	Rev. 01	Status FINAL	Ref. no.125_R5_570	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title: Screen testing - 12.5 mm screen trials - Replica 5			Project no. B1950200	
JACOBS 1st Floor, Kenneth Dibben House, Enterprise Road, Southampton Science Park, Southampton, SO16 7NS, UK Tel: +44(0)2380111250 Fax: +44(0)2380111251 http://www.jacobs.com	Client: Environment Agency	Drawn by: VG	Check'd by: LI	Rev'd by: LI	Appr'd by: MR

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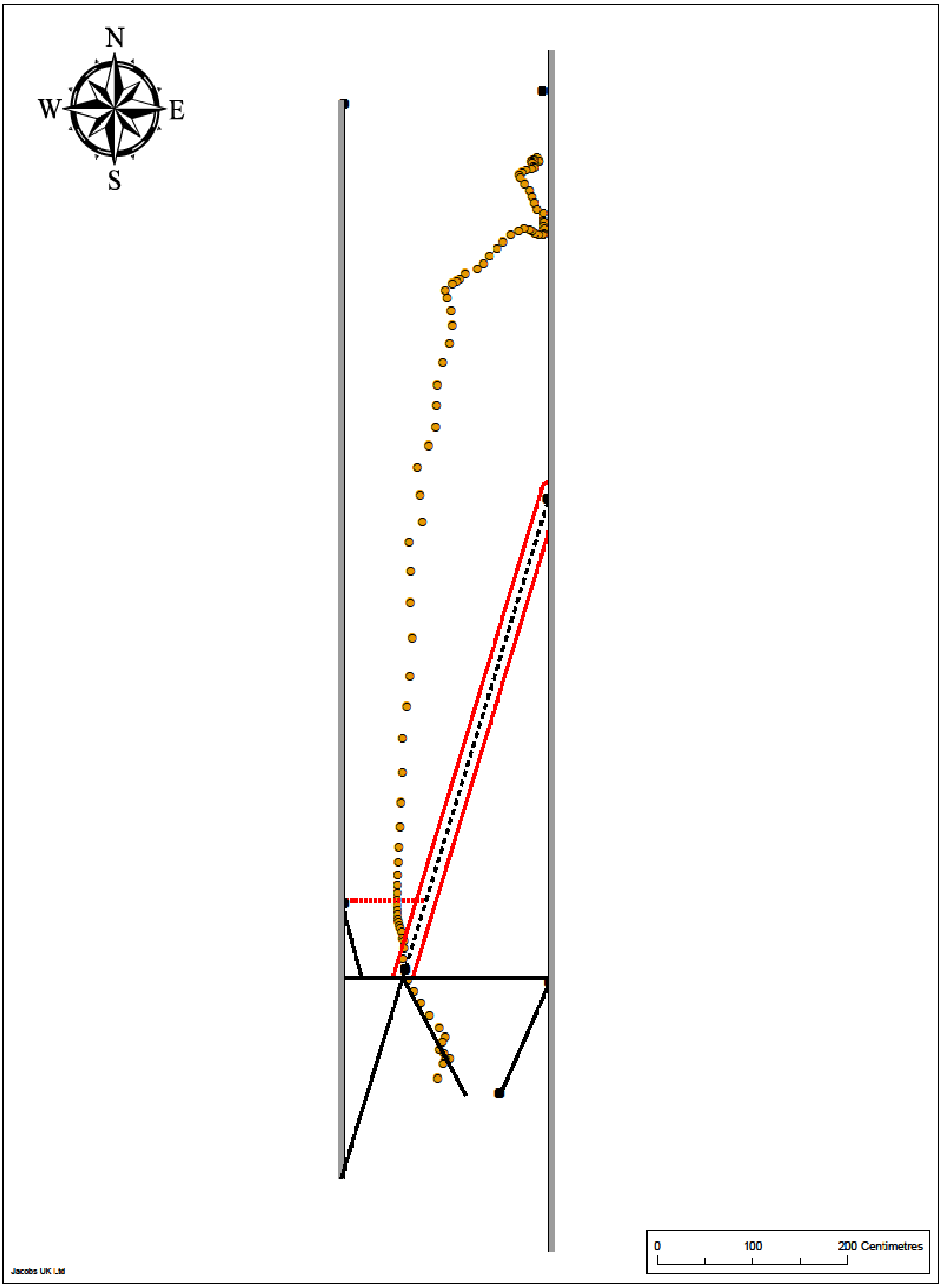

Legend

12.5 mm - Replica 6

- Tag no. 570
- 10 cm Screen Buffer
- Line of Deflection

Structure

- Structure
- Trialled Screen
- River Bank

Project EA Hydropower Screen Testing	Figure E - 6	Rev. 01	Status FINAL	Ref. no.125_R6_570	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - 12.5 mm screen trials - Replica 6				Project no. B1950200
JACOBS 1st Floor, Kenneth Dibben House, Enterprise Road, Southampton Science Park, Southampon, SO16 7NS, UK Tel: +44(0)2380111250 Fax: +44(0)2380111251 http://www.jacobs.com	Client Environment Agency	Drawn by VG	Check'd by LI	Rev'd by LI	Appr'd by MR

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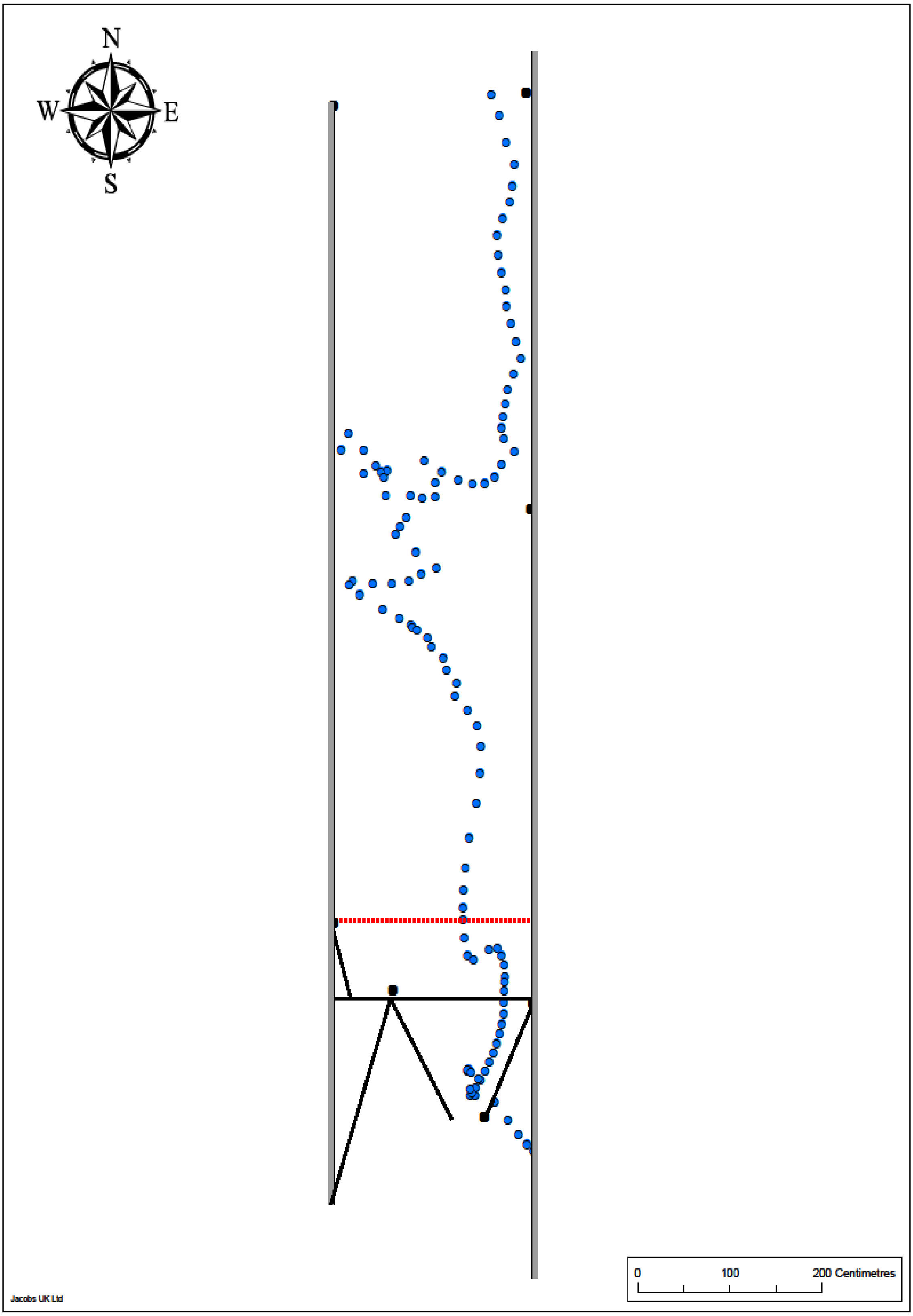

Legend

Control - Replica 1

- Tag no. 500
- Line of Deflection

Structure

- Structure
- River Bank

Project: EA Hydropower Screen Testing

Figure E - 7 | Rev. 01 | Status FINAL | Ref. no.C_R1_500 | Date 20/03/15

Scale @ A3 1:35 DO NOT SCALE

Drawing title: Screen testing - Control trials - Replica 1

Project no. B1950200

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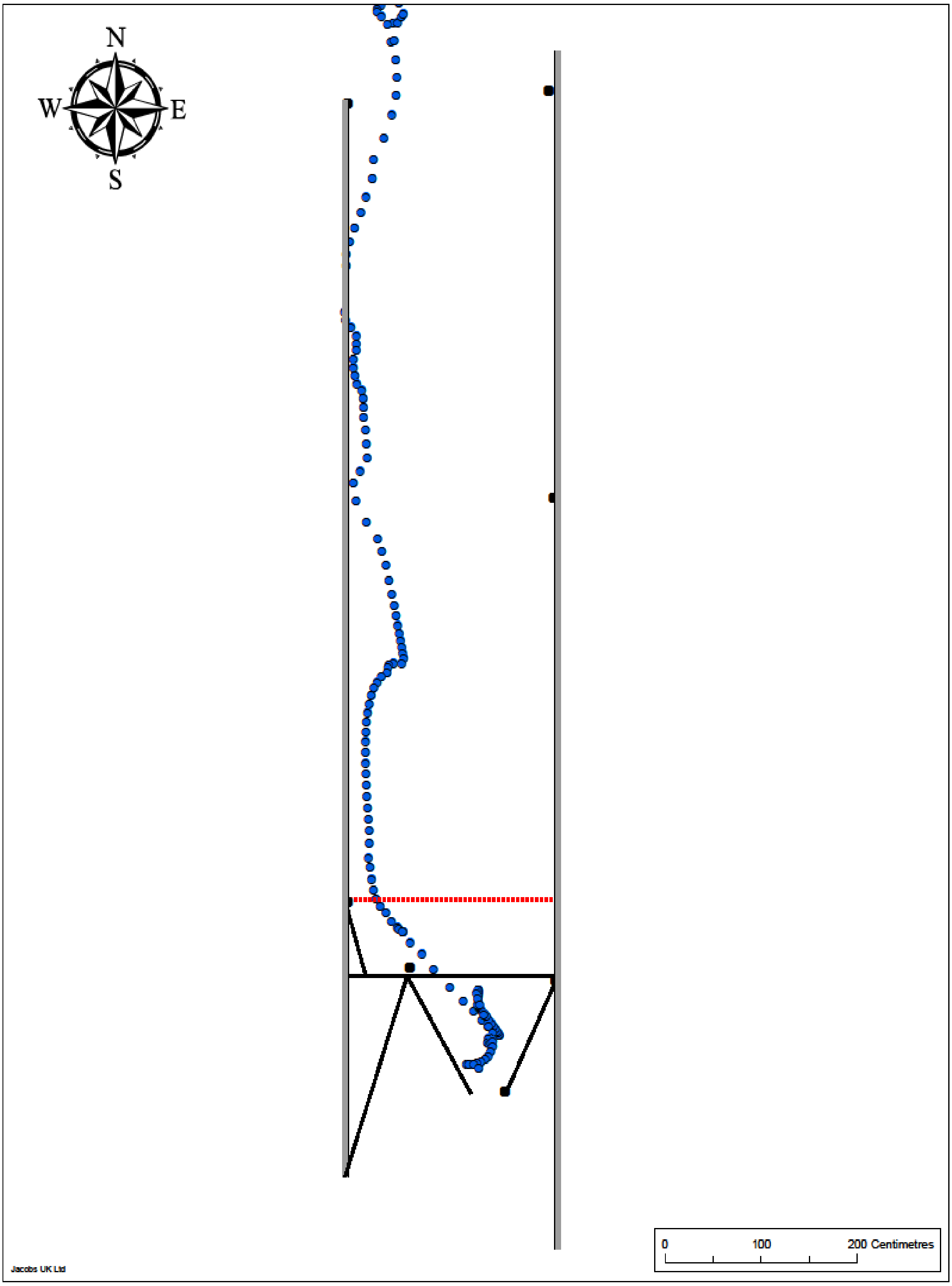

Legend

Control - Replica 2

- Tag no. 500
- Line of Deflection

Structure

- Structure
- River Bank

Project EA Hydropower Screen Testing	Figure E - 8	Rev. 01	Status FINAL	Ref. no.C_R2_500	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - Control trials - Replica 2			Project no. B1950200	
JACOBS 1st Floor, Kenneth Dibben House, Enterprise Road, Southampton Science Park, Southampton, SO16 7NS, UK Tel: +44(0)2380111250 Fax: +44(0)2380111251 http://www.jacobs.com	Client Environment Agency	Drawn by VG	Check'd by LI	Rev'd by LI	Appr'd by MR

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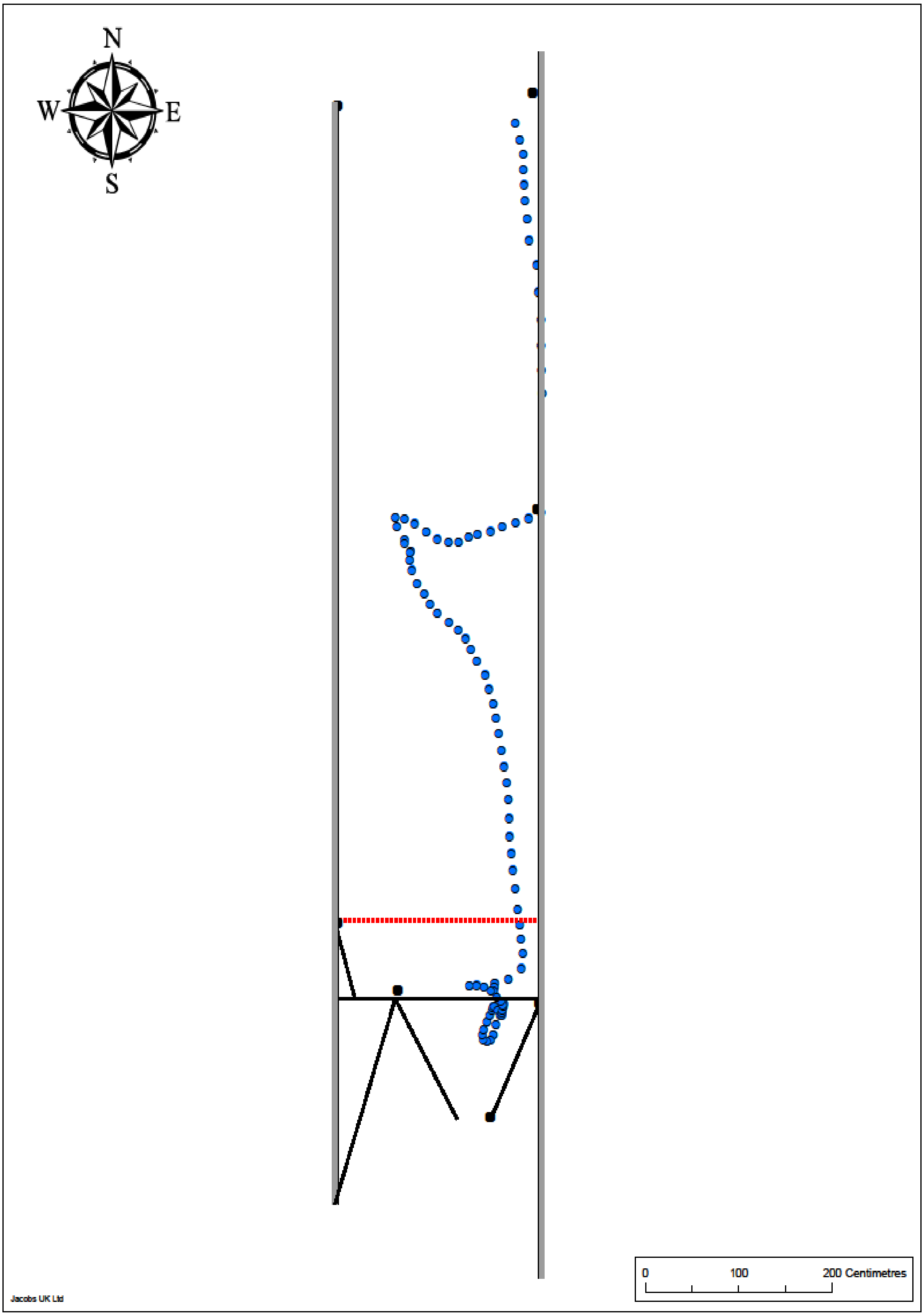

Legend

Control - Replica 3

- Tag no. 514
- Line of Deflection

Structure

- Structure
- River Bank

Project: EA Hydropower Screen Testing	Figure E - 9	Rev. 01	Status FINAL	Ref. no.C_R3_514	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title: Screen testing - Control trials - Replica 3			Project no. B1950200	
JACOBS 1st Floor, Kenneth Dibben House, Enterprise Road Southampton Science Park, Southampton, SO16 7NS, UK Tel: +44(0)2380111250 Fax: +44(0)2380111251 http://www.jacobs.com	Client: Environment Agency	Drawn by: VG	Check'd by: LI	Rev'd by: LI	Appr'd by: MR

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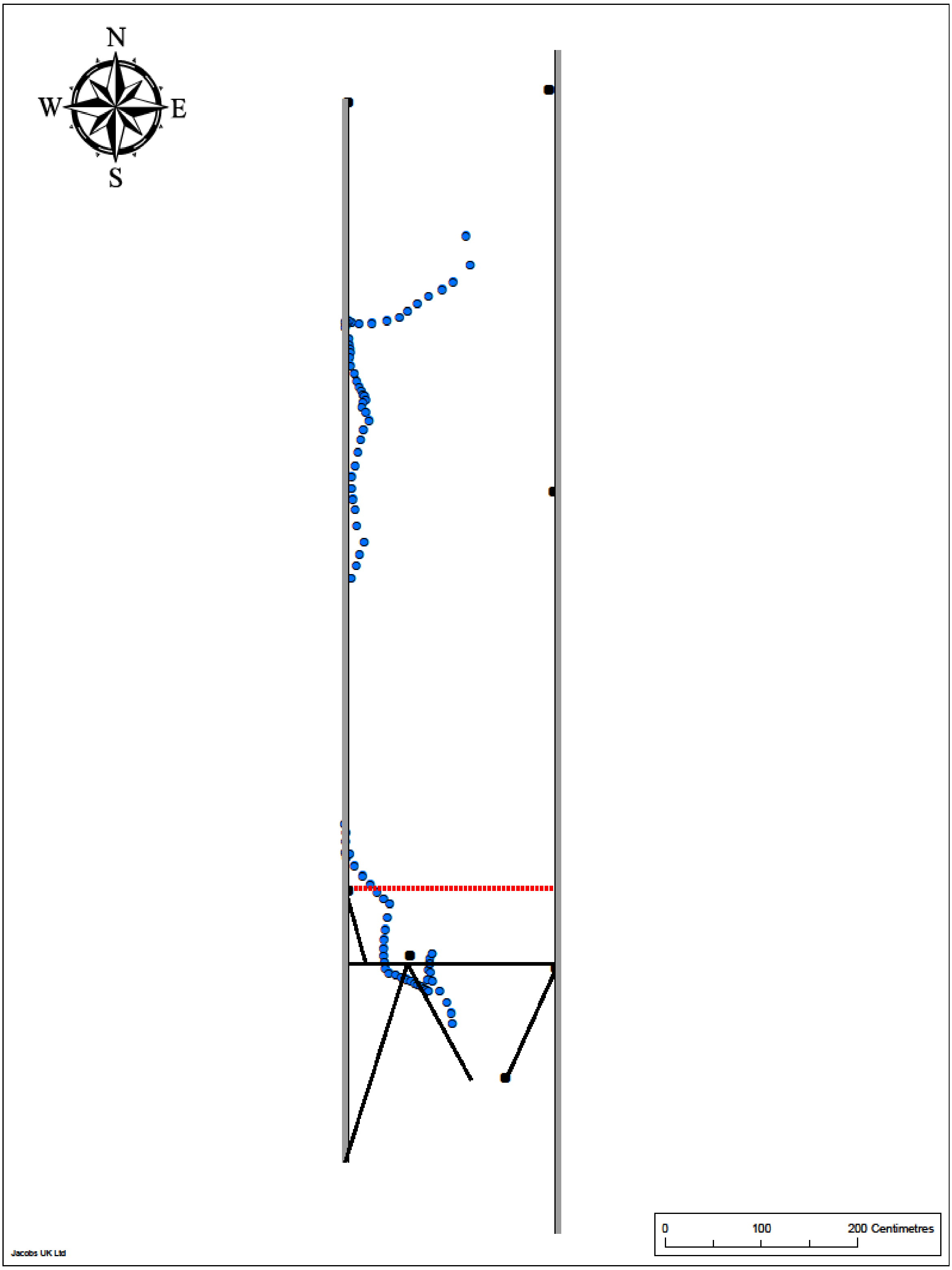

Legend

Control - Replica 4

- Tag no. 736
- Line of Deflection

Structure

- Structure
- River Bank

Project EA Hydropower Screen Testing	Figure E - 10	Rev. 01	Status FINAL	Ref. no.C_R4_736	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - Control trials - Replica 4				Project no. B1950200

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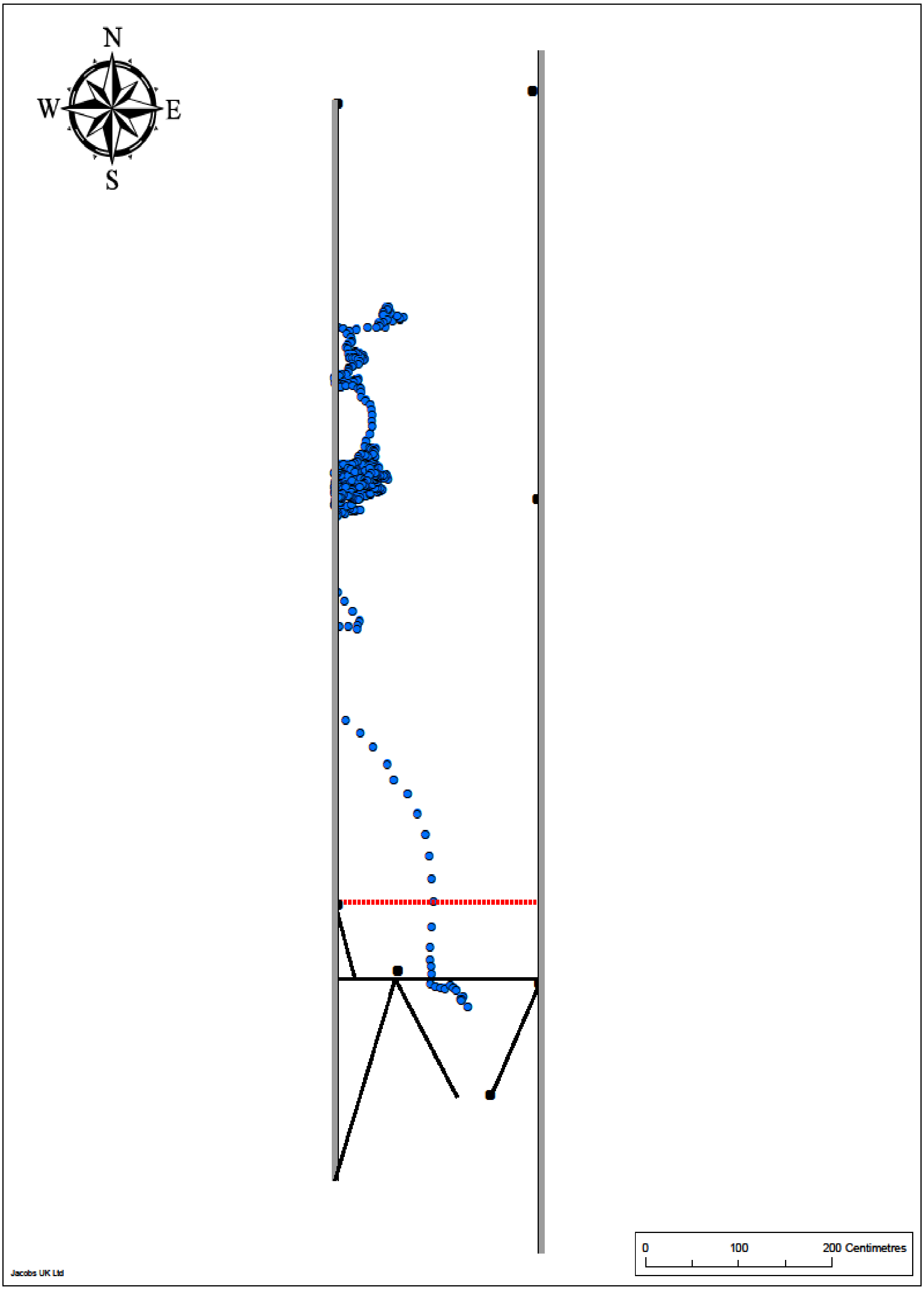

Legend

Control - Replica 5

- Tag no. 514
- Line of Deflection

Structure

- Structure
- River Bank

Project EA Hydropower Screen Testing	Figure E - 11	Rev. 01	Status FINAL	Ref. no.C_R5_514	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - Control trials - Replica 5			Project no. B1950200	
JACOBS 1st Floor, Kenneth Dibben House, Enterprise Road Southampton Science Park, Southampton, SO16 7NS, UK Tel: +44(0)2380111250 Fax: +44(0)2380111251 http://www.jacobs.com	Client Environment Agency	Drawn by VG	Check'd by LI	Rev'd by LI	Appr'd by MR

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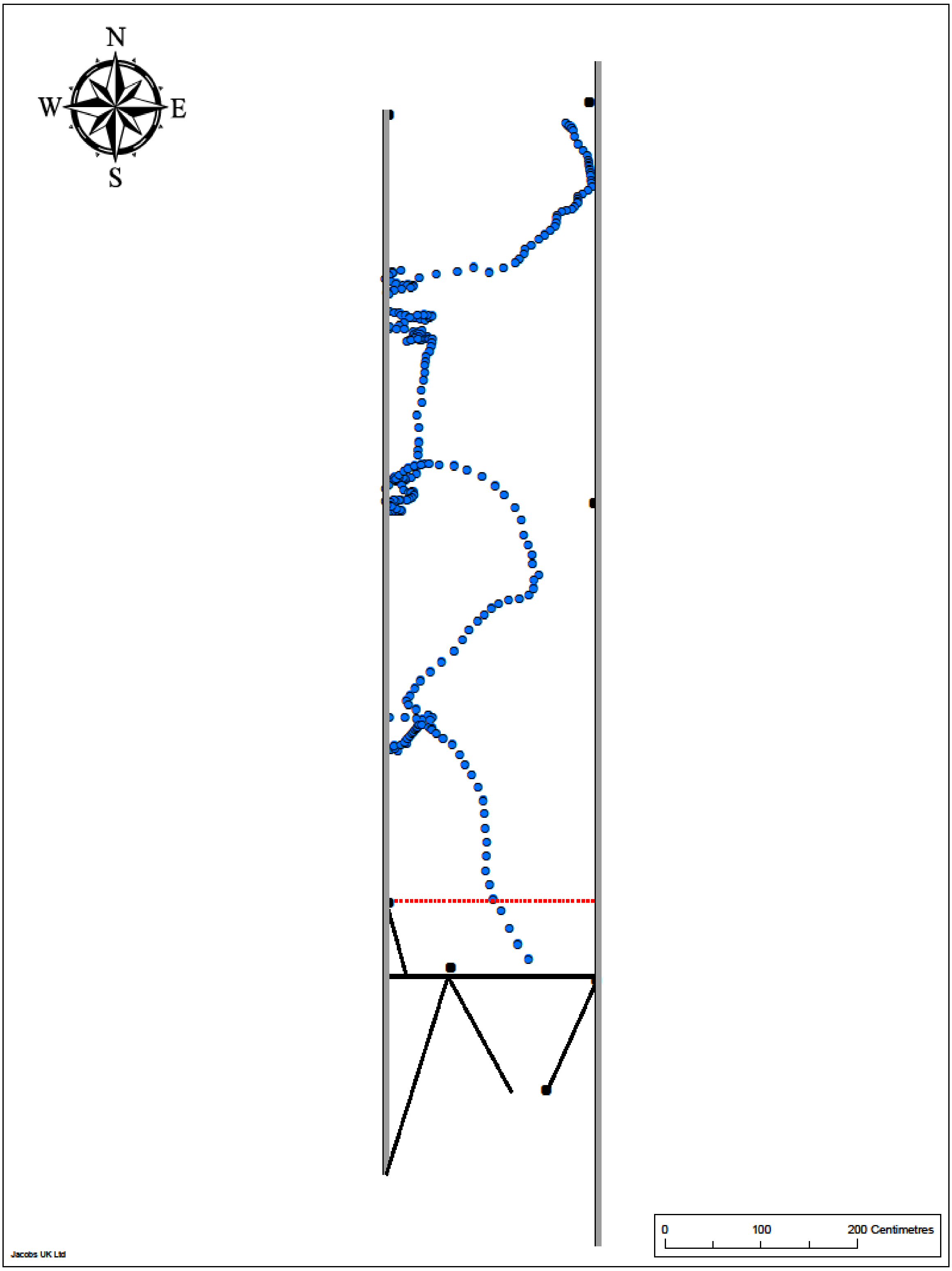

Legend

Control - Replica 5

- Tag no. 770
- Line of Deflection

Structure

- Structure
- River Bank

Project EA Hydropower Screen Testing	Figure E - 12	Rev. 01	Status FINAL	Ref. no.C_R5_770	Date 20/03/15
Scale @ A3 1:35 DO NOT SCALE	Drawing title Screen testing - Control trials - Replica 5			Project no. B1950200	
JACOBS 1st Floor, Kenneth Dibben House, Enterprise Road Southampton Science Park, Southampton, SO16 7NS, UK Tel: +44(0)2380111250 Fax: +44(0)2380111251 http://www.jacobs.com	Client Environment Agency	Drawn by VG	Check'd by LI	Rev'd by LI	Appr'd by MR

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Appendix F: Silver eel chronological results, fish body lengths and predictions from fineness ratio

Results for eel trials of 12.5mm screen and control screen

E = Possibly entrained, I = Possibly impinged, NI = Did not interact, D = Deflected, U = Unknown. SL = Standard length (mm). Deflection prediction based on fineness ratio (Def = deflected expected, Not = not deflected).

Date	Trial	Rep	Tag ID	Acoustic data	SL (mm)	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U
01/12/2014	12.5mm	1	500	Yes	455	16	15.5	Def	16.2	15.4	Def	D
01/12/2014	12.5mm	1	514	Yes	399	16	14.2	Def	19.4	12.4	Not	D
01/12/2014	12.5mm	1	528	Yes	391	16	14.0	Def	18.6	12.6	Def	D
01/12/2014	12.5mm	1	542	Yes	523	16	17.0	Def	14.9	17.7	Def	D
01/12/2014	12.5mm	1	556	Yes	355	16	13.0	Def	17.0	12.5	Not	D
01/12/2014	12.5mm	1	570	Yes	344	16	12.7	Def	17.1	12.1	Not	D
17/12/2014	12.5mm	2	500	Yes	515	16	16.8	Def	16.8	16.3	Def	D
17/12/2014	12.5mm	2	514	No	555	16	17.6	Def	17.6	16.6	Def	U
17/12/2014	12.5mm	2	528	Yes	495	16	16.4	Def	18.5	14.9	Def	D
17/12/2014	12.5mm	2	542	Yes	410	16	14.4	Def	19.0	12.8	Def	D
17/12/2014	12.5mm	2	556	Yes	545	16	17.4	Def	18.7	15.8	Def	D
17/12/2014	12.5mm	2	570	Yes	335	16	12.5	Def	18.5	11.2	Not	D
17/12/2014	12.5mm	2	584	Yes	345	16	12.7	Def	19.5	11.0	Not	D
17/12/2014	12.5mm	2	598	No	520	16	16.9	Def	16.6	16.5	Def	U

Date	Trial	Rep	Tag ID	Acoustic data	SL (mm)	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U
17/12/2014	12.5mm	2	612	No	465	16	15.7	Def	18.0	14.5	Def	U
17/12/2014	12.5mm	2	626	Yes	483	16	16.1	Def	18.3	14.7	Def	D
17/12/2014	12.5mm	2	640	No	369	16	13.4	Def	18.9	11.9	Not	U
17/12/2014	12.5mm	2	654	No	360	16	13.1	Def	18.1	12.0	Not	U
19/12/2014	12.5mm	3	500	Yes	381	16	13.7	Def	21.4	11.1	Not	D
19/12/2014	12.5mm	3	514	Yes	496	16	16.4	Def	17.6	15.5	Def	D
19/12/2014	12.5mm	3	542	Yes	527	16	17.1	Def	17.5	16.2	Def	D
19/12/2014	12.5mm	3	598	No	378	16	13.6	Def	18.8	12.2	Not	U
19/12/2014	12.5mm	3	612	No	366	16	13.3	Def	18.2	12.1	Not	U
19/12/2014	12.5mm	3	626	Yes	483	16	16.1	Def	18.3	14.7	Def	D
19/12/2014	12.5mm	4	514	Yes	496	16	16.4	Def	17.6	15.5	Def	D
19/12/2014	12.5mm	4	542	Yes	527	16	17.1	Def	17.5	16.2	Def	D
19/12/2014	12.5mm	4	626	Yes	483	16	16.1	Def	18.3	14.7	Def	D
21/12/2014	12.5mm	5	528	No	464	16	15.7	Def	16.1	15.6	Def	U
21/12/2014	12.5mm	5	556	Yes	427	16	14.8	Def	20.0	12.7	Def	D
21/12/2014	12.5mm	5	570	Yes	476	16	16.0	Def	17.3	15.2	Def	D
21/12/2014	12.5mm	5	584	Yes	344	16	12.7	Def	17.8	11.8	Not	D
21/12/2014	12.5mm	5	564	No	399	16	14.2	Def	19.7	12.2	Not	U
21/12/2014	12.5mm	5	640	Yes	369	16	13.4	Def	18.9	11.9	Not	D
21/12/2014	12.5mm	6	556	No	427	16	14.8	Def	20.0	12.7	Def	U
21/12/2014	12.5mm	6	570	Yes	476	16	16.0	Def	17.3	15.2	Def	D
21/12/2014	12.5mm	6	584	Yes	344	16	12.7	Def	17.8	11.8	Not	D
21/12/2014	12.5mm	6	564	No	399	16	14.2	Def	19.7	12.2	Not	U

Date	Trial	Rep	Tag ID	Acoustic data	SL (mm)	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U
21/12/2014	12.5mm	6	640	Yes	369	16	13.4	Def	18.9	11.9	Not	D
01/12/2014	Control	1	500	Yes	455	16	15.5		16.2	15.4		
01/12/2014	Control	1	514	Yes	399	16	14.2		19.4	12.4		
01/12/2014	Control	1	528	Yes	391	16	14.0		18.6	12.6		
01/12/2014	Control	1	542	Yes	523	16	17.0		14.9	17.7		
01/12/2014	Control	1	556	Yes	355	16	13.0		17.0	12.5		
01/12/2014	Control	1	570	Yes	344	16	12.7		17.1	12.1		
22/12/2014	Control	2	500	Yes	531	16	17.2		15.5	17.5		
22/12/2014	Control	2	514	Yes	522	16	17.0		17.1	16.3		
22/12/2014	Control	2	542	Yes	366	16	13.3		17.3	12.6		
22/12/2014	Control	2	556	No	338	16	12.6		17.6	11.7		
22/12/2014	Control	2	570	Yes	339	16	12.6		16.7	12.2		
22/12/2014	Control	2	584	Yes	347	16	12.8		17.3	12.1		
22/12/2014	Control	3	500	Yes	531	16	17.2		15.5	17.5		
22/12/2014	Control	3	514	Yes	522	16	17.0		17.1	16.3		
22/12/2014	Control	3	542	Yes	366	16	13.3		17.3	12.6		
22/12/2014	Control	3	570	Yes	339	16	12.6		16.7	12.2		
22/12/2014	Control	3	584	Yes	347	16	12.8		17.3	12.1		
23/12/2014	Control	4	500	No	507	16	16.6		26.3	13.5		
23/12/2014	Control	4	514	Yes	476	16	16.0		29.5	11.9		
23/12/2014	Control	4	528	Yes	482	16	16.1		26.8	12.8		
23/12/2014	Control	4	542	No	451	16	15.4		25.9	12.5		
23/12/2014	Control	4	737	Yes	453	16	15.4		26.7	12.3		

Date	Trial	Rep	Tag ID	Acoustic data	SL (mm)	Fineness ratio (Turnpenny and O'Keeffe 2005)	Calculated mesh size (mm)	Deflection predicted by published fineness ratio	Fineness ratio calculated for each fish	Calculated mesh size (mm)	Deflection predicted by calculated fineness ratio	E, I, NI, D, U
23/12/2014	Control	4	770	Yes	506	16	16.6		25.7	13.7		
23/12/2014	Control	5	500	No	507	16	16.6		26.3	13.5		
23/12/2014	Control	5	514	Yes	476	16	16.0		29.5	11.9		
23/12/2014	Control	5	528	Yes	482	16	16.1		26.8	12.8		
23/12/2014	Control	5	542	No	451	16	15.4		25.9	12.5		
23/12/2014	Control	5	737	Yes	453	16	15.4		26.7	12.3		
23/12/2014	Control	5	770	Yes	506	16	16.6		25.7	13.7		

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