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# Castleford Mill Hydro Power Proposal
# River Aire -Fisheries Assessment

**Client: Yorkshire Hydro/Mann Power Consulting**

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## Executive Summary

The installation of a series of Archimedean screw turbines, taking up to 30 cumecs of water in total is planned for Castleford Mill weir. This report was commissioned to investigate the potential impacts on fisheries of such an installation, with particular reference to the impacts on coarse fish spawning and juvenile habitat.

A survey was conducted to assess the hydrology and morphology of the weir pool and this data was related to published literature on the habitat preferences of coarse fish and how this might change as a result of the installation of the hydroturbines. In addition, assessments were made as to the likely impact that the installation of the hydroturbines would have on the general hydrology and fisheries ecology of the weir pool.

The results of the survey showed that much of the weir pool is deep, with a substrate comprised of large boulders, stones and pebbles in many parts. As such, the quantity of suitable habitat available for rheophilic/lithophilic spawning species is limited. Similarly, the depth of the water and lack of many emergent macrophytes limits the quantity of juvenile habitat available in the main body of the weir pool.

Alterations in the hydrology and morphology of the weir pool as a result of the installation of the hydroturbines are unlikely to have an impact on the quantity and quality of spawning and juvenile coarse fish habitat available.

The increase in dissolved oxygen concentrations downstream of the weir as a result of re-aeration as water passes over the weir may be affected by the turbine installation. As a result of changes in the weir morphology, it is predicted that the turbines may cause a slight decrease in the degree of re-aeration, relative to the current situation. Further work or monitoring is recommended if this issue is judged to be sufficiently important.

Due to alterations in the hydrology of the weir pool, the attraction flow from the current fish pass will be reduced if the turbines are installed. It is recommended that a second fish pass be placed alongside the turbines to mitigate for this effect. A multi species super active baffle Larinier would be the most suitable to provide passage for weaker swimming coarse fish as well as migratory salmonids.

If this second fish pass is installed, a Hands Off Flow of 8 cumecs is potentially possible as this would still ensure a sufficient flow of water through both fish passes as well as leaving a ‘sweetening’ flow passing over the weir face.

# Contents

# 1. Introduction

## 1.1 Castleford Mill and weir pool

The site discussed in the report is on the River Aire, in Yorkshire, Northern England. The River Aire is a large tributary of the River Ouse and flows for approximately 70 miles from its source at Malham Tarn in the Yorkshire Dales to its confluence with the River Ouse at Airmyn. A large section of the river is canalised and forms a canal route between Leeds and the Humber.

There has been a major change in the quality of the river from a fisheries perspective in the last few decades. As little as 20 years ago, much of the river was fishless due to inputs of both sewage and industrial effluent. A dramatic improvement in the quality of the effluent discharged into the river has seen fish stocks return to a healthy level and even the return of migrating salmonids to the river.

The specific site discussed in this report is the weir at Castleford, near Leeds. Yorkshire Hydro LLP are proposing to install three large Archimedean hydroturbines at the site, which will change the flow dynamics of the weir-pool. A view of the site from the sluices where the turbines are proposed to be installed is given in figure 1a. An annotated aerial view of the site is given in figure 1b. This report was commissioned to assess the potential impacts on fisheries of the scheme. A site visit was undertaken on 01/07/2009 during which the authors met with Neil Trudgill (EA Fisheries Technical Specialist) to discuss the issues and main areas of concern.

**Figure 1a: View from the sluices across the weir apron**

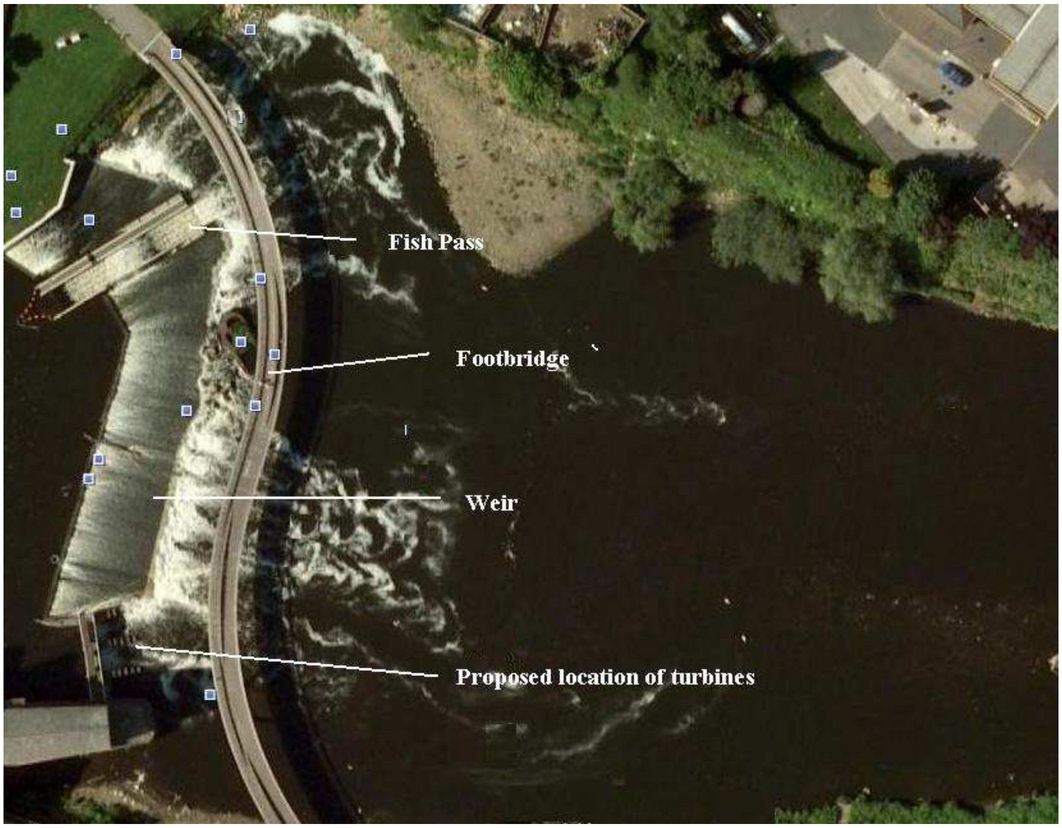


**Figure 1b: aerial photograph of the weir pool at Castleford. The location of the proposed turbine installation is given**

### 1.2 The Archimedean Screw

The Archimedean Screw Turbine is a hydraulic screw turbine that operates at low rotational speeds of 22-30 rpm. It is generally considered to be fish friendly and indeed has been used in the US as a fish pump (running in the reverse direction from when acting as a turbine) to move fish.

Water enters at the top (through the sluice) and drives the screw as it moves down the trough towards river level at approximately 1 m/s. A gearbox steps up the speed and drives a generator producing electricity. These turbines are typically between 1.5-4.0 m in diameter and are particularly well suited to low head sites of up to 8 m. The length of the screw is determined by the head height (vertical drop) of water. A diagrammatic representation of this type of turbine is given in figure 2.

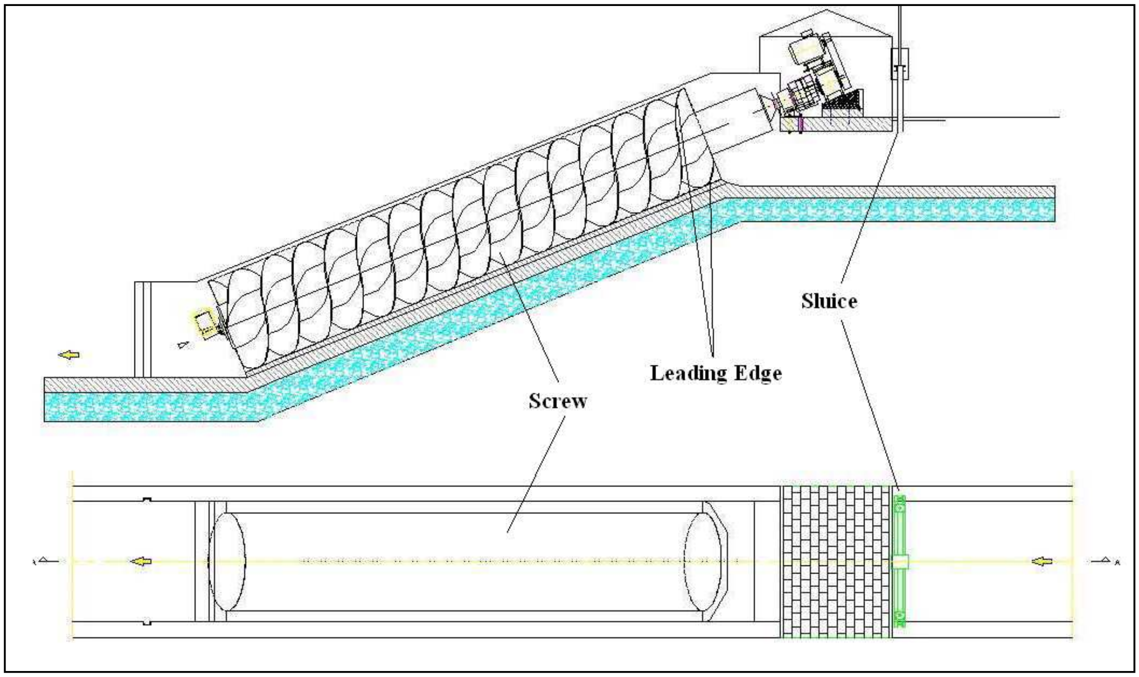


**Figure 2: Diagram of an Archimedes hydraulic turbine, shown from the side (top) and overhead (bottom)**

Previous studies have shown minimal effects on both salmonids (salmon smolts, kelts, trout) passing through this type of turbine (Fishtek Consulting, 2007; Fishtek Consulting, 2008) and also on coarse fish species, including chub, roach, barbel, pike, perch and eels. (Spah, 2001, Vis Advies 2007, Fishtek Consulting, 2009).

Assessment of the impact of an Archimedes Screw Turbine on salmonids (Fishtek, 2007) showed that in over 1000 passages of fish through the turbine, across the full range of operating speeds up to a maximum of 31 rpm, there was no damage to trout ranging in size from 8 to 63 cm. Smolts passing through the turbine naturally also suffered minimal damage with light, recoverable scale loss observed in a few individuals.

### 1.3 Flow at site

Information about the flows at the site are available from the gauging stations at Lemonroyd and Methley – the flow at Castleford weir being equal to the combination of these two flows. The flow duration curve for the site is given in figure 3.

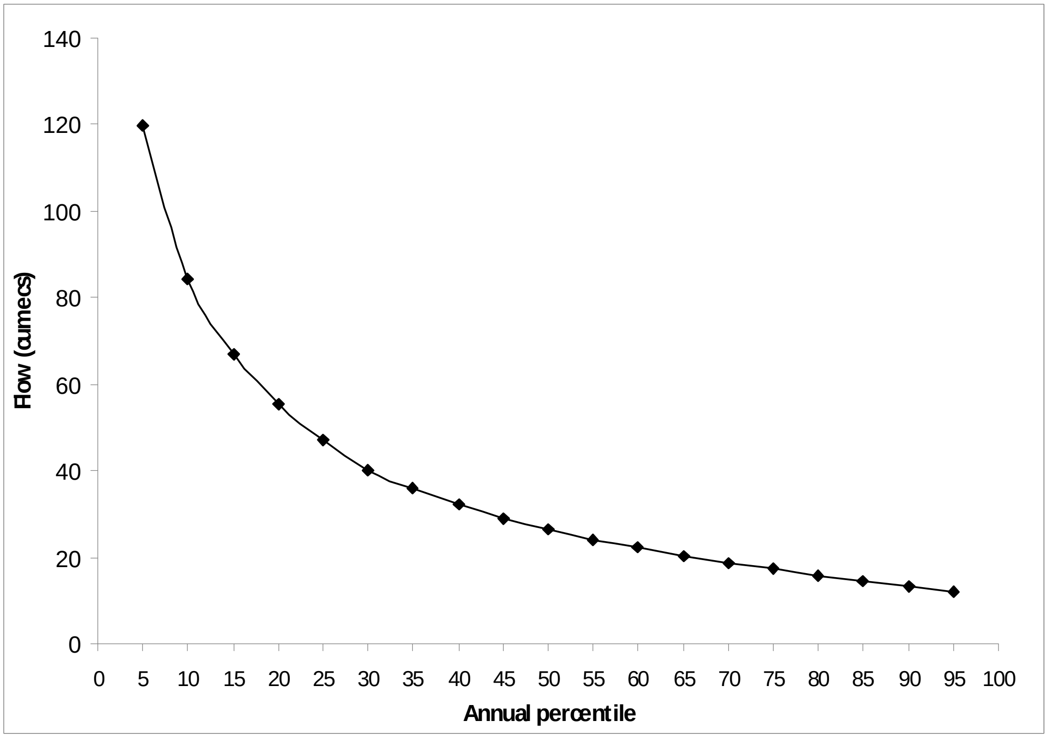


**Figure 3: flow duration curve for the River Aire at Castleford weir**

The River Aire at Castleford is a relatively large river, with a Q95 value of 12.11 cumecs and Q20 value of 55.54 cumecs. The flow characteristics of the river are typical of those of a large, lowland river. Figure 4 is a plot of the Mean Daily Flows (MDFs) for 2007 and 2008 at Castleford weir.

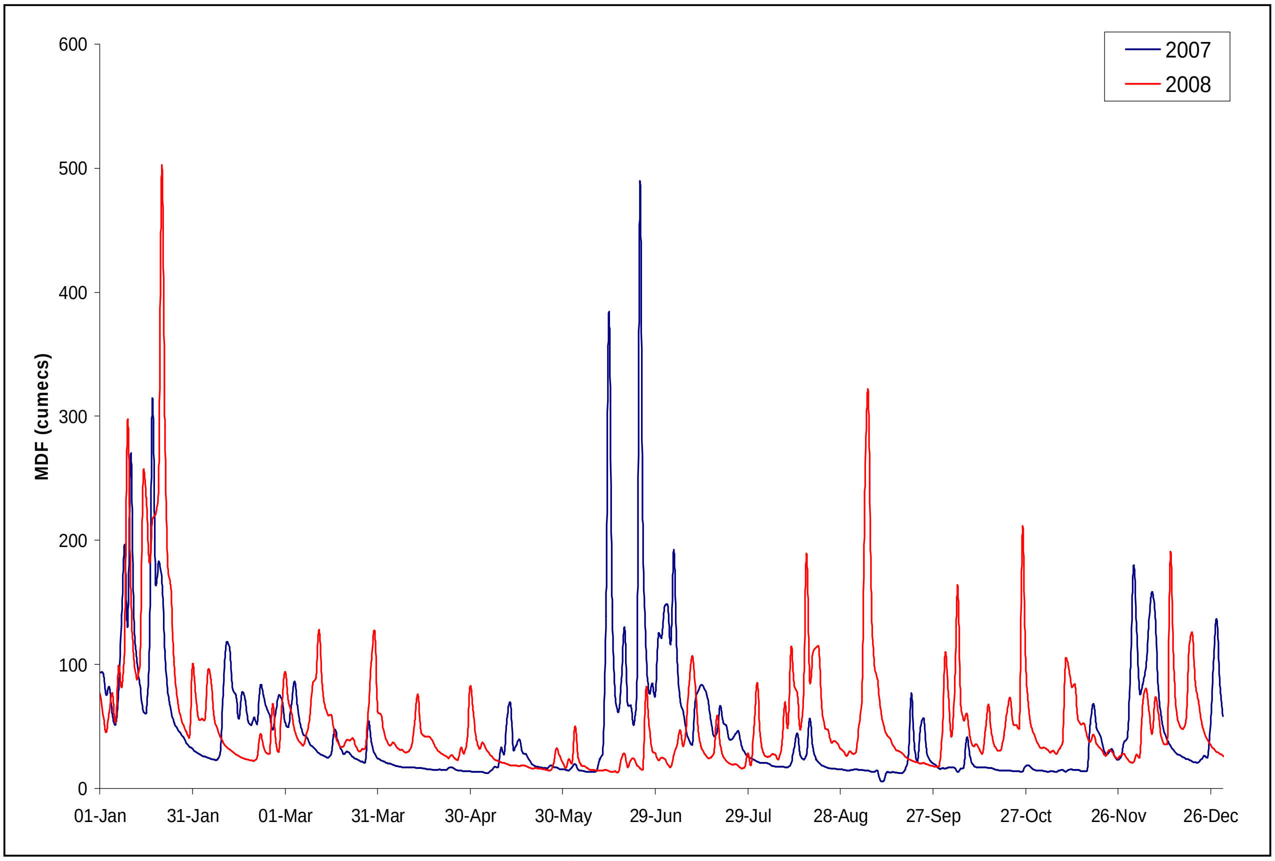


**Figure 4: MDF in the River Aire at Castleford weir in 2007 and 2008**

**1.4 Fisheries ecology within the River Aire and general fisheries ecology of relevance to the proposed development**

Fish populations within the River Aire are primarily comprised of coarse fish of a number of species. Previous electro-fishing surveys by the Environment Agency within the weir pool (conducted for 300m along the bank and then across the face of the weir and pool) have found the following species: bleak, chub, dace, perch, roach, tench, pike, gudgeon, minnow, stoneloach, three-spined stickleback and brown trout. The number of individuals of each of the major species is given in figure 5.

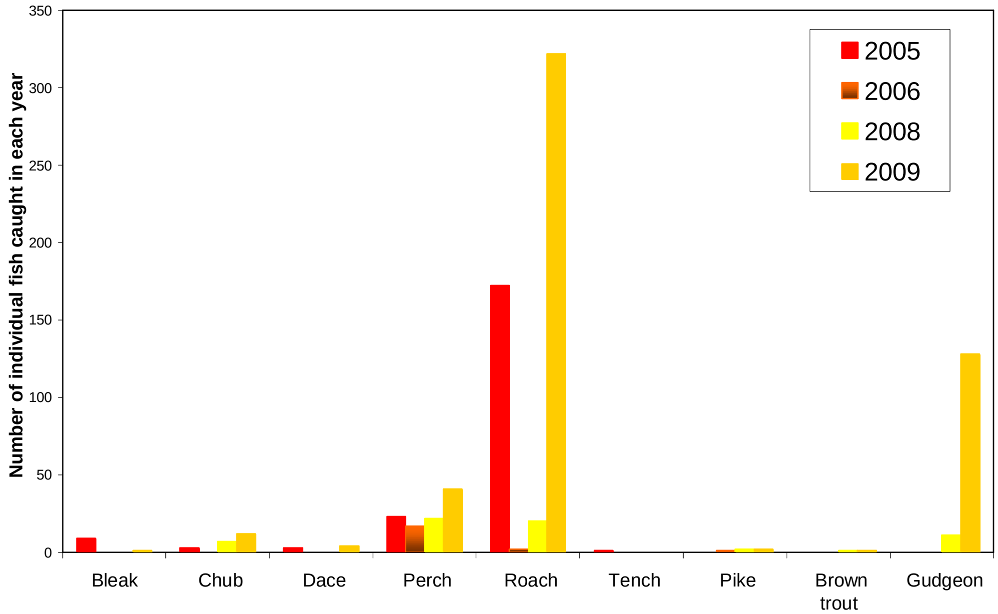


**Figure 5: number of fish of each species caught in the weir pool at Castleford weir and in the river immediately downstream, in the years 2005, 2006, 2008 and 2009**

From the graph it is clear that there are a number of species present within the River Aire at Castleford. In particular, the results from the electro-fishing surveys show high numbers of perch, roach and gudgeon were caught, particularly in 2009.

The overall number of fish caught, however, is lower than might be expected. Weir pools are important, heterogeneous habitats within modified river systems, where much of the natural heterogeneity has been lost as a result of anthropogenic activity. As such, they often contain substantial populations of coarse fish. It is possible that the hydrology of the weir pool limited the efficiency of the electro-fishing equipment, possibly due to deep sections of the weir pool.

Previous meetings with the Environment Agency highlighted two main areas of concern with regards to the potential impact of the hydroturbines. These are:

- Changes in spawning habitat as a result of alterations in the hydrology of the weir pool
- Changes in juvenile fish habitat as a result of alterations in the hydrology of the weir pool.

It is therefore important to consider the typical spawning and juvenile habitats used by the fish species found in Castleford weir (see figure 5). Fish populations within the River Aire at Castleford are comprised almost totally of coarse fish. As such, there are two principle spawning habitat types that need to be considered: rheophilic/lithophilic and phytophilic (Mann, 1996).

Rheophilic fish species typical to lowland coarse fish populations in the UK include barbel (*Barbus barbus*), chub (*Leuciscus cephalus*) and dace (*Leuciscus leuciscus*). These species utilise riverine areas with a relatively rapid flow, shallow depth and gravel substrate to spawn (Kennedy, 1969; Hancock *et al*, 1976; Lucas and Batley, 1996; Caffrey *et al*, 2008).

In contrast phytophilic species (which include roach (*Rutilus rutilus*), perch (*Perca fluviatilis*), pike (*Esox lucius*) and carp (*Cyprinus carpio*)) utilise in-stream vegetation or woody debris as the preferred spawning substrate (Gillet and Dubois, 1995; Mills 1981; Clark, 1950; McCarreher and Thomas, 1972).

Spawning sites for these species are often in shallow areas, whereas some species such as bream (*Abrama bramis*) have been observed to spawn in deeper areas of river channels (Interesova *et al*, 2009). However, no bream have been caught in the fish surveys at Castleford weir in the past few years.

Consultation with the Environment Agency prior to the production of this report indicated concerns over the impact that alterations in the hydrology of the weir pool may have on the abundance and quality of rheophilic/lithophilic spawning habitat, as such habitat (fast-flowing over a gravel bed) is relatively limited in the River Aire.

There has been a substantial amount of work carried out investigating the particular small-scale habitat (microhabitat) preferences of juvenile coarse fish. The habitat used by particular juvenile species corresponds with the spawning habitat of those species (Copp, 1992a). The juveniles of species that spawn in shallow, lotic, stony-pebbly channels (chub and dace for example) are found in this habitat and the juveniles of plant spawners (such as roach and perch) are found in close association with submerged macrophytes.

Work on the use of slow, lentic sites has identified the importance of such areas for juvenile coarse fish of a variety of species, including roach, chub, bream and dace (Nunn *et al*, 2007). Other studies have found that juvenile coarse fish are often found in close association with submerged macrophytes or ligneous material, in generally shallow water depths (Copp, 1992b; Copp, 1997; Baras and Nindaba, 1999; Jurajda, 1999).

### 1.5 Specific information about the proposed hydropower development at Castleford weir

Yorkshire Hydro are proposing to install 3 large Archimedean Screws, one in each of three sluice channels adjacent to the mill building. Each turbine would be 4 m in diameter and draw 10 $m^3$/s of water from above the weir, discharging directly into the weir pool. The total maximum abstraction of 30 $m^3$/s would generate up to 442 kW of electricity, with a net carbon saving of 778 tonnes a year, based on 0.43 tonnes per MWh and a capacity factor of 48%. The gross operating head is 2.4 m.

### 1.6 Aims of the project

The work detailed within this report was commissioned to investigate the potential impact of the proposed hydropower installation at Castleford weir on the fish populations within the River Aire.

The results and recommendations contained in the report essentially address two areas:

1. General impacts of Archimedes hydroturbines and extrapolation of general assessment techniques to the site at Castleford weir.
2. The potential impact of the hydroturbine on the availability of spawning habitat (particularly rheophilic/lithophilic spawning habitat) and juvenile fish habitat within the immediate vicinity of the weir pool and proposed hydropower installation.

# 2. Approach and Methodology

## 2.1 Assessment of the general impacts of a hydropower installation at Castleford weir

In order to determine the potential impact of a hydropower installation at Castleford weir, several different factors were considered and examined, with reference to the published literature and previous work conducted in the field:

- Impact on any fish passing through the turbine itself as a result of downstream migration or downstream drift
- The proportion of fish entrained and passing down the turbine. This is a function of the hydrological profile of the turbine channel and the proportion of water passing through the turbine. Without detailed hydrological measurements of the turbine channel, the calculations give a crude idea of the proportion of total river flow passing through the turbine throughout the year. It is then assumed that an equal proportion of downstream migrating fish will be entrained through the turbine. Entrainment was calculated using two HOFs, Q95 (equal to approximately 12 cumecs) and 8 cumecs.
- Impact of the turbine installation on the general hydrology of the weir pool
- Impact of the turbine installation on dissolved oxygen concentrations within the weir pool. This was assessed using a theoretical approach based on available published literature.

## 2.2 Assessment of specific impacts on coarse fish spawning and juvenile habitat

Specific measurements were taken at Castleford weir to enable the determination of the current quality and extent of rheophilic/lithophilic spawning (and therefore by extension, juvenile habitat) within Castleford weir pool. Transects were taken down the weir pool, parallel to the downstream water flow, every 10m across the weir pool. Each transect was approximately 70 m long. A schematic diagram of the way in which the transects were conducted is given in figure 6. The GPS co-ordinate of each sampling point was taken so that they could be accurately mapped within the weir-pool.

Hydrological and morphological data was collected at points 7m apart along the transect line. At each point, the following data was collected:

- Water velocity, measured in m/s using a Valeport 801 Flow Meter.
- Water depth, measured in m
- A sample of gravel from the river bed, obtained using a remote grab.

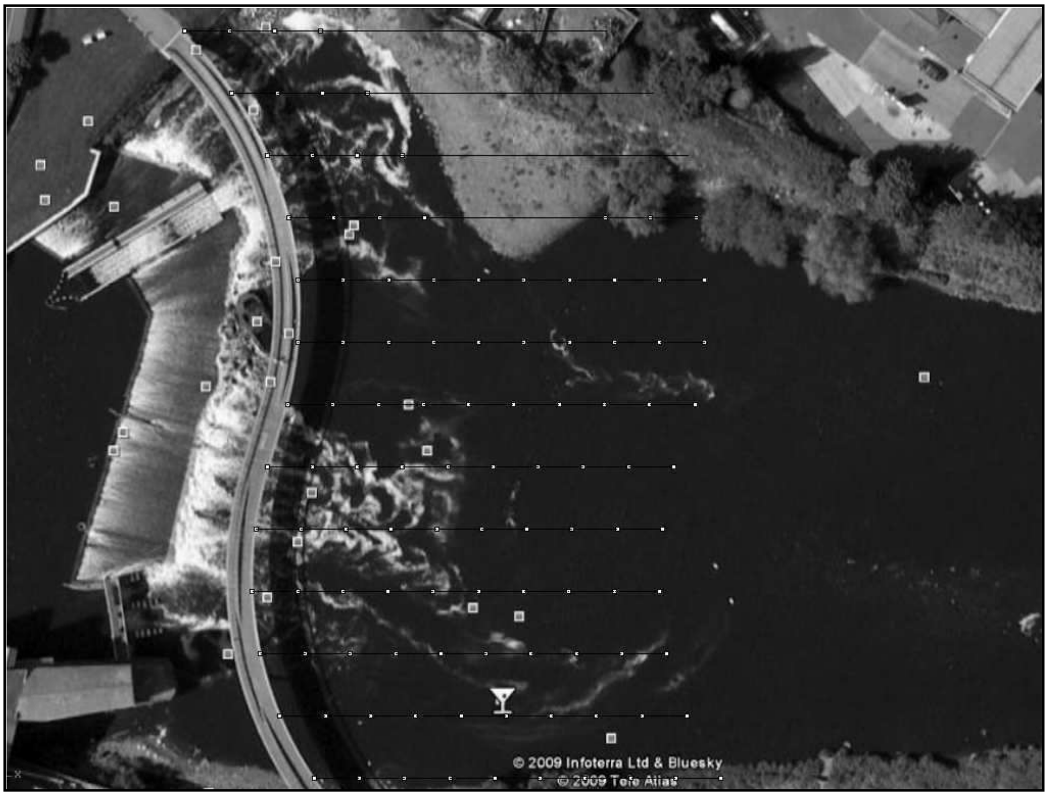


**Figure 6: approximate location of the transects and sampling points performed within Castleford weir pool**

The gravel samples obtained were later analysed and the proportion (by weight) of different class sizes of gravel in each sample was calculated. This was done by using graded sieves to separate the different size fractions. The different size classes used were:

- < 2mm (fines – essentially fine sand and silt)
- 2-5mm (coarse sand and fine gravel)
- 5-10mm (pea gravel)
- 10-20mm (gravel)
- 20-40mm (large gravel and pebbles)
- > 40mm (cobbles, rocks and large stones)

In order to quantify the quality of spawning habitat at each sampling point, an index was developed, based on the published literature on the spawning habitat preferences of the rheophilic and lithophilic species found in Castleford weir pool (chub and dace). This index utilised the three measurements of water velocity, water depth and the nature of the substrate.

The quality of each of these three measurements was classified by relating it to the following published habitat preferences of such species, whilst adopting a precautionary approach throughout:

- Water velocities, generally between 0.15 and 0.75 m/s, although successful spawning in still water has been observed (Mills, 1981; Arlinghaus and Wolter, 2003). *Acceptable flow velocities were therefore considered to be a flow between 0 and 0.75 m/s.*

- Water depths, generally between 0.1 and 0.5 m, although successful spawning of chub at depths up to 1.28 m has been observed (Kennedy, 1969; Mills, 1981; Arlinghaus and Wolter, 2003). *Acceptable water depths were therefore considered to be a depth between 0.1 and 1.3 m.*
- Substrates are generally described as being comprised of gravel and coarse sand up to a size of around 40mm (with a minimum reported gravel size for chub of 5mm (Cowx and Welcomme, 1998), with egg survival decreasing as the percentage of fine sand and silt within the substrate increases (Kennedy, 1969; Mills, 1981; Arlinghaus and Wolter, 2003). Gravel sizes < 2mm have previously been shown to reduced the dissolved oxygen concentration (Meyer *et al*, 2008) and information in the salmonid literature has shown that substrates with > 30% of fine particles significantly decrease egg survival (Kondolff, 2000). *Acceptable substrates were therefore considered to have not greater than 30% by weight of fines <2mm or >50% by weight of material > 40mm.*

For each sampling point, the velocity, depth and substrate were classified as either acceptable or unacceptable for spawning. A classification of 'acceptable' was given a value of 1 and a classification of 'unacceptable' a value of -1.

The index of spawning quality for each point was then calculated according to:

$I = V+D+S$

*Where: V = the velocity value, D = the depth value and S = the substrate value.*

By definition, the index can have one of four values: -3, -1, 1 or 3. These four values were then classified as the following spawning site quality:

-3 = Very poor
-1 = Poor
1 = Marginal
3 = Good

As a result, each of the sampling points within the weir pool was able to be given a quantifiable assessment as to the quality of the spawning habitat at that point. From this, the extent of suitable spawning habitat throughout the weir pool was then assessed.

# 3. Results and Discussion

## 3.1 Potential impacts on fish resulting from downstream passage through the turbine

Hydraulic screw turbines are generally considered to be very fish friendly, having a slow rotational speed of 22-30 rpm and no rapid pressure changes or hydraulic shear forces. After passing the leading edge, fish remain in the same chamber of water until released at the outflow.

*River Dart Trials*

Previous work has been done aimed at determining the extent of damage caused by passage through a screw turbine on the River Dart in Devon. This study passed brown trout, rainbow trout, salmon and eels through the turbine and found that fish up to 98 cm (7.4 kg) passed through the turbine with no damage at all.

*River Derwent Trials*

Extensive trials at Howsham Mill on the River Derwent involved a wide range of coarse fish species and sizes, as shown in Table 1. No damage was caused by passage through the turbine. The potential delay to downstream migration caused by fish unwilling to pass through the screw was also assessed by determining any preference for the bywash vs the turbine. It was found that fish naturally passing downstream and those experimentally introduced into the intake area did not show an active preference for either route, but passed through the by wash in proportion to the flow split, suggesting that passage through the bywash was by passive downstream drift (see table 2).

A number of large barbel and chub electro-fished from the river and introduced above the intake did not pass down either the turbine or bywash but remained in the intake area.

**Table 1: Species used in the study, including the maximum length for each species**

| Species | Number of fish used | Maximum Length (cm) |
|---|---|---|
| **Pike (*Essox lucius*)** | **53** | **77** |
| **Barbel *(Barbus barbus)*** | **10** | **61** |
| **Chub *(Leuciscus cephalus)*** | **52** | **48** |
| **Perch *(Perca fluviatilis)*** | **14** | **30** |
| **Trout *(Salmo trutta)*** | **8** | **34** |
| **Grayling *(Thymallus thymallus)*** | **11** | **28** |
| **Roach *(Rutilus rutilus)*** | **14** | **22** |
| **R.Lamprey *(Lampetra)*** | **10** | **32** |
| **Salmon *(Salmon salar)*** | **1** | **14** |
| **Bullhead *(Cottus gobio)*** | **3** | **8** |
| **Gudgeon *(Gobio gobio)*** | **4** | **15** |
| **Ruffe *(Gymnocephalus cernua)*** | **1** | **11** |
| **Minnow *(Phoxinus phoxinus)*** | **6** | **9** |
| **Eel *(Anguila anguila)*** | **1** | **46** |

**Table 2: Results from chi-squared tests on the raw numbers of fish passing down the turbine or by-wash or remaining in the intake area. Chi-squared critical values (2 degrees of freedom): 5.99 at α = 0.05, 9.21 at α = 0.01, 13.82 at α = 0.001**

| Species | $X^2$ value | Significant? | Route favoured |
|---|---|---|---|
| **Pike (*Essox lucius*)** | **69.5** | **Yes (p<0.001)** | **Turbine** |
| **Chub (*Leuciscus cephalus*)** | **15.16** | **Yes (p<0.001)** | **Turbine** |
| **Barbel *(Barbus barbus)*** | **6** | **Yes (p<0.05)** | **Remain in intake** |
| **Perch *(Perca fluviatilis)*** | **22.4** | **Yes (p<0.001)** | **Turbine** |
| **Trout *(Salmo trutta)*** | **3.71** | **No** | **--** |
| **Roach *(Rutilus rutilus)*** | **26** | **Yes (p<0.001)** | **Turbine** |
| **Grayling *(Thymallus thymallus)*** | **22** | **Yes (p<0.001)** | **Turbine** |
| **Lamprey *(Lampetra)*** | **5.2** | **No** | **--** |

*Leading edge Study*

Large screw turbines such as those proposed for Castleford have tip speeds of up to 4.8m/s, slightly higher than the 4 m/s stated as the threshold injury level for a turbine blade (Turnpenny, 2003). Assessment of three leading edge profiles, 8mm steel edge, hard rubber and compressible bumper, found that the unprotected steel edge did not give adequate protection. Hard rubber extrusions gave reasonable protection on smaller screw turbines, < 2.5 m diameter with lower tip speeds. Compressible rubber bumpers were found to give excellent protection to the largest fish likely to pass through and reduced the impact of a direct strike to well within the damage threshold of 2.5 $kg/cm^2$ (Fishtek Consulting, 2009). The cushioning effect of the compressible bumper and strike force relative to the damage threshold for a 6.5Kg fish is shown in figure 7.

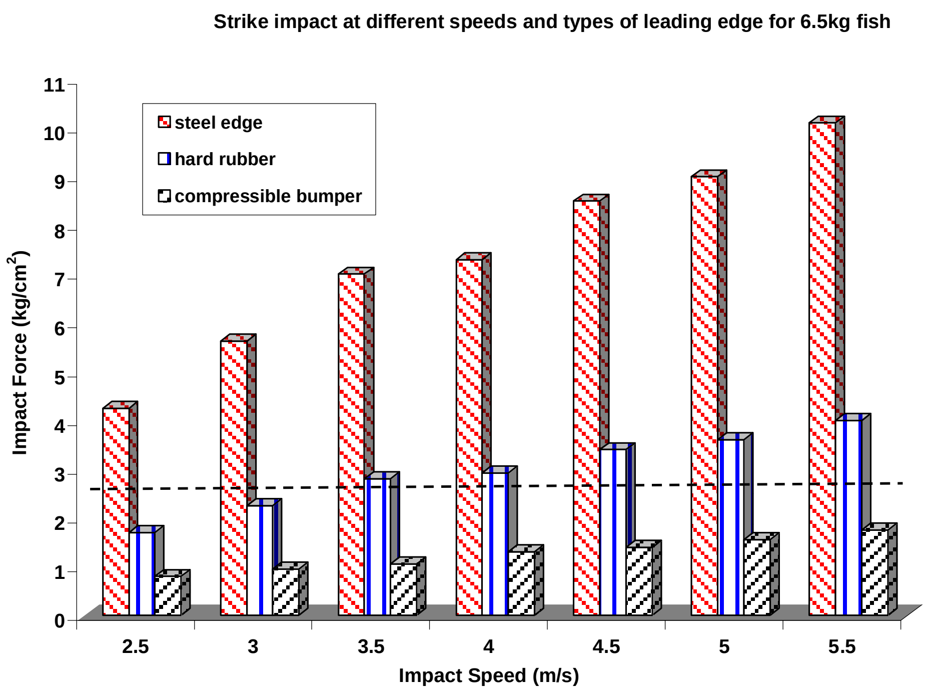


**Figure 7: the strike impact force exerted by different leading edge types on a 6.5 kg fish**

### 3.2 Proportion of fish entrained by the turbine

The proportion of fish entrained by the turbine and passing down it was calculated using the flow data for 2007 and 2008. The proportion likely to be entrained each day (under a condition of neutral flow drift) was then converted to an average for each month for the flow data for 2007 and 2008. This was done using two HOFs, either Q95 or 8 cumecs. The results are given in table 3.

**Table 3: the average proportion of fish moving downstream likely to be entrained through the turbine at different HOFs, in each month and under the river flows seen in 2007 and 2008**

| | ***HOF of Q95 (12.11 cumecs)*** | | | ***HOF of 8 cumecs*** | |
|---|---|---|---|---|---|
| | *Flow for 2007* | *Flow for 2008* | | *Flow for 2007* | *Flow for 2008* |
| *January* | 38.1 % | 31.9 % | | 39.8 % | 32.1 % |
| *February* | 45.7 % | 51.2 % | | 52.4 % | 62.7 % |
| *March* | 52.6 % | 31.8 % | | 65.3 % | 42.3 % |
| *April* | 19.5 % | 36.3 % | | 51.9 % | 41.1 % |
| *May* | 26.9 % | 34.0 % | | 54.5 % | 40.3 % |
| *June* | 24.7 % | 27.2 % | | 39.5 % | 45.5 % |
| *July* | 47.1 % | 44.2 % | | 51.1 % | 48.5 % |
| *August* | 32.3 % | 47.7 % | | 58.5 % | 54.0 % |
| *September* | 18.5 % | 41.7 % | | 46.0 % | 43.8 % |
| *October* | 17.3 % | 52.0 % | | 50.3 % | 53.3 % |
| *November* | 27.5 % | 32.4 % | | 54.1 % | 34.5 % |
| *December* | 40.7 % | 49.2 % | | 50.1 % | 53.6 % |

As can be seen from the results, the proportion of fish passing through the turbine during downstream movement will change dramatically as a result of daily and annual changes in river flow. The proportion of fish passing down the turbine changes depending on whether the HOF is set at Q95 or 8 cumecs and as would be predicted a lower HOF results in more fish passing down the turbine.

### 3.3 Changes in oxygen levels as a result of the turbine installation

There is currently a paucity of literature concerning the impacts of hydroturbines on dissolved oxygen concentrations. What literature is available is concerned with techniques used to increase the oxygen concentration in water leaving reservoirs or dams, in which oxygen concentrations may be low (Cada *et al*, 1983; Cushman, 1985).

Work has, however, been conducted previously investigating the degree to which dams and weirs may re-oxygenate water flowing over them. In sluggish streams, more oxygen may be absorbed by water flowing over a weir or dam than in a long reach between dams.

It is possible to calculate the reaeration of water passing over a dam or weir using the following formulae (taken from Lee and Lin, 2000):

$$r = 1 + 0.11qb(1 + 0.046T)h$$

Where: $r$ = dissolved oxygen deficit ratio at temperature T
$q$ = water quality correction factor
$b$ = weir correction factor
$T$ = water temperature, in $^{o}$C
$h$ = height through which the water falls, in ft

The deficit dissolved oxygen ratio is defined by:

$$r = (C_s - C_A)/(C_s - C_B) = D_A/D_B$$

Where: $C_A$ = dissolved oxygen concentration upstream of the dam, in mg/L
$C_B$ = dissolved oxygen concentration downstream of the dam, in mg/L
$C_s$ = dissolved oxygen saturation concentration, in mg/L
$D_A$ = dissolved oxygen deficit upstream of the dam, mg/L
$D_B$ = dissolved oxygen deficit downstream of the dam, mg/L

Values of $q$ are assigned using three generalised classifications of water. They are $q$ = 1.25 for clean and slightly polluted water; $q$ = 1.0 for moderately polluted water; and $q$ = 0.8 for grossly polluted water. A slightly polluted water is one in which there is no noticeable deterioration of water quality as a result of sewage discharges; a moderately polluted stream is one which receives significant quantities of sewage effluent and a grossly polluted stream is one in which noxious conditions exist.

The value of $b$ is obtained by taking the geometrical shape of the dam into consideration, as this influences the extent of re-aeration of water passing over the weir. Values of $b$ have been calculated for various spillway types as follows:

| **Spillway type** | ***b*** |
|---|---|
| Free | 1.0 |
| Step | 1.3 |
| Slope (ogee) | 0.58 |
| Sloping channel | 0.17 |

In the case of the installation of the hydroturbine, the unknown is the degree to which $b$ will be changed as a result of the passage of a proportion of water flowing downstream through the turbine, rather than passing over the weir.

An estimation of this can be obtained using the formulae above. For the current situation at Castleford weir (spillway type = slope, so $b$ = 0.58 and $h$ = 8ft, $q$ = 1.0) in summer conditions ($T$ = 20°C) we can use the formula to obtain $r$:

$$r = 1 + 0.11qb(1 + 0.046T)h$$

$$\text{Therefore: } r = 1 + 0.11*1.0*0.58(1 + 0.046*20)*8 = 1.98$$

The dissolved oxygen saturation concentration ($C_s$) at 20°C under typical atmospheric pressure is around 9 mg/L. If the dissolved oxygen concentration upstream of the weir is assumed to be 5mg/L, we can calculate the dissolved oxygen concentration downstream of the weir as follows:

$$r = (C_s - C_A)/(C_s - C_B)$$

$$\text{Therefore: } C_B = C_s - (C_s\text{-}C_A)/r = 9 - (9\text{-}4)/1.98 = \mathbf{6.98\ mg/L}$$

Therefore, using the parameters as defined above, water passing over the weir at an oxygen concentration of 5 mg/L will be re-aerated such that the oxygen concentration below the weir increases to 6.98 mg/L.

If it is assumed (taking a precautionary approach) that the turbine will reduce the value of $b$ to that of a sloping channel, 0.17, it is possible to recalculate the degree to which the installation of the hydroturbine will alter the dissolved oxygen concentration downstream of the weir, at each point on the Flow Duration Curve and at a variety of HOFs. Under each scenario, the split in flow has been calculated between the turbine and weir and the increase in oxygen downstream due to each calculated. These are then averaged to produce the total oxygen concentration downstream of the weir. The results are presented in table 4.

**Table 4: theoretical, predicted oxygen concentrations (in mg/L) downstream of Castleford weir (assuming a temperature of 20°C and upstream oxygen concentration of 5 mg/L) at a range of river flows and with three different turbine HOFs and a maximum turbine take of 30 cumecs**

| Flow Duration | Hands Off Flow | | |
|---|---|---|---|
| | Q95 | 10 cumecs | 8 cumecs |
| *Q5* | 6.71 | 6.71 | 6.71 |
| *Q10* | 6.59 | 6.59 | 6.59 |
| *Q15* | 6.49 | 6.49 | 6.49 |
| *Q20* | 6.39 | 6.39 | 6.39 |
| *Q25* | 6.29 | 6.29 | 6.29 |
| *Q30* | 6.22 | 6.17 | 6.17 |
| *Q35* | 6.26 | 6.20 | 6.14 |
| *Q40* | 6.30 | 6.23 | 6.16 |
| *Q45* | 6.35 | 6.27 | 6.19 |
| *Q50* | 6.39 | 6.30 | 6.22 |
| *Q55* | 6.44 | 6.35 | 6.26 |
| *Q60* | 6.49 | 6.38 | 6.29 |
| *Q65* | 6.54 | 6.43 | 6.32 |
| *Q70* | 6.61 | 6.48 | 6.36 |
| *Q75* | 6.66 | 6.53 | 6.40 |
| *Q80* | 6.72 | 6.58 | 6.44 |
| *Q85* | 6.79 | 6.63 | 6.49 |
| *Q90* | 6.88 | 6.71 | 6.54 |
| *Q95* | 6.98 | 6.79 | 6.61 |

From the results it can be seen that altering the shape of the weir (which could be argued to be homologous to the installation of a hydroturbine) has an effect on the re-aeration of the water and subsequent downstream dissolved oxygen concentration. However the degree to which this will occur depends on the extent to which the installation of a hydroturbine alters the weir correction factor, which is currently unknown. The calculated values in table 4 are very precautionary and do not account for increased aeration due to the fish pass or reduced re-aeration at higher laminar flows.

Turbulence and mixing caused by baffles of the Larinier fish passes (existing and new pass) would increase re-aeration and partly offset any reduction caused by the turbines. In view of this it is unlikely that a HOF below Q95 (8 cumecs) would have any significant impact on dissolved oxygen levels. Additionally, the degree of re-aeration reduces as water depth increases above the weir apron. Assuming an average surface roughness for the weir, above 15-20cm water depth, the flow is far more laminar and less turbulent. This depth corresponds to approximately Q75. At flows above this level, the turbine would have less impact on Oxygen levels than the values given in table 4.

Without accurate empirical work, it is difficult to determine the exact impact the hydroturbine will have. However, if summer oxygen concentrations in the River Aire fall to around the critical value of dissolved oxygen concentration for coarse fish (generally accepted to be ~ 2-5 mg/L (Moore, 1942; Wilding, 1939), fish may be using the weir pool and increased dissolved oxygen present as a physiological refuge from low oxygen concentrations. In this instance, significant disruptions to the dissolved oxygen concentrations in the weir may be detrimental to fish populations.

### 3.4 Morphology and hydrology of the weir pool

The measured values of depth and velocity throughout the weir pool were used to create schematic maps of the hydrology in the area immediately below Castleford Mill Weir (see figures 8 and 9). The river was flowing at approximately Q50 while the survey was undertaken.

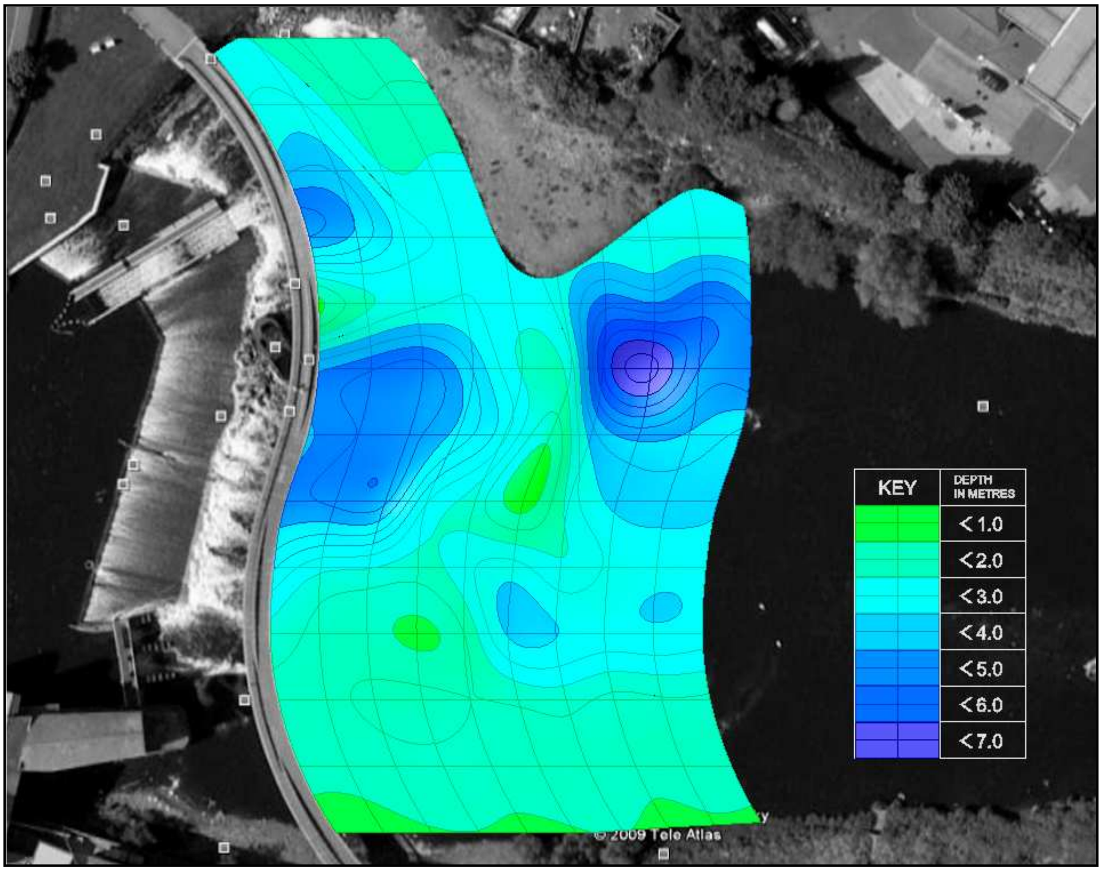


**Figure 8: schematic map illustrating the depths throughout Castleford Mill weir pool**

It is clear from figure 8 that the region immediately downstream of the proposed turbine outflow is between 2 and 3 m deep. The deepest areas are below the centre of the weir and the far bank below a spit of low lying land.

Velocities vary considerably in the pool between 0 m/s and 0.9 m/s (see figure 9). While there are pockets of sluggish and fast flowing water throughout the pool, the area below the turbine and especially the right bank looking downstream is particularly slow flowing. The high velocities in the central section are due partly to a broken 6m section of weir board in the centre of the weir that allows a considerable flow through this section. See appendix.

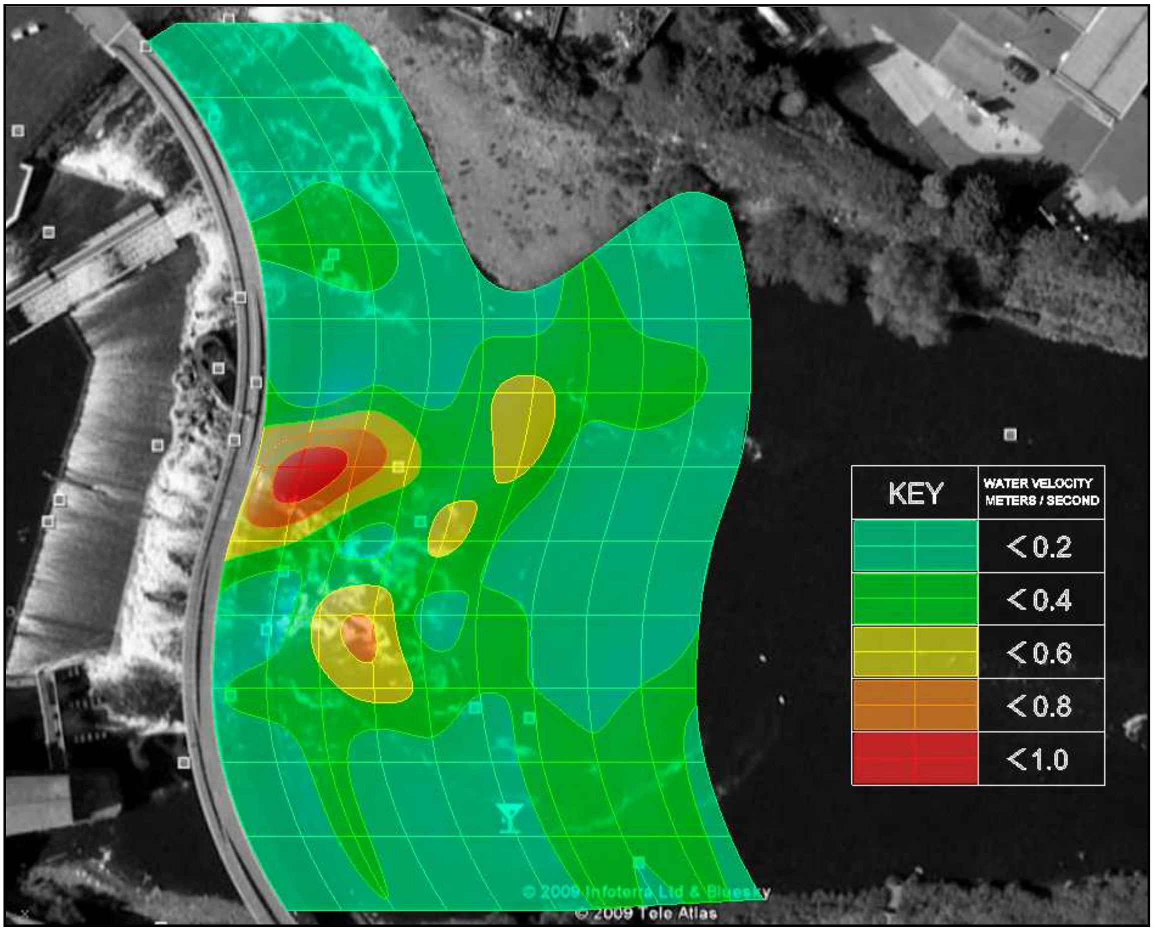


**Figure 9: schematic map illustrating the water velocities throughout Castleford Mill weir pool**

### 3.5 Changes in the weir pool hydrology as a result of the turbine installation

The installation of a hydroturbine will alter the hydrology of the weir pool. The most obvious way in which it will do this is by reducing the quantity of water passing over the weir crest and diverting it through the hydroturbine instead.

To accurately predict the changes in velocity caused by the turbines would require a complex flow modelling approach. However, an approximation can be made by using the turbine discharge volume, transects through the river channel immediately downstream produced by 3D CAD software and Mannings formula. This gave the expected velocities at different points in the channel that were used to create the velocity contour map, shown in figure 10. It was assumed that the maximum alteration of flow would occur when the turbines were drawing 30 cumecs. The HOF was assumed to be 8 cumecs spread across the existing fish pass and weir crest.

It can be seen from figure 10, that immediately downstream of the turbines, velocities will increase from 0.2-0.4m/s to 0.6-0.8 m/s. This increase would soon dissipate within the pool, although flows along the right hand bank (looking downstream) which are currently very sluggish would increase to 0.2-0.4 m/s and continue towards the tail of the pool. Velocities towards the existing fish pass bank would decrease from an average 0.2-0.4 m/s to below 0.2 m/s. The change in depth was determined using Mannings formula and found to be insignificant at less than 50 mm at the turbines maximum abstraction.

It is evident from figure 10 that the increased velocity extends to the deep channel on the far bank and would likely increase the attraction of upstream migrants to the turbine discharge.

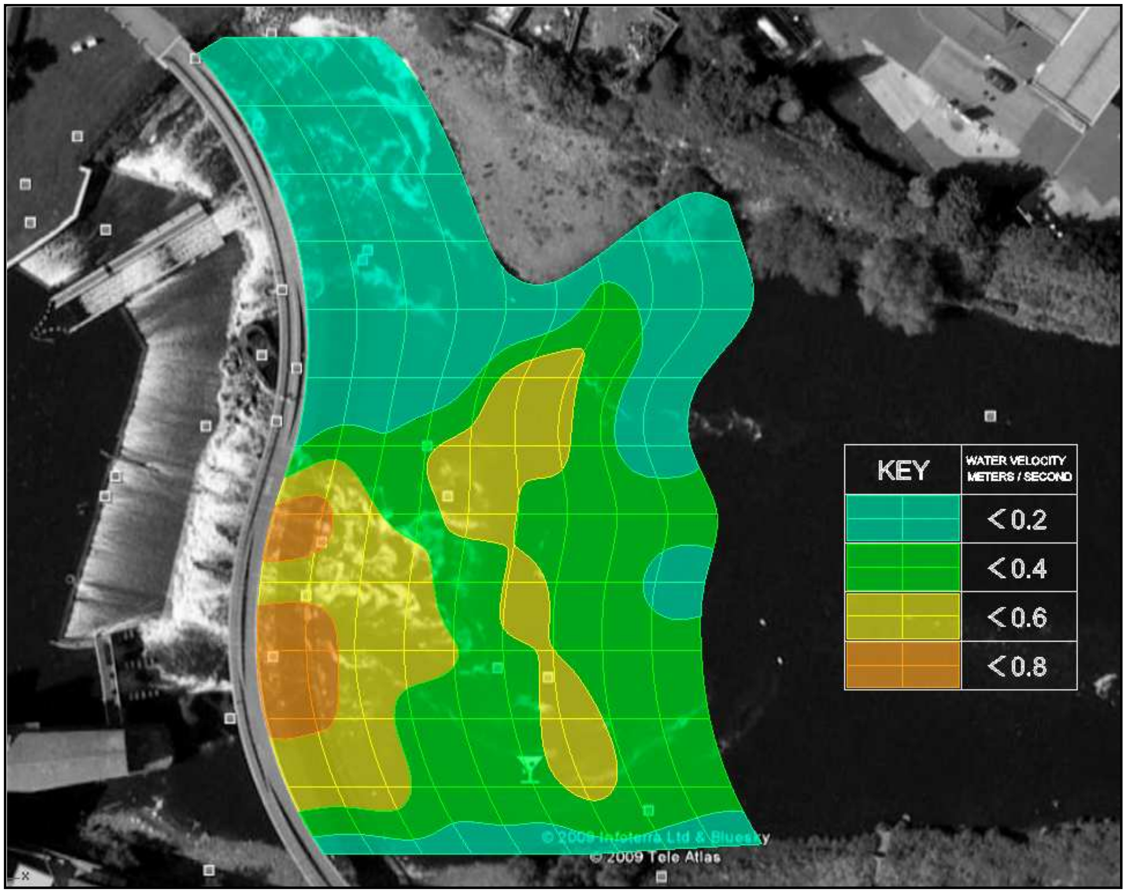


**Figure 10: predicted alterations to water velocities in Castleford Mill weir pool, based on the flows already reported and a turbine abstraction of 30 cumecs**

## 3.6 Spawning and juvenile habitat availability within the weir pool

The index of spawning habitat availability gives an idea of the extent and quality of rheophilic spawning habitat available within the weir pool. The number of sampling points (out of a total of 77) that correspond to each of the four spawning habitat classifications is given in table 5.

**Table 5: The number of sampling points within the weir pool classified into each of the four spawning habitat classes, according to the index based on substrate, water velocity and water depth**

| Spawning Habitat Classification | No. of sampling points |
|---|---|
| Very poor | 1 |
| Poor | 41 |
| Marginal | 31 |
| Good | 4 |

From table 5 it is clear that the majority of the spawning habitat within the weir pool can be classified as poor or marginal for rheophilic spawners. The location of the spawning habitat of the various classes is given in figure 11.

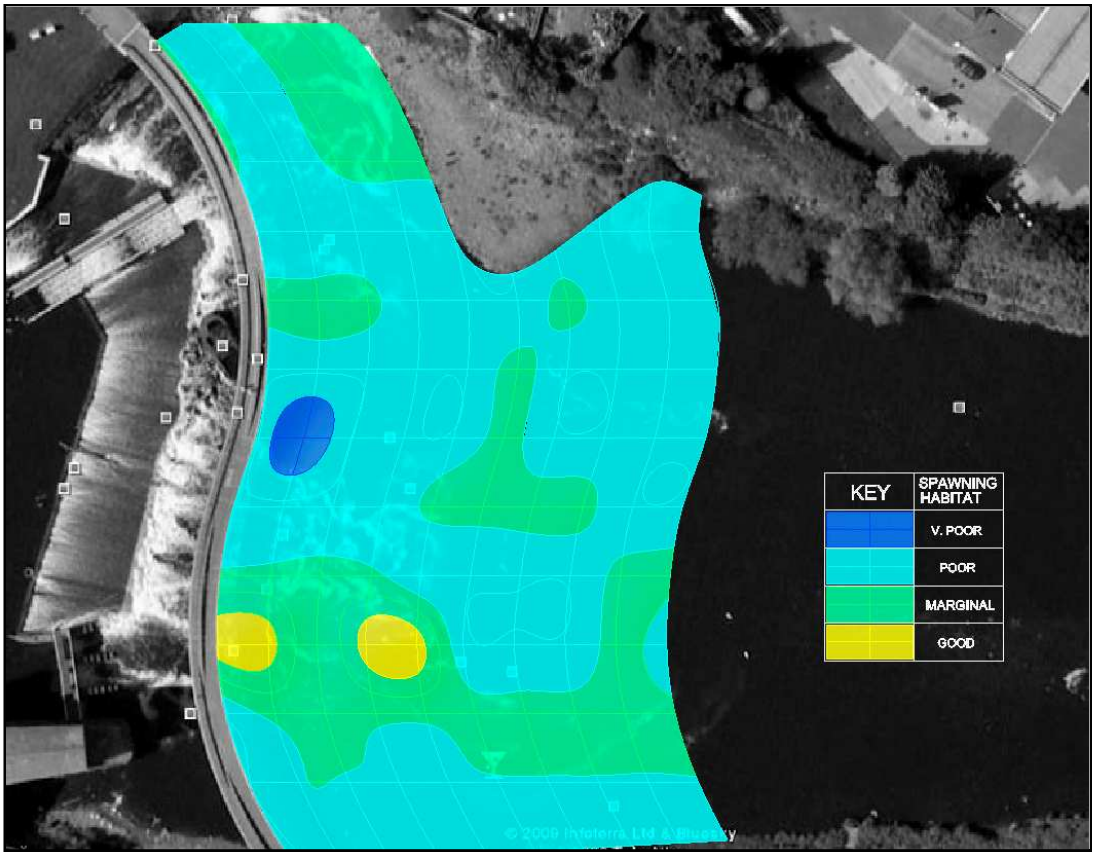


**Figure 11: extent of spawning habitat of each of the four habitats available within Castleford Mill weir pool**

It would appear from the index that there is a reasonable quantity of ‘marginal’ spawning habitat present in the weir pool. However a close examination of the data (see figures 8 and 9) shows that much of this habitat is either quite deep (> 1.3 m) or has a substrate comprised principally of large cobbles, boulders or stones. It is therefore possible that much of this habitat is questionable as even marginal rheophilic/lithophilic spawning habitat for species such as chub and dace, which typically use shallow, lotic channels flowing over a substrate of gravel.

There are a few points where all three requirements are met and the quality of the spawning habitat can be classified as ‘Good’. As can be seen from figure 11, this habitat is located in two small areas in the weir pool, both of which corresponded to the location of shallow, gravel bars. Given the limited availability of such habitat in a lowland, highly modified river such as the River Aire, this habitat is likely to be important for rheophilic/lithophilic spawning fish.

Much of the weir pool is deep and has a substrate comprised principally of large cobbles or rocks. Although the flows are often of a sufficient velocity for rheophilic spawning, the lack of significant shallow areas of gravel probably limit the spawning and juvenile habitat of lithophilic species. As such, it is unlikely that the installation of a hydroturbine will have a detrimental impact on the spawning habitat available within the weir pool.

Velocities downstream of the turbine and across the weir pool are predicted to change by between 0.1 m/s and 0.3 m/s, however the resulting velocities are still within the range 0 – 0.75 m/s. As a result, this would be unlikely to impact significantly on spawning.

Impacts on the abundance of phytophilic spawning habitat as a result of the hydroturbine installation are likely to be negligible as little evidence of submerged macrophytes was found, within the weir pool as a whole or in the vicinity of the turbine outflow. Phytophilic spawning will probably be restricted to areas around the river edge, in association with marginal and terrestrial vegetation. As such, the alteration in the hydrology of the weir pool will not affect the abundance of this habitat.

The highest densities of juveniles of many coarse fish species have been shown to be found in shallow areas, such as gravel beaches or around the margins of rivers, often in close association with instream vegetation or ligneous material (Copp, 1992b; Coop, 1997). We observed the presence of such areas around the edges and margins of the river channel and weir pool.

The main area of the weir pool was deep with depths between 3 and 6 m. The area of turbine outflow is also relatively deep averaging 2-3 m. It is unlikely therefore that there would be any disruption to the quantity and quality of juvenile habitat available in the River Aire in the vicinity of the weir pool.

### 3.7 Fish Passage

A Larinier fish pass (see figure 12) on the left bank (looking downstream) provides the only route for upstream migrants. It is unlikely that fish could ascend the weir directly even at very high flows due to boards at the top. Abstraction of up to 30 cumecs through the turbines would form a considerable attraction flow, drawing fish towards the turbine bank and away from the Larinier flume. The weir is over 70 m long with an irregular toe that would make it difficult for fish initially attracted to the turbine outflow to work along the weir and find the Larinier.

In view of this, a second fish pass would be required alongside the turbines. A multi species pass such as a Larinier with 100 mm baffles is the preferred option as this would provide a route upstream for coarse fish attracted to the outflow. A single species pass would effectively trap weaker swimming fish at the turbine bank, delaying them from finding the existing Larinier on the right bank.

**Figure12:Larinier pass on bank opposite proposed turbine location.**

*New Larinier*

The minimum pass discharge is generally given as 5-10 % of turbine flow (EA Fish Pass Manual), 5 % being used for larger schemes such as this. Locating the fish pass adjacent to one of the three screws, ensuring that the pass/turbine discharges are confluent and that the turbine adjacent to the fish pass operated first above HOF, would mean that the turbine flow formed an auxillary flow, enhancing the fish pass attraction.

If the scheme design can accommodate all of these points, then a smaller Larinier and hence pass discharge should be acceptable. Figure 13 shows the attraction flow from a 1.8 m Larinier (3 x 600 mm units of 100 mm baffles) as a % of turbine flow with and without the 3rd screw discharge operating as auxillary flow. The fish pass discharge was taken as 700 l/s until Q30 (turbine satiation) after which upstream water level and pass discharge increase.

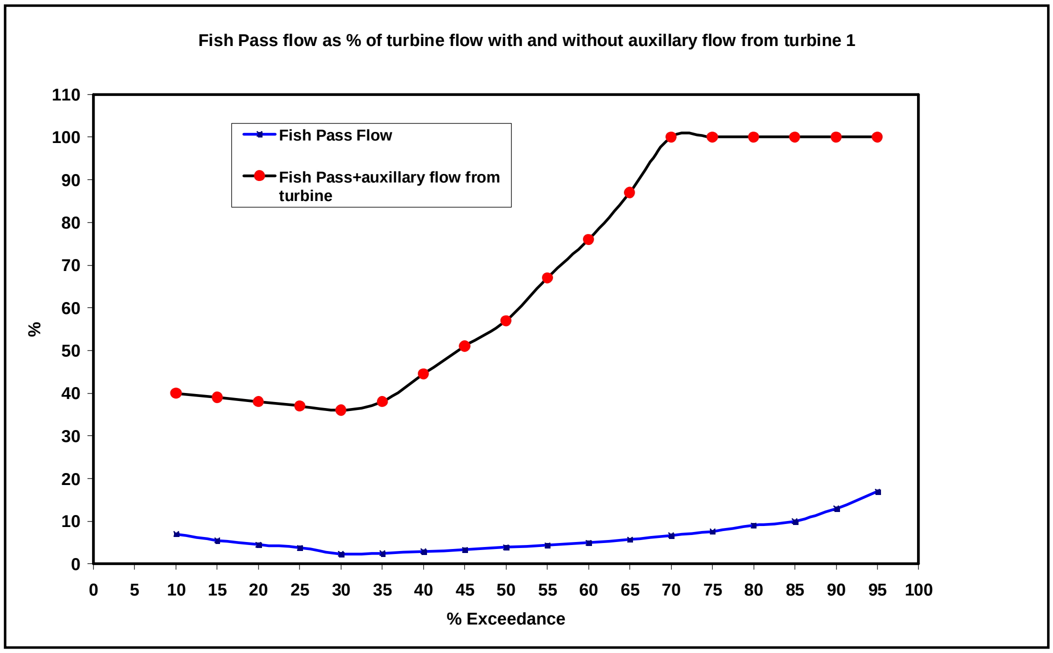


**Figure 13: fish pass attraction flow as a % of turbine flow**

A HOF of 8 cumecs (< Q95) increases the relative attraction flow from the turbines across the migration window (Q50 - Q20 for coarse fish, Q95 - Q10 for migratory salmonids). From Figure 14 we can see that a 10 cumec HOF has a lower overall proportional attraction than 8 cumecs. If a Larinier is installed, a lower HOF is unlikely to cause any issues for fish migration. Installing a fish pass such as a Plain Baffle Denil that is less suitable for weaker swimming species would require a higher HOF (> 10 cumecs) to reduce the turbine attraction during the Q50 - Q20 migration window.

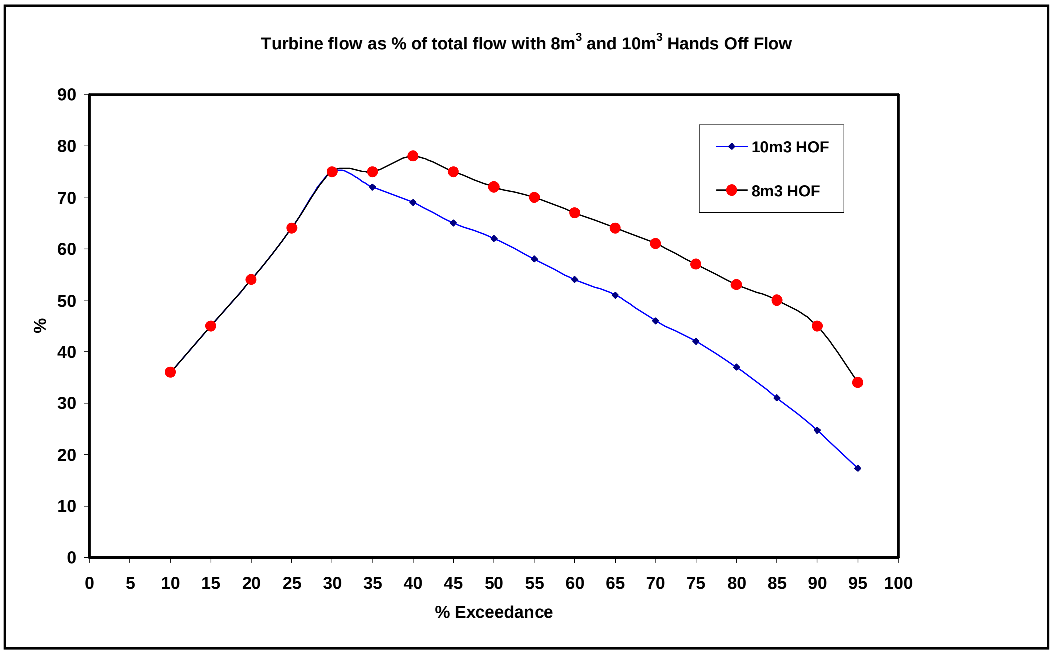


**Figure 14: attraction flow from the turbines as % of total flow with different HOFs**

*Impact of abstraction on existing pass*

The existing Larinier on the left bank is set at Ha on head baffle 0.33 m at Q95, rising to 0.78 m at Q10 (pass specification supplied by Neil Trudgill, EA). The pass velocity is relatively high for coarse fish (> 1.5 m/s) during the migration flows (Q50-Q20). The high Ha may have been set to maximise discharge and hence attraction, given as 13% at Q95 reducing to 4% at Q10.

Setting a HOF of 8 $m^3$ would reduce the Ha on the head baffle to 0.27 m and the velocity to 1.18 m/s with a pass discharge of 1.05 $m^3/s$. The pass dynamics would remain at this level until the turbines were at full capacity at Q30. The reduced flow and velocity should not affect the pass adversely and may improve efficiency for weaker swimming species.

If a new pass is created alongside the turbines, it is important that an acceptable migration route exists to the pass entrance. The deepest channel with 5-6 m depth is on the far bank opposite the proposed turbine location. This would form the best migration route for salmonids and other species. However, it can be seen from figure 8 that the channel shallows considerably 40-50 m below the existing fish pass to an average depth of 2 m. At this point there is sufficient depth (2-3 m) to the existing pass and to the turbine outflow, providing fish with a reasonable migration route to the new fish pass.

# 4. Conclusions and Recommendations

- The installation of the Archimedean Screw Turbine will have a negligible impact on fish passing down it. Due to the potential size of the installation at this site, a significant proportion of fish moving downstream may pass through the turbine.

- The hydroturbine is likely to cause a slight decrease to the level of dissolved Oxygen due to the change in weir form and lower turbulence and interface with the air in the turbine as opposed to water flowing over the weir crest and down the face of the weir.

- Changes in the hydrology of the weir pool will occur as a result of the hydroturbine being installed. The average velocity immediately downstream of the turbine outlet will increase by approximately 0.4m/s. There will be a comcomitant reduction in velocity towards the opposite bank of about 0.2m/s. Depth would remain almost unchanged.

- The quantity of good quality spawning habitat available within the weir pool is very limited. The hydrology and morphology of the river bed is generally unsuitable for rheophilic/lithophilic spawners.

- The installation of the hydroturbine is unlikely to have a measurable effect on either the quantity or quality of spawning habitat (for rheophilic/lithophilic or phytophilic spawning fish) available within the weir pool.

- The availability of juvenile coarse fish habitat is also unlikely to be affected as a result of the installation of a hydroturbine.

With the findings of this report in mind, the following are a series of recommendations in order to conserve or improve the fisheries ecology of the River Aire at Castleford Mill weir:

- No actions are necessary to protect or mitigate against the impact of the hydroturbine installation on the availability of coarse fish spawning habitat or coarse fish juvenile habitat.

- Compressible bumpers should be fitted to the turbines leading edges

- A Hands Of Flow of 8-10 cumecs, assuming a new Larinier fish pass is installed alongside the turbines. The lower HOF (8 cumecs) is recommended only if the turbine adjacent to the fish pass is the first to generate above HOF and the last to shut down as flows decrease. If a fish pass less suitable for weaker swimming coarse fish is used such as a Plain Baffle Denil, a HOF of at least Q95 is recommended.

- The fish pass entrance should be several metres downstream of the turbine discharge point where the discharged water is less turbulent and unlikely to mask the pass exit jet. Monitoring salmonid movements at the turbine discharge on the River Dart (Fishtek Consulting 2007) showed fish to lie several metres downstream of the turbine.

- A HOF of 8 cumecs is unlikely to have any significant impact on dissolved Oxygen levels for fish. However, as a precaution, it would be prudent to monitor levels of D.O. in the weir pool during warm, dry periods in the summer. If they drop below a critical value (to be determined) the HOF should be increased and the turbine automatically shut down until a higher HOF, perhaps Q95, is reached.

If there are concerns regarding the potential impact of the hydroturbine on dissolved oxygen concentrations downstream of the weir it is recommended that this issue be investigated further by comparing sites at which Archimedes turbines have been installed with weirs or dams without hydroturbines.

# 5. References

Arlinghaus, R. and Wolter, C. (2003) Amplitude of ecological potential: chub *Leuciscus cephalus* (L.) spawning in an artificial lowland canal. *Journal of Applied Ichthyology*, **19**: 52-54

Baras, E. and Nindaba, J. (1999) Seasonal and diel utilisation of inshore microhabitats by larvae and juveniles of *Leuciscus cephalus* and *Leuciscus leuciscus. Environmental Biology of Fishes*, **56**: 183-197

Cada, G.F., Kumar, K.D., Solomon, J.A. and Hildebrand, S.G. (1983) Analysis of Dissolved Oxygen Concentrations in Tail Waters of Hydroelectric Dams and the Implications for Small-Scale Hydropower Development. *Water Resources Research*, **19**: 1043-1048

Caffrey, J.M., Acevedo, S., Gallagher, K. and Britton, R. (2008) Chub (*Leuciscus cephalus*): a new potentially invasive fish species in Ireland. *Aquatic Invasions*, **3**: 197-205

Clark, C.F. (1950) Observations on the spawning habits of the northern pike, *Esox lucius*, in Northwestern Ohio. *Copeia*, **1950**: 285-288

Copp, G.H. (1992a) An empirical model for predicting microhabitat of 0+ juvenile fishes in a lowland river catchment. *Oecologia*, **91**: 338-345

Copp, G.H. (1992b) Comparative microhabitat use of cyprinid larvae and juveniles in a lotic floodplain channel. *Environmental Biology of Fishes*, **33**: 181-193

Copp, G.H. (1997) Microhabitat use of fish larvae and 0+ juveniles in a highly regulated section of the river Great Ouse. *Regulated Rivers: Research and Management*, **13**: 267-276

Cowx, I. G.; Welcomme, R. L. (1998) *Rehabilitation of Rivers for Fish.* Oxford, UK: Food and Agricultural Organization of the United Nations and Fishing News Books.

Cushman, R.M. (1985) Review of ecological effects of rapidly varying flows downstream from hydroelectric facilities. *North American Journal of Fisheries Management*, **5**: 330-339

Fishtek Consulting (2007) Fish monitoring and live fish trials. Archimedes Screw Turbine, River Dart. *Phase 1 Report: Live fish trials, smolts, leading edge assessment, disorientation study, outflow monitoring.*

Fishtek Consulting (2008) Archimedes Screw Turbine Fisheries Assessment. Phase II: Eels and kelts.

Fishtek Consulting (2009) Assessment of three leading edge profiles.

Gillet, C. and Dubois, J.P. (1995) A survey of the spawning of perch (*Perca fluviatilis*), pike (*Esox lucius*), and roach (*Rutilus rutilus*), using artificial spawning substrates in lakes. *Hydrobiologia*, **300/301**: 409-415

Hancock, R.S., Jones, J.W.and Shaw, R. (1976) A preliminary report on the spawning behaviour and nature of sexual selection in the barbel, *Barbus barbus* (L.). *Journal of Fish Biology*, **9**: 21-28

Interesova, E.A., Yadrenkina, E.N. and Savkin, V.M. (2009) Spatial organization of the spawning grounds of Cyprinidae and the regulated flow of the Upper Ob. *Journal of Ichthyology*, **49**: 73-79

Jurajda, P. (1999) Comparative nursery habitat use by 0+ fish in a modified lowland river. *Regulated Rivers: Research and Management*, **15:** 113-124

Kennedy, M. (1969) Spawning and Early Development of the Dace *Leuciscus leuciscus* (L.). *Journal of Fish Biology*, **1**: 249-259

Kondolf, G.M. (2000) Assessing salmonid spawning gravel quality. Transactions of the American Fisheries Soceity, **129**:262-281

Lee, C.C. and Lin, S.D. (2000) *Handbook of environmental engineering calculations*. McGraw-Hill.

Lucas, M.C. and Batley, E. (1996) Seasonal movements and behaviour of adult barbel *Barbus barbus*, a riverine cypinid fish: implications for river management. *Journal of Applied Ecology*, **33**: 1345-1358

Mann, R.H.K. (1996) Environmental requirements of European non-salmonid fish in rivers. *Hydrobiologia*, **323**: 223-235

McCarraher, D.B. and Robert E. Thomas, R.E. (1972) Ecological significance of vegetation to northern pike, *Esox lucius*, spawning. *Transactions of the American Fisheries Society*, **101**: 560-563

Meyer, E.I., Niepagenkemper, O., Molls, R. and Spanhoff, B. (2008) An experimental assessment of the effectiveness of gravel cleaning operations in improving hyporheic water quality in potential salmnoid spawning areas. *River Research and Applications*, **24**: 119-131

Mills, C.A. (1981) The Spawning of Roach *Rutilus rutilus* (L.) in a Chalk Stream. *Aquaculture Research*, **12**: 49-54

Mills, C.A. (1981) The attachment of dace, *Leuciscus leuciscus* L., eggs to the spawning substratum and the influence of changes in water current on their survival. *Journal of Fish Biology*, **19**: 129-134

Moore, W.G. (1942) Field Studies on the Oxygen Requirements of Certain Fresh-Water Fishes. *Ecology*, **23**: 319-329

Nunn, A.D.; Harvey, J.P. and Cowx, I.P. (2007) Benefits to 0+ fishes of connecting man-made waterbodies to the lower River Trent, England. *River Research and Applications*, **23**: 361-376

Spah, H. (2001) Fishery biological opinion of the fish compatibility of the patented hydraulic screw from Ritz Atro. Bielfield, Germany.

Turnpenny,A.W.H, et al (2000), Risk assessment for fish passage through small low head hydro turbines. ETSU-H/0600054/Rep.

Wilding, J.L. (1939) Oxygen Threshold for Three Species of Fish. *Ecology*, **20**: 253-263

# 6. Appendix

**Broken weir board in centre of weir**