ENVIRONMENT AGENCY

INVESTIGATING THE IMPACT OF THE SETTLE ARCHIMEDES HYDRO-POWER SCHEME ON ADULT SALMONID MIGRATION.

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CONTENTS

1 INTRODUCTION

1.1 Project Background

Originally used as a mechanism to pump water, Archimedes screws are one of the oldest hydraulically driven engines (Müller & Senior, 2009). Following the installation of the first generator in the United Kingdom (UK) on the River Dart in 2007, reverse Archimedes screws have become a popular option as hydro-power energy converters in low-head, high-flow locations. Archimedes screws are considered “fish friendly”, as a small number of limited studies have suggested that they do not cause immediate significant physical damage to downstream migrating salmonids (Kibel, 2007; Kibel & Coe, 2008), European eel, *Anguilla anguilla* (Kibel & Coe, 2008), coarse fish (Kibel *et al*., 2009), and river lamprey, *Lampetra fluviatilis* (Bracken & Lucas, 2012). Thus, Archimedes screws are increasingly becoming the preferred engineering option where hydro-power generation schemes have been deemed appropriate. However, the longer term impacts of these structures on fish populations have not been investigated, and in general there is an overall lack of peer-reviewed sources dealing with the relationship between fish migrations and Archimedes screws.

Diadromy in fish describes a requirement for populations to be afforded uninterrupted passage between marine and freshwater environments in order to complete their life cycle. Anthropogenic structures (weirs, sluices etc.) or activities (e.g. abstraction, noise, pollution etc.) can have deleterious impacts in fish populations which undertake upstream and/or downstream migration, in both the long and short term (Aarestrup *et al*., 2003; Legault, 1990; Bruijs *et al*., 2003). Thus, to maintain good ecological status within river networks, there is a necessity to maintain continuous longitudinal connectivity (Weyand *et al*., 2005).

Instream barriers (including hydro-power schemes) have the potential to impact on migration performance in two ways. They can either represent a completely impenetrable barrier or make passage more challenging. While not necessarily denying longitudinal access, the latter impact can result in significant delays to migrations (Larinier, 2002). Fish may accumulate immediately downstream of a structure resulting in elevated predation pressure, which can be further exacerbated by predators learning areas of congregation (Peake *et al*., 1997). Migratory obstruction may also increase susceptibility to anthropogenic capture, both legal and illegal. Therefore, any restriction to fish migrations may have negative consequences for the reproductive capacity of fish populations, ultimately impacting on recruitment success (Geen, 1975; Schlosser, 1991; Deegan, 1993). Due to their highly dynamic life cycle and contrasting habitat requirements (Armstrong *et al.* 2009), anadromous salmonid populations are highly vulnerable to fractures in river connectivity.

Archimedes screws may adversely affect fish passage due to variation in hydraulic conditions within the immediate vicinity of the machine. If, for example, a localised concentration of high velocity flow is present at the tailrace of the Archimedes screw, then upstream moving fish may be attracted to the higher velocity water exiting the non-passable tailrace (SEPA, 2010) rather than the main migration route (e.g. main channel or a fish pass). Indeed, significant delays to fish migration can occur in the absence of a large physical structure due to changes in water depth, velocity, and variation in discharge caused by in-river anthropogenic activities. For example, during flume based studies Kemp *et al*. (2005; 2008) observed that downstream migrating Pacific salmonid smolts avoided accelerating flow, with similar results being observed by Russon & Kemp (2011) for brown trout (*Salmo trutta*). In addition, Archimedes screws (in common with other hydro-power schemes) may reduce the natural heterogeneous flow regime within a watercourse, delaying or completely inhibiting fish movement. As peak migrations of salmon are typically triggered by spate conditions (Baxter, 1961; Bradley *et al*., 2012; Enders *et al*., 2009; McCormick *et al*., 1998; Tetzlaff *et al*., 2008), anthropogenic alteration of natural flow regimes in rivers could potentially delay migrations. Accordingly, Poff *et al*. (1997) reported that flows should be managed to mimic the natural flow regime of the watercourse, which has further advantages such as maintaining sediment motility and geomorphological processes throughout the watercourse. For fish passage it is important to consider the flow conditions likely to be present when the fish are migrating to provide adequate passage conditions for a sufficient amount of time to allow migrants to pass. Finally, peak runs of returning adult salmon demonstrate variability in terms of geography and flow, but the main upstream run times are generally May to January (EA, 2011).

1.2 The Settle Hydro-power Project

Settle hydro-power is a community owned and operated hydroelectric scheme which utilises the former mill race and weir structure at Settle on the River Ribble. This project was initiated to promote local environmental sustainability and to create revenue through the generation of green energy. Revenue generated is reinvested in local community projects focused towards regeneration of the area.

The scheme plans to generate 165,000 kWh of electricity per year and is expected to have a lifespan of 40 years. Planning permission was granted in February 2009, with construction completed in October 2009 and electrical generation beginning in late 2009/early 2010. The scheme is subject to a licensed Hands Off Flow (HOF) at a river height of 64mm above the weir crest (equating to a Q70 flow value) although variance in measurement due to wave height has resulted in this figure being the lowest potential HOF with a maximum of 74mm.

1.3 Project Aims

This project consisted of two phases:

1. Meta-analysis which incorporated almost three years of turbine operation, river height and fish passage data and;
2. A focused case study from late 2012.

Although a small number of studies have investigated the physical impact of Archimedes turbine operation (e.g. strike likelihood and lethality) on downstream salmonid migrations (see Section 1.1), there is a distinct paucity of published or even grey literature dealing with impacts on upstream salmonid migration. Therefore this project was initiated to investigate the value of routinely collected relevant data to identify an overt relationship between turbine operation and adult salmonid migration (Phase 1).

Following the investigations that formed the basis of the original release of this report in February 2012, further data collected during a period of experimental turbine operation from September to December 2012 were provided by the EA. This increase to the original project scope aimed to investigate the likelihood that experimental data would prove more suited towards the overall objective of assessing the impact of the Settle Archimedes Screw. This was to be achieved by operating the turbine over fixed periods of time, independent of prevailing flow conditions, thereby potentially removing the link between high flows and turbine operations (and river migrations).

Key objectives

Using river level, turbine operation and fish counter data, this study has focussed on the following key questions:

- Does operation of the Settle Archimedes turbine impact on upstream migration of salmonids?
- Are any potential impacts more evident under certain flow conditions?
- Are currently available data suitable to assess the impact of this relatively new technology on adult salmonid migrations?

To examine the above, analysis of the following key variables was undertaken:

- Number of migrants as identified at the Locks Weir resistivity fish counter, approximately 1km upstream;
- Height of river as gauged at Locks Weir;
- Height of the river at the turbine intake
- Power output from the turbine.

2 MATERIALS AND METHODS

2.1 Study site

Settle Weir

Settle weir is approximately 36m wide and 2.1m high with a vertical downstream drop. A plunge pool is not present downstream of the weir. A pool and traverse fish pass is present (Figure 2.1), with its downstream entrance close to (within 2m) the tailrace of the installed Archimedes Screw turbine (proximity of which may increase the attraction flow towards the fish pass entrance; Kibel, 2008) on the left hand bank.

Figure 2.1. Settle Hydro Site with the location of the turbine intake and outflow and fish pass detailed. © The GeoInformation Group. Accessed Google.co.uk, 14/12/12.

The Ribble

The Ribble is one of Northwest England's longest rivers and rises in the Yorkshire dales before discharging into the Irish Sea at Preston. The Ribble at Settle is designated at Good Ecological Potential (GEP, the relevant waterbody of the Ribble containing the reach at Settle is designated as Heavily Modified for flood protection), with waterbodies upstream of Settle varying from Good to Poor Ecological Status (GEP to PEP) (EA, 2008, see Table 2.1). Despite GEP at Settle, the Ribble catchment waterbodies are all failing to meet Good Status for fish at Settle and above. Objective setting calls for GES/P by 2015 for the Ribble and 2027 for the Cam beck, an upstream tributary.

The Ribble is an important regional river for Atlantic salmon with adults returning to the river at any time of the year and peak migrations can be observed at Settle Weir from August to December. The river produced a rod catch of almost 1000 salmon in 2011 (585 single sea winter fish [grilse], 414 multi sea-winter, EA, 2012).

The most recent data available (2011) demonstrate that, although Atlantic salmon ova deposition rates on the river are above the conservation limit required (8.42×10^6 ova), the management target of 10.16×10^6 (the figure required to ensure high confidence of meeting conservation limits four out of every five years) was not reached. However, a trend of increasing ova deposition was observed in the period 2002 – 2011(EA, 2012). Nonetheless the Ribble does echo a regional recent decline in returning grilse linked to reduced marine survival whilst multi-sea winter returnees appear to be increasing (EA, *pers.comm.*).

Table 2.1. WFD classifications of Waterbodies on the Ribble from Settle upstream.

WB ID	WB Name	Current Status	Ecological Status	Fish Status
GB112071065640	River Ribble	Good Potential	Good Potential	Poor
GB112071071570	River Ribble	Moderate	Moderate	Moderate
GB112071071580	Cam Beck	Poor	Poor	Poor

2.2 Data availability

Data were provided by the Environment Agency to APEM Ltd. A summary of data variables is provided below in Table 2.1.

Table 2.1. Study variables with length of time series and frequency of recording.

Variable	Temporal extent	Frequency of recording
Fish passage	01/09/2009 – 18/12/2012	Every pass.
River height (cm)	01/09/2009 – 18/12/2012	15 minute.
Intake height (cm)	01/02/2009 – 18/12/2012	1 minute until Nov 2010, 15 minute after.
Power output (kWh)	01/02/2009 – 18/12/2012	1 minute until Nov 2010, 15 minute after.

Fish passage

Fish passage was recorded using a resistivity counter at Locks Weir, approximately 1km upstream of the Settle Weir. It was not possible to differentiate salmon and sea trout migrants, although numbers of fish recorded during the peak migration period (August – December) are known to be dominated by Atlantic salmon (Brian Shields, pers. comm.). Time stamped fish passage counts were tallied to enumerate fish passing both upstream and downstream through the Locks Weir fish pass. These data were aggregated into 15 minute blocks before being summed into daily counts of fish passage.

River height

River height measured at Locks Weir (approximately 1km upstream from Settle Weir, SD 81758 65421), was averaged into daily means.

Intake height and power output

As intake height and power output were recorded every minute until November 2010, these data were averaged into 15 minute blocks for consistency with the river height and fish passage data.

Data gaps

Data were absent in some cases and, following consultation with the EA, days with over 50% of records missing were excluded from the analytical dataset. Days were excluded if data from any one of the four variables listed in table 2.1 were absent and this accounted for 5.13% of the total data.

2.3 Data preparation and analysis

Data preparation and pre-analysis

Data were truncated to ensure all variables were represented equally and 15min data were averaged into daily means to limit overdispersion (excessive variability) resulting from the large number of zeroes in the 15-minute fish passage data. This resulted in a dataset encompassing the 1st Feb, 2010 to the 16th of September, 2012 inclusive. Independent data (i.e. predictor variables - river height, intake height and power output) were log transformed where appropriate.

Data were checked for long-term trends which could potentially impact analysis. All three independent variables were found to have significantly increased over time (weir height, d.f. = 918, *t.* = 8.962, p. < 0.0001; intake height, d.f. = 918, *t.* = 8.102, p. < 0.001; and power output, d.f. = 918, *t.* = 6.181, p. < 0.001).

Differencing was used to remove the long term trends present in the predictor variables. This is a method of filtering data so as to ensure stationarity (non-trended) and, although simple, is quite effective. Removal of trends is a necessary step towards ensuring that subsequent analysis describes the true relationship between dependent and independent variables and is not simply reflecting background, long term change. This was undertaken using the following equation (Chatfield, 1997):

$$z_t = x_{x+1} - x_t$$

where z_t - z_i is the differenced dataset.

Seasonal trends were not removed due the inherently linked seasonal nature of salmonid migrations and flows.

Data analysis

A number of important considerations guided the choice of analysis. Preliminary data assessment revealed a strong relationship between river height and intake height (d.f. = 918, t = 80.58, p > 0.001) and river height and power output (d.f. = 9.18, t. = 29.74, p < 0.001 [GLM]). Consequently it was decided to introduce a model covariate indicating the “ON” or “OFF” status of the turbine as opposed to using the [differenced] power output and intake height data. This provided a buffer against the effect of collinearity and the non-normal distribution of the power output data, which was heavily populated with zeros. Secondly, as count data, the dependent variable was non-normally distributed. (Count data are constrained within limits and variance increases with increasing mean [i.e. Poisson distribution], Quinn and Keough [2003]). Therefore standard ordinary least squares (OLS) regression was considered unsuitable and General Liner Modelling (GLM) was selected (Crawley, 2009). GLM was also selected to provide a standard model across continuous and categorical (i.e. river height frequency) datasets.

All statistical procedures were carried out using R (http://www.r-project.org/) with the **glm** function available on R base statistics package. Charts were drawn using either Microsoft Excel (descriptive) or R (model fits and plots of means, using **gplots** package).

2.4 Case Study

Between the 18th of September and the 18th December 2012, an informal agreement between the EA and the operators of the Settle HEP facility allowed for an experiment which attempted to control the relationship between high flows and HEP generation during the peak migration phase by altering the operational state of the turbine (on or off) every seven days. This pattern was to be followed irrespective of flows (although within the abstraction license requirements); however in practice operation of the turbine did not follow such a concise programme. The resulting experimental operational phases are presented below in Table 2.2.

Table 2.2. Periods of experimental turbine operation at Settle. Although originally designed in a week on/week off format, operational requirements resulted in a less structured pattern.

Start Date & time	End date & time	Operational phase	Total days
18/09/2012; 0930	25/09/2012; 1800	off	7
25/09/2012; 1800	02/10/2012; 0915	on	7
02/10/2012; 0915	12/10/2012; 0845	off	10
12/10/2012; 0845	15/10/2012; 1315	on	3
15/10/2012; 1315	28/10/2012; 2045	off	13
28/10/2012; 2045	30/10/2012; 1015	on	2
30/10/2012; 1015	08/11/2012; 0915	off	9
08/11/2012; 0915	11/11/2012; 1730	on	3
11/11/2012; 1730	12/11/2012; 1815	off	1
12/11/2012; 1815	13/11/2012; 1345	on	1
13/11/2012; 1345	20/11/2012; 0930	off	7
20/11/2012; 0930	27/11/2012; 1115	on	7
27/11/2012; 1115	04/12/2012; 1015	off	7
04/12/2012; 1015	05/12/2012; 1600	on	1
05/12/2012; 1600	07/12/2012; 0300	off	2
07/12/2012; 0300	07/12/2012; 1830	on	0
07/12/2012; 1830	07/12/2012; 2215	off	0
07/12/2012; 2215	11/12/2012; 0100	on	4
11/12/2012; 0100	18/12/2012; 0900	off	7

Data were managed in the same fashion as Section 2.3 and no data gaps were observed. Time series were analysed for trends and data distributions described. No temporal trend in river height data was observed, presumably due to the relatively short temporal extent of the case-study period; however a log10 transformation was required. Turbine operational data was factored into "ON" and "OFF" states as before, with Poisson distributed fish data requiring general linear models (GLMs) to model the interrelationships between fish passage, turbine operation and river heights, and days when the turbine was both on and off were excluded for consistency.

3 META-ANALYSIS RESULTS

3.1 Salmonid migration.

A total of 912 upstream salmonid passes were recorded at the Locks Weir between the 2nd of February, 2010 and the 16th of September, 2012 inclusive. The maximum number of fish that passed over the weir in any one day was 50 (29th of October, 2010) with the maximum monthly count occurring in October 2010. Due to known local variations in the intra-annual migratory patterns of sea trout and salmon, it was considered likely that the majority of fish from this month were Atlantic salmon (Brian Shields, pers. comm.). The temporal distribution of upstream fish counts is illustrated below in Figure 3.1.

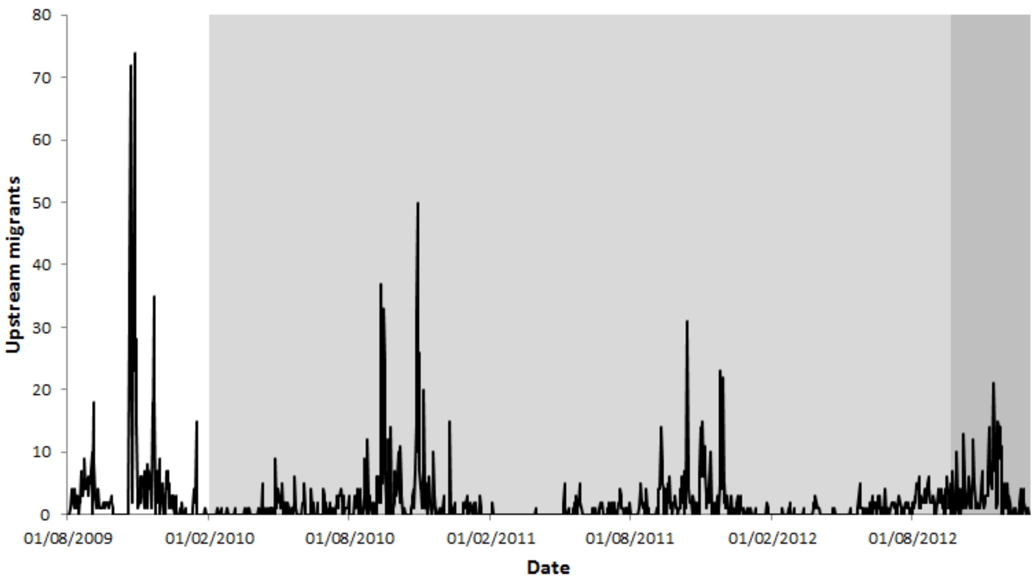

Figure 3.1. Salmonid passage past Locks weir. The study periods (initial and experimental) are highlighted, light grey – extended study; dark grey – experimental phase). This chart demonstrates the year-on-year decline in the Ribble Atlantic salmon population; a regional pattern echoed across numerous Northern English catchments.

3.2 River height and turbine operation

River height varied between a minimum of 0cm during the period 18th April – 5th May 2011 to a maximum of 110.9 cm on the 25th of September 2012. Excessive variation (as indicated by a Coefficient of variation (CoV) >1, Quinn and Keough, 2007) was only observed on two days (25th December, 2010 and 6th of May, 2011). This relatively low level of variation is not unexpected given the high stream order of the Ribble at Settle.

The Archimedes turbine was operated on 402 (43.5%) of the 923 total study days and the maximum output of 40kWh was recorded on the 5th of April 2011 at 0600hr. Incidentally, the maximum output recorded was below the maximum values proposed elsewhere (45 kWh, Fishtek, [2008] and 50 kWh, Settle Hydro [2011]). Although continuous data were present for turbine output, the high proportion of zeros compounded by collinearity of the turbine output data with the main independent variable (river height) resulted in an inconsistent data distribution. Therefore turbine output data was transformed to a binary predictor variable (hereafter referred to as the turbine operation state) consisting of “ON” or “OFF”. River height data (based on 15 minute records) is presented along with turbine operational state in Figure 3.2.

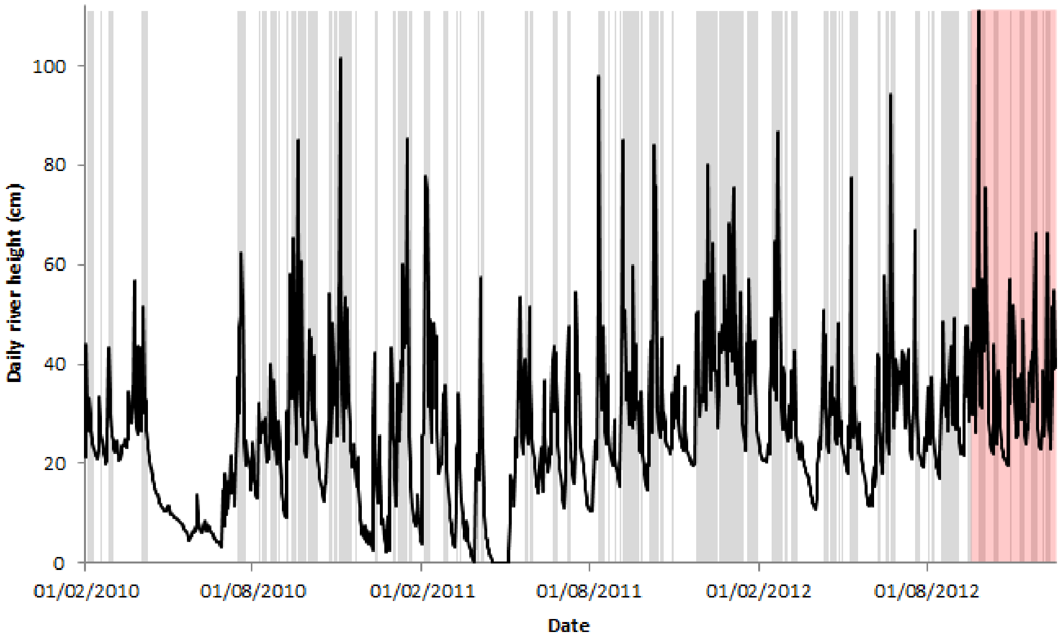

Fig 3.2. Daily average river height records from Locks Weir on the Ribble. Greyed sections indicate periods of power generation with the experimental period highlighted in red.

3.3 Relationship between river height, turbine operation and upstream fish passage throughout the year.

Poisson distributed GLM was used to model the upstream passage of salmonids, with river height as predictor and turbine operation state as a covariate. GLM model output describing the interaction between salmonid passage, river height and turbine operation is presented below in Table 3.1.

Table 3.1. GLM of upstream migrants against river and intake height.

Interaction	d.f.	z.	p.
MODEL 1 *: Upstream migrants ~ weir height*turbine operation*			
a. Weir height	918	0.695	ns
b. Turbine operation (on/off)	917	18.03	< 0.001
*c. Height * Turbine*	916	-3.246	<0.001
MODEL 2 *: Upstream migrants ~ intake height*turbine operation*			
a. Intake height	918	0.942	ns
b. Turbine operation (on/off)	917	17.93	<0.001
*c. Height * Turbine*	916	-3.006	0.002

The results for both models demonstrate that there was a significant difference in the number of migrants ascending on days the turbine was ON compared to OFF (interaction *b*., Model 1 & 2, see Figure 3.3, demonstrates a higher average migrations during on periods). However river height or intake height had no impact on the count of upstream migrants (interaction *a*. Model 1 & 2).

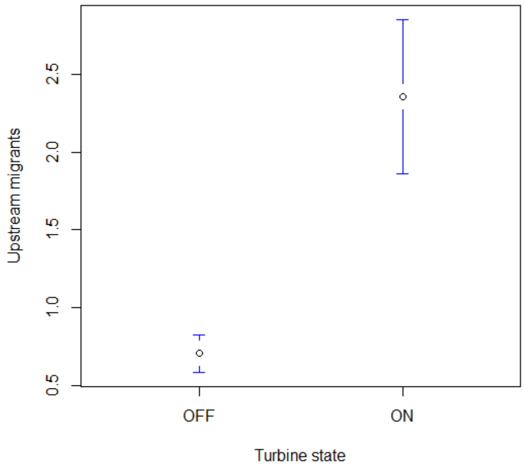

Figure 3.3. Comparison of average daily upstream migrants between turbine operation states.

Model outputs also demonstrated a significant interaction between turbine operation states (interaction *c*., Models 1 & 2). However, a visual inspection of the interaction *c.* predicted fit over the data range present (Figure 3.4, below), highlights the likelihood that turbine operation is not reducing fish passage throughout the year and that this interaction has being influenced by the greater range of flows utilised by fish when the turbine is being operated. This interpretation is further supported by the lack of a singular relationship between migrants and river height shown in interaction *a*.

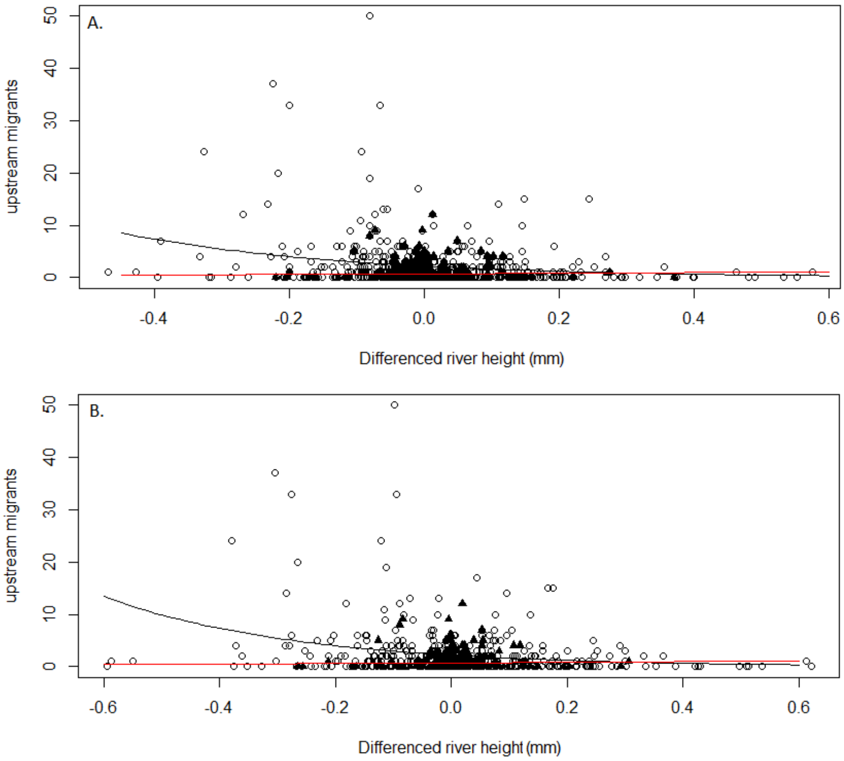

Fig 3.4. Relationship between river heights and migrants during ON state (open circles, black line) and OFF (closed triangles, red line) increasing river height (differenced) at weir (A.) and river height at intake (B.).

3.4 Relationship between river height, turbine operation and upstream fish passage during peak migration period.

The approach presented in Section 3.3 was repeated using data from the peak migration period between August and December (as outlined by the EA), which corresponded to 78% of upstream migrants. Model outputs are shown below in Table 3.2.

Table 3.2. GLM of upstream migrants against river and intake height during peak migration periods August to December.

Interaction	d.f.	z.	p.
MODEL 3 *: Upstream migrants ~ weir height*turbine operation*			
a. Weir height	918	-0.282	ns
b. Turbine	917	14.148	<0.001
*c. Height * Turbine*	916	-1.382	ns
MODEL 3 *: Upstream migrants ~ intake height*turbine operation*			
a. Intake height	918	-0.385	ns
b. Turbine	917	14.188	<0.01
*c. Height * Turbine*	916	-1.071	ns

The results for both models (3 & 4) demonstrated that although there was a difference in the number of fish running between turbine operation states (interaction *b*.), there was no turbine impact on the range of flows utilised during these migrations (interaction *c*.)

3.5 Relationship between categorical river height, turbine operation and upstream fish passage.

River height data from Locks Weir were categorised into Q-values (via percentiles) within the boundaries shown below in Table 3.3.

Table 3.3. Model 5. River height categories (based on daily averages)

Percentile	Q	Weir Height (cm)	Intake Height (cm)
1	Q99	0.00	0.00
5	Q95	4.21	0.00
10	Q90	7.18	31.74
25	Q75	15.85	65.68
50	Q50	24.11	95.52
75	Q25	33.91	152.27
90	Q10	46.60	274.84
95	Q5	55.51	354.81
99	Q1	83.27	569.39

River heights were allocated to flow range bins (categories) and a comparative model developed to examine the relationship between river height category and passage over Settle Weir (i.e. using fish recorded at Locks Weir as a surrogate for passage at Settle Weir). The simplified model outputs are shown in Table 3.4 and illustrated in Figure 3.5.

These comparisons demonstrate a higher likelihood of migration during periods of higher flows, although the mean number of migrants declines abruptly as flows decline below Q25 (measured as river height), (Figure 3.5). Furthermore, these results also identify cessation of migration below Q90 (see Figure 3.5).

Table 3.4. Categorical GLM model investigating the relationship between frequencies of river height and fish migration (based on comparison with Q05 values). Addition of an interactive turbine operation factor resulted in no significant difference between the numbers of fish migrating within each Q category during alternative turbine operation phases. D.f. = 9,912.

Height Category	*z.*	p.
Q01	2.052	0.04
Q05	3.271	0.001
Q10	3.45	>0.001
Q25	3.681	>0.001
Q50	1.578	NS
Q75	1.452	NS
Q90	0.904	NS
Q95	-0.039	NS
Q99	-0.3	NS

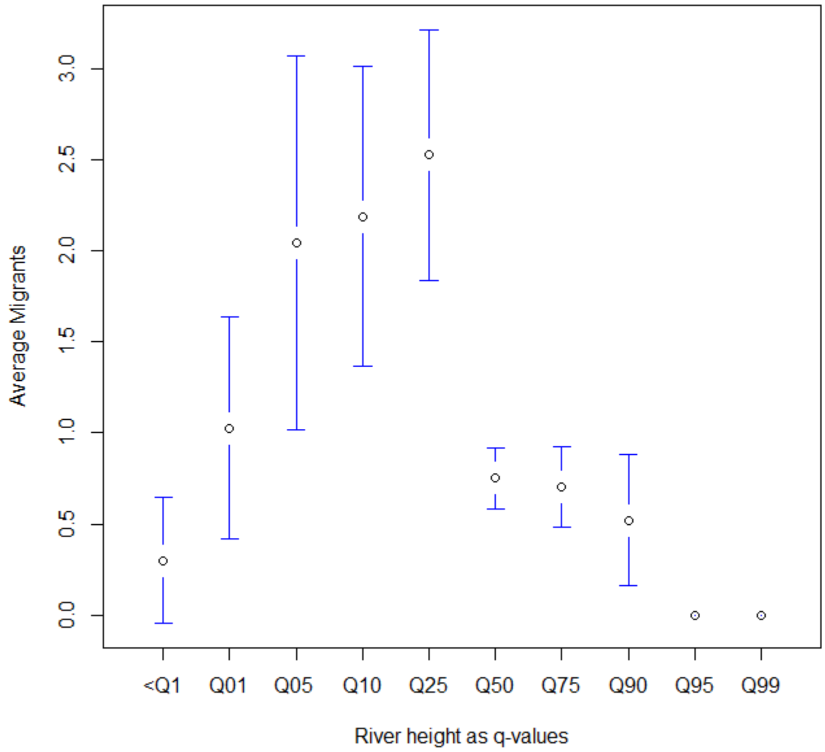

Figure 3.5. Average number of migrants per day per river height category. Whiskers represent 95% confidence intervals.

3.6 Relationship between river height, turbine operation and upstream fish passage during peak migration river height.

Based on the observation that optimum (based on daily average migrants) upstream migration occurs at between Q05 and Q25 (Section 3.5), a final model was run on the data incorporated by those categories. The results of this model are presented below in Table 3.5.

Table 3.5. Relationship between river height, turbine operation and upstream fish passage

Interaction	d.f.	z.	p.
MODEL 6 *: Upstream migrants ~ weir height (Q05-Q25)*turbine operation*			
a. Weir height	197	-0.237	ns
b. Turbine	196	3.191	0.001
*c. Height * Turbine*	195	-1.326	ns
MODEL 7 *: Upstream migrants ~ weir height (Q05-Q25)*turbine operation*			
a. Intake height	197	-0.177	ns
b. Turbine	196	3.152	0.001
*c. Height * Turbine*	195	-1.249	ns

As with previous models there remains a difference between the numbers of migrants during alternate turbine operation states, with more migrants during ON phases. However once again, no significant impact of turbine operation on the relationship between river height and passage was observed, and the only significant difference apparent is the difference in migrants between turbine states.

4 CASE STUDY RESULTS.

The maximum river height recorded during the experimental period was 110.9cm on the 25th of September, while the lowest was observed 5 days later on the 30th (7.62cm). A total of 327 fish successfully passed the weir, with the maximum number of fish passing on the 14th of November (21 fish). However, once fish counts from days with both turbine operation states occurring were removed the total count of upstream fish passage was 276. Daily fish passage count (with river heights for comparison) throughout the experimental period is presented in Figure 4.1.

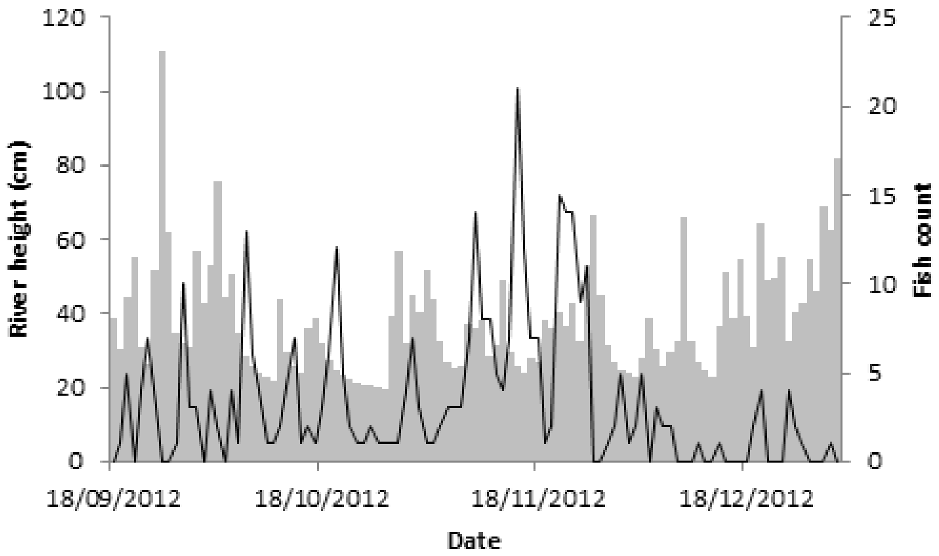

Figure 4.1. River height and fish passage at Locks Weir. The background bar chart (left axis) presents average daily river heights, while the daily count of fish passages (right axis) is presented in the foreground.

4.1 Relationship between river height, turbine operation and fish passage during experimental period.

Average river height and fish passage for turbine operational states is presented below in Table 4.1. The Settle Archimedes screw generated power during approximately 27% of the survey period. This departure from the proposed 50:50 (ON:OFF) design resulted in only 36% of fish passes occurring during the ON phases although, on average, more fish successfully passed Locks Weir during turbine operation days. However, average river height was higher during turbine operation than turbine “OFF” periods, and the attempt to have controlled for river height/turbine impact may have been compromised.

Table 4.1. Average river height and fish passage during turbine operational states.

Variable	Turbine On	Turbine Off
Average daily upstream migrants	4.9 (± 4.8)	3.29 (± 3.95)
Average daily river height (cm)	42.41 (± 13.04)	32.38 (± 11.96)

GLM output showing the modelled relationship between river heights, fish passage and turbine operation during the experimental period is shown below in Table 4.2.

Table 4.2. Relationship between river height, turbine operation and upstream fish passage during experimental period. Although a relationship exists between river height, turbine operations and migrations individually, there is no significant difference in the relationship between river height and passage during alternative turbine operational states.

Interaction	d.f.	z.	p.
MODEL 8 : *Upstream migrants ~ weir height*turbine operation*			
a. Height	72	-2.2	0.02
b. Turbine	72	1.9	0.05
*c. Height * Turbine*	72	-1.53	ns

Although there was a significant relationship between river height and fish passage (increasing flows led to a reduction in fish passage highlighting that, over a certain threshold, passage ceases) and a significant difference in the mean daily fish passage during the alternative turbine operation states, there was no significant difference in the relationship between flows and fish passage during turbine operational states. This interaction (Model 8C) is illustrated below in Figure 4.2.

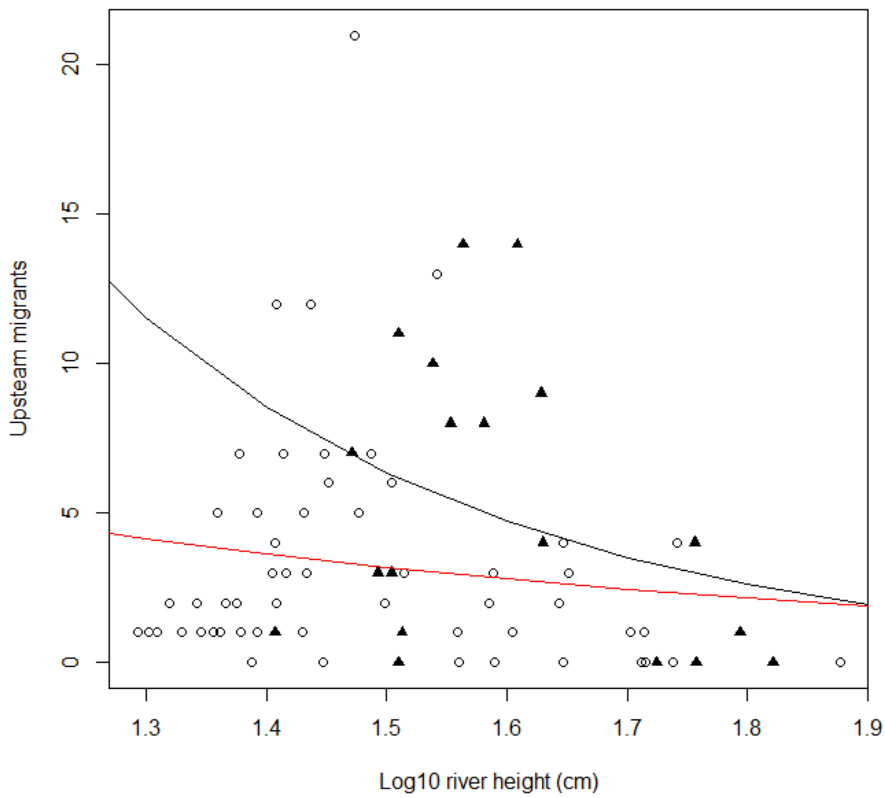

Figure 4.2. The relationship between river height (log10) and fish passage during turbine "ON" state (black line) and "OFF" state (red line). There was no significant difference between the regression slopes for either turbine state (see Table 4.2). Although likely that the highest count of upstream migrants is an outlier, removal of this point would simply have increased the similarity between the two slopes and it was therefore not removed.

4.2 Relationship between River height frequencies and fish passage

Using the Q-values developed in Section 3 (see Table 3.3), river heights were allocated to flow range bins (categories) and a comparative model developed to examine the relationship between river height category and passage over Settle Weir (with fish passage data from the counter at Locks Weir being used as a surrogate for passage at Settle Weir). The mean daily fish passage per river height category is illustrated below in Figure 4.3.

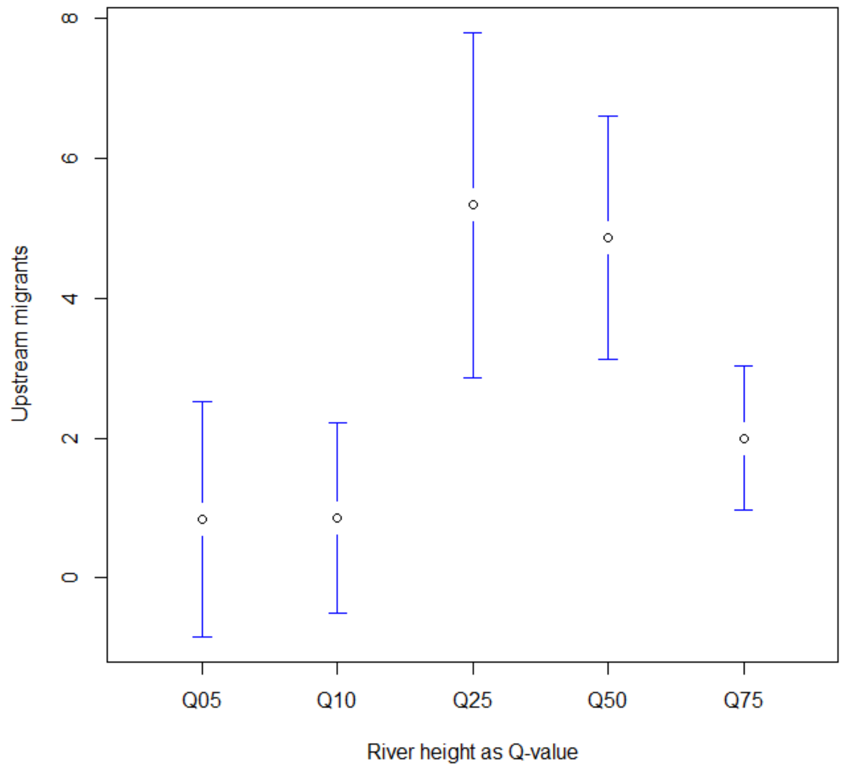

Figure 4.3. Average number of migrants per day per Q-category during the experimental period. Whiskers represent 95% confidence intervals.

In common with the results from the meta-analysis, frequency analysis from the case study implies that there are threshold values of river height (and by proxy, river flows) that trigger migration. There were significant differences between the number of migrants within river height categories (see Table 4.3 below); however turbine operation did not interact in a significant manner with these relationships (GLM, upstream migrants ~ Q height category*turbine, d.f. = 68, p = ns)

Table 4.3. Categorical GLM model investigating the relationship between frequencies of river height and fish migration (based on comparison with Q05 values). Addition of an interactive turbine operation factor resulted in no significant difference between the numbers of fish migrating within each Q category during alternative turbine operation phases.

Interaction	d.f.	z.	p.
MODEL 9 : *Upstream migrants ~ Q height Category*			
Q10	69	0.047	ns
Q25	69	4.047	<0.0001
Q50	69	3.879	<0.0001
Q75	69	1.803	ns

The number of migrants increased significantly during Q25 and Q50 periods compared to lower and higher river height periods. Although similar to the pattern observed in Section 3.5, the elevated migration occurring under Q50 values during autumn 2013 is not typical of the long term pattern seen in the earlier section, suggesting that the pattern of migrations and flows observed during the experimental period may be atypical of the long term pattern on the Ribble.

5 DISCUSSION

5.1 Meta-analysis

The results presented do appear to demonstrate that the turbine is not having a major impact, with fish commonly found upstream of the Settle Weir. However, there are a number of important considerations which must be taken into account when interpreting the results of the meta-analytical component of this study. Firstly, it should be recognised that the operation of the turbine under higher flows is likely to have had a bearing on the results and, although there is a relatively even split of ON and OFF, mean river heights during turbine operation days were almost twice that of OFF days (nonetheless it is understood that not all days will have been conducive to fish passage). Secondly conclusions are tempered somewhat by the necessary constraints placed on the study; namely the limited study period (three years overall data availability and only the period encompassing approximately 80% of the migration run has been included) and the location of the recording apparatus (at Locks weir) being one kilometre distant from the location of the turbine (Settle weir). Furthermore, this data has not been collected with the express purpose of studying the impact of turbine operations, and as such will be subjected to a range of other factors (such as declining adult returns). There is also a fundamental lack of robust scientific information on the overall impact of Archimedes turbines on salmonid populations and it has not proved possible to contextualise the results from this study within a wider body of scientific literature. However, this highlights the importance of the current study.

Due to the manner and form of the data, it has not proved possible to assess other, more subtle, potential impacts. The analysis undertaken could only attempt to understand the relationship between river heights, turbine operation and fish migration at a relatively crude level given the distance between the fish counter at Locks Weir and the turbine at Settle Weir. There was no investigation into the effect of hydromorphologically-mediated impacts of the impoundment and turbine operation on adult refuges and juvenile salmonid habitat above and below the weir; potential increased mortality due to delays in migration and increased predation caused by reduced flow rates through the fish pass; and the effect of increased attraction flow from the turbine outflow. Furthermore no investigation could be undertaken into the impact on seaward migrations of salmonids (kelts and smolts) or the impacts on other diadromous fish species which will require passage of the weir, such as lamprey and eel. Given the limitation of the present data set, investigations of these interactions would require, at a minimum, increased and dedicated monitoring and, for certain questions, a dedicated experimental design with similar non-turbine weir locations for baseline comparison and operational control of the Settle turbine.

While robust statistically-based inference may be unachievable with this current dataset, due to issues regarding the collection of the data, the potential collinearity between turbine operation, fish passage, and flows; the data examined during the present study do facilitate discussion on the possibility of some of these factors affecting salmonid populations. In the case of residence time/retarded passage, the pre-construction impact assessment (Kibel, 2008) suggested that operation of the turbine could increase passage by creating a greater attraction flow in the vicinity of the fish pass entrance, provided that the turbine and fish pass discharges are correctly co-located. Furthermore, Kibel (2008) suggested that during high flow conditions the fish pass could become functionally inoperable due to excessive high water energy levels within the individual pools (for up to 60% of the time during March to November). Within this study, the available data suggests a benefit of the turbine operation where Figure 3.4 illustrates the extended range of flows under which fish migrate past the fish counter, as well as the large number of fish which pass when the turbine is operating, although admittedly the latter is potentially an artefact of the range of flows under which the turbine operates. Therefore the case could be argued that the operation of the Archimedes Screw turbine will inevitably relieve some of the flow passing down the fish pass and thus provide greater opportunities for fish to pass via this route (a view expressed in the initial scoping report). However, the results presented herein cannot support this opinion as this concept cannot be directly tested, and any inferences drawn (with reference to the benefit of turbine operation) are merely informed speculation. Other hypotheses which cannot be tested with the current dataset include; the effect of residence time between the counter and turbine area and the overall effect of the year on year decline in returning adult salmon on the ability of statistical tests to investigate the turbine's impacts.

With regard to the hydrological and morphological impact of the turbine, it is likely to remain secondary to the impact of the weir and to morphological degradation of the reach due to urbanisation pressure. The weir is a relatively large structure with associated over-widening downstream and impounded water persisting for approximately 250m upstream of the weir. Furthermore, the channel below the weir is relatively shallow and does not contain a holding pool for salmonids to gather before attempting to pass the weir. In combination, this suite of modifications is considered likely to have the greatest impact on the upstream migratory performance of salmonids and turbine operation may not significantly add to this impact.

5.2 Case study

The case study was initiated prior to the original release of this report however the results only became available post release of the report. The case study attempted to answer questions raised during the initial investigations by analysing new data collected in a fashion that potentially controlled for collinearity between river flows, power generation and salmonid migration. However, due to factors beyond the control of the project group, it was not possible to guarantee a completely random (in terms of the river heights at which the turbine operated) programme of operation and, consequently, questions remain on the nature of the relationship between the three main variables of interest (fish passage, river height and turbine operation). Furthermore the case study was unable to investigate other relevant areas of interest, such as the failure rate of fish attempting passage during turbine operations; or confirm the assumption that the number of fish passing Locks Weir is related to migration past the Settle weir on the day (of turbine operation) in question. Therefore many of the considerations discussed in Section 5.1 remain relevant.

Nonetheless, there is some evidence which supports the overall conclusion that fish passage beyond the Settle Weir is not severely impacted by operation of the turbine. Both the relationship between river height and migrants, and the categories of river height which salmonids are using to pass the weir are unaffected by turbine operation. The evidence also supports the concept that fish prefer passage during periods of turbine operation (higher average daily counts), although maximum fish passage (highest number of migrants in a day) occurred on a day the turbine was not operating. Ultimately however, due to the persistent link between high flow and turbine operation, this study cannot categorically confirm this concept. Finally the case study supports the conclusion from the original study which identifies discrete windows of passage at which migration is most likely to occur. Further investigation into these defined phases may permit the development of an ecologically sensitive operation programme without limiting power generation at higher flows, a precautionary approach to management which would be recommended in the absence of more robust conclusions.

The presence of any impact can only be determined through a focused experimental design and this was the reason behind the addition of the case study. However an optimal design may have required a longer term approach which investigated the temporal pattern of migration past the weir under a wider range of flow conditions under either of the turbine operational states and, although the case study did attempt to address this; it could be argued that this has not been completely achieved.

5.3 Remaining considerations.

The effect of the regional decline in salmon returns has implications for establishing the effects of the turbine on migratory passage. From the simplest perspective, a reduced number of test subjects will limit the power of analyses. Also, inconsistent patterns of within-year and between-year variance in fish counts (caused by the rate of stock decline) will also limit the ability to test for population declines directly attributable to the turbine.

The case study highlighted the difficulty in establishing a programme to address those issues identified by the original analysis, and this is exacerbated by the fact that the pressure in question is not the only structure affecting passage by migrating fish beyond Settle. Therefore, to ultimately satisfy the project objectives, the Ribble site may need to be paired with a control site to provide a contrasting, non-impacted (in terms of turbine operation) description of salmonid movement. This study would also require a tagging element to understand the immediate pre- and post- passage behaviour of salmonids following interaction with structures incorporating Archimedes technologies. Finally, the spatial disparity between the turbine and the location where data is recorded would require remediation.

5.4 Implications for operational monitoring and data collection

There is a developing understanding that the concept of a constant relationship between flows and salmonid flow requirements across catchments and rivers is unfeasible (Milner *et al.*, 2012), with individual salmonid populations requiring individually tailored flow management procedures. Furthermore, hydromorphological conditions caused by the Settle Weir and turbine operation are unique to that river reach. Taken together these two considerations limit the applied regional or national relevance of the results presented here. However, issues with regard to the data collection and data quality raised herein, specifically with reference to the appropriateness of the data to investigate more subtle impacts of Archimedes screw turbine operations, are of national relevance and may highlight the need for a collective rethink on data collection and monitoring strategies. This will ensure the potential impact of such new technological applications can be robustly assessed and quantified.

6 CONCLUSIONS AND RECOMMENDATIONS

- Both the broad meta-analysis and the experimental case study present little firm evidence that operation of the Settle Archimedes screw turbine has a negative impact on the efficacy of the fish pass to accommodate upstream passage of adult salmonids.

- However, questions remain on the applicability of the data collected to assess the complete effects of the Settle turbine and to control for other factors which may mask or exaggerate the impact of its operation.

- The fixed hydromorphological effect of the weir may dominate the potential impacts of turbine operation, and it is recommended that further investigations are carried out to define the relative pressure from both.

- Until these questions have been answered, the identification of passage windows (combined with the relatively stable natural temporal pattern of salmonid migrations) suggests it may be possible to design an operational programme that limits exposure of adult anadromous salmonids to impacts from turbine operation.

- A reassessment of data collection methods for the management of salmonid populations on the Ribble in response to new pressures, such as low-head power converters, may have implications for data collection across other salmonid catchments.

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