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Acoustics of weirs: Potential implications for micro-hydropower noise

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ABSTRACT

There is great potential for the expansion of the small or micro scale hydropower network. Of the 43 thousand weirs in the UK there are only 500 consented hydro schemes. Planning applications for such schemes require a noise assessment. Noise evaluation of a proposed renewable scheme is often complicated by the turbine sites having distinct noise characteristics in the first instance, which are often caused by the weirs themselves. Three types of weir were studied: Broad Crest weirs were studied in detail; this is complimented by further studies in Flat V and Crump weirs. Flow data was collected for ten sites from the Environment Agency and the National Rivers Flow Archive to assess the collected Sound Pressure Level (SPL) and calculated Sound poWer Level (SWL) in relation to various river flows. Weir head height, width and meteorological data were also collected. It has been shown that the SPL data collection method used was the right choice, as the greatest amplitudes at the water impact interface at all weir types was recorded. SPL and SWL were found to be within a 36–82 dBz and 45–86 dBz range respectively for all weir types. These values can be used in computer simulations of sound propagation. The mean SPL and SWL difference between the weir types are 6.1 dBz and 6.3 dBz. Head height has the greatest effect on SPLs. Attenuation with distance was found to be similar to that of a free field line source in general.

1. Introduction

Energy security and an increasing understanding of environmental awareness have and are continuing to lead a trend into the diversification of energy supplies [1–3]. According to the Department of Energy and Climate Change [4], 1.5% of the United Kingdom's (UK) energy was generated from hydroelectric schemes in 2011. This department indicates that whilst the development of further large-scale hydro is limited, there is ample opportunity to develop sustainable small-scale hydro resources. Such schemes are usually “run of river” and constructed on existing barriers to the flow, usually manmade weirs [5]. Studies by Driscoll and others [5–8] indicate that there are 20–30 thousand weirs in the UK alone. Micro-hydropower is one of the energy supplies which are gaining in popularity in the UK, particularly hydrodynamic screws. This type of machine is perceived by many as having few environmental impacts in a water environment [4,9,10]; however this is contested by Ref. [11]. Globally only 5% of the small hydro potential has be utilised [12]. China has the largest installed capacity of small hydro power schemes (SHP), with some 100,000 schemes, and Europe has the second highest level of SHP installations [11]. In contrast, in the UK for example, by end of 2012, there were only some 500 consented hydro schemes [10]. Planning applications for hydro schemes have increased rapidly in recent years within the UK. Full applications more than doubled between 2009 and 2012 and pre applications increased by 1500% in the same period [10].

In addition to the Town and Country Planning (Assessment of Environmental Effects) Regulations 1988 (where an Environmental Impact Statement (EIS) including an assessment of noise levels would be required in sensitive areas [13]), previous studies have shown that along with concerns related to fish [10], there is some public concern related to the noise that these turbines will produce [14]. However, some community schemes, Torrs Hydro, believe that having turbines unenclosed is seen as positive for educational purposes [15]. Resulting in a risk of increased noise in such locations even with the masking effect of the water [16–18]. Noise evaluation at the planning stage is often complicated by the turbine sites having distinct noise characteristics in the first instance, usually caused by the weirs themselves [19]. Further to this, remembering how perceptibly loud a source is when away from

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that sound, or shown images in a public meeting for instance, may be distorted by the absence of that source [17,20–23]. Baseline data of weir sounds for comparison with that of combined weir and micro-hydropower installations is essential to accurately assess the relative contribution or detraction of the turbine to the sound environment.

The acoustic environment of water features has been studied for a variety of types, often in order to assess the benefits for masking intrusive sounds from roads [16–18]. Many of these features display similarities to weirs. Fastl [24], Al-Musawi [22] and Galbrun & Tahrir [25], indicated that increasing flow does not easily generate low frequency sounds in cascades and sloping surfaces in small to medium water features. Al-Musawi [22] continues by indicating that low frequencies can be generated by waterfalls by increasing flow, especially if they have a plane edge and that larger amounts of water produce more bubbles [22,25,26]. Extensive works by Leighton [26] examines bubbles in-depth and bubble generation at the hydraulic jump is shown in Ref. [27], which is relevant as weirs create differing amounts of bubbles and have a variety of hydraulic jump size. Al-Musawi, Galbrun & Tahrir [22,25], and Watts et al. [17] also found that the sound generation from all water features studied were mid to high frequency dominant. Width has been shown to have a small effect on Sound Pressure Level (SPL) whereas the head had a significant effect [22,25]; though changes in SPL become less and less significant with flow and height. Materials at the impact point also affect the frequency component [22,25]. For example, impact onto water increases the mid-low frequencies and impact onto hard materials (stone or concrete) or combined water and stone for example increases the higher frequency ranges. Fastl [24] conducted studies on stepped and sloped waterfalls, finding a near linear relationship for stepped waterfall in SPL, with increasing flow, whereas flow did not significantly affect the loudness of sloped waterfalls. Studies have also been carried out in terms of perception of water sounds, relating to the masking effects of traffic sounds, for example [16].

There are, however, only a very limited number of studies investigating the acoustics of micro-hydro turbines. Johnson et al. [19] examined both the Sound poWer Level (SWL) and the SPL of a micro-hydro turbine and Broad Crest weir. Other data are from manufacturers but rather limited. The limitation of such data often cause great difficulties in estimations of acoustic impacts during planning stage (e.g. Ref. [14].)

This paper will provide information on the existing sound environment around weirs, essential for evaluating the alteration due to the installation of a hydro power turbine. The evaluation of the sound environment around micro-hydropower turbines is essential to assessing a scheme's viability.

With this and the aforementioned in mind, this paper, as part of a larger research project, aims to evaluate several weir types in order quantify the SPL and SWL characteristics, which are important for the understanding of the acoustic effects of weirs, given that existing work has been very limited. It is important to calculate SWL data, for comparison of pre and post development, whether physically or computer simulated, as SWL data is used to determine SPL at a given source-receiver distance in any environment and hence the level of nuisance from the sound [28]. This paper will examine the SWLs and spectral analysis of ten weirs at various river flows and examine the near field environment in order to help to understand the acoustic environments around weir sites. The spatial distribution of several weirs will be shown. Overall, the following questions will be answered: What are the SPLs and SWLs of different weir types? What effect do flow, head, width and type of weir have on SPLs? Are there any correlations between these parameters and SPLs by frequency? What are the spatial distribution characteristics of noise around the weirs?

2. Methods

2.1. Case study sites

A weir, in this paper manmade, is a dam where there is little or no storage, and the water flows continuously over the crest; it can be described as a run of river feature which does not exceed the height of the river banks, but traverses the entire width [27]. There are many types of weir and some of the most common ones can be found in the literature [29,30] along with idealised sketches. Three main types of weir from these were chosen, namely Broad Crest (BC), Crump (CR) and Flat V (FV). The ten weir sites (A-I) and (Z) studied are shown in Figs. 1 and 2. These were chosen as they are reasonably common on UK rivers [29]. The National Rivers Flow Archive (NRFA) [31] from the Centre for Ecology and Hydrology (CEH) and the Environment Agencies (EA) HiFlows pages [32] were used to identify gauged weir sites and flow data.

Table 1 shows the summary widths, water head height and flow ranges [33] of the nine main weirs (A-I). The table also shows ten year flow data for river mean, 95 percentile and 10 percentile flows [34].

2.2. Measurement method

2.2.1. Near field sound pressure level

The methodology for SPL data collection was tested at three sites, B, C & Z; one Flat V, one Broad Crest (stepped) and one Crump weir, as shown in Figs. 1 and 2. This was to develop and ensure that the method used to measure the greatest source of sound at the weirs, in subsequent data collection periods at the nine main sites, was taken from the loudest point. The measurement points were arranged at 2 m intervals starting at 4 m above the weir crest and ending at the last white water turbulence river interface. As expected, the greatest sound generation is at the water impact point, as annotated in Fig. 2. Therefore, extra measurement points at the water impact point from the falling water into the weir pool were taken. For the stepped Broad Crest weir a change in the sampling method was utilised as there were numerous water impact points, measurement points were taken at 1 m, 3 m and 4 m.

The main study SPL measurements were taken from a suspended microphone receiver, (receiver B in Fig. 2) at an average of 1.6 m above the water's surface, depending on the hydraulic wave position. The distance from the river bank was between 2 and 4 m, which was dependent on river bank height and the angle of inclination. A reference receiver point was on the bank in line with the weir crest (receiver A in Fig. 2) approximately 1 m from the bank top. This was to test that the suspended microphone at a height of 1.6 m above the main water impact point was producing higher amplitudes than possible extraneous sounds at site. At each of the nine sites, three, 30-s samples were recorded on four days at four different flows; these samples were then divided into three 5-s samples, excluding the beginning and ends of the clips and any noted external noise periods.

Sound was recorded using class 1 microphones on the Symphonie and NetdB systems (01 dB- Metravib, France) [35]. The SPL, un-weighted (dBz) in 1/3 octaves, was measured at the nine main sites (sites A-I).

Temperatures on the sampling days were between 17 and 23 °C on the first three sampling days and 12–20 °C on the fourth. Wind speeds were <5 ms^{-1}on all sampling days and generally tended to zero with gusts up to 5 ms^{-1}. Wind direction had a south, southwest tendency on the sampling days.

SPSS 20 was utilised to perform statistical analysis on the SPL data presented in the results [36].

Fig. 1. Images of the nine main weir sites. Sites A, C, D, H and I are variations of Broad Crest Type; sites B and F are Flat V type and sites E and G are Crump type weirs.

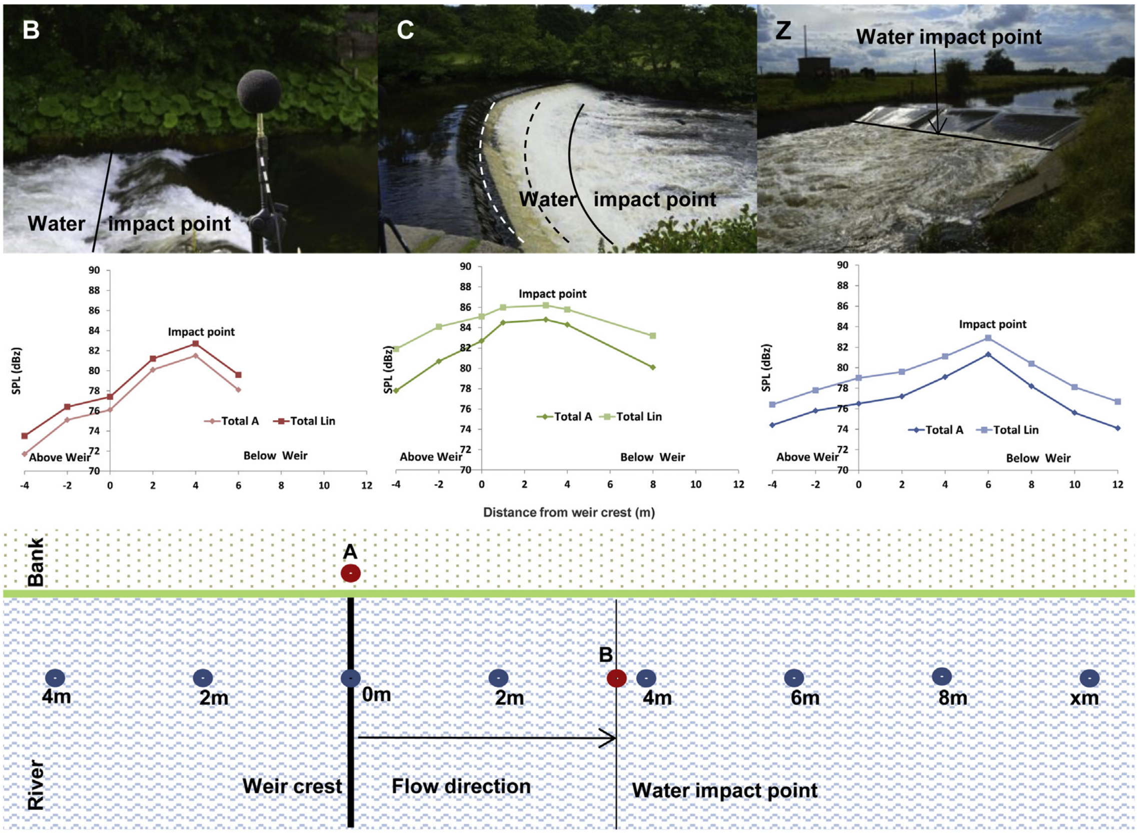

Fig. 2. Sound pressure level methodology test sites: B (Flat V), C (Broad Crest) and Z (Crump). The solid black line denotes main water impact point dashed lines indicate example of other impact points. Central graphs show SPL with distance from weir crest. The lower schematic drawing demonstrates the approximate horizontal measurement of the receiver points along the river (not to scale). These receivers are a minimum of 2 m from bank at a height of 1.6 m above the water's surface. Receivers in red, (A) is the reference receiver on the bank and (B) is the additional water impact point receiver. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Summary of measured width, head and flow range during measurements and 10 year means by site and weir type.

Measured Data					NRFA[b] Data		
Site	Type	Width (m)	Head range (m)	Flow range[a] (m^3S^{-1})	10year Mean (m^3S^{-1})	10year Q95 (m^3S^{-1})	10year Q10 (m^3S^{-1})
A	Broad crest	26	0.50–1.20	2.57–6.06	3.3	1.0	6.1
B	Flat V	10	0.30–0.75	2.57–6.06	3.3	1.0	6.1
C	Broad crest	37	1.80–2.10	3.40–15.50	6.3	1.5	14.0
D	Broad crest	46	0.20–1.30	18.17–74.40	35.0	8.0	78.0
E	Crump	35	0.30–0.50	11.00–27.80	18.2	5.2	39.2
F	Flat V	11	0.15–0.50	1.24–2.99	2.1	0.5	4.7
G	Crump	12	0.98–1.20				
H	Broad crest	19	2.00–2.14				
I	Broad crest	12	2.00–2.40	0.50–1.68	1.4	0.3	2.9

[a] [32].
[b] >[33].

2.2.2. SWL Calculation using SPL measurements

From earlier pilot work [19] it was determined that 30-s samples would be sufficient so three, 30-s samples were recorded and divided to test for deviation and eliminate any extraneous sounds where possible. The source-receiver distance was on average 1.6 m and the smallest weir 10 m wide; therefore, the SWL equation (1) below was utilised, for a line source close to a reflecting surface, although some weirs by their nature do not have a single flat face and varying degrees of inclination are apparent as shown in Figs. 1 and 2. The additional reflection from these other surfaces may have an effect; however this is normally only within 3 dB maximum.

$$\mathrm{swl}\pm 0.3 = \mathrm{spl} + 10\log(d) + 5 \qquad (1)$$

where d = water impact point/source–receiver distance 1.6(m) average with a range of 1.5–1.7(m), the 0.2 m difference in range would account for a ±0.3 dBz difference. As this is very small it has been omitted within the results.

2.2.3. Spatial distribution method

The NetdB system with class 1 microphones was utilised to collect sound distribution data at three sites, B, C and Z, see Figs. 1 and 2. A basic measurement plan was followed, as shown in Fig. 3 and explained below.

The receivers were placed approximately 1 m from the bank top/water's edge at a height of 1.6 m at 0, 5, 10, and 20 m from the weir crest. Again, three sets of 30-s samples were taken; these were then trimmed to three 5 s intervals to eliminate extraneous vehicular sounds that were time noted at site, and provide standard deviations for the spectral analyses. Data was collected once at each of the sites.

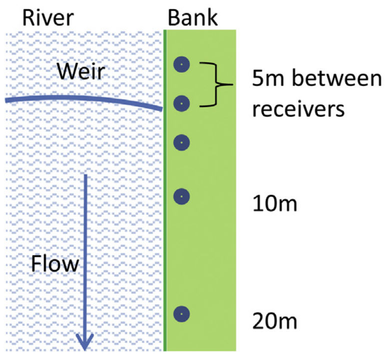

Fig. 3. Sound distribution measurement plan, where each circle is a receiver point with a height above ground of 1.6 m and at a distance of 0, 5, 10 and 20 m relative to the weir crest (not to scale).

3. Results and discussions

3.1. Weir sound pressure level and sound power level

SPL and SWL for all the sites, separated by weir type, are shown in Figs. 4 and 5, respectively. The results of all weirs combined are shown in Figs. 4D and 5D, indicating the measurement range at each frequency alongside the mean result.

Figs. 4D and 5D show that SPLs were found to be within a 36–82 dBz and SWLs 45–86 dBz range for all weir types across the frequency range measured. Total mean dBz (combined frequencies) values indicate that mean SPLs for the weirs are between 63 and 71 dBz With Broad Crest weirs being consistently louder at 67–71 dBz compared to 63–66 dBz for Crumps and Flat V. The mean difference of the SPL and SWL, between all weir types averaged over all frequencies is approximately 6 dBz for both SPL and SWL. Total mean SWL values (across all frequencies) show that the weirs fall between a range of 70–78 dBz. Broad Crests range between 74 and 78 dBz, Crump 71–73 dBz, and Flat V 70–72 dBz. Encouragingly the mean variation in SWL shown in Fig. 5D is small, therefore it should be possible to use this data to predict the SPL and SWL at other weir environments within the size range tested here. Within each weir type the variation is less than 4 dB. This result will provide baseline data for evaluating the changing sound environment from the installation of a micro-hydro scheme. There is some variation between weir types with Broad Crest weirs showing higher SPLs than Flat V and Crump weirs. The Flat V has consistently the lowest SPL, whereas the Crump weirs behaviour depends on frequency; being closer to the Flat V at frequencies (>100 Hz) and closer to the Broad Crest frequencies (<100 Hz).

The higher mean SPLs and SWLs of the Broad Crest weirs are likely to be a function of their size in comparison to the other weir types (see Table 1). Observations indicated that the mean amplitude difference between Crumps and Flat V is likely to be a function of the water interface profile differences and bubble burst.

Figs. 4 and 5 show there is a greater dynamic range at low frequencies particularly for Broad Crest weirs. Considering the variation across the frequencies the crump profile is the flattest, with SPL varying the least across the different frequencies. Whereas the Flat V profile has the lowest SPL at the lowest frequencies of the three weir types and the Broad Crest has the highest SPL occurring at 1.6 kHz.

Due to the small number of sites considered the greater variation in the SPL at lower frequencies (<125 Hz) may be due to the individual site characteristics that result in different waterfall effects (e.g. drop height, weir pool depth, cavitation, impacting surfaces.). For instance, impacting surfaces such as the concrete ramp at site I, steps and boulders at site C increase the high frequency components of these profiles. Furthermore, the site with the lowest values at these low frequencies was D for the Broad Crest type. Considering the sites (Fig. 1), it can be seen that site D was a drowned weir, in comparison to site A which has a large head drop. The SPL recorded at site D corresponded to water splash elements generated by shear effects with the stone walled riverbank, and there is little cavitation, bubble burst and impact sound at site D due to the presence of a standing water wave and surface water flow profile and therefore less low frequency sound. Site A, in contrast, is a ‘typical’ Broad Crest weir with a large curvilinear impact point and greater head height, and thus increased cavitation occurs in comparison, with more energy, leading to higher amplitudes (<25 Hz and <125) in relation to site D. Flat V weirs in comparison tended to be smaller in size. Crump weirs have a

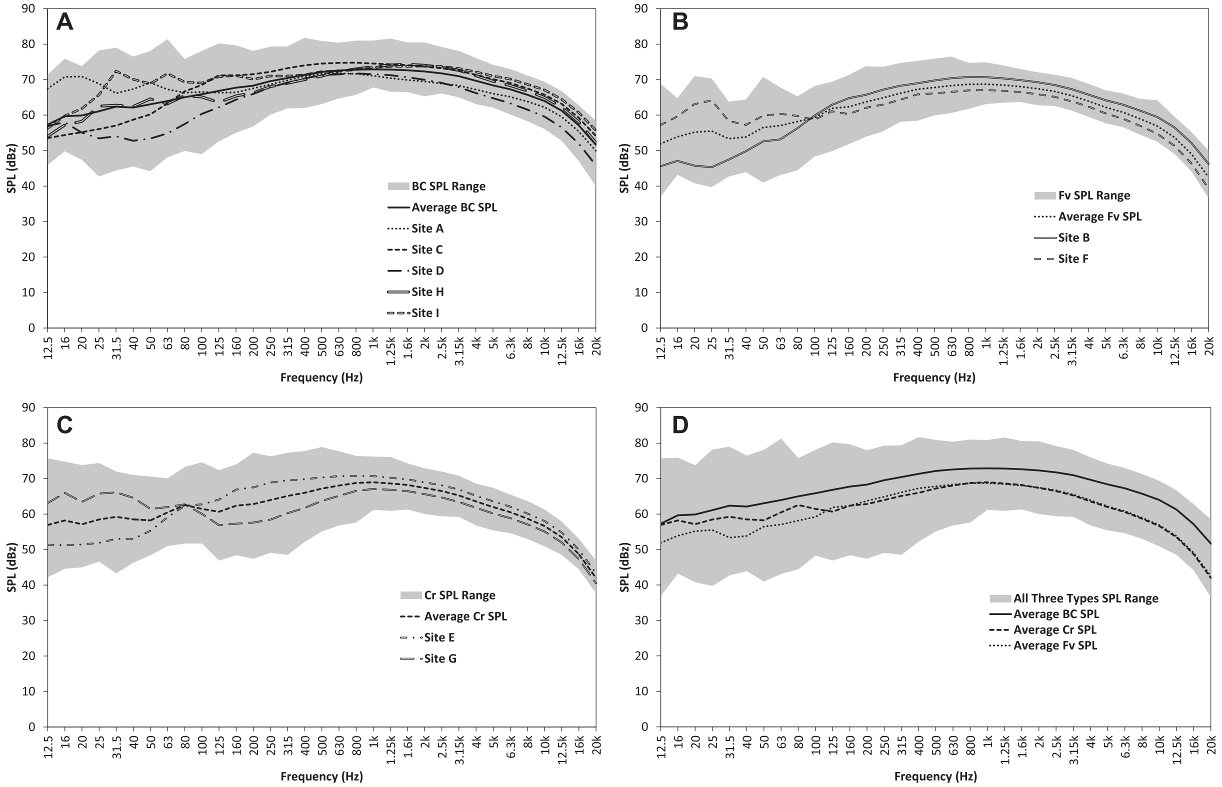

Fig. 4. Measured weir sound pressure levels. The grey shaded area indicates the total dynamic range (over 5 s) of SPL (dBz) values by 1/3 octaves recorded from the measured weirs, by type and site, with the dashed/dotted and solid black lines indicating the mean values. 4A, Broad Crest (BC); 4B, Flat V (FV); 4C, Crump (CR); and 4D, Combined plot of all types.

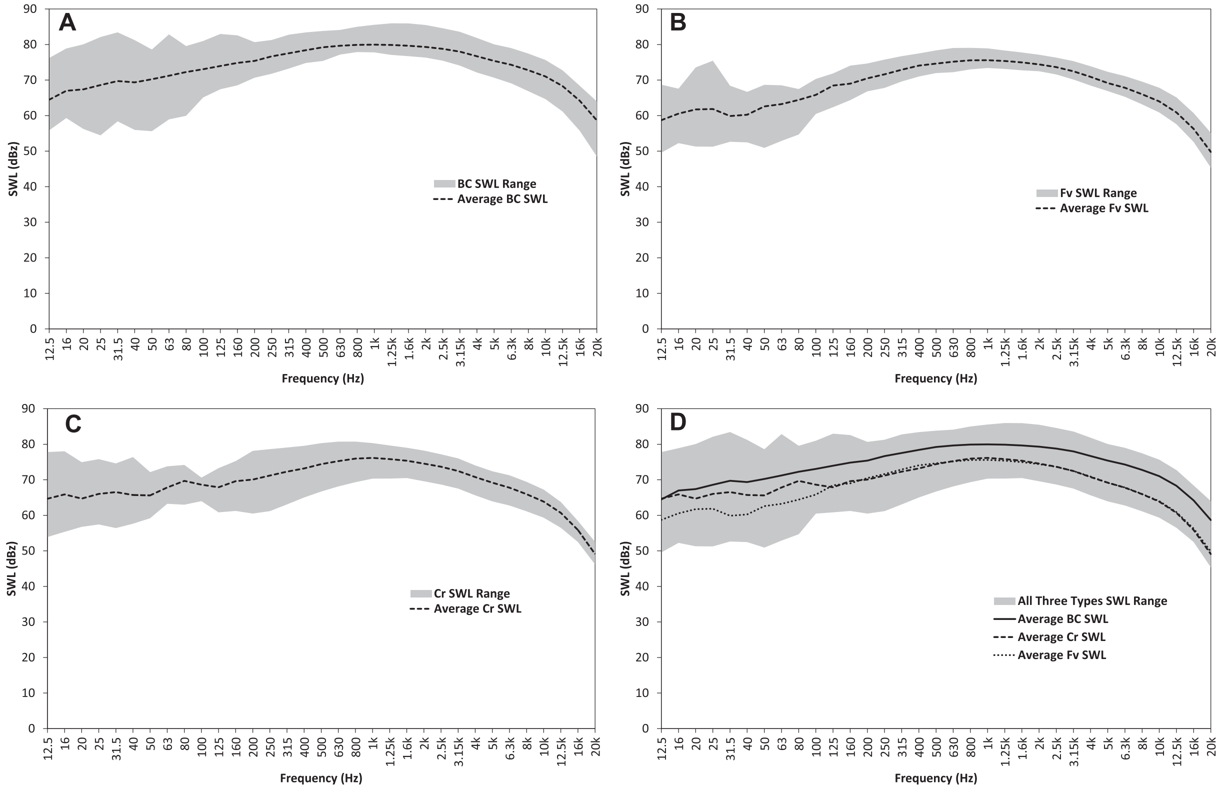

Fig. 5. Weir sound power levels. The grey shaded area indicates the total dynamic range (over 5 s) of SWL (dBz), by 1/3 octaves recorded from the measured weirs, by type, with the dashed/dotted and solid black lines indicating the mean SWL values recorded. 5A, Broad Crest (BC); 5B, Flat V (FV); 5C, Crump (CR); and 5D Combined plot of all types.

similar amplitude range to that of Flat V weirs. It is thought that this may be due to the downstream slope of the face of the weir. However, similar amplitudes in the lower frequencies of the Crump type to those observed in the Broad Crest type can be explained by the similarity of a long water impact interface.

The results above show that at all frequencies the Broad Crest weirs have higher mean SPLs and SWLs than the other weir types studied. Although at very low frequencies the measured sounds could be from far-distance sources, previous work suggests that these low frequencies (<80 Hz) are a feature of waterfall sounds [17,18]. Broad Crest and Crump both have higher values than Flat V type weirs at these frequencies; whereas, between (200–630 Hz) and (2 k–20 kHz) Flat V type weirs have higher mean amplitudes than Crumps. Figs. 4D and 5D demonstrate that on average the weir types measured have a spectrum similar to that expected of a broadband signal. Statistical tests showed that based on the estimated marginal means, that the mean difference is significant ($p < 0.05$) between most weir types, frequencies and especially between Broad Crest and the two other types at all frequencies. These tests also indicated that there was no significant difference between; Broad Crest and Crump weirs at 12.5 Hz, Flat V and Crumps at 160 Hz, 800 Hz, 1.25 k–2.5 kHz and 5 kHz. The pairwise test significance level was not adjusted for multiple comparisons as least significant difference was utilised.

3.2. *Effect size of flow, width, head and type results*

The effect size of flow, width, head, type and site on SPL, as a percentage of variance, is given in Table 2.

The effect size of these factors on SPL varies by frequency. Generally head has the greatest impact shown by the larger effect sizes in Table 2. At the lower frequencies (<80 Hz) type and flow have strong effect sizes. This is also the case at higher frequencies (>5 kHz). At some frequencies there is a notable effect from the site. The greater effect of head on SPL may be due to head height being a determining factor in cavitation and bubble jet plume size. Increased flow can also lead to lengthened bubble burst zone. However, increasing flow usually reduces head height (related to the downstream site characteristics) and hence there is a dependency between these two variables. With regards to hydropower, the louder sound from higher head heights at Broad Crest designs may mask noise generated from the scheme at frequencies (<125 Hz). Therefore, since head affects energy output there might be less concerns of changing the sound environment with larger schemes. As shown in Ref. [19], the diversion of water at lower flows, at a micro-hydropower site, reduce the low frequency component (<125 Hz) and increase the 160–20 kHz frequency components of the sound environment, thus increasing acoustical comfort as found by Watts et al. [17].

Table 2
Effect size as a percentage of the variance in SPL by frequency.

Frequency (Hz)	Flow	Width	Head	Type	Site
SPL 12.5	10.9	8.2	35.2	46.3	0.2
SPL 16	14.1	17.9	42.2	57.0	0.5
SPL 20	10.2	17.6	25.3	41.9	2.6
SPL 25	4.2	24.1	11.9	33.5	8.2
SPL 31.5	0.4	53.5	3.5	54.6	18.6
SPL 40	5.1	54.9	8.6	60.2	0.9
SPL 50	8.3	41.3	8.2	46.7	0.9
SPL 63	2.2	40.1	0.03	41.1	0.9
SPL 80	0[a]	18.9	10	27.4	1.7
SPL 100	0.1	5.1	12.1	14.7	8.0
SPL 125	0[a]	1.5	20.2	4.6	4.7
SPL 160	0.2	0[a]	31.4	15.2	9.9
SPL 200	0.2	0.6	14.1	5.3	6.8
SPL 250	0.1[a]	1.1	13.8	5.8	7.6
SPL 315	0.4	4.5	13.9	2.3	11.3
SPL 400	1.1	6.7	9.8	0.2	10.2
SPL 500	0.4	5.5	11.1	0.6	11.5
SPL 630	0.2	5.9	12.1	0.2	12.9
SPL 800	0[a]	6.4	17.2	0.1[a]	12.5
SPL 1 k	0.4	2.7	22.4	0.5	7.8
SPL 1.25 k	1.4	1.7	27.8	0.5	3.8
SPL 1.6 k	2.6	0.7	33.3	1.0	3.2
SPL 2 k	3.1	0[a]	36.2	1.6	2.6
SPL 2.5 k	3.6	0.5	38.4	2.8	2.2
SPL 3.15 k	2.8	1.6	39.4	5.6	4.1
SPL 4 k	2.9	3.7	42.2	8.1	5.7
SPL 5 k	2.9	4.9	42.6	12.0	8.7
SPL 6.3 k	2.6	7.4	41.8	15.5	11.0
SPL 8 k	2.2	8.5	39.7	18.0	14.6
SPL 10 k	2.7	10.7	37.6	20.3	17.8
SPL 12.5 k	3.5	11.4	37.4	20.9	21.3
SPL 16 k	4.7	13.4	38.0	22.3	24.2
SPL 20 k	7.0	15.1	34.0	22.9	28.0

[a] $=p(>0.05)$.

3.3. *Relationship between measured parameters and SPL by frequency*

Pearson's Correlations among width, head, flow, and their correlations with SPL by frequency and by weir type are shown in Table 3, and a selection (31.5 Hz, 2 kHz and 16 kHz) is shown graphically in Fig. 6. Significance tests in Table 3, show that the majority of correlations considered were significant ($p < 0.01$).

Table 3
Correlations of width, head flow and SPL frequency for Broad Crest Weirs.

	Width	Head	Flow
Width		−0.643[a]	0.626[a]
Head	−0.643[a]		−0.638[a]
Flow	0.626[a]	−0.638[a]	
SPL_12.5 Hz	−0.029	−0.498[a]	−0.098[a]
SPL_16 Hz	−0.198[a]	−0.394[a]	−0.196[a]
SPL_20 Hz	−0.413[a]	−0.123[a]	−0.382[a]
SPL_25 Hz	−0.698[a]	0.222[a]	−0.475[a]
SPL_31.5 Hz	−0.843[a]	0.432[a]	−0.553[a]
SPL_40 Hz	−0.815[a]	0.387[a]	−0.610[a]
SPL_50 Hz	−0.774[a]	0.375[a]	−0.617[a]
SPL_63 Hz	−0.746[a]	0.519[a]	−0.641[a]
SPL_80 Hz	−0.633[a]	0.611[a]	−0.541[a]
SPL_100 Hz	−0.449[a]	0.525[a]	−0.521[a]
SPL_125 Hz	−0.272[a]	0.457[a]	−0.502[a]
SPL_160 Hz	−0.247[a]	0.499[a]	−0.497[a]
SPL_200 Hz	−0.102[a]	0.347[a]	−0.412[a]
SPL_250 Hz	−0.074[a]	0.324[a]	−0.373[a]
SPL_315 Hz	0.033	0.273[a]	−0.341[a]
SPL_400 Hz	0.112[a]	0.199[a]	−0.279[a]
SPL_500 Hz	0.087[a]	0.227[a]	−0.281[a]
SPL_630 Hz	0.044[b]	0.296[a]	−0.267[a]
SPL_800 Hz	−0.012	0.387[a]	−0.280[a]
SPL_1 kHz	−0.164[a]	0.512[a]	−0.308[a]
SPL_1.25 kHz	−0.249[a]	0.593[a]	−0.304[a]
SPL_1.6 kHz	−0.328[a]	0.667[a]	−0.324[a]
SPL_2 kHz	−0.414[a]	0.722[a]	−0.378[a]
SPL_2.5 kHz	−0.471[a]	0.758[a]	−0.410[a]
SPL_3.15 kHz	−0.520[a]	0.787[a]	−0.462[a]
SPL_4 kHz	−0.563[a]	0.815[a]	−0.503[a]
SPL_5 kHz	−0.582[a]	0.822[a]	−0.531[a]
SPL_6.3 kHz	−0.611[a]	0.825[a]	−0.552[a]
SPL_8 kHz	−0.627[a]	0.824[a]	−0.568[a]
SPL_10 kHz	−0.648[a]	0.821[a]	−0.572[a]
SPL_12.5 kHz	−0.652[a]	0.822[a]	−0.561[a]
SPL_16 kHz	−0.661[a]	0.821[a]	−0.546[a]
SPL_20 kHz	−0.643[a]	0.773[a]	−0.497[a]

[a] Correlation is significant at the 0.01 level (2-tailed).
[b] Correlation is significant at the 0.05 level (2-tailed).

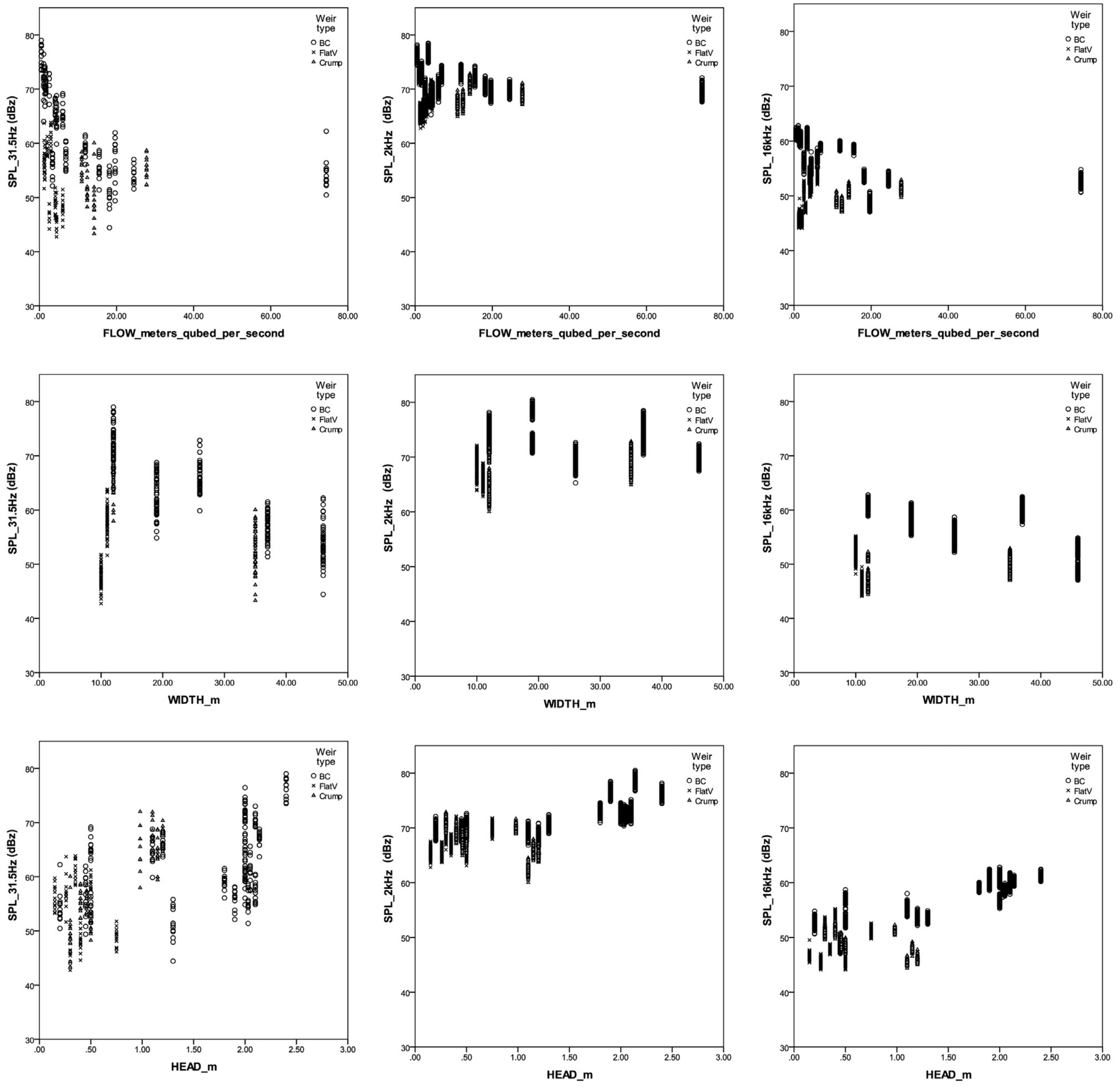

Fig. 6. A selection of the correlations as shown in Table, where the correlations shown are between SPL and: flow by weir type for a low, two high frequencies, width by weir type for a low and two high frequencies, and head by weir type for a low and two high frequencies.

In order to compare the site characteristics with SPL it is necessary to understand the relationship with each characteristic. There are significant correlations between width, head and flow respectively. This is unsurprising, as described previously, since a higher flow is likely to reduce the head. At many sites the width of the river will be related to the size of the river, and hence the flow.

Correlations between physical site characteristics and SPL are only shown for Broad Crest weirs. Due to the small number of sites in the other categories and the resulting limited variation in head and flow it was not possible to consider the relationship with site characteristics for these weir types.

For Broad Crest weirs correlations between head and SPL are very strong and positive at high frequencies (>4 kHz), indicating the higher the head the greater the SPL. The opposite effect is seen with flow which gives strong negative correlations at these high frequencies. This is expected, considering the relationship between head and flow. There are strong negative correlations between width and flow at lower frequencies (25–80 Hz). This is also shown with moderate correlations between width and SPL at high frequencies (>2 kHz), with the correlations increasing with frequency.

This work expands on and is in agreement with that of [24] and some agreement with work conducted on small-scale water features [18,19,22,25–27], where increasing flow does not easily generate low frequency sounds in cascades and sloping surfaces. All the weirs studied here were mid to high frequency dominant (>160 Hz) as [17,22,25], though lower frequencies (<125 Hz) had a high dynamic range. The effect of water impact materials, boulders, steps, concrete ramp, water; impact angle via kinetic energy differences; hydraulic jump features changes; and bubble generation as discussed by Refs. [25–27] also appears to affect the frequency component in this study. The small effect of width and large effect of head shown here was also in agreement with Al-Musawi and Galbrun & Tahrir [22,25].

3.4. Sound attenuation with distance by weir type

One third octave (average) attenuation in SPL (dBz) is illustrated in Fig. 7 at increasing distances from the weir crest along transect perpendicular to the rivers as shown in Fig. 3. The curved nature of the attenuation profiles relates to where the main water impact source is; zero metres is not the water impact point, but the weir crest. As expected, higher frequencies attenuate at a greater rate for all weir types, and upstream (negative distance on the *x* axis) has lower SPL amplitudes than downstream at the same distance (the water impact point distance being taken into account).

At the lower frequencies (<125 Hz), Broad Crest weirs tend to have the highest amplitudes, and average attenuation between the weir crest and 20 m is 3.3 dBz within a range of 2–4.4 dBz (Fig. 7 $\mathrm{BC_L}$, $\mathrm{FV_L}$, $\mathrm{CR_L}$). Flat Vs' have an average attenuation of 3 dBz and a range of 0.5–7.6 dBz and Crump have an average attenuation of 2.7 dBz in the lower ranges (<125 Hz) and a range of 0.6–5 dBz. The mid frequency ranges (160–1.6 kHz) in Fig. 7, $\mathrm{BC_M}$, $\mathrm{FV_M}$, $\mathrm{CR_M}$, have the following average attenuation and ranges respectively: 6.7 dBz with a range of 5.5–8.4 dBz; 10.2 dBz with a range of 8.1–14.6 dBz, and 6.0 dBz and with a range of 3.7–7.2 dBz. At higher frequencies (2 k–20 kHz), $\mathrm{BC_H}$, $\mathrm{FV_H}$, $\mathrm{CR_H}$, have the following average attenuations over the 20 m between the crest and receiver: 10 dBz with a range of 6.5–13.7 dBz, 12.8 dBz with a range of 10.5–14.6 dBz and 7.6 dBz with a range between 7 and 8.2 dBz. A noteworthy point here is that the range of average attenuation increases with frequency in the Broad Crest type which is in direct contrast to Flat V and Crump type weirs studied.

The average attenuation of the three weir types is ~3 dBz to a distance of L/π, and then ~6 dBz with each doubling of distance, where L is the source length. This is approximately consistent with that of a free field line source, where attenuation with distance is 3 dB to a distance of L/π, and where each doubling thereafter tends to a reduction of 6 dBz [37]. There are discrepancies with the Broad Crest stepped weir. In the distance from source to L/π the attenuation is less, and after this distance the attenuation rapidly decreases resulting in greater than 6 dBz with a doubling of distance. The average attenuation between 10 and 20 m is less than 3 dBz, which could be due to the curved nature of the weir and reflections from the weir pool or the large boulders creating further impact sound sources in the downstream section. There are clear profile differences between the three weir types studied here.

All the frequencies in Fig. 7 $\mathrm{BC_L}$ tend to follow the same curvilinear path. In contrast, $\mathrm{FV_L}$ displays both positive and negative curvilinear paths, which have a much flatter profile overall. These profiles are in all likelihood a function of near field sound effects as the microphones are well within two source lengths and within the wavelengths at these frequencies. $\mathrm{CR_L}$ frequency profiles are more tightly grouped and follow a similar frequency profile pattern as in the $\mathrm{BC_L}$ frequencies but with a less pronounced peak around the water impact point. In the mid frequency ranges (160–1.6 kHz) of Fig. 7, in $\mathrm{BC_M}$, $\mathrm{CR_M}$ and $\mathrm{FV_M}$, it can be seen that these weir types have a similar profile shape to $\mathrm{BC_L}$, $\mathrm{FV_L}$ and $\mathrm{CR_L}$, but the individual frequencies are more tightly grouped by SPL. The shape of the profiles displayed in $\mathrm{BC_H}$, $\mathrm{FV_H}$ and $\mathrm{CR_H}$ become more apparent with increasing frequency. It can be seen that $\mathrm{FV_H}$ and $\mathrm{CR_H}$ display similar shaped profiles within these ranges when compared to $\mathrm{BC_H}$.

These attenuation profiles follow the theory of higher frequencies attenuating faster, and that low vegetation also leads to

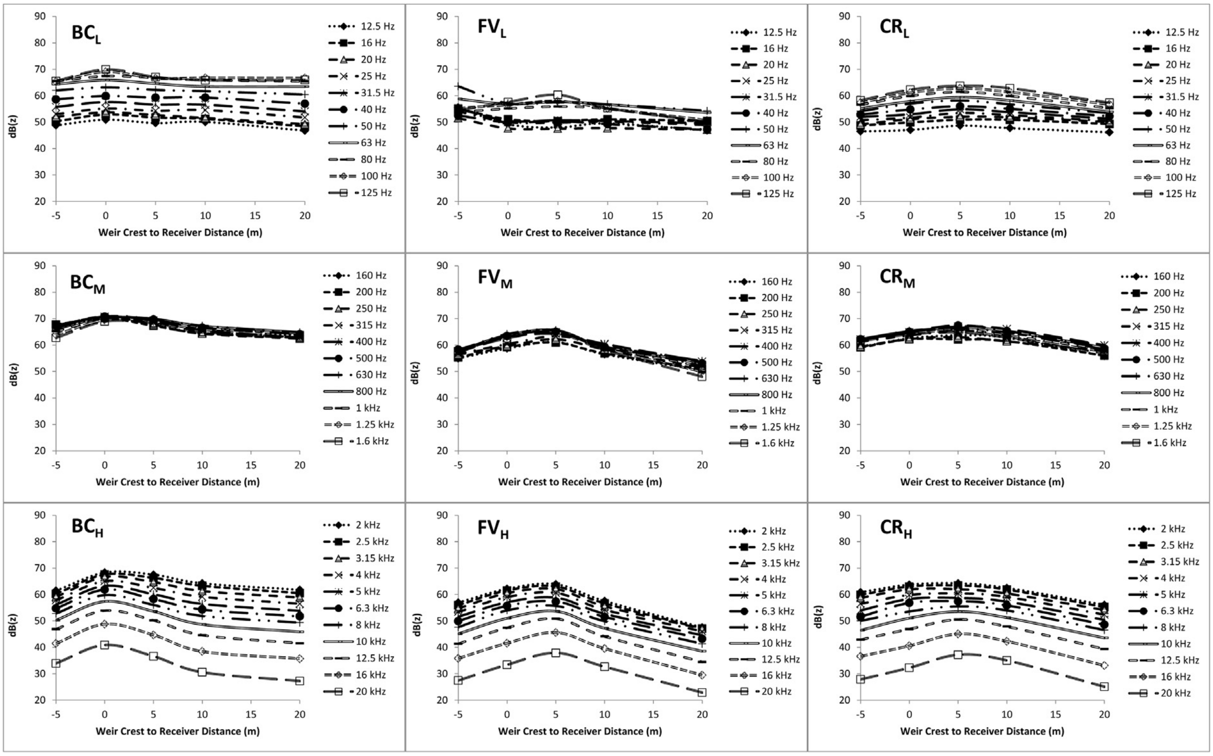

Fig. 7. The average attenuation of sound with distance, by weir type. The first column is the Broad Crest (BC) type, second Flat V (FV) and third Crump (CR). Zero metres is the weir crest, negative values are upstream of this point. Each plot is denoted by their abbreviation followed by a suffix of $_{\mathrm{L}}$ for Low frequencies (<125 Hz), $_{\mathrm{M}}$ for mid frequencies (160–1.6 kHz) and $_{\mathrm{H}}$ for high frequencies (>2 kHz) e.g. $\mathrm{BC_L}$ Broad Crest Low frequency (<125 Hz.). These denotations do not represent true low, mid and high frequency categories but instead formed a convenient split point for illustrative purposes.

greater attenuation rates in the high frequency ranges [38]. All the sites used in the spatial section had open field situations covered in grass ranging from 0.1 m to 0.4 m. These profiles, Fig. 7, lend weight to previous results, see Fig. 4, which show that Broad Crest and Crump have similar dynamic ranges and amplitudes. This is probably due to the physical similarities of the water impact profiles generated by these weir types as seen in Figs. 1 and 2. As some larger Crump weirs are capable of generating larger low frequency components (<125 Hz) like Broad Crest weirs, installing hydro turbines on these type of weir would be the least likely to generate nuisance.

4. Conclusions

Growing interest in low head hydro power means there is increasing demand to evaluate the risk of noise from such schemes. However, rivers are noisy places. In order to thoroughly investigate the impact of a hydro scheme on the sound environment it is necessary to first understand how rivers themselves contribute. This study has carried out a comprehensive field study to evaluate the sound environments around a selection of typical low head weir sites. The study systematically answers: what are the SPLs and SWLs of the weir? What is the effect flow; head, width and type of weir have on SPLs and their correlations? And what are the spatial characteristics of noise around the weirs? The methods employed in this study enabled these questions to be answered. The main findings are:

- Total dBz values indicate that SPLs are between 63 and 71 dBz; by weir type this being 67 to 71 dBz for Broad Crest and 63 to 66 dBz for Crumps and Flat V.
- The mean SPLs range of the three weir types across all frequencies are between 36 and 82 dBz with a SPL range of 40 dBz in frequencies (<100 Hz), around 30 dBz between (100–500 Hz) and approximately 20 dBz in frequencies (>500 Hz).
- Total dBz SWL values shows that the weirs fall between a range of 70 and 78 dBz. Broad Crests range between 74 and 78 dBz, Crump 71 and 73 dBz, and Flat V 70 to 72 dBz. The derived weir SWLs given here can be used in hydropower simulations for future renewable developments using manufacturers' turbine SWL results. In fact this paper forms part of a larger body of work including acoustic simulations of hydropower.
- Mean SWLs ranges (minimum–maximum), across all frequencies, are between 45 and 86 dBz, with a SWL range of up to 30 dBz in the frequencies <125 Hz, and around 20 dBz between 160 and 20 kHz. These values could be used in micro-hydropower noise simulations within the flow ranges 0.5 m^{3}s^{-1} & 74.4 m^{3}s^{-1}, head heights 0.5 m & 2.1 m, and widths of 12 m & 46 m.
- The mean SPL and SWL difference between the weir types are 6.1 dBz and 6.3 dBz, respectively.
- Head has the greatest effect on SPL though, type and width have a large effect at frequencies <80 Hz and some effect at frequency ranges >5 kHz. Special features at each site were found to contribute to the size effect in the 160–20 kHz frequency ranges. Flow was found to have a small effect on SPL amplitudes.
- The expected strong negative correlation between flow & head was found within the Broad Crest type, and strong to very strong positive correlations at frequency ranges above 4 kHz between SPLs & head were also found. More SPL data is required for validation of correlation between flow and SPL for Flat V and Crump weirs.
- The average attenuation of the three weir types is approximately consistent with that of a free field line source; however, the Broad Crest weir type is less consistent.

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References

[1] Lior N. Energy resources and use: the present (2008) situation and possible sustainable paths to the future. Energy 2010;35:2631–8.
[2] Wicks M. Energy security: a national challenge in a changing world, DECC. Crown Copyright London; 2009.
[3] Asif M, Muneer T. Energy supply, its demand and security issues for developed and emerging economies. Renew Sustain Energy Rev 2007;11:1388–413.
[4] Department for Environment and Climate Change DECC. Harnessing hydroelectric power: how hydroelectric power works, regional schemes and information on installing your own micro-hydro scheme. DECC Crown Copyright; 2013 [Online] 1.5.2013, https://www.gov.uk/harnessing-hydroelectric-power.
[5] Paish O. Small hydro power: technology and current status. Renew Sustain Energy Rev 2002;6:537–56.
[6] Driscoll HJR. Micro-hydro power in Dorset: a re-assessment of potential installed capacity. Earth Environ 2008;3:52–114.
[7] Reynolds TS. Stronger than a hundred men. Baltimore & London: J. Hopkins University Press; 1983.
[8] Salford Civil Engineering Ltd. Small scale hydroelectric generation potential in the UK. Report No. ETSU-SSH-4063. London: Dept. of Energy; 1989.
[9] Department for Environment and Climate Change DECC. Increasing use low-carbon technol feed-in tariffs scheme. DECC Crown Copyright; 2013b.
[10] Environment Agency. EA, hydropower. Environment Agency, Crown Copyright; 2013 [Online] 4.5.2013, http://www.environment-agency.gov.uk/business/topics/water/32022.aspx.
[11] Abbasi T, Abbasi SA. Small hydro and the environmental implications of its extensive utilization. Renew Sustain Energy Rev 2011;15:2134–43.
[12] IRENA. Renewable energy technologies: cost analysis series: hydropower. International Renewable Energy Agency; 2012. Online.
[13] Town and country planning (assessment of environmental effects) regulations 1988 in: SI 1199. Crown Copyright; 1988.
[14] Acoustics ZBP. Ham hydro CIC project, Teddington, Richmond (application number11/3908/FUL): revised noise impact assessment. Ref 3207-R01. London Borough Richmond Upon Thames; 2013 [Online] 16.5.2013, http://www2.richmond.gov.uk/plandata2/ShowCaseFile.aspx?appNumber=11/3908/FUL&DocTypeID=6#divShowDocuments.
[15] Peak Digital Limited. Torrs Hydro New Mills: 2009.
[16] Jeon JY, Lee PJ, You J, Kang J. Perceptual assessment of quality of urban soundscapes with combined noise sources and water sounds. J Acoust Soc Am 2010;127:1357–66.
[17] Watts GR, Pheasant RJ, Horoshenkov KV, Ragonesi L. Measurement and subjective assessment of water generated sounds. Acta Acust United Acust 2009;95:1032–9.
[18] You J, Lee PJ, Jeon JY. Evaluating water sounds to improve the soundscape of urban areas affected by traffic noise. Noise Control Eng J 2010;58:477–83.
[19] Johnson N, Kang J, Steve S, Hathway A, Dökmeci P. Acoustic impact of an urban micro hydro scheme. In: World renewable energy congress. Linköping, Sweden: Linköping University Electronic Press, Linköpings universitet; 2011. pp. 1448–55.
[20] Yost WA. Auditory perception of sound sources. New York; London: Springer; 2007.
[21] Mershon DH, Desaulniers DH, Kiefer SA, Amerson TLÿ, Mills JT. Perceived loudness and visually-determined auditory distance. Perception 1981;10:531–43.
[22] Al-Musawi TTA. Acoustical design of water features and their use for road traffic noise masking. Edinburgh: School of the Built Environment, Heriot-watt University; 2012. p. 260.
[23] Yang W, Kang J. Acoustic comfort evaluation in urban open public spaces. Appl Acoust 2005;66:211–29.
[24] Fastl H. Recent developments in sound quality evaluation. In: Proc. of Forum Acusticum. Budapest, Hungary: AG Technische Akustik, MMK, TU München; 2005. pp. 1647–53.
[25] Galbrun L, Ali TT. Acoustical and perceptual assessment of water sounds and their use over road traffic noise. J Acoust Soc Am 2013;133:227–37.
[26] Leighton TG. The acoustic bubble. San Diego; London: Academic Press; 1997.
[27] Csiki S, Rhoads BL. Hydraulic and geomorphological effects of run-of-river dams. Prog Phys Geogr 2010;34:755–80.
[28] Maling GCJ. In: Rossing TD, editor. Springer handbook of acoustics. New York, N.Y.: Springer; 2007.
[29] Gopi S. Basic civil engineering. New Delhi: Dorling Kindersley (India) Pvt. Ltd.; 2010.
[30] Rickard C, Day R, Purseglove J. River weirs: good practice guide. Report No W5B-023/HQP. In: DEFRA/Environment Agency Flood and Coastal Defence R&D Programme. Bristol: Environment Agency; 2003.
[31] Natural Environment Research Council (NERC) Centre for Ecology and Hydrology (CEH). The national rivers flow archive. search by regional maps. North-East England: NERC; 2012a.

[32] Environment Agency. EA, HiFlows: maps. Environment Agency, Crown Copyright; 2012a.
[33] Environment Agency. In: Johnson N, editor. National data requests: flow data. Environment Agency, Crown Copyright; 2012b.
[34] Natural Environment Research Council (NERC) Centre for Ecology and Hydrology (CEH). The national rivers flow archive, Search by regional maps. North-East England. NRFA gauging station information sheet. NERC; 2012b.
[35] ACOEM. ACOEM; 2012 [Online] 28.5. 2013, http://www.acoemgroup.com/.
[36] Corp IBM. IBM SPSS statistics for windows. Version 20.0. Armonk, NY: IBM Corp.; 2011
[37] Eargle J. Electroacoustical reference data. New York: Van Nostrand Reinhold; 1994.
[38] Yang H, Kang J, Cheal C. Random-incidence absorption and scattering coefficients of vegetation. Acta Acust United Acust 2013;99:379–88.