Babbling brook to thunderous torrent: Using sound to monitor river stage.

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Abstract

The passive, ambient sound above the water from a river has previously untapped potential for determining flow characteristics such as stage. Measuring sub-aerial sound could provide a new, efficient way to continuously monitor river stage, without the need for in-stream infrastructure. Previous published work has suggested that there might be a relationship between sound and river stage, but the analysis has been restricted to a narrow range of flow conditions and river morphologies. We present a method to determine site suitability and the process of how to record and analyse sound. Data collected along a 500 m length of the River Washburn during July 2019 is used to determine what makes a site suitable for sound monitoring. We found that sound is controlled by roughness elements in the channel, such as a boulder or weir, which influences the sound produced. On the basis of these findings, we collect audio recordings from 6 sites around the North East of England, covering a range of flow conditions and different roughness elements, since 2019. We use data from those sites collected during storms Ciara and Dennis to produce a relationship between this sound and river stage. Our analysis has showed a positive relationship between an R^2 of 0.73 and 0.99 in all rivers, however, requires careful site selection and data processing to achieve the best results. We introduce a filter which is capable of isolating a rivers' sound from other environmental sound. Future work in examining the role of these roughness elements is required to understand the full extent of this technique. By demonstrating that sound can operate as a hydrometric tool, we suggest that sound monitoring could be used to provide cost effective monitoring devices, either to detect relative change in a river or, after more research, a reliable stage measurement.

Keywords
river sound; river stage; sonohydrograph; FFT; flood; flood monitoring; Storm Ciara; Storm Dennis

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Introduction

Hydrometry, the measuring of components of the hydrological system such as river flow characteristics, is crucial in flood mitigation strategy and monitoring (Chacon-Hurtado *et al.*, 2017). The methods by which rivers are monitored are ever evolving with new techniques such as particle image velocimetry (PIV) and acoustic Doppler current profiling (ADCP) measuring flow velocity, and ultrasonic depth meters (UDM) measuring stage (Muste *et al.*, 2004, 2008; Kruger *et al.*, 2016). There is a drive for greater ease of use of this kind of technology, being spurred on by the internet of things approach (IoT) to create an easy to use framework that everyone can contribute to (Moreno *et al.*, 2019). These approaches are designed to supplement the 1,500 hydrometric stations currently operational in the UK (Marsh and Hannaford, 2008). Although the UK network of government agency hydrometric stations is dense, this equates to one monitor per 130 km of the river network (Marsh, 2002). All of these technologies, both existing and emerging, have infrastructural issues to overcome to work efficiently, such as power, direct line of sight and calibration, limiting their wider implementation. There is a need for an innovative, non-invasive, cost-effective method for monitoring river stage, which could be distributed throughout parts of catchments that currently are not monitored.

Imagine being beside a river, what do you hear? In this study we propose that sound can be used as an alternative method to calculate river stage and track flood peaks. The use of sound is based upon the assumption that a river gets louder as its depth increases, such as a babbling brook becoming a thunderous torrent, generating a soundscape that is dependent on river condition. We focus on sound because it has a number of potential advantages over alternative methods for measuring river stage. Measuring sound is power efficient as the monitor measures passively, rather than actively generating a signal, such as an ultrasonic pulse from a UDM. PIV requires illumination at night, which can be a significant drain on energy. Sound can be measured from the banks of a river, reducing the need for extensive in-stream infrastructure. Despite its potential advantages, we do not currently know under what range of conditions sound can be used to monitor river stage. A method that works across a wide range of conditions is necessary for this technique to be used to manage flood risk.

The sound of a river has been studied through the use of seismic (ground), infrasonic (air) and hydroacoustic (water) surveying, examining how sound production can be linked to sediment transport, flood processes and turbulence within a natural environment (Manasseh *et al.*, 2006; Ronan *et al.*, 2017; Schmandt *et al.*, 2017). The sub-aerial sound of a river is primarily produced by the entrainment and collapse of air bubbles in the flow, through turbulent features such as hydraulic jumps, rapids or waterfalls generating waves and whitewater (Bolghasi *et al.*, 2017). Minnaert (1933), first described how the sound of "musical" air bubbles and running water were complex in nature. The Minnaert resonance is the idealised sound frequency at which a bubble bursts, without the effects of surface tension, viscosity of the liquid and the thermal conductivity of the gas (Gaunaurd and Überall, 1981). Bubbles monitored underwater were found to burst in the frequency range of 400 - 2000 Hz, with bubble radius determining the frequency (Chicharro and Vazquez, 2014). The larger the bubble, the lower it's corresponding frequency, such as a 10 cm bubble radius has a frequency of 32 Hz and a 1 cm radius of 326 Hz (Leighton, 1994). We expect that this frequency range will determine the frequencies in the sound made by rivers sub-aerially.

The relationship between sub-aerial sound and stage level has been investigated by Morse *et al.* (2007). They concluded that as stage changes, then sound pressure, the deviation of air pressure from ambient, will change in unison. The presence of geomorphic features, such as a cascade or riffle, were found to affect the sound pressure ranges. The study, however, had limited observations, with 6-8 sound points over a range of flow conditions that did not include flooding, nor were the mechanics of what controlled the sound considered. The extrapolation of a relationship found during low flow to high flow has not been tested, with high flows having an inherently different flow regime, with surface turbulence structures emerging (Chanson, 1996). A relationship between seismic noise, sediment transport and river discharge was found by Govi *et al.* (1993); Anthony *et al.* (2018) and with river stage by Burtin *et al.* (2008) , determining that hydrodynamics were the most probable source of the signal. Infrasound monitoring by Schmandt *et al.* (2013) suggests that waves on the water surface generated sound, showing a link between discharge and sound. The use of passive sound above the water is also seen as an emerging way of measuring the air-water gas exchange velocity (K), which is essential for ecological processes (Morse *et al.*, 2007; Klaus *et al.*, 2019). Klaus *et al.* (2019) found that there was a positive relationship between sound pressure and K in the frequency range 31.5 Hz - 1000 Hz. The riverbed morphology had a significant control over the sound produced by each reach, with large scale roughness elements (RE), such as boulders, having a larger effect than a gravel bed. A large obstacle will also cause the most deflection of the water, called form drag, at low and high flow (Bathurst, 2002). Looking at the self-aeration process, the mixing of gases from the atmosphere into the water, Kucukali and Cokgor (2008) found that there was a relationship between the blockage ratio (upstream area blocked by an obstacle) and aeration caused by turbulence. With a relationship between the size of an RE and turbulence, this supports the idea that REs are important to sound generation. We therefore seek to expand our understanding about a link between sound and REs and whether this has any influence on sound and stage relationships.

The aims of this paper are to: (1) identify sites suitable for sound monitoring; (2) determine if river sound can be isolated from a complex, seasonal soundscape, outwith clement conditions; (3) investigate how factors such as REs may influence a relationship between sound and stage.

Methods

We first introduce our process for determining site suitability and the techniques to record and analyse sound data from rivers. We then examine the relationship between the recorded sound and river stage, and explore the factors that contribute to the relationship.

Sound collection

All audio from our field locations (introduced below) was recorded in the WAV format at 16 kbps as it preserves more data in a recording compared to a compressed format such as MP3. Mennitt and Fristrup (2012) used consumer level recorders for outdoor audio recording and found that although MP3 allowed long, continuous recordings to be made, it did reduce the frequency resolution that could be used. Recording at a sampling rate of 44.1 kHz, with the Nyquist frequency of 22.05 kHz, the recording captures all data in the frequency range between 1 Hz and 22.05 kHz, which is greater than the range of normal human hearing of 20 Hz to 20 kHz (Horii *et al.*, 2018). However, because of limitations in the response of consumer grade microphones to low-frequency sound (Table 1) and due to power-source noise, we only consider frequencies > 50 Hz in this study. We define river sound as the sound that can be audibly heard by a person since we expect that someone can audibly tell the difference between a river at low and high flow. Infrasound, below 20 Hz, is not considered as consumer microphone frequency ranges rarely go below 20 Hz and with the frequency humans can hear at, a change of rivers sound is audibly noticeable. Bubbles would also need to be bigger, at greater than 30 cm diameter to produce sound below 20 Hz (Leighton, 1994).

In this study, three types of microphone are used, with their technical specification shown in Table 1. Although less than ideal to use different microphones, once converted into sound pressure level (SPL), our sound value is measured in decibels of SPL (dB SPL) in reference to 20 µPa. Understanding how the sound changes is more relevant to our study and not why one river is louder than another since other factors such as sound attenuation would need to be accounted for for direct comparison. All microphones were recessed within an enclosure to protect against wind and rain, but not blocked to the environment.

Site suitability

In order to identify the most suitable sites we need to know how the sound produced by a river channel changes spatially and what river features influence it. We deem a site suitable if (1) we can hear the river and (2) if there is a significant response in the sound between river stages. We addressed this at the River Washburn, Yorkshire, UK, where there was a unique opportunity to record audio in the same day during a low compensation discharge of 0.08 m^3s^{-1} and a high continuous discharge of 8.55 m^3s^{-1}. The Washburn is a natural river channel connecting a series of reservoirs, and occasional high discharges move water between the reservoirs. These releases are used for whitewater sports, and the channel has been managed by introducing rapids and boulder gardens (REs), altering it from what it would have been naturally.

To investigate site suitability an acoustic map along 500 m of the river was generated to help us identify regions that had a markable change in sound from low to high flow. Markers were placed at 10 m intervals along the course of the river, and each point was referenced using a dGPS. Recordings were taken at an elevation of 1.5 m above the bank during high and low conditions from the marked location. An additional section of the river was identified for a more in depth examination which had a flat floodplain around a RE to examine how sound behaves at different monitoring points around a channel. Mapping the sound at 10 m intervals along the river, and at 1 m points away from the river we are able to describe how sound behaves. Audio was recorded for 8 seconds at each location, using the RØDE VideoMic (supercardioid) with a sensitivity azimuth of 210° which is more directional in comparison to omnidirectional microphones at 360°. We used a supercardioid microphone to record the majority of sound produced by each specific section of the channel, and to limit sound from sections further up/downstream. However, components of upstream and downstream will still remain.

Photographs of each marker section were taken to assess what was generating the whitewater at each reach and to designate if a section had: no REs (Rank 1), small REs (Rank 2), or large REs (Rank 3). Qualitative ranking of the REs is used as direct measurements of these obstacles was not possible. Determining rank was done by eye, with rank 2 and 3 differentiated by if there was a large RE (height approximately >1 m) and how the REs were dispersed, such as how directly in the flow they were. It was assumed that a RE in the middle of the flow will have more impact on the flow than at either bank side.

Sound analysis

With the sound captured, we needed to find a way to filter any noise from our expected river signal. Audio clips were converted from the time to frequency domain using a fast Fourier transform algorithm (FFT) in MATLAB R2020a. To examine at a resolution of 1 Hz, a minimum sample length of 1 second is required.

We aim to identify a river sound zone (RSZ), which is the frequency range that best correlates with river stage. To derive a single sound value for each recording, which can be compared against the corresponding river stage measurement, we use the spectral centre (median) of the data. The median is calculated from all values of SPL within a certain frequency range, known as a bin. As the FFT produces a SPL value for every 1 Hz, we have 22,050 individual sound values, with 0 Hz being the mean of the data. Therefore when we calculate a median from a 1 kHz bin, it is calculated from 1000 values. We use this instead of the spectral centroid (average) or maximum volume, because the median of the data yields a more representative signal that is not skewed by erroneously large or low values in the frequency range. Median filters are useful in scenarios where periodic patterns are found (Ohki *et al.*, 1995). The first bin of 1 - 1000 Hz is clipped to 50 - 1000 Hz, as due to the switching power supply used, noise from the power supply affects readings below 50 Hz.

It is unrealistic to assume that the only sound source is the river. To further constrain the RSZ, other environmental noise needs to be removed. Certain frequency domains that may be of influence are: the human voice in mainly the 100 Hz - 8 kHz range; birdsong at 1 - 8 kHz; and vehicles at 0 - 4 kHz (Monson *et al.*, 2014; Liu *et al.*, 2013; Slabbekoorn and Ripmeester, 2008). These noises will primarily affect monitoring during low flow conditions as during high conditions these will either be absent, or drowned out. Figure 1 shows the spectrogram of each of these individual noises. Each sound has its own unique fingerprint, compared to a pure river signal. Birdsong has excitable chirps and trills, car sound is a wideband, flat noise, and talking is in pulses of speech. To reduce the number of noise related errors the RSZ will have to be both strongly linked to the river, while maintaining its independence from these other environmental noises.

Wind and rain are not associated with a certain frequency range, and are dependent on intensity instead. The fluctuating nature of wind and rain intensity makes this sound known as Brownian noise, with a rumbling, roaring sound (Yackinous, 2015). Rain was found by Burtin *et al.* (2011) to have caused a seismic signal when landing on rocky debris near monitors. Wind can be the most intrusive sound on a recording and if the wind is constantly louder than the river, blowing out the microphone, then it is not possible to extract a river component. In a remote location away from cultural noise sources, wind has also been recorded on seismic monitors at the surface, contaminating the recorded signal at speeds of only 6.5 mph (Withers *et al.*, 1996). Ronan *et al.* (2017) found wind to be the most probable source of high power, low spectral coherence noise on infrasound recordings. With Anthony *et al.* (2018) suggesting that without wind filters and if deployed close to a river, infrasound acoustic signals were likely unsuitable for smaller river systems. To reduce wind impact on the monitor, the microphone can be placed in the opposite direction to the prevailing wind or placed in an area with adequate wind baffling from trees or shrubs. But, even with adequate protection, wind can still be heard in some recordings. Figure 1B shows a spectrogram of a gusty signal, with the bright peaks caused by intermittent wind spreading into the higher frequencies. If the entire recording was run through the FFT code, then these peaks spanning the entire frequency range would dominate the results.

To remove the impact of the wind we apply an additional filtering step to our data (Figure 2). We record each sample for as long as possible as it provides a better chance of getting a continuous section of recording without wind noise. Changing the recording length is subject to the site and how confident we are that we can filter out the wind physically. In this study we considered a minimum recording length of 5 seconds to be necessary. To filter out the wind noise, we split the recording into 1 second rectangular windows, with 0.5 second overlap between them. We do this to allow a frequency resolution of 1 Hz to be maintained through the FFT, as this matches our sampling rate. A rectangular window also does not smooth out the boundaries of the clip. Reducing the total recording length reduces the number of windows, and thus the potential samples to get the lowest median from. The overlap is to increase the number of windows that can be taken from any given recording. The audio data from each of these new windows are processed with the same FFT code, resulting in one median value per frequency bin for each window. The minimum value for the RSZ, the region of frequencies found to have the maximum correlation with stage, from across all the different time windows is chosen. We take the minimum value from all the different time intervals because it is expected that river sound is constant in any recording and will always be the loudest of any constant base sound but will also be quieter than sporadic noises caused by wind, thunder etc. By taking the minima of each audio sample in the RSZ, we can significantly improve the processing of noisy recordings. We call this the lowest median filtering (LMF). When assessing this technique to determine any bias in the window that is chosen, we found that the window with the lowest value is equally taken from across all the windows and one is not preferentially choosing one.

The following section introduces our workflow of collecting and processing river data, which was applied to all study sites and is the basis for any future work or different sites (Figure 2).

Study site monitoring

Six sites were selected for monitoring between November 2019 and February 2020 based upon the findings of data collected at the River Washburn for site suitability, chiefly the occurrence of REs (see Figure 3 and Table 2 for characteristics). These locations were selected to be typical of many rivers and not highly specific. Sites A-C were deemed to have good site suitability. Sites D-F were not explicitly chosen for good suitability, for instance many have small REs and site F has a large amount of wind noise. They are predominantly alluvial rivers but include two bedrock channels (site D and F), and range between 8.0 - 34.5 m wide. Stage at Sites A-C was measured using a pressure transducer (TD- Diver), calibrated to atmospheric pressure, and Sites D-F were Environment Agency operated gauges recording at 15 minute intervals.

A Bushnell E3 trail camera was used to record sound at Site A as this provided a "ready to go" setup at the start of the project. A purpose built monitor was created from a Raspberry Pi Zero, a CMA-4544PF-W microphone and a WittyPi Mini (timer) for use at all subsequent sites. Monitors were attached as close as possible to the river on existing structures and out of danger of high water. At Site A sound was recorded for up to 10 seconds, once an hour due to running off of AA batteries. A reading once an hour is the minimum frequency to monitor at, as anything longer than this becomes unconducive for meaningful flood monitoring. Higher frequency sampling rates of every 15 minutes were achieved with the Pi Zero at Sites B-F, allowing comparison against the 15 minute interval EA station data. Each device has a finite number of recordings it can take, due to the size of battery used, meaning it can either sample at a high rate for a short time, or last longer and only sample every hour. Using a 7 Ah, 12 v lead acid battery allowed up to 1,400 recordings to be made with the Pi. The length of individual recordings varied due to power saving management, with the wildlife camera varying between 8- 10 seconds and the Pi Zero, 9-10 seconds.

With exception of the acoustic mapping, an omnidirectional microphone was used in the monitors as this captures audio from an identified reach, without the need to target the microphone during installation. There would be a risk of a supercardioid microphone moving during any long term experiment, which would incur an extra source of error. The ambition to make a sensor that can be widely deployed means that it is advantageous if it can use cost effective and easily procured components. Higher resolution and frequency response data could be captured with a higher specification microphone and digital audio recorder, but with the problems of power and cost becoming an issue. We expect that the frequencies that will be of interest are less than 15 kHz, so the microphones used should be sufficient (Klaus *et al.*, 2019).

During our monitoring, the UK was subjected to substantial rainfall in February 2020, with Storm Ciara on 8th – 9th February, and Storm Dennis on 15th- 16th February. These events produced river levels that reached the highest levels monitored in some of our stations, and higher than levels reached from Storm Desmond (5th- 6th December 2015) for others but not quite beating long standing records. Having both storms back to back was an incredibly rare opportunity. We use the data from the storms as our primary dataset, because it ranges from very low to very high levels, and therefore can be used to test the range of conditions across which sound can be used to predict stage. We supplement this data with a longer dataset collected at Site A from 24th July 2019 to 20th February 2020.

Results

We present our results in three stages: (1) analysing what features within a river may control the sound emitted and determine a suitable site, (2) demonstrating how the LMF helps to improve the data collected from the river and (3) examine whether the filtered sound data has any correlation to river stage.

Acoustic mapping

River Washburn

An acoustic map of the River Washburn is shown in Figure 4 during low and near bankfull flow. The River Washburn has a SPL of 30 - 60 dB SPL across its course during low conditions, with higher values at a weir and a constrained section. At high discharge certain reaches become very loud, where there are substantial REs with heights > 0.5 m. When observing the photographs at each section, we found a correlation between the presence of whitewater and the SPL, with more whitewater being associated with higher SPL values, agreeing with (Ronan *et al.*, 2017). Every section of the river experienced a rise in SPL from low to almost bankfull flow. When comparing to the qualitative REs rankings in the channel: Rank 1 generates a median range of SPL between 40 - 60 db SPL; Rank 2, 46 - 64 db SPL and Rank 3, 45- 66 dB SPL (Figure 5). Therefore between low and high flow, SPL rises by around 20 dB SPL no matter what rank is used. However, choosing the rank in which the loudest sound is produced is beneficial as it provides a higher likelihood of being louder than any possible environmental noise.

An in-depth look at a section of the river with an large RE, with a rank of 2, is shown in Figure 6. In Figure 6A , as we walk 10 m away from the river, the SPL drops from 66 to 55 dB SPL during high flow. At every point, the SPL measured at high flow is larger than that measured at low flow. Moving upstream or downstream, Figure 6B shows that SPL drops as we move away from the RE. The highest SPL is not at the RE as a tree was between the microphone and the RE. Without the tree we would expect a smooth convex shape to continue. Sound does not drop as much as when moving away from the river, with a 10 m movement causing a drop from 66 to 61 dB SPL.

Lowest median filter

River sound/ stage relationship

Long term audio data, recorded using the trail camera at Site A are compared against the river stage data from the pressure transducer in Figure 7. The audio data were processed to calculate the median SPL within the frequency range 0.05- 1 kHz. The frequency range was chosen to illustrate how well the filter works, although may not be the best frequency range to use in the study due to the prevalence of wind. We call the resulting profiles of how sound changes over time sonohydrographs. In Figure 7A there is little similarity between the sonohydrograph and the actual hydrograph. In contrast in Figure 7B, after LMF, the sonohydrograph has the same shape as the hydrograph, with the steep sides of the rising limbs and the slower lowering of the falling limbs. In Figure 7A the wind noise produced by winter storms is clearly highlighted in the large fluctuations of the blue line such as on the 9th February 2020, with no clear signal being given during this time period. If used to interpret river stage, the river would appear to be in a state of flooding and sudden drainage repeatedly. In contrast, in the filtered data, there are no fluctuations. We therefore apply the LMF in all subsequent data analysis.

Wind noise

The Killhope Burn, at Site F, is a far noisier site in comparison to the more secluded locations such as Haltwhistle, with traffic and wind noise (Figure 8). As shown in Figure 1, these pollutants share the same frequency space as the river sound, meaning we needed to use a higher frequency range of 5-6 kHz as it was shown later in the study to be the best to use at this site. The readings are affected by wind even during periods of more settled weather, with Storm Atiyah, 8th- 9th December 2019. The filtering has an enhanced effect compared to Figure 7, removing most of the fluctuating readings and reducing the scatter of the data. We still have some wind noise artefacts in the data in Figure 8C, but significantly less than in Figure 8A. The number of points in the data where the SPL is an order of magnitude greater than the value of the previous point is reduced by 70% after application of the filter. The fit and smoothness of the sonohydrograph also improves, when viewed in relation to river stage. When we plot river sound and it's co-current river stage we are able to fit a function to this, with Figure 8B and D showing that an exponential relationship is able to be found, with a R^2 of 0.85 after the LMF, when before it was not possible. The wind noise that was persistent at low stages has all but been eradicated.

To allow the LMF to operate efficiently, a recording length has to be long enough to include a gap in any concurrent noise. We ran our LMF code with different lengths of recordings, from one second to total recording length. These new SPL values were then compared against stage, and the R^2 found of the best relationship between the two. In Figure 9 the difference between the calmer Haltwhistle and the windier Killhope site becomes clear. Haltwhistle is able to achieve a better relationship against river stage at very short recording times, with a one second recording giving an R^2 of 0.90 in the 1 - 2 kHz bin. Conversely a one second recording at Killhope only has an R^2 of 0.7. There is a upwards trend in R^2 against recording time for both sites, but this trend is more substantial at Killhope. At a total recording time of greater than two seconds there is a substantial increase in R^2 in the Killhope data, with R^2 reaching 0.97. After four seconds there is a gradual increase of the fit. The filter is also improving the lower frequencies of the Killhope burn, however, longer recording times would be needed to match the mid-frequencies. This demonstrates that the LMF is effective at reducing the impact of wind noise on our data.

Storm Ciara and Dennis

Figure 10 represents February for the study sites located throughout the North East of England. For each site we calculated the median sound value after LMF filtering in bin widths of 1 kHz, plotted these values against river stage, and calculated an R^2 value of a logarithmic and exponential fit. Two fit options are used as some data fits better with an exponential compared to a logarithm. Our aim is to identify whether there is a relationship in the data, regardless of the form, rather than having a prior assumption about what the shape of the relationship should be. The variations in R^2 values with frequency range are shown in the first column of Figure 10. We use all the sound data during February (inclusive of storms) to determine the RSZ that is most likely to be the best region to use going forward. Site D has relatively poor, but consistent correlations throughout the spectrum between 0.05 - 15 kHz. We see that the highest R^2 values occur in the 0.05 - 3 kHz range in 4 out of the 6 rivers (Sites A, C, D and E). The RSZ used subsequently for each of these rivers is the highest R^2 found from fitting a relationship. Two sites have their best relationship with a logarithm, and four with an exponential. The R^2 values can vary across the frequency range in each river, with some being very consistent (Site B), to others being less consistent (Site C).

With the best RSZ determined, column 2 in Figure 10 compares the river stage data against the sound data recorded during February using the chosen bin (RSZ) highlighted in column 1. Each river shows a correlation between recorded sound and river stage, with certain reaches better than others. Sites A, B and C had very good site suitability and have been found to have amongst the highest and most consistent R^2 of between 0.89 - 0.94. In these sites stage modeled from sound is within 0.2 m of the actual stage at the 95% confidence interval. Sites D, E and F were not explicitly chosen for good site suitability but they do all still have a strong relationship, with R^2 of between 0.73 - 0.99. Data below 0.3 m at Site E has been removed since no comparable river stage data is available.

The highest river level was recorded at Site E at 2.2 m. When the stage reaches 1 m, we see a large increases in SPL with subsequent increases in stage. Bankfull for this reach is at an average depth of 1.5 m, above which the river flows through riparian vegetation. At these levels any riverbed morphology will have been submerged, but other obstacles such as trees start to interact with the flow. Site E is the only site to have experienced significant above bankfull flow during this time period. Flow in other channels was kept within the banks by features such as built up footpaths and flood defences. Site D was located at a weir/ natural waterfall complex, with the shape of the graph perhaps reflecting this, with large variation of SPL below 0.25 m at 47 - 52 dB SPL. At low flow there may be two competing sound sources, the REs and the weir/waterfall. As river stage increases one sound source may become dominant, most likely the waterfall, and a less varied signal emerges.

Column 3 shows the hydrograph compared against the sonohydrograph. From the sonohydrographs we can see that there are a few peaks caused by wind, with some still found in Figure 10*xv* and *xviii*. High gusts of 50 mph, and a sustained wind speed of 30 mph, in combination with low river level are the likely cause. The general shape between the two curves are the same during flooding. There is divergence between the graphs in Figure 10*xi* at lower river levels, before the peak emerging at 0.3 m. Site E does not record stage below 0.3 m, however, we have included our sound data in the sonohydrograph to show that we were still able to measure sound below 0.3 m.

Discussion

We have shown that sound shows a strong correlation with river stage after determining the best frequency range. Consequently we think that it might be possible that given reliable sound measurements and site calibration, a corresponding river stage can be estimated. Producing reliable estimations of river stage from sound requires consideration of how the river sound can be isolated from ambient noise and how sound is produced by a river.

Although this is preliminary work, it has shown promising results, albeit with requiring post processing at this stage.

Controls on sound generation

In order to be able to implement monitors at different locations without the need for calibration, we need to be able to predict the form of the stage/SPL relationship. We expect that this will be a function of factors including the size of the largest obstacle, obstacle density, bankfull level, how close the monitor is to a RE, and if there are any barriers between them which was shown to impact sound propagation (Figure 6). Our Washburn dataset leads us to the conclusion that for a site to be suitable for monitoring it beneficial to have a RE within the channel since it produces the loudest sound. The variability in sound along the 500 m section is proposed to be entirely down to the REs presence, prominence or absence. The REs of these reaches impede the river, forcing flow around/ and or over. The river has to exert its energy to overcome these, and some of this is released as sound energy, from the entrapment of air and bursting of bubbles. When observing the photographs at each section (Figure 5), we found a correlation between the presence of whitewater and the SPL, with more whitewater being associated with higher SPL values. An entirely featureless reach, such as a culvert, would be less than ideal for this method, unless there was some sort of texture.

In our data we see upticks in the trend of the sound/stage data in Figure 10*viii* , *xi* and *xvii* . The interruptions occur when a RE feature has either been submerged or perhaps when a new RE is activated. Site D, with its weir and waterfall, is an alluvial channel, with boulders of between 0.2 - 0.3 m. We believe that once the boulders have been submerged the loudest sound is generated from the waterfall complex, which at low levels is quieter than the boulder sound. Site F's RE is from stepping within the bedrock channel, with step heights of 0.35 - 0.45 m. Similarly with Site D, once these features are submerged, the trend seen in the data shows an exponential trend in sound being produced, with an increase from 0.5 to 1.4 m, having a SPL range of 40 -45 dB SPL. The trend means that as stage increases, the SPL will increase, but not at the same rate as during lower levels at the RE submergence height. The continued upward trend in data is hypothesised to still be originating from these RE, however from a different mechanism arising from the higher discharges. Turbulence structures created by the changes in flow may be generating different bubble structures for example, with fluctuations in intensity. Standing waves are the most likely cause of new turbulence at higher stages with submerged boulders, with localised increases in Froude number (Comiti and Lenzi, 2006). The preference of a either an exponential or logarithmic function being fitted to the data is hypothesised to be linked to a self limiting part of the system, with a river reaching a point that there are no other sound sources being activated. Sites with an exponential fit have their REs covered at low levels, and do not activate new ones even at above bankfull. Sites with logarithmic functions have either not had their REs covered or have broken their banks and activated new ones. To further test this hypothesis a river would have to be monitored at both in bank and over bank storm conditions.

In ranking the river reaches in Figure 5, sections without any REs still had an increase in SPL between low and high flow. We could conclude that generally there is noise bleeding in from sections up/downstream, or that there are other sound generating elements in a reach. Figure 6B has sound generated from an RE being observable 10 m up or downstream of it, which is within our 10 m sampling range. Therefore the change in sound observed at a site with smaller REs (Rank 1), may in fact be affected by REs further away. The design of the river means that there were REs found throughout, and attributing a specific RE for bleeding is difficult. Bank resistance is another possible source of sound, such as from protruding tree roots or alluvial deposits. However, we expect that REs are the main sound source of sound within a river environment. Our Washburn data suggests that the larger the RE in the river, the greater the SPL at high conditions. Being louder is seen to be beneficial to monitoring, since the river is more likely to be louder than environmental noise and is broadcast over greater distances, meaning monitors can be located further away. Rivers with smaller REs may still be able to be used, with the caveat of monitors perhaps needing to be more sheltered or closer to the river. In general we can say that the larger the RE, the louder it can become, and therefore opens more flexibility in the monitoring regime. Assuming that large obstacles are near permanent fixtures in the river, they remain stable even during high flow events. This stability should make any long term data and future extrapolation of stage far easier than if the environment was constantly shifting. A moving obstacle would have the same effect as moving the microphone (Figure 6), changing the sounds that are monitored. Further long term studies will need to be undertaken to determine how long a site's relationship remains stable, however, in Figure 7 over the course of 6 months the signal does not change drastically. Over this time, bedload will have been transported, but this movement did not change the signal we observed. In a more dynamic environment, a change in bed configuration may have a significant change in sound.

We can use the Storm Ciara data (Figure 10), where data were collected from channels with different REs, to determine whether a RE has any influence on a relationship. The data show that, regardless of RE size, a smooth relationship exists after RE submersion. However, the trend of that relationship appears to be ultimately controlled by the RE, such as in Figure 10*viii* , *xi* and *xvii*. As all sites had REs, we cannot be sure if these sorts of relationships would still persist at sites without REs. We have shown that when using co-located measurements of sound and stage, we can derive a relationship to predict stage to within 0.2 m at the 95% confidence interval. However, the ideal frequency band used to get stage information and the nature of the relationships are both highly site specific, and so it is not currently feasible to predict the form of that relationship without some paired measurements of sound and stage. But, at all sites SPL has increased with increasing stage. Consequently the relative change in SPL of the river could be used, without calibration, to determine whether the peak of a flood has passed.

RSZ isolation

When trying to determine the best frequency range to use in our research, we defined the best zone as the RSZ. We found the RSZ to change between different rivers within the range 0.05 - 6 kHz, with no set zone for all (Figure 10). The RSZ is influenced by how noisy the signals fed into the LMF were. The greatest challenge faced by this study was the isolation of a river sound component from the ambient soundscape. Without the benefit of generating our own signal, we rely on the continuous burbling of a river and if this primary sound source is obscured by other noises we need to actively search for a clean signal, which is why the RSZ is influenced. We expect that the main frequency range for sound production in rivers is in the lower frequencies, < 3 kHz, as we experienced our most consistent R^2 values there, with one site B having a marginally better R^2 at 3 - 4 kHz but only by 0.03 compared to 2 -3 kHz. We do still have very high R^2 values in higher frequencies, and a very good 0.99 for Site F. However, 0.05- 3 kHz is heavily affected by wind noise, which if strong enough may require the switching to higher frequencies as observed at Site F. Potentially Site F may have had a strong relationship in the lower frequencies, but due to persistent wind noise we cannot identify it.

Research using hydrophones is consistent with our RSZ, with surface turbulence having a frequency range of between 500 - 2000 Hz over varying flow regimes (Geay *et al.*, 2017). Tonolla *et al.* (2009) examined how relative submergence of an obstacle influenced the sound, stating that a frequency swap may occur once a relative submergence limit is passed, such as a riffle producing mid-frequency noise during low discharge, changing to a low frequency at high discharge. We do not see the complete abandonment of a frequency range after a RE is submerged, such as in Figure 10*xiv* and *xvii* , as there is still a relationship with stage present beyond RE submergence. A frequency switch might be causing the change in direction of a relationship once an RE is submerged, but we cannot be certain on this since the low frequency needed to confirm this at our sites that display this behaviour is obscured by the wind. Other sources of sound produced from within a river, such as sediment transport, can exist in the same frequency space as turbulence, around 1 kHz (Krein *et al.*, 2016). But, we have not seen any indication from our data of sudden changes in our trends at high discharges. It might be that our rivers do not generate bedload sound loud enough to overcome the sound of turbulence, but in other rivers it might be a different case. The sound from sediment moving is not strongly transmissible through the water to the air, with acoustic pressure reducing by 2000 times when sound transfers between the two, meaning either there has to be a lot of bedload movement or for the turbulence sound to be lower than it for it to be heard (Leighton, 2012).

We use a frequency range instead of a single frequency to measure river level because as river level increases, changes in the turbulence cause the bubble size to change, altering the frequency of the sound that is produced, the Minnaert resonance. Using a range also adds stability to the data. In the frequency range of 0.05 - 3 kHz, we are in the Goldilocks zone for sound production from surface turbulence, with filtering helping to remove any environmental noise. Within this range, each river has a different most efficient frequency to look at. But, not all rivers have their best efficiency in this region, so the RSZ may need to be altered subject to analysis of previous data. We do however see that the sites chosen for good sound potential, (Sites A and C), have the RSZ in the 0.05 - 3 kHz region. The reason for better stage/ sound relationships being found at higher frequencies when the lower frequencies are polluted, despite sound being produced in the 0 - 3 kHz region, is perhaps down to harmonics. If there is a fundamental frequency of 1.5 kHz, we can expect to see upper harmonics at 3 kHz, 4.5 kHz etc. reducing in SPL magnitude at each jump. Similarly a range of fundamental frequency may have these harmonics. Kumar and Brennen (1991) showed that sound of bubbles bursting in water showed harmonics, with defined peaks occurring at higher frequencies above the fundamental frequency. It is perhaps with harmonics and overtones of the bubbles that we continue to see a river/ sound relationship at higher frequencies.

Having identified that sound production is focussed at < 3 kHz, we need to ensure that we are able to monitor this region as easily as possible. The basics of sound isolation lie in the design and placement of the monitor. Eldwaik and Li (2018) noted that wind noise was notoriously difficult to filter in an outdoor environment, due to its time varying nature and broadband frequency. We show that our LMF can help to reduce noise from the wind (Figure 8), but better still would be to not have the noise in the first place, achieved by having a microphone properly shielded from the wind. We recessed our microphones to protect them from the rain and wind, but still had wind noise present meaning without recessing our data may have been more affected. Adding a wind dampening sponge could also be used, having the effect of quietening down the recording, but also baffling the wind (Lin *et al.*, 2014). Even with these preventative measures, wind noise will still be present since it is part of the soundscape. Rivers that are however found in exposed areas, such as moorland that are subject to frequent low level wind, and placement of the monitor then becomes crucial. Placing a monitor as close to the river as possible has two benefits, the likelihood of hearing only the river, and also offering the highest range in sound, with a better resolution of data (Figure 6). We see that through acoustic mapping at the River Washburn, when the microphone is moved further away from the river, it begins to quieten. At every point, the SPL measured at high flow is larger than that measured at low flow. SPL decreases upstream and downstream of the RE, with the highest SPL near the RE. The decrease in SPL as you move up/downstream, is less than that observed when heading away from the river due to other sound components being introduced from the river. We do however acknowledge that placement beside a river is not always possible, and find that being within 5 m is advantageous, with being able to move up to 10 m and still having a difference between high and low (Figure 6). The limitation of how far a monitor can be placed is when the sound from high and low flow overlap, meaning you cannot monitor changes acoustically anymore. The distance of how far a monitor can be placed is determined by the river itself; larger, more energetic rivers, may be still within a zone of high relationship further than 5 m. Conversely, a smaller, less energetic river may need to have a closer monitor.

Sound as a hydrometric

We are encouraged by the trends between sound and river stage we see in each river that we have monitored. Currently we are able to model with certainty when river level is changing, with all sites in Figure 10 showing their flood peaks clearly from sound data. We acknowledge that an absolute measurement is not currently of a standard that could be used for essential management. Consequently we do not see sound as a method for absolute value monitoring, but rather a warning system, capable of detecting flood peaks when they occur or when the river might be starting to flood. If absolute measurements are needed, alternative channel monitoring techniques are available.

Sound varied with stage in all the river reaches that we monitored, and so we are confident that noisy rivers will have a relationship with stage. The more data that is collected and correlated with the river stage, the greater the confidence we have in sound being used as a measurement. On reflection on what makes a good section of river to monitor to measure sound, our Washburn data gave us ideas on sound generation from large obstacles, making lots of noise was shown to be largely correct. Further work will need to be undertaken to allow a SPL/ stage relationship to be predicted from the channel characteristics and without the need for previous stage data.

Conclusion

At the start of this study, we set out to isolate river sound from a soundscape. The isolation of the river from the soundscape was achieved through the use of the LMF, which is capable of turning a poor, windy relationship, into a promising, predictable signal. A perfect scenario, with no wind or rain noise, is still advantageous, but we have shown that even with these sources that river sound is a monitorable source of river stage information. Future work will need to be undertaken to allow stage measurements to be calculated without the need of calibration. The relationship between sound and a river's stage has been shown to have a strong relationship, with positive correlation seen in every site chosen. River morphology was shown to influence the sound that we were able to measure and find relationships from. Our results suggest that there is significant geomorphic control on sound production and that sound is unique to each river, like a fingerprint, but it is still able to be monitored after site calibration.

When assessing the usefulness of this technology, it has to be considered in the benefits it may bring to some places that require some sort of monitoring. The technology may not be used to determine an exact river stage, but to show if a flood peak has past or if the river is rising or lowering. Using sound as a method for measuring a river is a novel approach to remotely monitor rivers. Established methods of gathering hydrometric data are not going to be abolished thanks to this, but can work in harmony, with a larger catchment scale network envisioned, made up of several IoT devices that each work in their own specialised sector. Sound can fill the gaps where other hydrometric stations cannot be deployed, either due to infrastructure or cost. With continued research into this field, it may be possible to embed sound monitoring into a network scale approach to river flood management, rather than isolating it to a sole source of information.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

There are no conflicts of interest.

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Monitor	Microphone	Directionality	Frequency range	Signal to noise ratio (dBA)	Sensitivity (dB) (1 kHz at 94 dB, 1Pa)
River Washburn	RØDE VideoMic	Supercardioid (rejects 150° to rear)	40 Hz - 20 kHz	79	-38
Bushnell E3	ECM-60C	Omni	50 Hz - 13 kHz	40	-64
Raspberry Pi	CMA-4544PF-W	Omni	20 Hz - 20 kHz	60	-44

Table 1: The monitors and their associated microphones units within them. Technical specification of the microphones is freely available online. Values that are important to the study are frequency range, signal to noise ratio and sensitivity. These determine the range we can measure at and also the conversion into sound pressure level. Each microphone has a quasi flat response to frequency as per the technical specifications but was not tested in this study. Any frequency bias will have a negligible effect on our data.

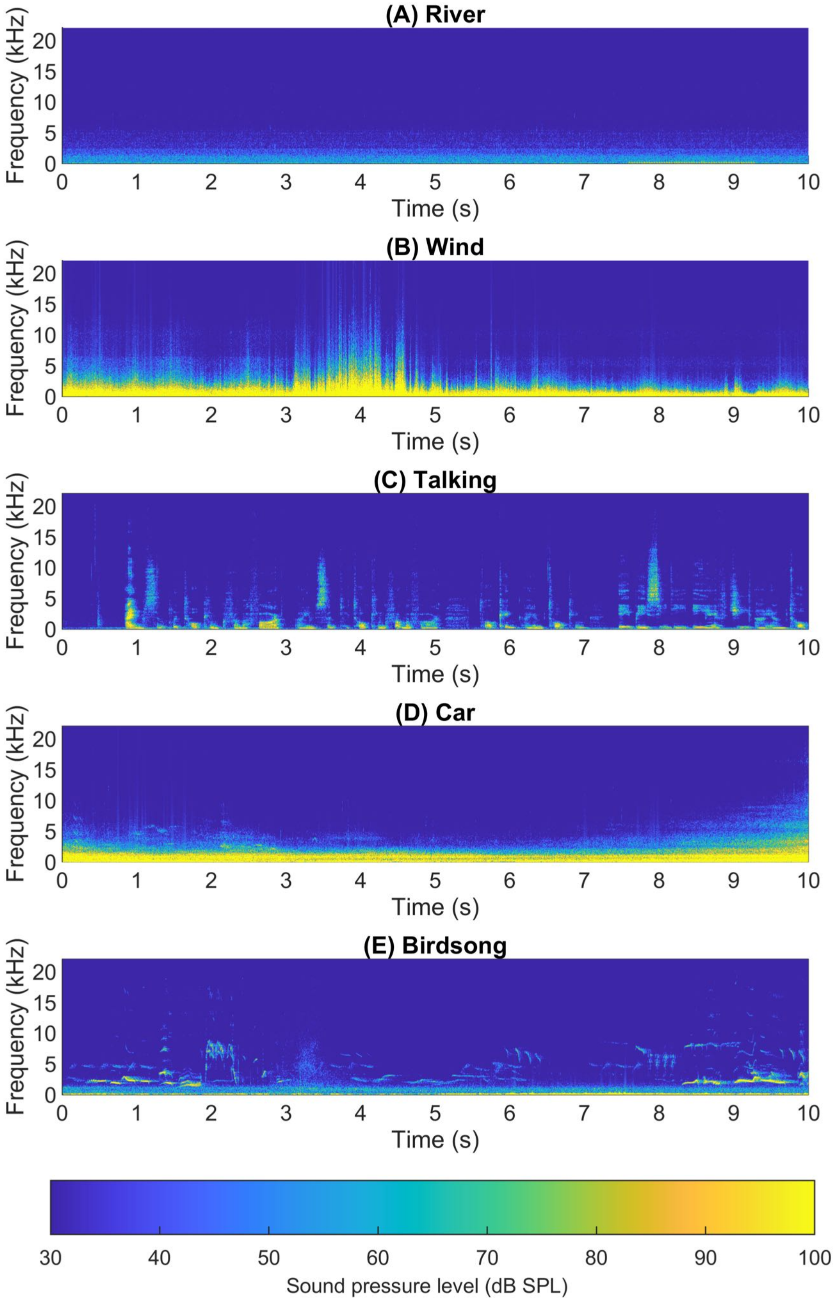

Figure 1: Spectrograms for different sources of environmental noise. Each recording is only of that sound. (A) Chainley Burn during average flow condition on a calm day, (B) Trout Beck, County Durham during continuous high wind, (C) Reciting of the alphabet, (D) main road with cars going past and (E) Black bird. Plots are produced by the spectrogram function using short-time Fourier transforms, which allows both frequency and the time domain to be viewed concurrently. Bin width is set to 1 Hz to show a finer resolution of data.

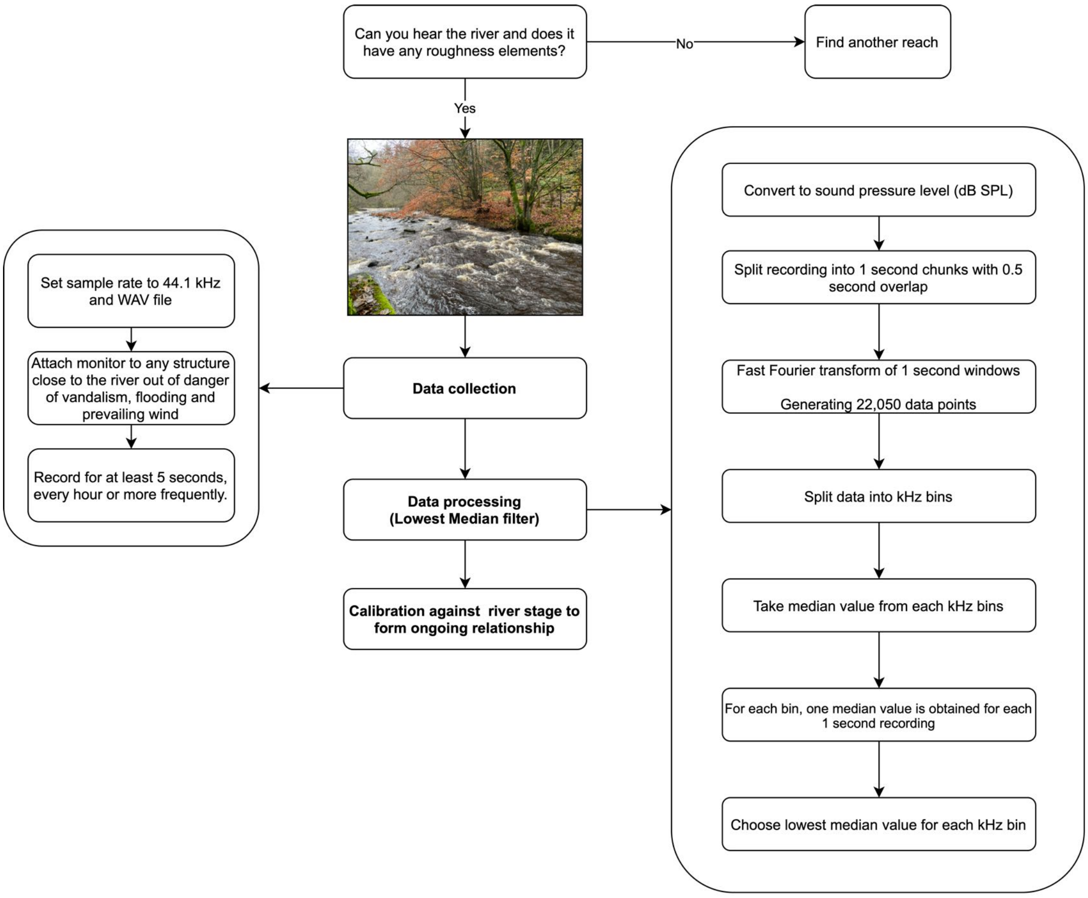

Figure 2: Our workflow of how to monitor a river using sound with the required steps needed to perform lowest median filtering.

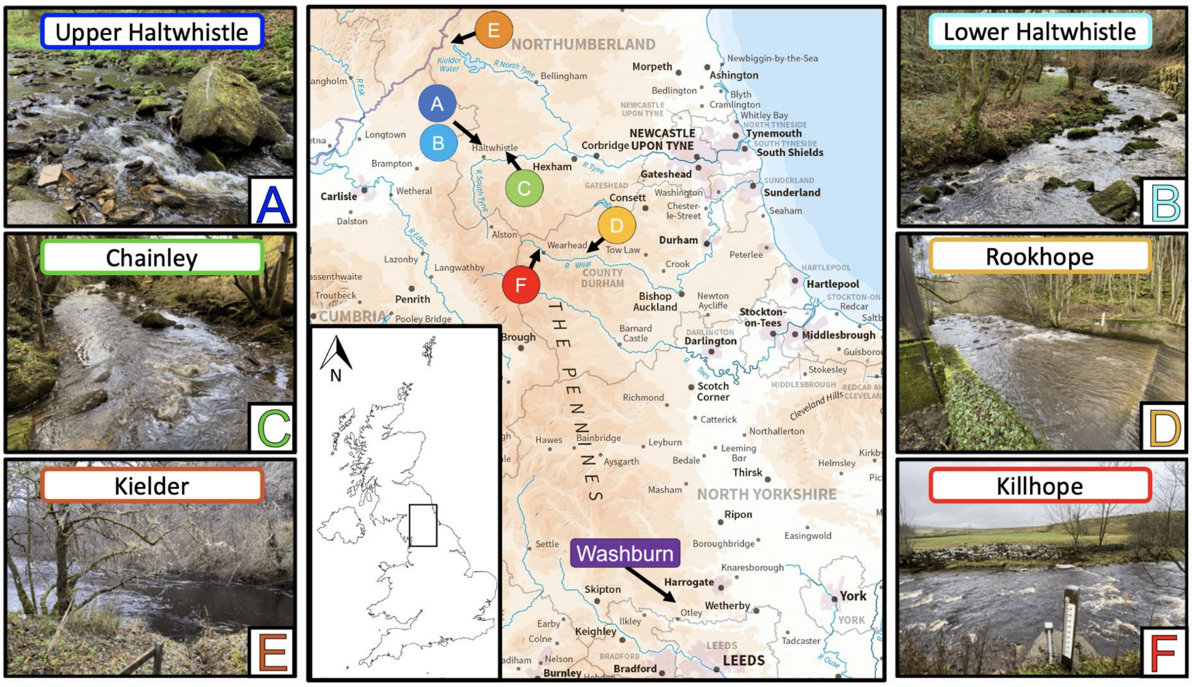

Figure 3: Map of study site locations with corresponding photographs taken from each site showing the morphology of the river and the general surroundings. A-D were taken during low river levels, with E-F taken during above normal levels. Approximate channel widths A: 6.0 m, B: 6.0 m, C: 5.0 m, D: 8.0 m, E: 13.5 m and F: 5.0 m.

Site	River	Coordinates	Data collection period	Gauging	Distance from monitor to river bank (m)	Bankfull depth (m)	Bankfull width (m)	Substrate
A	Haltwhistle Burn (Lower), Northumberland	5458’43.5"N 227’40.6"W	24/07/2019 -19/02/2020	Diver	1.0	1.6	14.3	Cobble
B	Haltwhistle Burn (Upper), Northumberland	5458’47.2"N 227’36.4"W	28/01/2020 -19/02/2020	Diver	5.0	1.1	19.9	Cobble
C	Chainley Burn, Northumberland	5458’51.1"N 221’22.7"W	6/12/2020 - 19/02/2020	Diver	1.5	1.4	9.8	Cobble
D	Rookhope Burn, County Durham	5444’51.0"N 204’31.0"W	27/11/2019 -14/02/2020	EA	4.5	0.8	8.0	Cobble/ Bedrock
E	Kielder Burn, Northumberland	5513’50.9"N 234’54.0"W	27/11/2019 -16/02/2020	EA	13.0	1.5	34.5	Gravel
F	Killhope Burn, County Durham	5445’11.7"N 213’27.5"W	27/11/2019 -18/02/2020	EA	7.5	0.8	8.7	Bedrock

Table 2: Study site location properties.

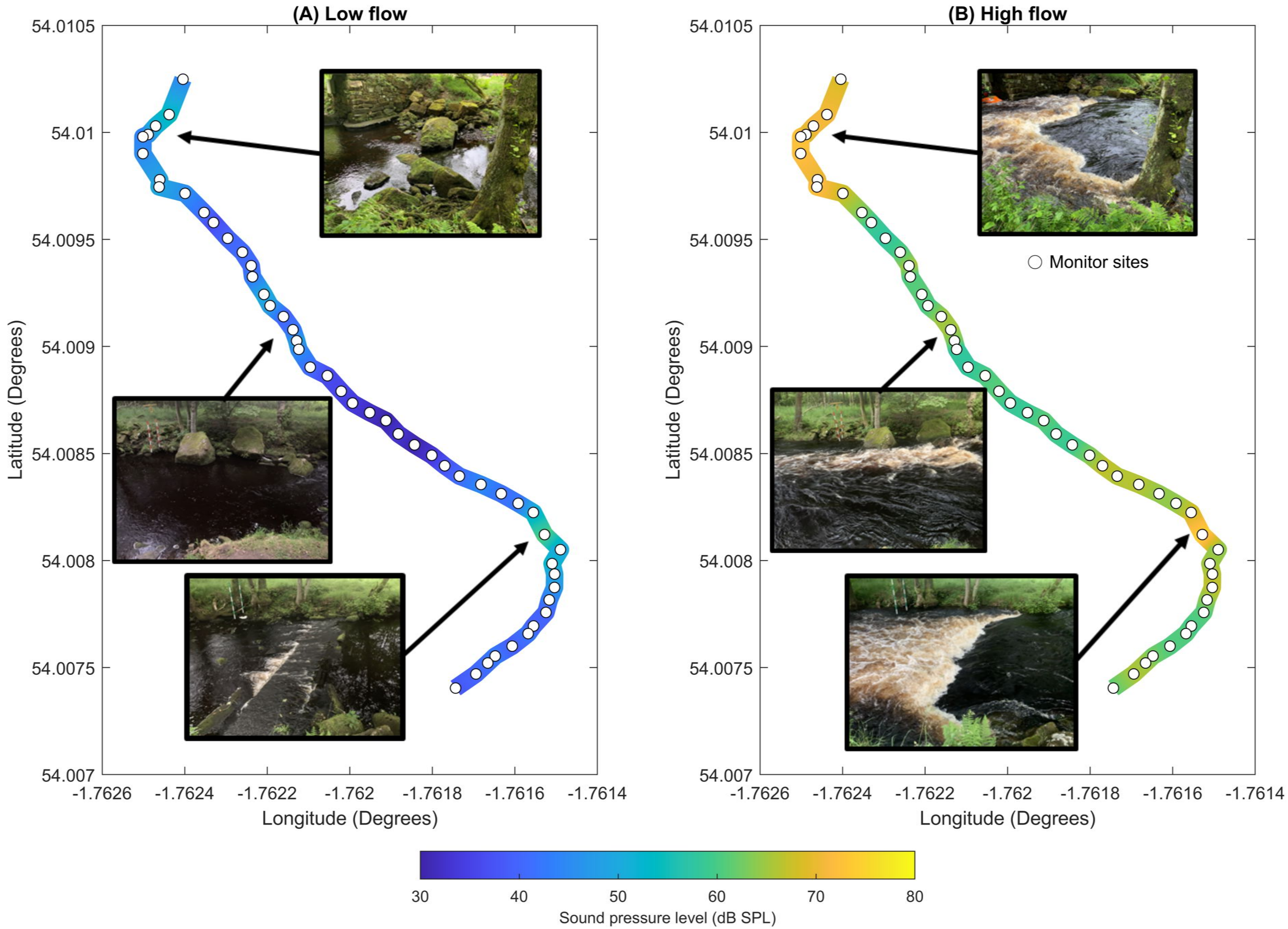

Figure 4: Acoustic map plotted of a 500 m course of the River Washburn during low and high flow. Markers show recording locations with the coloured line being a 1D interpretation between these points. Images shown highlight the main areas of change along with photographs of the sites. Sound values are obtained using the lowest median filter with a frequency of 0.05 -1 kHz. 0.05- 1 kHz is used due to the site being sheltered from wind meaning any sound generated will be purely from the river.

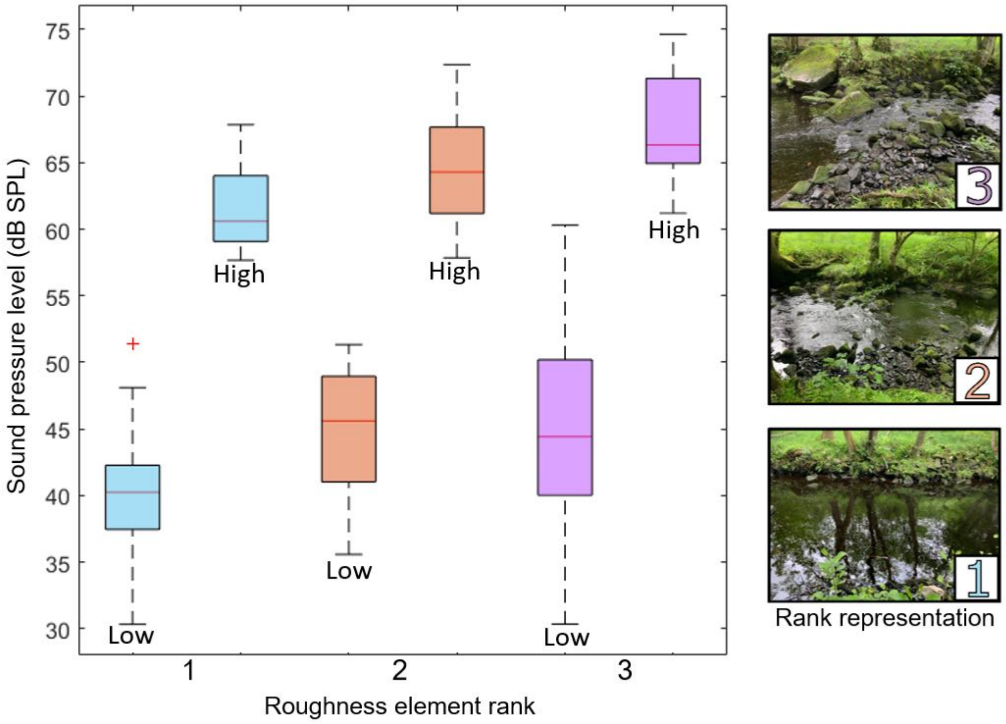

Figure 5: Box plot of normalised amplitude at low and high flow conditions, grouped by the qualitative rankings of roughness elements at the River Washburn. Photographs show a representative example of each rank. Roughness element rank is chosen by eye, with dominant REs, i.e. the largest element, being easily identifiable in Rank 3. Number of samples: Rank 1, 22; Rank 2, 15; and Rank 3, 13.

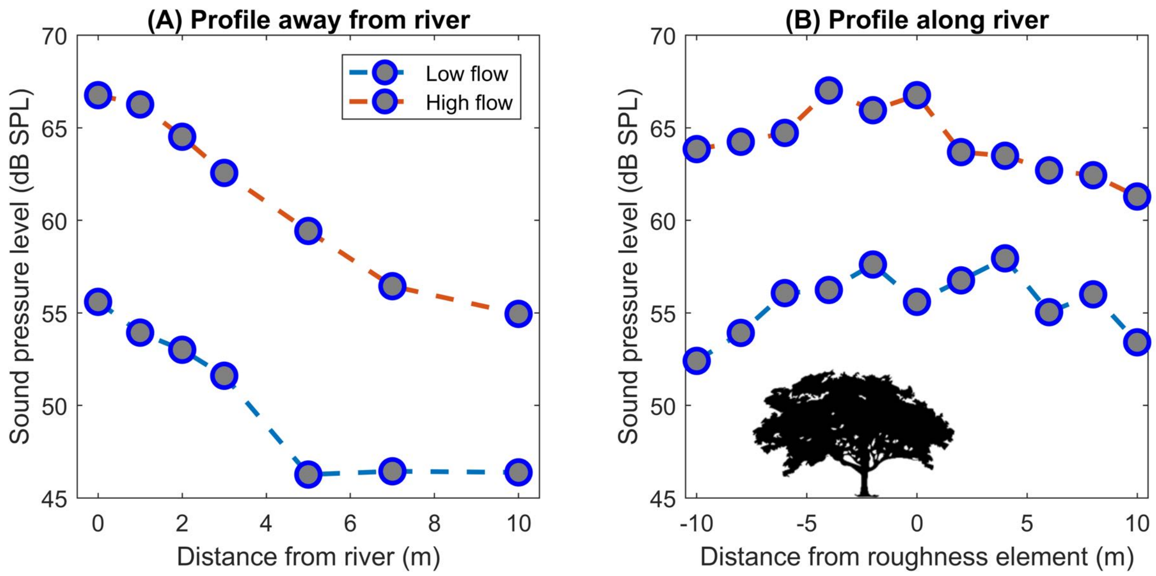

Figure 6: At the River Washburn, acoustic mapping was done around a dominant RE with a rank of 2. (A) moving away from the river and (B) along it. Recordings were done at the same points during low and high flow. Sound value relates to the 0.05 - 1 kHz band after lowest median filtering.

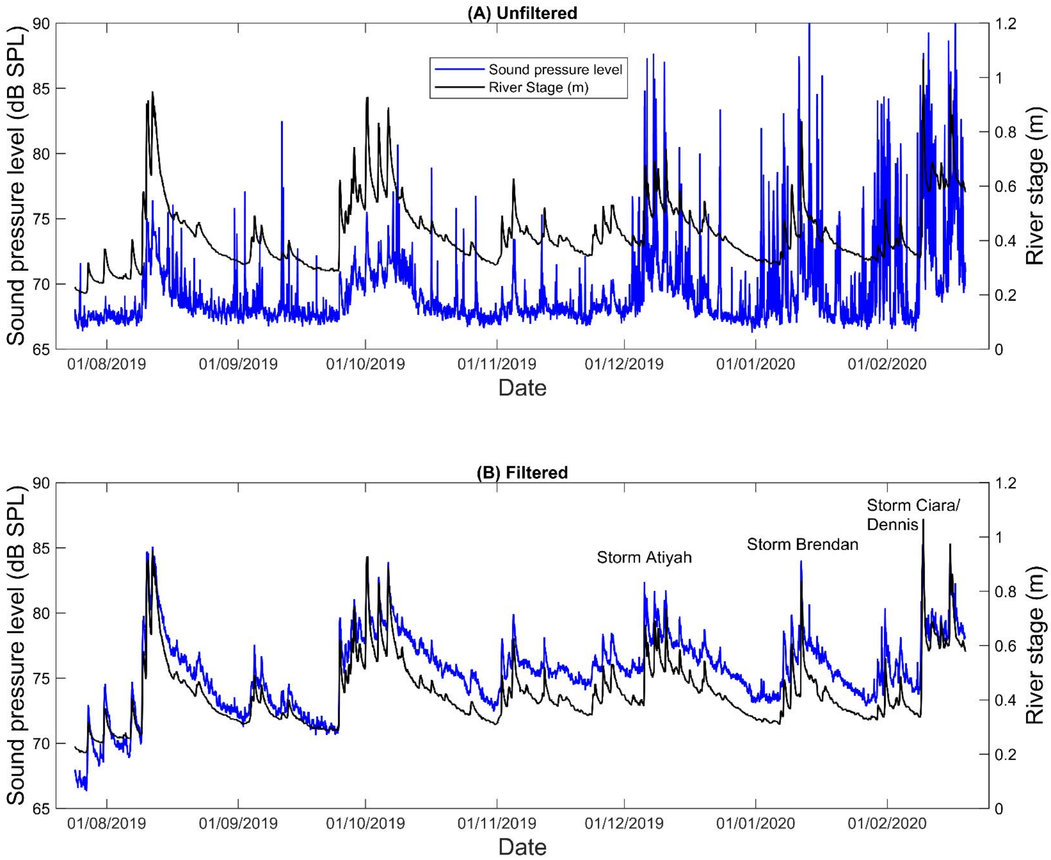

Figure 7: Sonohydrographs (blue) and hydrographs (black) of the Haltwhistle Burn over a Summer/ Winter season. (A) Unfiltered data at 0.05-1 kHz and (B) LMF filtered data at 0.05-1 kHz. Unfiltered data is a FFT of the entire audio clip, and the median taken from the 0.05 - 1kHz bin.

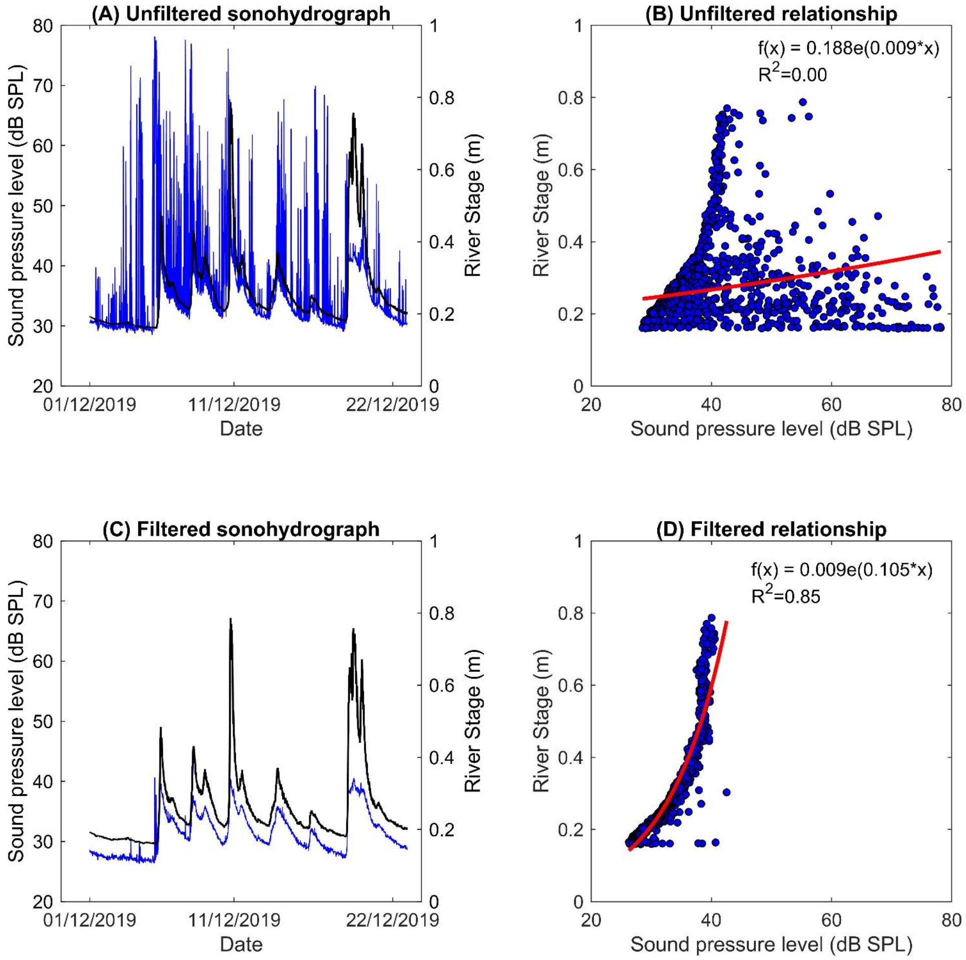

Figure 8: Comparison of river data with substantial wind noise from the Killhope Burn, Wearhead between 5 - 6 kHz. (A) Unfiltered sonohydrograph, (B) unfiltered river stage/ sound relationship, (C) LMF sonohydrograph and (D) LMF river stage/ sound relationship.

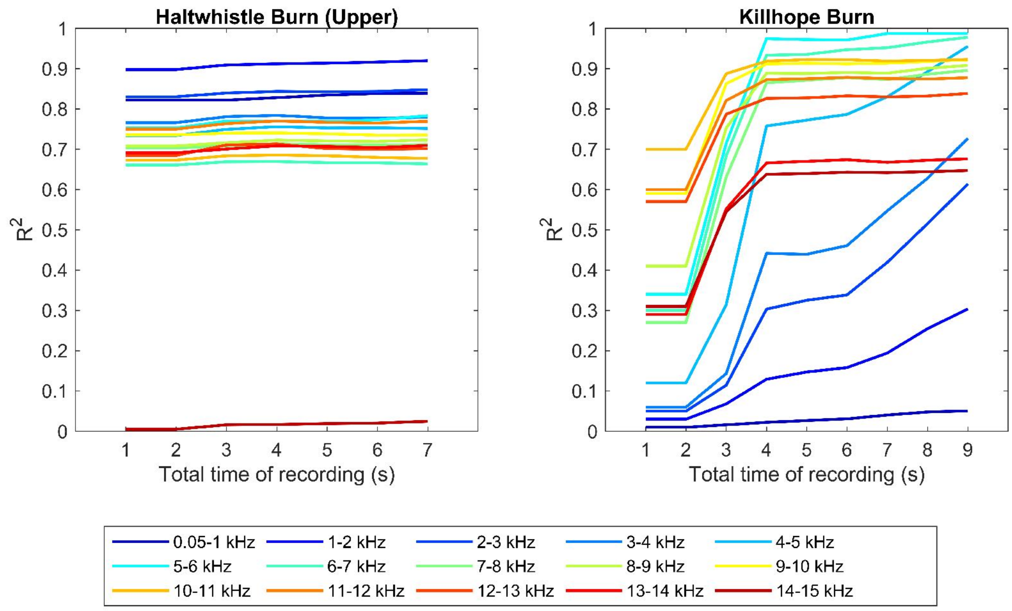

Figure 9: Sound data from Haltwhistle and Killhope filtered through the LMF using different total recording times and its affect on the stage/ sound relationship R^2 value. Haltwhistle burn uses a logarithmic function to fit to the data, and Killhope uses an exponential function.

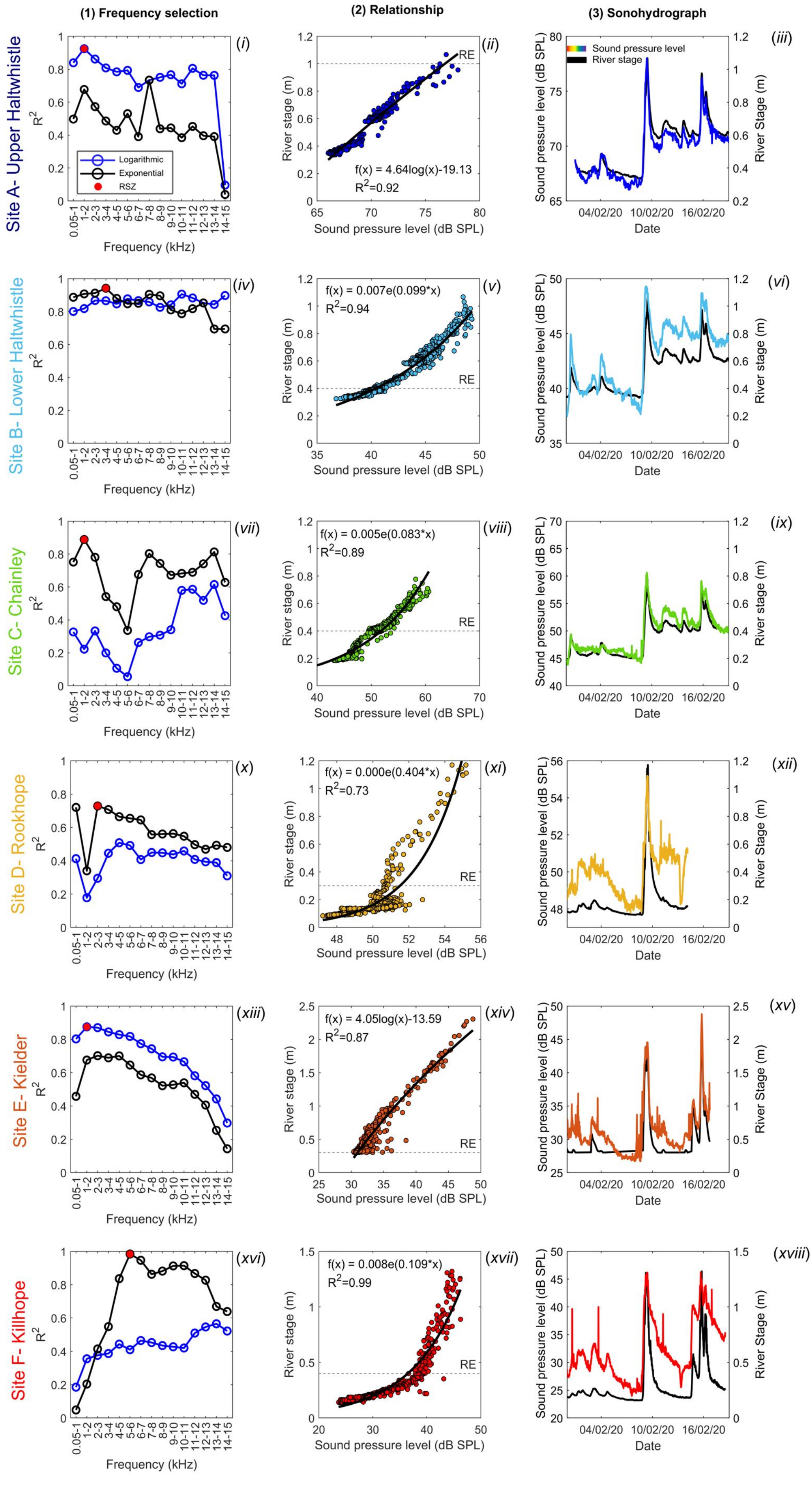
(1) Frequency selection
(2) Relationship
(3) Sonohydrograph
Site A- Upper Haltwhistle
Site B- Lower Haltwhistle
Site C- Chainley
Site D- Rookhope
Site E- Kielder
Site F- Killhope
Logarithmic
Exponential
RSZ
Sound pressure level
River stage
f(x) = 4.64log(x)-19.13
R^2=0.92
f(x) = 0.007e(0.099*x)
R^2=0.94
f(x) = 0.005e(0.083*x)
R^2=0.89
f(x) = 0.000e(0.404*x)
R^2=0.73
f(x) = 4.05log(x)-13.59
R^2=0.87
f(x) = 0.008e(0.109*x)
R^2=0.99
RE
R^2
Frequency (kHz)
River stage (m)
Sound pressure level (dB SPL)
River Stage (m)
Date
04/02/20
10/02/20
16/02/20
(i)
(ii)
(iii)
(iv)
(v)
(vi)
(vii)
(viii)
(ix)
(x)
(xi)
(xii)
(xiii)
(xiv)
(xv)
(xvi)
(xvii)
(xviii)

Figure 10: Workflow for identifying the best RSZ and obtaining the best river sound/ stage relationship for our 6 sites during Storm Ciara and Dennis. Column 1- the plotting of Storm Ciara/Dennis sound data against stage forming an R^2 value for both a logarithmic and exponential function. Highlighted point is the chosen RSZ for the rest of the figure which is the highest R^2 value. Column 2- The sound data and river stage plotted for the highlighted RSZ. Column 3- The sonohydrograph and hydrograph comparison for the RSZ. Horizontal dashed line shows the highest point of the largest roughness element found in the channel.