

SOUNDING OUT THE RIVER: AN END-TO-END FRAMEWORK FOR MONITORING BIOACOUSTIC EVENTS AND SEDIMENT MOVEMENT IN FRESHWATER SOUNDSCAPES

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1 ABSTRACT

Despite rivers' cornerstone place in global biodiversity and the key ecosystem services they provide to human societies, their soundscapes are severely understudied. Three challenges are in part responsible for this gap: the active nature of rivers complicates deployment logistics, their structural noise hinders the detection of significant events, and occurring sounds are largely under-characterised and unattributed to specific species. Here, we present a hardware set-up designed for long-term underwater river monitoring, and a computational framework to identify and analyse the highly diverse events that occur in this still largely unexplored acoustic environment. Our low-cost/low-power hydrophone recording solution is comprised of a portable weighted hydrophone mount and a separate land-based audio recording unit, well-suited to flexible deployment in freshwater streams and rivers. Our software protocol then allows us to detect and analyse stand-out events of geomorphic or biological nature despite the major background noise variations that naturally occur in fluvial settings. Applying this method on the River Ness allows us to monitor sediment movements across environmental conditions, and to detect significant bioacoustic signals including salmonid redd-cutting, water surface events, and bird vocalisations. Further application of the framework proposed in this paper will allow for continuous monitoring of rivers across Scotland, a clearer grasp of both sedimentary and biological events happening in underwater soundscapes, and a stronger understanding of their interactions.

2 INTRODUCTION

Despite the vital part freshwater environments play in both global biodiversity^{1,2} and the welfare of human societies^{3,4}, they are severely understudied^{2,5}. Among growing monitoring efforts, freshwater wildlife research has seen an increase in the adoption of passive acoustic monitoring (PAM) as a cost-effective and viable alternative to traditional, often more invasive modes of survey^{6,7}. However, the lack of available acoustic data⁸ and the inherent acoustic richness and complexity of these environments^{9,10} have so far prevented soundscape studies to reach the amount and coverage of their marine and terrestrial counterparts¹¹.

Two major survey design choices are required to fully address the under-characterisation of freshwater soundscapes. The first is long-term monitoring, that allows the capture of seasonal, environmental and anthropophonic soundscape variations, which are particularly high in these environments^{12,13}. The second is constant recording schedules, necessary to account for diurnal soundscape variation¹⁴ and monitor a wide range of cryptic or sparsely vocalising species^{7,15}. While these requirements typically result in prohibitive hardware deployment and maintenance costs, we present in this paper a portable, low-cost set-up capable of continuously monitoring river soundscapes with month-long periods of full autonomy. We demonstrate its potential, and develop an associated acoustic analysis method, in the context of monitoring salmonids and their interplay with sediment movement in Scottish rivers.

In Scotland, Atlantic salmon (*Salmo Salar*) and brown trout (*Salmo Trutta*) fulfil a major cultural, economic and ecological purpose^{16–18}. This role is threatened by their plummeting population counts over the last 50 years^{17–19}, likely the combined result of global warming, intensive fishing, predation and diseases^{20–25}. Conservation efforts would thus heavily benefit from long-term monitoring of spawning timings, population trends, and their response to environmental stressors, human activity or potential competition with the invasive Pink salmon (*Oncorhynchus gorbuscha*) recently observed in Scottish rivers^{26,27}.

The clearest acoustic event we use for monitoring salmonid spawning is the repeated displacement of river gravels through tail movements lasting up to a few seconds, a process known as redd cutting/digging and successfully detected by acoustic or seismic monitoring for other salmonids like trout and charr^{28,29}. This phenomenon is ecologically useful for the protection and oxygenation of salmon eggs, and is also known to have a measurable impact on overall sediment mobility^{30,31}. If successful in the detection of both redd-digging and flow-induced gravel movements, a long-term acoustic monitoring set-up would allow for a more comprehensive account of how fish- and flow-related sediment disturbances interact over time, assess their seasonal and diel patterns, and support the viability of hydrophones as a portable, non-invasive alternative to both traditional fish survey methods^{28,32} and common gravel impact detection systems for bedload transport monitoring^{33–35}.

Aside from redd cutting, salmonid sound production is also characterised by very diverse signals, in majority air movements (e.g. short coughs, gulps or snitches typically released from the mouth or gills of the fish) and surface events (splashes and movements at the surface of the water)^{36,37}. Both sound categories have been successfully monitored in natural, semi-natural and hatchery settings, but not yet over longer deployments with highly varying flow conditions. A long-term, heavy-recording schedule survey could thus offer a complementary evaluation of their potential for salmon monitoring in the wild.

The routine analysis of fluvial acoustic data relies on a robust understanding of the different characters of sound events and background soundscape under a wide range of typical river conditions. Here we present a scoping of these dimensions and show how this understanding enables us to isolate the dynamics of trout spawning along the River Ness.

3 METHODS

3.1 Study Location

The River Ness is a 10-km long reach flowing the short distance from Loch Ness to the Morray Firth, an inlet of the North Sea. It is both a mandatory passage for salmon spawning further upstream in Loch Ness tributaries, and a salmon and trout spawning ground in its own right. A notable feature of the River Ness is its water temperature, buffered unusually high during autumn and winter by Loch Ness, which results in delayed salmon spawning³⁸. Our monitoring site (Figure 1a,b) is located on the inner bend of a meander near the south end of the river, directly upstream of an artificial riffle, where redds were visually spotted by the water bailiff during previous spawning seasons.

3.2 Hardware & Deployment

Hydroacoustic recordings were made using an Aquarian H2D Hydrophone (Aquarian Audio & Scientific) and an Audiomoth acoustic logger (Open Acoustic Devices). The hydrophone was connected to the Audiomoth's external microphone contacts, thereby bypassing the recorder's internal MEMS microphone.

To extend deployment time, external battery holders were connected to the Audiomoth. Six D-cell alkaline batteries in a 3 series/ 2 parallel configuration provided the required operating voltage (4.5V) and over 20Ah of battery capacity. The Audiomoth and battery holders were mounted on a custom

3D printed backing plate and housed within an IP67 rated weatherproof enclosure (Figure 1c,d). A sealed cable gland was installed on the bottom of the enclosure, to admit the hydrophone lead while providing cable strain relief and enclosure watertightness.

To minimize disturbance to salmonid spawning redds, each hydrophone was mounted within an individual river stone of sufficient mass (~20 kg) to resist the river current (Figure 1e). These stones were easy to move and install, and were not as disruptive as the construction of permanent hydrophone mounting structures. A 30 mm diameter through hole was cored in the centre of each stone, and a 3D printed thermoplastic polyurethane (TPU) insert was used to secure the 25 mm diameter hydrophone body within the bore. The TPU insert also attenuated vibrations transmitted through the stone to the hydrophone receiver housing. The TPU insert held the metal hydrophone housing inside the stone, while the rubberised hydrophone transducer body was allowed to sit outside the stone surface, minimizing the mounts interference with the transducer. The hydrophone mount was positioned a few meters from the shore, with the rocks bore hole orientated towards the centre of the river channel, perpendicular to the flow of the river (Figure 1f).

The hydrophone cables were wrapped in split loom conduit for mechanical protection. The cables were routed to shore, and the audiomoth enclosures were mounted to trees. This allowed the enclosures to be accessed from shore, allowing for data recovery and battery changes without the need to enter the river and disturb the redds.

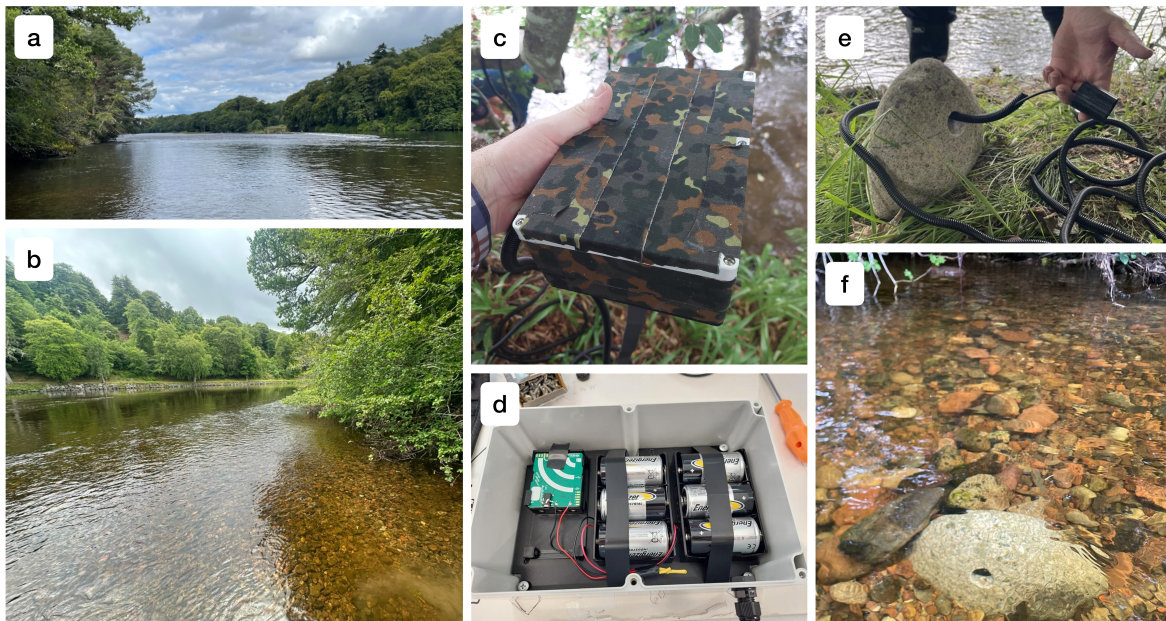


Figure 1: (a-b) Site on the river ness (c-d) enclosure containing the Audiomoth and battery holders (e) TPU insert and cable (f) stone-mounted hydrophone after the install

Recorders were programmed to operate continuously (24 h day⁻¹) recording 55s of audio per 60 s period. The sampling rate was set to 48 kHz, and input gain was set to the High setting with low range enabled in the AudioMoth configuration application. Data were stored on 256 GB microSD cards.

3.3 Data Processing

Hydrophone data consisted of one recording per minute, stored as WAV files with a customized header including recording settings, current battery voltage and temperature inside the logger. Whilst the dataset consists of two separate hydrophones, here we focus on information extracted from the upstream one, which benefitted from audibly lower background noise and data collection in October.

As the sound events that occur in this environment are largely unknown and undescribed, manual labelling is still a necessary step to annotate and classify them. However, the large amounts of audio data make it unfeasible to listen to the full data. Three main steps were thus followed to analyse the collected recordings: preliminary exclusion of selected, short 'noisy' time periods, automatic attribution of a background-adaptive signal-to-noise ratio score to each file, and the manual annotation of high-score files.

To reduce certain types of environmental and deployment-related noise that can bias signal-to-noise ratio estimates and obscure bioacoustic signals, files were excluded according to the following criteria: (i) Recordings made within one hour of initial deployment, or at very low voltage (near-depleted batteries), where sound quality had audibly deteriorated, (ii) Periods with non-zero rainfall at any of the SEPA stations Inshes, Flichity, or Urquhart (5.5, 11.5, and 18 km from the study site, respectively)³⁹, to eliminate most rain-related noise and (iii) Periods when water level exceeded 1.75 m at the SEPA Ness-Side gauge (2 km downstream of the study site)³⁹. From an initial batch of 82,337 sound files, steps (i), (ii) and (iii) excluded 6655, 6735 and 901 files respectively, leaving a final selection of 68,046 files (82,6 %) to be further processed and analysed.

Signal-to-noise ratio was attributed file-by-file through spectral subtraction, the removal of an estimate of background noise to only keep sound events that significantly stand out from it. The spectrogram of each file was computed with a frame length of 1024, a 50% overlap and a Hanning window. Frequencies below 100 Hz and above 20 kHz were ablated from the spectrograms, to dampen the effect of low-frequency turbulences and confine our analysis to the audible spectrum. The background noise spectrum of each file was then estimated from the median frame power across time of each frequency bin. This estimate was subtracted from the original spectrogram, and files whose total remaining power ranked in the top 3% of the entire selection were picked for manual annotation — effectively corresponding to 2041 individual files of SNR higher than 2.7589 dB.

Manual annotation was performed in Raven Pro⁴⁰. High SNR files were processed in random batches of 50, and within each batch all visually salient signals on the waveform and/or spectrogram view were annotated and manually labelled into clusters according to their perceived acoustic similarity. At this stage, no inference was made on the possible source or location of each sound. Acoustic measurements were computed automatically in Raven for all sound events. They included peak frequency, 50% and 90% bandwidth (respectively the frequency difference between the 25th and 75th percentiles, and 5th and 95th percentiles, of acoustic power), average entropy and average power density.

After grouping sound event into definite classes, the plausible sources of each class were examined with local experts and compared against existing audio accounts. This process is further developed in the discussion section.

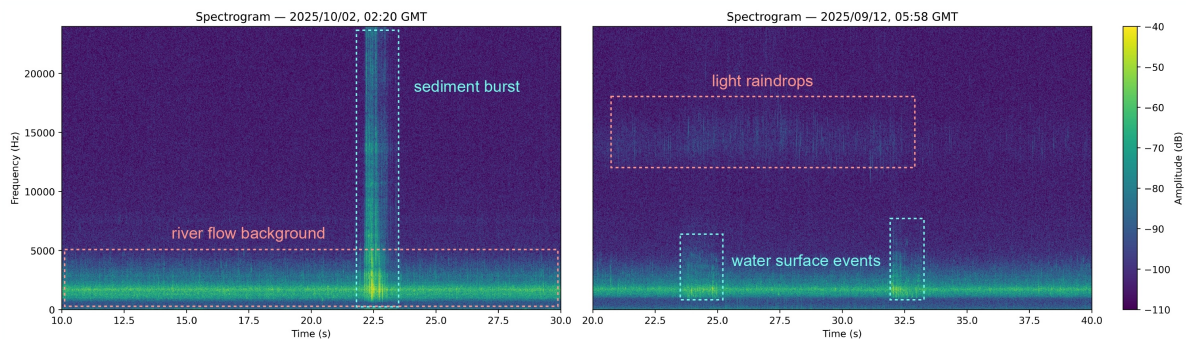


Figure 2: Spectrograms of several sound events (blue) and environmental background noises (red)

4 RESULTS

2041 files were reviewed, for a total of 2627 annotated sound events. Of those, 711 were too long or continuous to be confined to a unique, finite or single-file contained sound event (e.g. sounds of walking in the river, long-lasting water surface activity). Due to the inherent difficulty of measuring these events' sound properties or classifying them into robust categories, they were not included in the present analysis. We also excluded 80 events that unambiguously pertained to anthropophony (e.g. passing planes, metal spinning fishing lures), 370 events related to rainfall or water drops hitting the water surface and 150 low-frequency knocks and noises likely due to turbulences and external interference with the underwater cable or the logger itself.

All remaining sound events could be classified into three broad categories: 944 sediment-generated noise events, 312 surface events corresponding to movement at the surface of the water, and 60 other events of varying sound properties that occurred too rarely to form their own cluster.

There were 48 instances of two separate events overlapping in time. While these events were included in the global count, they were removed before computing any statistics about their respective categories' acoustic properties (e.g. peak frequency, volume) to avoid contamination. All intervals regarding these statistics are written below as $M \pm 2 \text{ SD}$ for volume (dB) and peak frequencies (Hz), and $GM \times / \div 2 \text{ GSD}$ for bandwidths (Hz) and durations (s), which followed log-normal distributions.

Category	Sub-Category	N	% of total
Sediment Movements	Collisions	348	13.2
	Bursts	596	22.7
Surface Events	Jumps	30	1.1
	Fast rhythmic sequences	118	4.5
	Other surface events	164	6.2
Other		60	2.3
Non-Included	Anthropophonic	80	3.0
	Long / Continuous	711	27.0
	Rainfall	370	14.1
	Knocks & Interferences	150	5.7
Total		2627	100

Table 1: Categories of detected sound types

4.1 Sediment Movements

Events classified as 'sediment movement' are sounds audibly caused by sediments of diverse size or shape colliding against each other or the riverbed itself. Two types of events were observed, 'collisions' and 'bursts'.

Collisions ($n = 348$) are short events ($0.18 \times / \div 5.33 \text{ s}$) consisting of 1 to 3 clearly separate but contiguous volume peaks of similar frequency profile, seemingly resulting from a singular impact sequence of a grain onto the bedload. Their peak frequency is $1722 \pm 433 \text{ Hz}$, with 90% and 50% bandwidths of $1001 \times / \div 2.43 \text{ Hz}$ and $303 \times / \div 2.77 \text{ Hz}$ respectively.

Bursts ($n = 596$) are on average significantly longer events ($0.76 \times / \div 2.57 \text{ s}$), often combining a longer continuous train of 'collision'-like volume peaks with an overall broadband rise in background volume, seemingly corresponding to the mobilisation of numerous sediments of different sizes. This results in larger and more variable 90% and 50% bandwidths ($2059 \times / \div 3.33 \text{ Hz}$ and $469 \times / \div 3.08 \text{ Hz}$). The frequency peaks of bursts are close to those of collisions ($1710 \pm 1241 \text{ Hz}$), including a subset of 21 events showing a very low frequency peak ($< 150 \text{ Hz}$) likely corresponding to co-occurring turbulence.

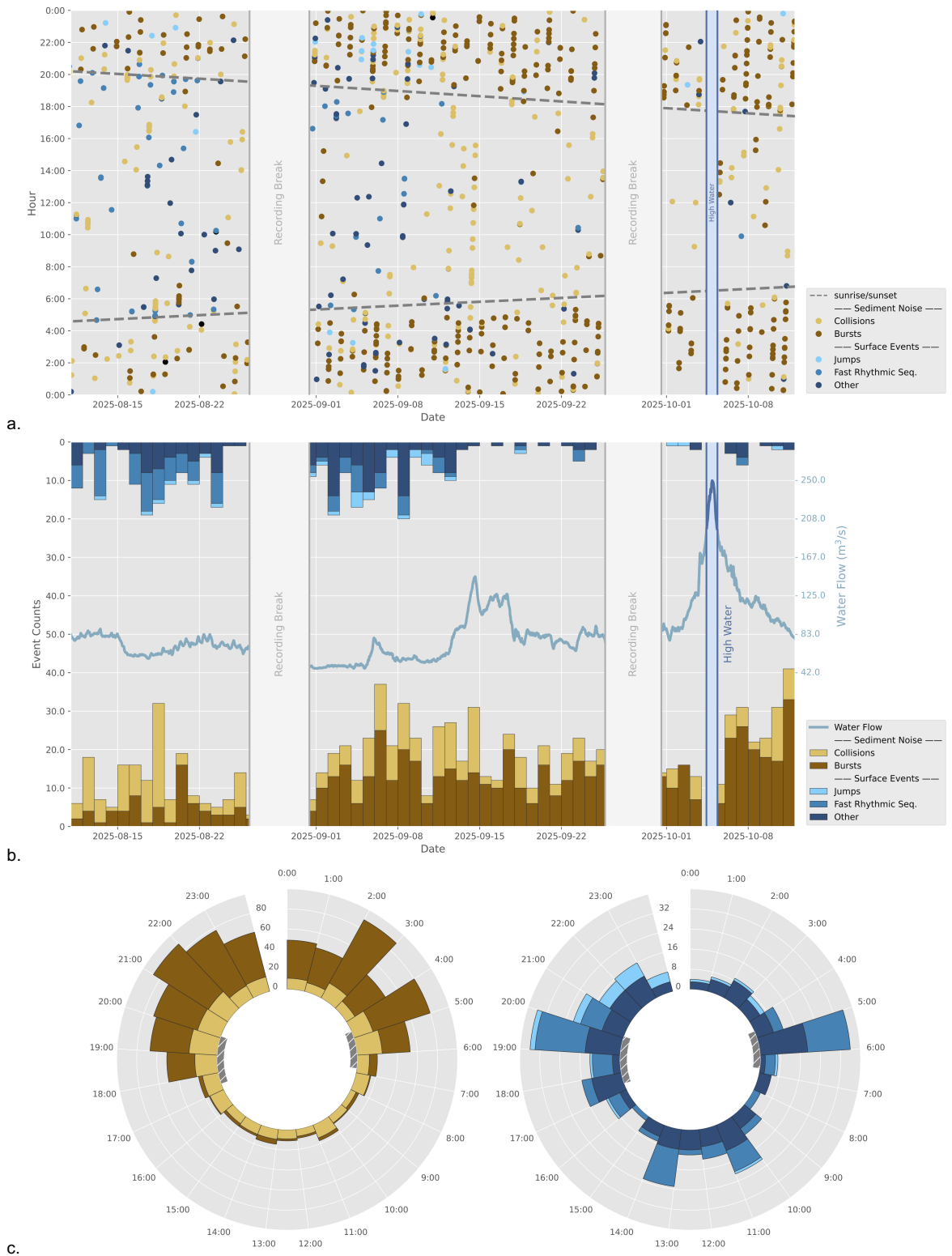


Figure 3: (a) Date and time of individual sound events from each studied category (b) daily sound event occurrences (c) hourly sound event occurrences (hatched grey zones correspond to sunrise/sunset ranges). All dates & times are indicated in GMT

Collisions and bursts showed clear differences in seasonal and diel patterns along the recording period. Collisions had a highly variable number of daily occurrences with single-day or multi-day peaks found all along the recording period, albeit more often in its first half. Significant hourly variation was also observed, with overall higher occurrence rates at night than day. Summed over the full recording period, the number of collisions per hour culminated during sunset and sunrise, where it reached up to twice the rates observed in the middle of the day. On the other hand, daily bursts rates followed a steady increase all along the recording period, from 1-8 events/day in mid-August to 17-33 events/day after the October 5th high water event. Diel differences were significantly starker than for collisions, as close to 16 times more events were recorded between 18:00 and 6:00. The peak hour for bursts was 2:00-3:00, with 72 recorded occurrences over the full survey period, against only 1 for 7:00-8:00, 9:00-10:00 and 16:00-17:00.

4.2 Surface Events

Events labelled as 'surface events' are sounds that were audibly the result of an object surfacing, entering water, or moving at its surface. They presented a wide diversity of patterns and acoustic characteristics which did not allow for an all-encompassing classification. However, two clusters of events labelled 'jumps' and 'fast rhythmic sequences', respectively encompassing 30 and 118 of the 312 surface events, were identifiable enough to be analysed as their own subcategory.

All 'jumps' follow a similar structure: a very short water movement ($0.12 \text{ x} \pm 2.74 \text{ s}$, on average 12.0% of total duration) followed by a silence ($0.18 \text{ x} \pm 2.53 \text{ s}$, on average 16.9 % of total duration) and a second, significantly longer water movement ($0.82 \text{ x} \pm 2.20 \text{ s}$, on average 70.9 % of total duration). Both water movements have similar peak frequency and average power density distribution, but the first tends to have a lower volume peak than the second: $-42.6 \pm 12.8 \text{ dB FS/Hz}$ against $-37.8 \pm 11.3 \text{ dB FS/Hz}$.

'Fast rhythmic sequences' are continuous trains of quick, regular and near-identical water movements. There are usually 6-10 movements per second, with extreme cases at 4 and 11, for a total event duration that ranges from a couple of seconds to over 15 secs ($4.05\text{s x} \pm 5.50$). Across the full duration of the sequence, the volume and frequency of individual movements can be stable or increase/decrease over time. The peak frequency of fast rhythmic sequences ($1709 \pm 573 \text{ Hz}$) is similar to those of jumps ($1631 \pm 485 \text{ Hz}$) and all other surface events ($1605 \pm 817 \text{ Hz}$).

While limited, occurrences of 'jump' events were localised in time: most happened between September 4th and 10th, and between 21:00 and 0:00. Fast rhythmic sequences happened at highly variable daily rates, the majority of which in the first third of the recording period. Hourly rates varied heavily as well, with peaks of occurrences in periods 5:00-6:00, 13:00-14:00 and 19:00-20:00. This pattern matches with the rest of all surface events: they tended to happen at very variable daily and hourly rates, and significantly more often over the first half of the recording period.

5 DISCUSSION

5.1 Attribution of Sound Categories

5.1.1 Sediment Movements

The duration, profile and broadband nature of 'bursts' heavily suggest that most correspond to fish redd digging gravel movements, previously recorded in salmonids⁴¹⁻⁴³. This account is fully supported by their diel patterns. Two redd-digging salmonid species historically inhabit the River Ness: brown trout and Atlantic salmon. Both conduct most of their movement and spawning during low light levels, at sunset or at night⁴⁴⁻⁴⁷. Not only do our observed hourly rates match this tendency, but they also aligned with the progressive shift in sunset and sunrise times over the recording period. In the absence of visual confirmation, the diggings cannot be strictly attributed to a species or another.

However, Atlantic salmon and brown trout historically spawn during different periods on River Ness. Brown trout typically start spawning in October and have their main activity in November, with some practice redds occurring as early as September, while Atlantic salmon tend to spawn particularly late compared to other Scottish rivers, between December and February. The redd cutting timings observed in this study therefore suggest that trout, rather than salmon, were recorded. Moreover, while the earliest occurrences of bursts also match with the spawning period of the invasive pink salmon in Scotland, typically from July to September, the species has very rarely been observed on the Ness and the 2023 eDNA pink salmon survey had negative results in this river⁴⁸. It is likely that the earliest occurrences correspond to brown trout exploratory/practice digging for site selection, possibly evolving into a larger proportion of actual redd cutting over time. While both behaviours are common to all salmonids, the movements involved are likely too similar to be discriminated on their own⁴⁹. Agonistic behaviour between males, common during salmonid spawning⁵⁰, may also have led to gravel displacement as previously observed in Arctic char⁴¹.

It should be noted that diving birds and punctual walking animals (e.g. deer, dogs) entering the river may produce bursts of gravel displacement sounds, potentially similar to redd cutting signals. However, the specific acoustic characteristics, hourly rates and temporal patterns observed in 'bursts', as well as the preliminary elimination of walking-like sounds from the selection, suggest that such occurrences would only account for a small proportion of this category's events.

Contrary to bursts, collisions cannot be clearly attributed to a known animal behaviour and more likely pertain to spontaneous gravel movements caused by water flow. However, the lack of a clear correlation between daily flow levels and collision rates suggests that other factors may be at play. The disturbance and fragilisation of bedload stability due to walking or redd digging is a possible explanation, congruent with the observed increase in collision rates during nighttime.

5.1.2 Surface Events

Surface events occurred in lower numbers than sediment movement, and contrarily to redd cutting they can be caused by a wide variety of animals, making their attribution significantly more difficult. Aside from 'jumps' whose characteristic structure is highly suggestive of salmonid jumps, other surface events could also be attributed to a variety of species known to inhabit the Ness, including otters, herons and various ducks. Fast rhythmic sequences, whose occasional co-occurrence with jumps suggest a fish origin for some, may also correspond to paddling otters or landing ducks. Objects being thrown in the river (e.g. fly lines) may also provoke surface events. At this stage, more visual confirmation is needed to disambiguate these signals, and determine if a more precise categorisation would successfully separate species.

5.1.3 Other Bioacoustic Signals

Of the events included in the final selection, 60 could not be classified in any of the other groups. While many are of unknown origin, several closely resemble characterised vocalisations or sound production from species known to inhabit the study site. In the absence of visual confirmation, they were provisionally attributed to those species. Two recordings matched with previous accounts of fish air movement sounds, one being extremely similar to a brown trout gill-bubble FRT³⁷, two closely resembled existing Xeno-Canto UK-based recordings of otter mating calls^{51,52} and at least two likely contained heron calls^{53,54}.

Air movements like gill-bubble FRTs and vocalisations are easier to attribute to singular species than surface events, potentially allowing for the disambiguation of other signals they co-occur with. However, it should be noted that in our selection those sounds were rare, usually low-volume, and that many were noticed precisely because of their co-occurrence with louder sounds (e.g. surface events) picked up by our detection process. Detecting these signals in the wild, and below water, seems to be a significantly harder task than detecting redd digging. In this regards, our results match

those of Bolgan et al.²⁸ who found that charr air movements, contrarily to gravel noises, were too weak and rare to raise acoustic indices.

5.2 Robustness of Diel and Seasonal Occurrence Patterns

A major interest of long-term surveys resides in the analysis of event occurrence and frequency over extended timelines. In our case, plotting daily occurrences across several sound categories reveals two clear trends: the constant augmentation of redd-cutting-like gravel movements along the recording period, suggesting a ramp-up in brown trout pre-spawn exploratory digging and/or actual redd digging in September through October, and the progressive rarefaction of surface events between August and October, possibly indicative of occupancy shifts or seasonal behavioural changes. The capture of significant soundscape trends over several months is thus a promising sign for the viability of the discussed set-up for long-term river monitoring.

However, this type of occurrence timeline should be interpreted with care as they are largely vulnerable to shifts in detection probability — which, in our case, would likely result from any significant change in river flow. Our manual labelling of the top 3% files in signal-to-noise ratio is a pre-selection based on the difference between sound events and automatically computed background levels. However, background volume itself in rivers is known to directly augment as a function of flow, an effect amplified by bedload sediment transport during high flow events^{55–57}. Our own account of river background volume during our survey period fully aligns with previous studies: average background volume steadily increased as a function of river flow, with a difference of 13 dB between the average background volumes for flows below 50 m³/s and above 200 m³/s, the two recorded extremes. Flow also affects background spectrum, water depth and river geometry, which are all known to significantly impact sound propagation⁵⁸. Combined with probable behavioural changes in salmonid movement as a response to flow variations^{49,59}, these physical constraints make it particularly difficult to determine the combined effect of river flow on detection probability. At this stage, it is therefore recommended to only directly compare event occurrences across similar flow levels.

On the other hand, comparisons of hourly rates across a summed 24-hour cycle are significantly more robust. Over our recording period, the difference in average background volume between the quietest and loudest hour was negligible compared to flow-induced standard deviation for the same hours across days, suggesting minimal impact of anthropophony on background noise and allowing for higher confidence in our analysis of diel patterns. Longer-term survey designs will however need to account for large shifts in sunrise and sunset hours when analysing these patterns over an entire period.

6 CONCLUSION

The deployment of long-term, constant monitoring surveys is both highly needed and largely missing in freshwater bioacoustics. In this preliminary study, we present a low-cost portable hardware set-up for continuous river monitoring and demonstrate its potential to capture diel and seasonal soundscape trends. We successfully record and detect a diverse array of geophonic, anthropophonic and biophonic signals, showing extensive soundscape coverage. Through our focus on redd-digging gravel movements and surface events, we also demonstrate the viability of this set-up for salmon monitoring, supporting its use and further deployment in salmon or trout rivers across Scotland. While these preliminary results are promising, we note that this line of research would strongly benefit from two kinds of efforts. First, the disambiguation of unattributed sound signals, particularly surface events, through in-person surveys or simultaneous visual recordings. Then, the characterisation of flow-induced detection probability shifts, to allow for reliable comparisons of sound event rates across periods of varying river flow.

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