



*Anthropogenic noise in a large lake*

**First observations of anthropogenic underwater noise in a large multi-use lake**

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**ABSTRACT**

Over the last fifty years, anthropogenic noise has increased dramatically in aquatic environments and is now recognised as a chronic form of pollution in coastal waters. However, this form of pollution has been largely neglected in inland water bodies. To date, very few studies have investigated the noise spectra in freshwater environments and at present no legislation exists to protect freshwater organisms from anthropogenic noise. The present study represents the first assessment of anthropogenic noise pollution in a large multi-use lake by characterising noise levels of the main ferry landings of the lake of Windermere, UK using Passive Acoustic Monitoring (PAM). During November 2014, acoustic samples (10 min long) were collected from such areas using a calibrated omni-directional hydrophone and their spectral content was analysed in 1/3 octave bands (dB re 1  $\mu$ Pa). Results indicate that the current noise levels in Windermere warrant further investigation as a potential threat to the

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fish community which occurs in this already delicate and pressured habitat. Based on results obtained, it is recommended that further studies focus on a wider geographical and temporal range in order to start to fill the knowledge and legislative gaps regarding anthropogenic noise monitoring in fresh waters.

## INTRODUCTION

Over recent decades, anthropogenic noise in aquatic environments has increased dramatically as a result of population growth, urbanisation, globalisation of transportation networks and expansion of resource extraction (Radford *et al.*, 2014; Shannon *et al.*, 2015). Considering the global extent and the wide ranging effects of anthropogenic noise pollution on aquatic life (Slabbekoorn *et al.*, 2010; Popper and Hawkins, 2015), anthropogenic noise has been identified as an international target for the monitoring of a good quality coastal environment; *e.g.*, inclusion in the US National Environment Policy Act and in the European Commission Marine Strategy Framework Directive (MSFD; 2008/56/EC), and as a permanent item on the International Maritime Organization Marine Environmental Protection Committee agenda (Radford *et al.*, 2014). In contrast, the threat that anthropogenic noise poses to aquatic life has been largely neglected in the freshwater domain (Amoser and Ladich, 2010). Although it is well recognised that the biological communities inhabiting inland aquatic habitats currently face unprecedented threats from human activities (Winfield, 2013) and anthropogenic pressures often act in a multimodal fashion (Halfwerk and Slabbekoorn, 2015), very few studies have investigated the spectral profiles of freshwater soundscapes (Wysocki *et al.* (2007). In particular, European Member States are required by the Water Framework Directive (WFD; 2000/60/EC, European Communities, 2000) to adopt an integrated management approach in order to achieve a good ecological and chemical status of inland waters; however, this directive does not require member states to integrate the monitoring of underwater anthropogenic noise into management plans. In fact, no legislative effort has been made toward the conservation of good quality inland waters through the consideration of noise as a form of pollution. The aim of this study was to investigate the level of anthropogenic noise in the main ferry landings of Windermere, a temperate, large multi-use lake in Europe.

## METHODS

### Study site

Windermere is situated (54° 22' N, 2° 56' W; altitude 39 m) in the English Lake District, UK. The fish community is relatively simple with Arctic charr (*Salvelinus alpinus*, L. 1758), Atlantic salmon (*Salmo salar* L., 1758), brown trout (*Salmo trutta* L., 1758), European eel (*Anguilla anguilla* L., 1758), perch (*Perca fluviatilis* L., 1758), pike (*Esox lucius* L., 1758) and roach (*Rutilus rutilus* L., 1758), although a number of minor species are also present (Winfield *et al.*, 2011). The lake is an important multi-use resource for the local economy, in terms of both general tourism (with an associated extensive ferry network) and recreational fishing for several species.

### Acoustic recordings

During November 2014, acoustic recordings were collected from all the main ferry landings of Windermere, namely Ambleside Ferry Landing, Bowness Yacht Landing, Bowness Cable Ferry Landing, Bowness Ferry Landing, Lakeside Ferry Landing and Brockhole Ferry Landing (Tab. 1, Fig. 1). Acoustic samples (10 min long) were taken during daylight (Tab. 1) using a calibrated omni-directional hydrophone Aquarian H2a (sensitivity -180 dB re 1V/Pa; frequency response 10 Hz-100 KHz) connected to a ZoomH1 recorder (sampling rate 44.1 kHz, 16-bit) operating on batteries and recording .wav files. Prior to each recording, the signal was calibrated using a pure wave of known voltage (100 mV rms @1 kHz; Welleman Instruments HPG1). Where possible (i.e. Ambleside Ferry Landing, Bowness Ferry Landing and Brockhole Ferry Landing), sampling was carried out using a bottom-mounted, custom-built support consisting of an ovoid 5 kg cement base with a metal pole, 1.5 m high, screwed down the middle, on which the hydrophone's cylinder was tied at ca. half bottom depth. At the remaining sites, the hydrophone cylinder was lowered to half bottom depth from the dock (Tab. 1).

All .wav files were analysed using Raven 1.5 for Windows (Bioacoustic Research Program, NY, USA) for auditory and visual assessment of the spectrograms (sampling rate 44.1 kHz, 16 bit). They were subsequently analysed for the 1/3 octave band standard centre frequencies in terms of Instantaneous Sound Pressure Level ( $L_{SP}$ , L-weighted, 63 Hz - 20 kHz, RMS fast) using SPECTRA Plus 5.0 software (Pioneer Hill Software, WA, USA; windows Hanning, FFT 512, overlap 75%), calibrated with a signal of 100 mV RMS @1 kHz. The equivalent

continuous Sound Pressure Levels (SPLs: LLeq, 10 min) were further calculated by averaging the  $L_{SP}$  over the entire 10 minute sample (after linear scale conversion).

### Ferry numbers

In order to estimate the intensity of motor traffic on the lake, the number of sailings by the lake's ferries was determined across both winter (3 November- 27 March) and summer (28 March- 2 November) months as the number of crossings per day for each of the landings. Ferry sailings details were obtained from [www.windermere-lakecruises.co.uk](http://www.windermere-lakecruises.co.uk).

## RESULTS

The underwater spectral profiles of all the main ferry landings were characterised by most acoustic energy occurring below 4000 Hz, peaking at about 2000 Hz (Fig. 2, Tab. 2). Overall, the lowest spectral values (Fig. 2) were recorded at the Ambleside Ferry Landing (SPL= 117 dB re 1 $\mu$ Pa, Tab. 2) when no moving boats were detectable, while the highest acoustic energy (both in term of spectral energy and continuous sound pressure level, SPL) was recorded during the passage of the Miss Westmorland passenger ferry (18m long, 128 passengers full capacity, Volvo Penta marine shaft V-drive engine, [www.windermere-lakecruises.co.uk](http://www.windermere-lakecruises.co.uk)) at ca. 15 m from the recording hydrophone at the same landing (SPL= 135 dB re 1 $\mu$ Pa, Tab. 2; Fig. 2). The Bowness Ferry and the Bowness Yacht Landings, which had consistent boat traffic (ferries, recreational boats and sailing boats), were characterised by SPLs of 130 and 123 dB re 1 $\mu$ Pa, respectively (Tab. 2). At the Bowness Cable Ferry Landing the SPL was 114 dB re 1 $\mu$ Pa, reaching up to 130 dB re 1 $\mu$ Pa during the passage of the cable ferry at ca. 20 m from the recording station (Tab. 2). The cable ferry main acoustic energy shift was at 1000 Hz (difference of 17 dB re 1 $\mu$ Pa). Finally, the SPL characterising the Brockhole and the Lakeside Ferry Landings was of 109 and 118 dB re 1 $\mu$ Pa, respectively (Tab. 2). Windermere is serviced all year round by three non-cable ferry lines, namely the Blue Cruise, the Red Cruise and the Yellow Cruise, which all operate out of Bowness Ferry Landing. During November 2014 (i.e. a winter month as defined in the sailings schedule), a total of 420 sailings was made by these ferries (for a total of 840 passages in the landings, altogether). Bowness Ferry Landing, which is located in the central part of the lake, is the most heavily used (Tab. 3). One of the ferries, the Miss Westmorland, was recorded passing 15 m from the recording station at the Ambleside Landing (Fig. 3). At low frequencies (i.e., from 63 Hz to 630 Hz), the mean acoustic energy increment during this passage was of 9 dB (SD=2.3; min=4; max=14 dB re

1 $\mu$ Pa); at 800 Hz the increment was 41 dB reaching up to the highest values at 1000 Hz, where the difference in acoustic energy was of 47 dB. At 2000 Hz the acoustic energy increment was still very elevated (difference of 46 dB), while at higher frequencies (*i.e.*, from 5 to 20 kHz) it was less pronounced ( $24 \pm 7$  dB, min=7; max=14) (Fig. 3).

## DISCUSSION

Anthropogenic noise is a complex and challenging source of pollution to quantify as it varies in duration, amplitude and frequency content, and as it can also be modified by the medium through which it travels (Shannon *et al.*, 2015). While the present study is a restricted snapshot of the underwater acoustic energy (frequency range 63 Hz to 20 kHz) characterising only the main landings of Windermere, it nevertheless represents the first report of anthropogenic noise pollution in a large multi-use lake in which a balance must co-exist between frequent shipping, recreational fisheries and rare fish.

The ranges of vessel noise and SPLs are generally characterised as extremely variable in relation to speed, load, pitch angle of propeller or age of the vessel (Amoser *et al.*, 2004). However, some cautious comparisons between this study and the few others available can be made. Regarding SPLs, the values characterising the landings of Windermere are similar to those recorded by Amoser *et al.* (2004) during a power boat race in Lake Traunsee (Austria) (*i.e.* 124- 128 dB re 1 $\mu$ Pa) and to those reported by Seppänen and Nieminen (2004) for eight different types of vessel recorded in Lake Jyväsjärvi (Finland) (*i.e.* 123- 128 dB re 1 $\mu$ Pa). The most remarkable difference between this study and that of Amoser *et al.* (2004) is that Amoser *et al.* (2004) found most acoustic energy at low frequencies (peak at 110 Hz), while in Windermere, most acoustic energy was concentrated between 1000 and 2000 Hz, peaking at the latter frequency. This dissimilarity can be explained by differences in both noise source (*i.e.* type of boat and propeller) and the extent of environmental filtering. Amoser *et al.* (2004) recorded a power-boat race, while at Windermere the traffic was mainly of small recreational boats (with outboard petrol engines) and cruise ferries (mounted inboard diesel engines), in addition to canoes, kayaks and sailing boats. Seppänen and Nieminen (2004) found that inboard diesel-powered boats produce most of their noise at high frequencies (1000-4000 Hz) with SPLs of 133 dB re 1 $\mu$ Pa, as was observed during the present study. In particular, the Bowness Ferry and Yacht Landings had consistent small recreational boat traffic when the present recordings were made. Such small recreational boats are most commonly powered by outboard engines; Seppänen and Nieminen (2004) found that outboard engines are the

loudest, producing noise with SPL of 140 dB re 1 $\mu$ Pa at 50-100 m distance and with the most energy centred to high frequencies (above 1000 kHz). The intense traffic of both cruise ferries and small recreational boats at the Bowness landings could therefore explain the overall higher level of noise recorded in these landings in comparison to Brockhole and Lakeside, which had fewer occurrences of both types of boat traffic. Finally, regarding environmental filtering, it should be noted that this study was conducted in very shallow waters (less than 2 m deep). Sound transmission in shallow water has a characteristic frequency-dependent behaviour; there is a critical frequency below which the shallow-water channel ceases to act as a waveguide, causing acoustic energy to propagate directly into the bottom (Kibblewhite, 1989). This cut-off phenomenon could therefore contribute to the relatively reduced amount of acoustic energy detected in the low frequency range (*i.e.*, below 500 Hz) in the shallow waters of Windermere's landings.

Quantifying the effects of anthropogenic noise on wildlife is challenging, since sensitivity to noise varies widely across taxa and may also vary depending upon context, sex, and life history; furthermore, anthropogenic noise often acts synergistically with other forms of environmental disturbance, such as habitat alteration (Shannon *et al.*, 2015). Some studies have investigated behavioural and physiological effects of ship noise on freshwater fish. Alarm responses to boat noise have been reported in roach and rudd (*Scardinius erythrophthalmus* (L., 1758)) (Boussard, 1981). Altered nesting behaviour was reported for the longear sunfish (*Lepomis megalotis* Rafinesque, 1820) (Mueller, 1980). Graham and Cooke (2008) reported a dramatic increase in heart rate and a slight decrease in stroke volume in the largemouth bass (*Micropterus salmoides* Lacépède, 1802); finally, Wysocki *et al.* (2006) demonstrated that ship noise elicited a cortisol stress response in common carp (*Cyprinus carpio* L., 1758), gudgeon (*Gobio gobio* (L., 1758)) and perch, regardless of their hearing sensitivities. The fish community inhabiting Windermere is relatively species-poor but includes a hearing specialist species (roach), and some hearing generalist species, such as the pike, Arctic charr, Atlantic salmon, brown trout, European eel and perch (Amoser *et al.* 2004; Mann *et al.* 2007; Miller *et al.* 2015). Of these, Arctic charr is defined as a species of high conservation value whose population has dramatically declined in recent years (Winfield *et al.*, 2008). It is possible that the detected levels of anthropogenic noise pollution may have differential auditory effects on different members of the Windermere fish community, based on species' hearing sensitivities (see Ladich and Fay, 2013), although it is likely that all species can detect the low frequency noise component of boat traffic (*i.e.* at 500 Hz the



average SPL was 92 dB re 1 $\mu$ Pa, which can probably be detected even by hearing generalist species). Although the present study did not directly investigate the effects of the detected levels of anthropogenic noise on the local fish community, the detected SPLs and noise spectra raise some concerns considering that: i) noise levels are elevated; ii) this study was conducted during a winter month, when recreational boat traffic on Windermere was at a relatively low level (it peaks during the summer); and iii) physiological effects have been shown for freshwater species regardless of their hearing sensitivity (Wysocki *et al.*, 2006). It is therefore suggested that long-term monitoring of underwater anthropogenic noise should be undertaken at Windermere in order to evaluate the extent of this pollutant. Such observations should be extended both temporally and spatially in order to cover parts of the lake where ferry traffic is less frequent, and over deeper water. Further studies addressing the potential effects of the detected noise levels on fish species' distributions are encouraged.

The biological communities inhabiting inland aquatic habitats currently face unprecedented threats from human activities (Winfield, 2013), therefore further studies are recommended across a wider geographical, temporal and taxonomic range. On a regulatory level, it might be advisable to consider an amendment to the EC Water Framework Directive (European Communities, 2000) to include underwater noise levels as an indicator of inland water quality and ecological status, using a similar legislative approach to that adopted under the MSFD (European Commission, 2008) for marine habitats. Ultimately, potential mitigation measures should be considered such as the definition of noise-free areas (*e.g.*, fish spawning grounds, essential fish habitats), and seasonal restriction of noisy activities during sensitive biological periods (Shannon *et al.*, 2015).

## CONCLUSIONS

Current noise levels in Windermere warrant further investigation as a potential threat to the fish community which occurs in this already delicate and pressured habitat. Based on results obtained and considering the small number of studies focusing on freshwater anthropogenic noise pollution and the lack of regulatory attention toward this type of pollutant in inland water bodies, it is recommended that further studies focus on a wider geographical and temporal range in order to start to fill the knowledge and legislative gaps regarding anthropogenic noise monitoring in fresh waters.

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Tab. 1. Details about the recording sites: geographical coordinates, date and time in which each recording cycle began and ended, bottom and hydrophone depth.

Recording site	Geographical coordinates		Recording date	Recording time		Depth (m)	
	(N)	(W)		Start	End	Bottom	Hydrophone
Ambleside Ferry Landing	54°25.198'	002°57.641'	05/11/2014	16:00	16:10	<1.50 m	0.70 m
Bowness Yacht Landing	54°21.406'	002°56.392'	05/11/2014	13:00	13:10	<1.50 m	0.70 m
Bowness Cable Ferry Landing	54°21.182'	002°56.266'	05/11/2014	11:00	11:10	<1.50 m	0.70 m
Bowness Ferry Landing	54°21.746'	002°55.415'	05/11/2014	13:00	13:10	<1.50 m	0.70 m
Lakeside Ferry Landing	54°16.799'	002°57.342'	23/11/2014	11:00	11:10	<1.50 m	0.70 m
Brockhole Ferry Landing	54°24.070'	002°56.757'	16/11/2014	15:00	15:10	<1.50 m	0.70 m

Tab. 2. Spectral levels and continuous equivalent SPL recorded during this study in each ferry landing of Windermere.

	Ambleside Ferry Landing	Miss Westmorland passage in Ambleside Landing	Bowness Cable Ferry Landing	Cable Ferry passage in Bowness Cable Ferry Landing	Bowness Ferry Landing	Bowness Yacht Landing	Brockhole Ferry Landing	Lakeside Ferry Landing
80 Hz	86	99	88	99	95	95	102	79
100 Hz	82	89	88	102	92	93	98	81
125 Hz	79	87	92	98	98	92	96	79
160 Hz	77	86	92	98	100	94	94	78
200 Hz	73	83	88	98	105	94	93	77
250 Hz	71	81	91	97	110	105	90	78
315 Hz	71	82	91	99	114	105	88	89
400 Hz	71	81	90	99	118	103	86	101
500 Hz	69	76	89	98	120	104	84	105
630 Hz	68	81	95	101	120	106	81	104
800 Hz	73	114	90	101	119	106	80	108
1000 Hz	76	124	87	104	119	111	82	111
1250 Hz	81	127	94	106	119	111	85	109
1600 Hz	86	130	94	105	123	113	93	111
2000 Hz	88	133	94	107	124	118	99	115
2500 Hz	87	132	89	104	122	115	97	113
3150 Hz	85	125	90	102	120	113	92	109
4000 Hz	81	120	84	100	116	110	85	104
5000 Hz	77	111	76	90	107	103	78	96
6300 Hz	73	105	71	80	99	96	74	89
8000 Hz	72	99	69	75	94	91	71	82
10000 Hz	71	92	69	72	89	85	71	78
12500 Hz	72	91	69	71	87	82	71	77

	Ambleside Ferry Landing	Miss Westmorland passage in Ambleside Landing	Bowness Cable Ferry Landing	Cable Ferry passage in Bowness Cable Ferry Landing	Bowness Ferry Landing	Bowness Yacht Landing	Brockhole Ferry Landing	Lakeside Ferry Landing	
Continuous sound pressure level (SPL, dB re1 $\mu$ Pa)	16000 Hz	72	92	70	71	87	82	72	78
	20000 Hz	70	84	68	68	81	77	70	74
		117	135	114	130	130	123	109	119

Tab. 3. Number of lake cruise daily passages in each ferry landing of Windermere.

Lake cruise ferry line	Ferry landings							
	Ambleside		Bowness		Brockhole		Lakeside	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
<b>Blue cruise</b> 45 min circular cruise; central part of the lake			4	36				
<b>Red cruise</b> 75 min cruise; Northern part of the lake	16	36	16	36	16	22		
<b>Yellow cruise</b> 90 min cruise; North to South			8	20			8	20
Total number of daily passages	<b>16</b>	<b>36</b>	<b>28</b>	<b>92</b>	<b>16</b>	<b>22</b>	<b>8</b>	<b>21</b>

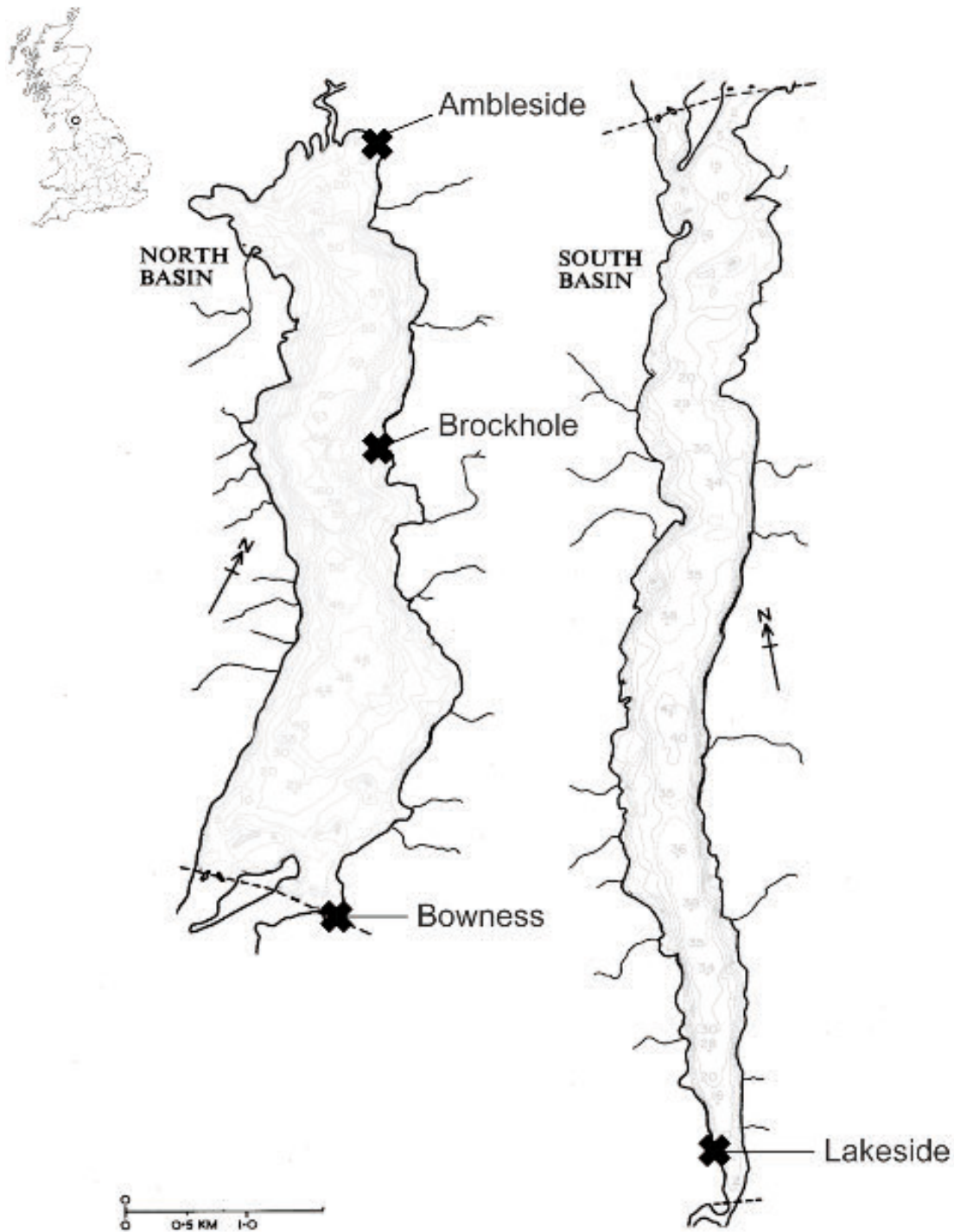


Fig. 1. Recording stations (*i.e.*, main landings) used in Windermere (UK). The Bowness Yacht, Ferry and Cable Ferry landings are all located in close proximity and are shown here as the single location of Bowness. The location of Windermere within the UK is shown in the insert. Original image from Ramsbottom AE, 1976. *Depth charts of the Cumbrian lakes. Sci. Publ. 33, Freshwater Biological Association* (redrawn with permission).



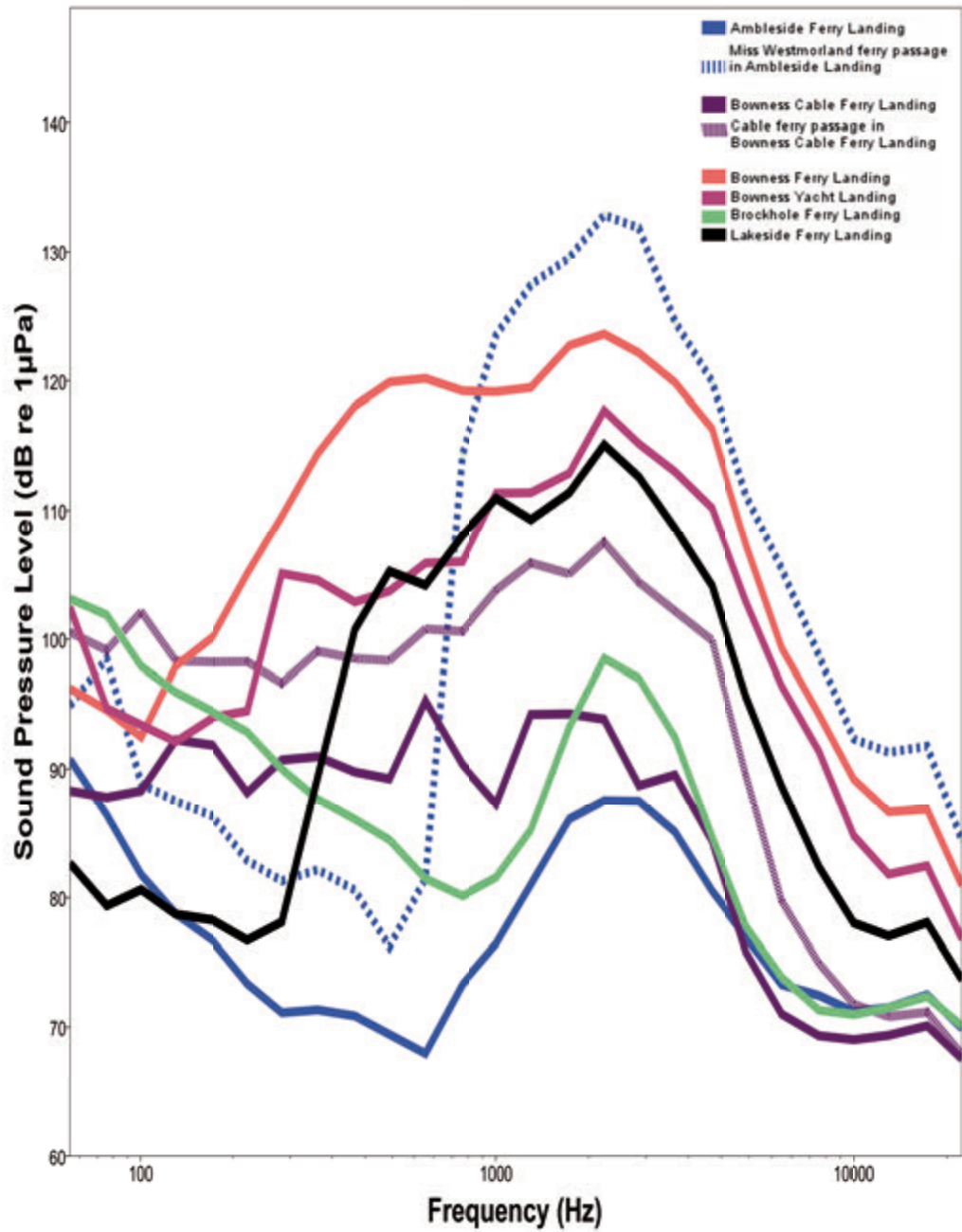


Fig. 2. Noise spectra (power spectral density, 1/3 octave bands in dB re 1 $\mu$ Pa) characterising the main landings of Windermere and the passage of both cable and cruise ferries.

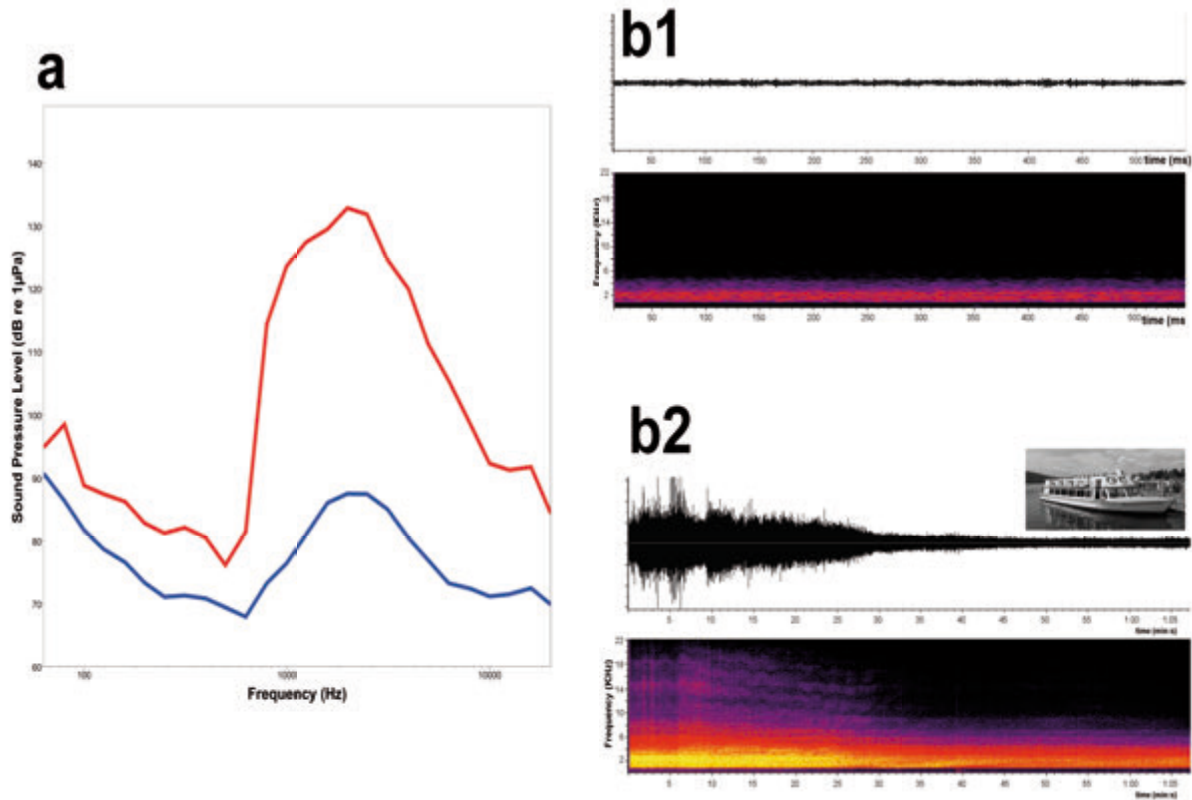


Fig. 3. On the left, (a): noise spectra (power spectral density, 1/3 octave bands in dB re  $1\mu\text{Pa}$ ) characterising the background noise detected in Ambleside Landing (blue line) and its increase during the passage of the Miss Westmorland cruise ferry (red line). On the right: oscillograms and sonograms (Hanning window; FFT 1024 Hz) of Ambleside background noise (b1) and of the passage of the Miss Westmorland cruise ferry (b2).