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A flume experiment to examine underwater sound generation by flowing water

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Abstract The hydrogeomorphology and ecology of rivers and streams has been subject of intensive research for many decades. However, hydraulically-generated acoustics have been mostly neglected, even though this physical attribute is a robust signal in fluvial ecosystems. Physical generated underwater sound can be used to quantify hydro-geomorphic processes, to differentiate among aquatic habitat types, and it has implications on the behavior of organisms. In this study, acoustic signals were quantified in a flume by varying hydro-geomorphic drivers and the related turbulence and bubble formation. The acoustic signals were recorded using two hydrophones and analyzed using a signal processing software, over 31 third-octave bands (20 Hz–20 kHz), and then combined in 10 octave bands. The analytical method allowed for a major improvement of the signal-to-noise ratio, therefore greatly reducing the uncertainty in our analyses. Water velocity, relative submergence, and flow obstructions were manipulated in the flume and the resultant acoustic signals recorded. Increasing relative submergence ratio and water velocity were important for reaching a turbulence threshold above which distinct sound levels were generated. Increases in water velocity resulted in increased sound levels over a wide range of frequencies. The increases in sound levels due to relative submergence of obstacles were most pronounced in midrange frequencies (125 Hz–2 kHz). Flow obstructions in running waters created turbulence and air bubble formation, which again produced specific sound signatures.

Keywords Acoustic · Hydrogeomorphology · Physical generated sound · Sound propagation · Hydrophone

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Introduction

Many organisms are adapted to hear and react to sound, hence sound provides important information about habitats and the ecosystem. Indeed, sound has been subject of intense scientific research. For example, acoustic techniques have been successfully applied to determine constraints upon acoustic communication in the aerial environment (Ellinger and Hödl 2003), for studying social communication among organisms (Slater and Catchpole 1990; Ruiz-Miranda et al. 2002; Da Cunha and Jalles 2007), and for determining the effect of anthropogenic noise on birds (Reijnen et al. 1997; Forman et al. 2002), bears (Gibeau et al. 2002; Dyck and Baydack 2004), amphibians (Sun and Narins 2005), and squirrels (Rabin et al. 2006). Research has also examined the human perception of sound (Southworth 1969; Carles et al. 1999), coupling visual and acoustic preferences (Anderson et al. 1983; Porteous and Mastin 1985; Yang and Kang 2005), in order to better understand noise as an impairing sound (Kariel 1990; Staples 1997; Gramann 1999).

In aquatic systems, acoustic research started with great vigor during WWI and II for military applications (Urick 1983). More recently, underwater acoustic measures have been used for assessing the diversity and distribution of marine mammals (McDonald et al. 1995; DiSciara and Gordon 1997; Clark and Clapham 2004) and for quantifying the effect of ship noise (Scholik and Yan 2002a; Wysocki et al. 2006; Vasconcelos et al. 2007) and ambient noise (Scholik and Yan 2001, 2002b; Popper 2003; Amoser and Ladich 2005) on fishes. Underwater acoustic recordings have also been used for estimating sediment transport (Rouse 1994; Rickenmann 1997; Mason et al. 2007), and substrate size distributions (Nitsche et al. 2004), analyzing rainfall events and drop size distribution (Nystuen 2001; Ma and Nystuen 2005; Ma et al. 2005), monitoring internal solitary waves produced in the ocean (Apel et al. 2007), and for measuring water temperature through differences in sound speed and propagation in the ocean (Terrill and Melville 1997; Vagle and Burch 2005). In addition, acoustic techniques were applied above the water surface for estimating reaeration (Morse et al. 2007).

The flowing water of rivers and streams is turbulent and often entrains air further released as bubbles that generates sound. This physical generated sound has captivated people for centuries as expressed in rhythmic poems and lyrics using well-sounding words. Rivers and streams bubble, gurgle, splash, whoosh, or roar, depending on water velocity and discharge, as well as on obstructions to flow created by different hydro-geomorphic features in the stream channel. Whereas hydrologic, morphologic, ecological, and also visual aspects of rivers have been the subject of intense research, the specific physical generated sound recorded beneath the water surface, and its potential as a quantitative indicator of habitat uniqueness, have only recently received few attention (Amoser and Ladich 2005; Wysocki et al. 2007).

In this study we quantified, for the first time, acoustic signals related to hydrogeomorphological parameters and induced turbulence in flowing water under controlled laboratory conditions. First, we examined the influence of increasing water velocity and discharge on sound levels. Second, we studied the role of flow obstruction and submergence on sound production. Third, we measured physical generated sound at different positions relative to the sound source to study how the sound signature changes relative to distance from its source. Specifically, we asked if different processes of physical sound generation influenced unique frequencies, or if they resulted in a broad band noise that spread equally throughout the channel. In particular, we sought to identify whether hydrogeomorphological factors influence sound in flowing water.

Materials and methods

Theoretical background

Turbulence created by strong velocity gradients and obstruction to flow by various structural elements that exist in a channel are ubiquitous sources of physical generated sound in flowing waters. Though an infinite number of interactions exist between flow and specific obstructions and bedforms, we limited our study to longitudinally non-uniform open-channel flow, which often occurs in natural streams (Fig. 1), and can be easily modeled in the laboratory. Moreover, this type of flow has a theoretical background that can be used as the framework for the interpretation of the experimental results.

Open channel flow in a non-uniform channel, composed of two parts with unequal depth (Fig. 1b), is represented by the Bernoulli equation:

$$p + \frac{\rho u^2}{2} + \rho g h = \text{const} \tag{1}$$

where p is pressure, u is bulk water (flow) velocity, ρ is density of water, g is the acceleration due to gravity, and h

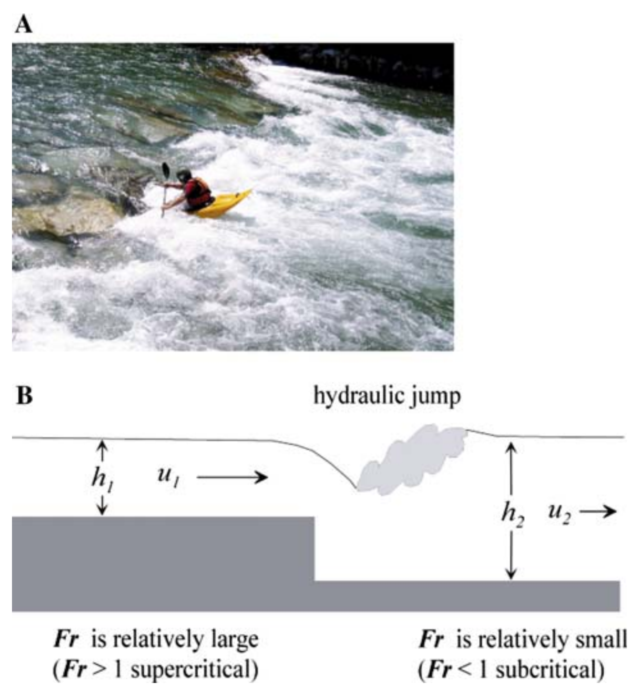


Fig. 1 **a** Picture example of a non-uniform open-channel flow in a stream (Tiroler Achen, Tirol, Austria) (photo by Anna Sukhodolova). **b** Schematic representation of a non-uniform open-channel flow composed of two parts with unequal flow depth (h_1 and h_2) and flow velocity (u_1 and u_2) (illustration by Alexander N. Sukhodolov)

is flow depth. The Bernoulli equation is derived as a one-dimensional approximation of the Navier-Stokes equations and expresses the law of conservation of energy. Equation 1 can be rewritten in a dimensionless form as:

$$\frac{p}{\rho gh} + \frac{u^2}{2gh} + 1 = c_0 \quad (2)$$

where c_0 is a constant. If pressure difference is small or attributed to the same effects of roughness, as can be assumed for river conditions, Eq. 2 simplifies to:

$$Fr = \sqrt{2(c_0 - 1)}, \quad Fr = \frac{u}{\sqrt{gh}} \quad (3)$$

where Fr is Froude number, which represents the ratio between inertia to gravity. $Fr = 1$ is considered as the critical state of flow (i.e. when water velocity is equal to the celerity c, or speed of a wave in a channel, so the waves have velocity $2c$ in the direction of flow), whereas, the flow can be in supercritical (i.e. when the velocity of the waves is greater than the critical flow: velocity > celerity; $Fr > 1$) or subcritical condition (i.e. when the velocity of the waves is less than the critical flow but greater than zero: velocity < celerity; $Fr < 1$). The transition from flow with larger Froude number to flow with smaller Froude number is accomplished with increased losses of energy through the adjustment of the pressure head and/or subsequent changes in depth. When both parts of the flow are in the subcritical condition, the transition zone is represented by a turbulent vortex. In the transition of flow from supercritical to subcritical regime, the transition zone is deformed into highly turbulent zone known as hydraulic jump, which is especially effective in entraining the air and releasing it as bubbles (Fig. 1). In small streams to large rivers, hydraulic jumps can be very powerful and produce a loud roaring sound. The same condition exists for breaking waves in riffles and rapids. These whitewater flow features arise because supercritical flow conditions ($Fr > 1$) have been reached resulting in wave breaking that traps and entrains air, which ultimately generates the sound of a roaring river. Moreover, this process of sound generation through wave breaking is vastly more ubiquitous process of turbulent energy dissipation and generation of sound that exists in rivers and streams.

Froude number can be more effective for detecting the energetic state and transition zones in laboratory studies in which the Reynolds number ($\mathrm{Re} = \frac{uh}{v}$, where v is kinematic viscosity of water) is often relatively small due to limited size of laboratory facilities. Equation 3 also provides the theoretical background for scaling flow depth and water velocity between laboratory studies and for comparing with field conditions. Indeed, as it can be readily demonstrated that we need to run experiments in which the velocity in the two parts of the flow (over elevated obstacles and deeper in the downstream part) will be varied over a certain range of values. Another measure, depth, should be varied and for the part of the flow over an obstacle, it will provide the range of relative submergences. Thus, the main aim of the present experimental research was to determine the relation between flow characteristics and the sound generated by turbulent structures in the transition zone between longitudinally developing flows.

Experimental design

Between January and April 2007, three experiments were set up in a flume located in the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at the Swiss Federal Institute of Technology (ETH) Zurich. The flume was six meters long and 40 cm wide. The bottom consisted of concrete, the walls of Plexiglas. Discharge was adjustable between 0 and 70 l s^{-1}. Water velocity could be manipulated by changing the slope and/or by damming the water at the end of the flume. First, we manipulated water velocity ($\sim$10 to $\sim$170 cm s^{-1}) at five different discharge levels (10–50 l s^{-1}) to assess its effect on sound generation. At each discharge level, 7–13 different flow velocities were generated (Table 1). Second, 5 cobbles of approximately the same size were arranged at the flume bottom (Fig. 2) to model the flow over the elevated area similar as depicted in Fig. 1. This experiment was repeated using two size classes of cobbles (average c-axis (=height): 11 and 16.8 cm) at a discharge of 20 l s^{-1} and of constant slope. Flow depth was manipulated to create relative submergence values of approximately 1, 0.8, 0.5, and 0 (without cobbles). Relative submergence was calculated as the ratio of average substrate size (average c-axis of cobbles) to flow depth (Table 1). Third, geomorphic bed structures were created using bricks with length, width, and height of 25, 12, and 6.5 cm, respectively. A set of three bricks was used to create a more complex flow pattern by allowing spaces between obstacles (Fig. 3), thus providing a greater degree of three-dimensionality compared to the basic scheme (Fig. 1). The acoustic signal was recorded at different locations relative to the position of the bricks (Fig. 9a). The experiment was repeated at a discharge of 20 l s^{-1} and at constant slope but at varying flow depths (22 and 16 cm) (Table 1). Additionally, Re and Fr were calculated to assess relative levels of turbulence and transition zones, respectively.

Data collection

Acoustic signals were recorded using two hydrophones (Type 8103, Brüel and Kjaer, Denmark), with the head facing upstream (Figs. 2b, 3). Hydrophone depth was set at 60% flow depth, and distance between the two heads was $\sim$2 cm. An amplifier (Type Nexus 2692 OS2, Brüel and Kjaer, Denmark), with sensitivity set at 3.16 mV/Pa, was

Table 1 Summary of the experimental conditions of the three experiments: water velocity, relative submergence, and bed structures

	Q (l s^{-1})	u (m s^{-1})	h (m)	D (m)	$D\ h^{-1}$	Fr	Re ($\times 10^4$)	Pos.
Water velocity	10.00	0.08–1.01 (7)	NA	NA	NA	NA	NA	NA
	20.00	0.26–1.56 (11)	NA	NA	NA	NA	NA	NA
	30.00	0.33–1.66 (13)	NA	NA	NA	NA	NA	NA
	40.00	0.26–1.69 (11)	NA	NA	NA	NA	NA	NA
	50.00	0.37–1.69 (11)	NA	NA	NA	NA	NA	NA
Relative submergence	20.00	0.56	0.11	0.11	1.00	0.54	6.16	NA
	20.00	0.48	0.14	0.11	0.79	0.41	6.72	NA
	20.00	0.37	0.22	0.11	0.50	0.25	8.14	NA
	20.00	0.26	0.17	0.17	0.99	0.20	4.42	NA
	20.00	0.20	0.21	0.17	0.80	0.14	4.20	NA
	20.00	0.05	0.32	0.17	0.53	0.03	1.60	NA
	20.00	0.25	0.22	0.00*	0.00	0.17	5.50	NA
Bed structures	20.00	0.24	0.22	0.19	0.89	0.16	5.28	1
	20.00	0.31	0.22	0.19	0.89	0.21	6.82	2
	20.00	0.48	0.22	0.19	0.89	0.33	10.56	3
	20.00	0.44	0.22	0.19	0.89	0.30	9.68	4
	20.00	0.48	0.22	0.19	0.89	0.33	10.56	5
	20.00	0.32	0.22	0.19	0.89	0.22	7.04	6
	20.00	0.16	0.22	0.19	0.89	0.11	3.52	7
	20.00	0.29	0.16	0.19	1.22	0.23	4.64	1
	20.00	0.46	0.16	0.19	1.22	0.37	7.36	2
	20.00	0.72	0.16	0.19	1.22	0.57	11.52	3
	20.00	0.90	0.16	0.19	1.22	0.72	14.40	4
	20.00	0.63	0.16	0.19	1.22	0.50	10.08	5
	20.00	0.53	0.16	0.19	1.22	0.42	8.48	6
	20.00	0.12	0.16	0.19	1.22	0.10	1.92	7
	20.00	0.35	0.22	0.00*	0.00	0.24	7.70	NA

Q discharge, u water (flow) velocity (in bracket number of velocity measurements), h flow depth, D submerged object size (c-axis, height), * no submerged objects, $D\ h^{-1}$ relative submergence, Fr Froude number, Re Reynolds number, Pos positions of the acoustic recording in the flume (see Fig. 9a), NA not available

used to amplify the signal sent by the hydrophones and stored with a digital recorder (Type R-4, Edirol, Japan). Sampling frequency was 44.1 kHz and amplitude resolution was 16 bits. This setting assured a frequency range between 20 Hz and 20 kHz and a dynamic range of >90 dB, and it guaranteed maximum compatibility with other digital sound devices (e.g. Compact Disc). Recording time was approximately five minutes and 30 s. Water velocity was measured with a handheld FlowTracker (Acoustic Doppler Velocimeter; SonTek, San Diego, USA) or a propeller velocity meter (MiniAir2, Schiltknecht, Switzerland). Water velocity and flow depth were measured in front of the hydrophones.

Acoustic data analyses

The first step in the analysis of acoustic data collected was to separate the signals that were produced by flowing water from the ambient noise generated by other sources. However, a common difficulty in recording and analyzing underwater sound is a low signal-to-noise ratio. This is due to a high background noise caused by turbulent flow around the hydrophones and internal noise of sensors and amplifiers. Our approach to improve the signal-to-noise ratio was the use of two hydrophones located close to each other. The advantage of this configuration is that by multiplying these two signals instead of taking the square of just one sensor, incoherent components between the two hydrophones are nullified (Norton 1989). This reduces internal noise components and contributions of turbulence around the hydrophones, resulting in a significantly improved signal-to-noise ratio. As a consequence, the spectral analysis of the actual sound produced by flowing water is much more robust. The suppression of noise by usage of two hydrophones is demonstrated in Fig. 4. Both sensors recorded the same sinusoidal signal with additional

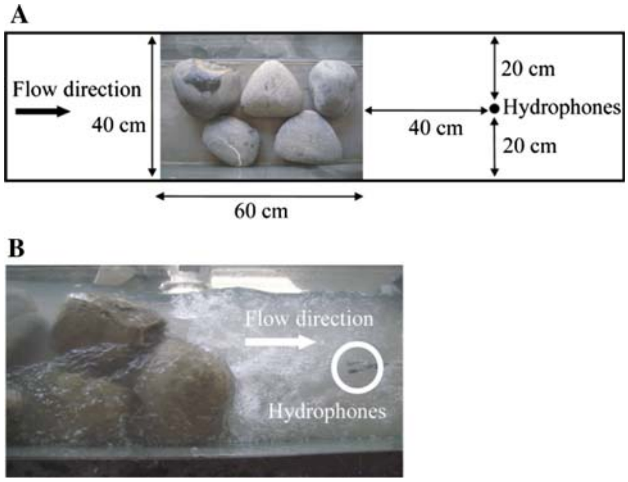


Fig. 2 **a** Top view schematic of the relative submergence experiment with a photograph insert showing one cobble arrangement. **b** Photograph taken from the side of the flume showing turbulence created, and the position of the two hydrophones. Relative submergence in the present photograph was 1

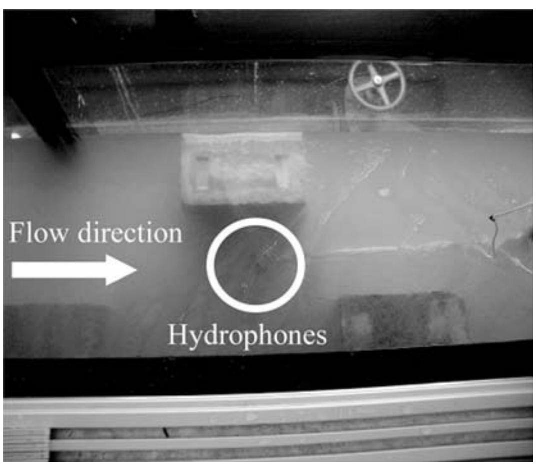


Fig. 3 Top view photograph showing the position of the hydrophones and relative level of turbulence produced by a three bricks arrangement (position 3 in Fig. 9a)

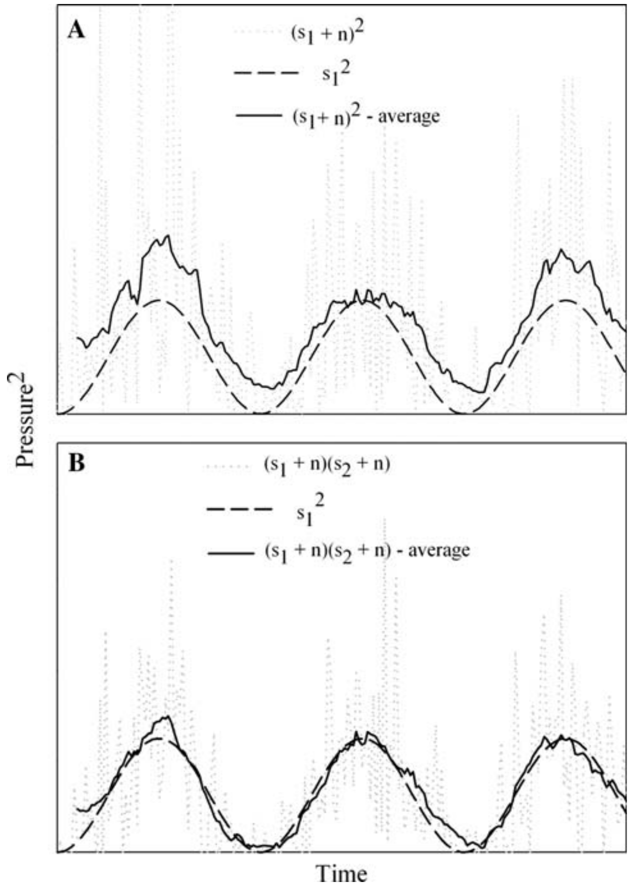


Fig. 4 Improvement of the signal-to-noise by usage of two hydrophones (see text for details). **a** One hydrophone. **b** Two hydrophones

uncorrelated noise. Figure 4a shows the squared signal of hydrophone 1, $(s_1 + n)^2$, and the corresponding averaged time response, $(s_1 + n)^2$ − average. This curve lies clearly above the squared pure sinusoidal signal, s_1^2. On the other hand Fig. 4b shows the product of the two hydrophone signals, $(s_1 + n)(s_2 + n)$, and the corresponding averaged time response, $(s_1 + n)(s_2 + n)$ − average, which is very close to and thus a good estimate of the squared pure sinusoidal signal, s_1^2.

Acoustic data analysis evaluated the hydrophone signal power as a function of frequency and time where signal power is defined as the mean value of the square of the signal. We evaluated the time-series of the hydrophone signal power by using a Fast Fourier Transform (FFT) analyzer to spectrally decompose the time-series. The FFT results in a spectrum with frequency resolution that is constant throughout the frequency range of recorded sound. By summing up the corresponding frequency lines, one-third octave band and octave band representations were evaluated (IEC 1995). Octave bands have a bandwidth that equals ~70% of the center frequency while the bandwidth of one-third octave bands is about 23%. Three-one-third octave bands span one octave, hence the resolution of this spectrum is three times finer than the octave band spectrum. A 44.1 kHz sampling frequency was chosen because it is a standard value for audio applications. With a 16,384 point FFT, the audio stream is transformed on a frame by frame basis into the frequency domain to get a description of it's spectral content. Three consecutive spectra were averaged at a time, which implies a temporal resolution of about 1.1 s.

The analysis of the hydrophone signals was performed with a signal processing audio analyzer software package written and developed by K. Heutschi specifically for this project. The audio analyzer captures audio data either directly from a sound card (real time mode) or from a wave file (post processing mode), as in the present study. Randomly selected 300 s of each audio file were analyzed with the audio analyzer for relative submergence and bed structures experiments and 30 s for velocity experiments. Shorter sound samplers were determined to be sufficient because of the immense amount of data collected for the velocity experiments after comparing the variance between a smaller subset of 300 and 30 s intervals.

Reduction of the acoustic data

Acoustic data were classified by a third-octave band analysis over 31 frequency bands (20 Hz–20 kHz). The evaluation of a power-band limited noise-like signal has uncertainty that depends reciprocally on the product of averaging time and bandwidth. The signal power in an octave band could be determined by adding up the signal power of the three corresponding third-octave bands. For constant averaging time, a reduction of the spectral resolution from third-octave bands to octaves lowered the uncertainty significantly. Therefore, for final analysis, we decided to combine the 31 third-octave bands in 10 octave bands. The average (energetic average) for each octave band was calculated. The averaging process is based on the square of the hydrophone pressure signal.

A reference value of the environmental noise in the laboratory was recorded with standing water (zero flow) and subtracted from the physical generated sound. Reliability of recorded data was checked by a threshold criterion to eliminate disturbing noise (generated by pumps and motors). The sound recordings in the flume were also influenced by noise produced by the fact that water cascades from the flume to a collection box at the end of the channel. We reduced this influence by placing an absorption mattress (of sponge rubber) at the end of the flume, thereby greatly reducing the level of background noise generated that had to be subtracted from the experimental data.

All data were expressed on a logarithmic scale as dB values relative to 1 micro-Pascal as a reference. The calibration of the measurement system was performed with a Brüel and Kjaer calibrator (Type 4223, Brüel and Kjaer, Denmark), which generates a highly reproducible nominal sound level of 166 dB at 250 Hz. Selected acoustic analysis results were plotted as 3-D sound graphs, where frequency bands were plotted along the x-axis, time along the y-axis and sound level (dB re 1 μPa) along the z-axis.

Statistical analysis

Analysis of variance between groups (one-way ANOVA) was applied to evaluate the effect of velocity on sound level. The fixed factor variables (discharge) divided the samples into five groups (10–50 l s^{-1}). Using a general linear model procedure, the null hypotheses about the effects of factor covariate (independent variable: velocity) on the means of various groupings of single dependent variables (sound level of each octave band) were tested. In addition, Pearson moment correlation analyses were used to identify the direction and strength of relationships. One-way ANOVA was also applied to evaluate the effect of relative submergence (independent variable) on sound level (dependent variable). Data were checked to test if variables clearly deviate from normality with a Kolmogorov–Smirnov test. All analyses were performed with SPSS (version 14.0, SPSS Inc., Chicago, USA).

Results

Effect of water velocity on sound level

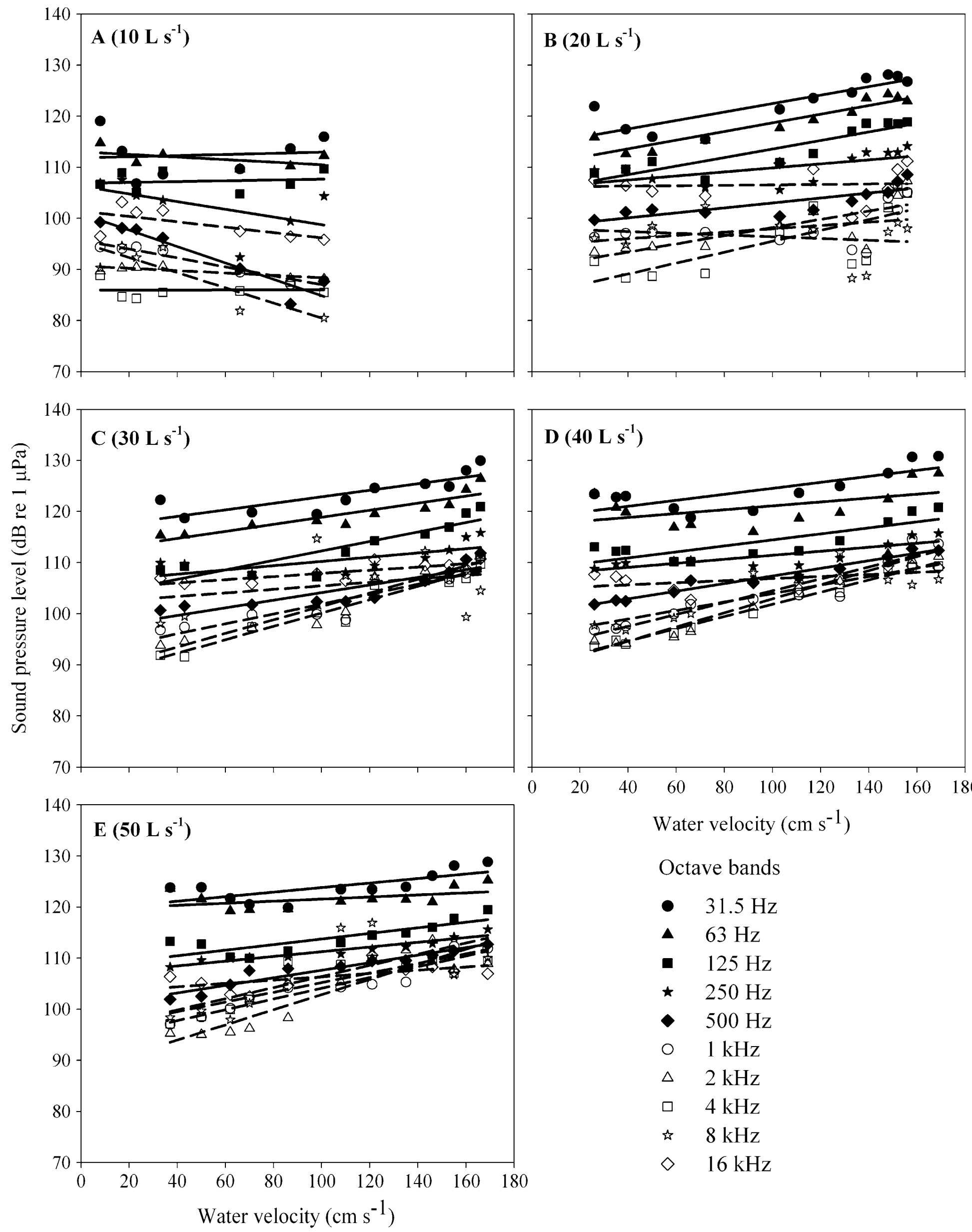
There was a positive relation between water velocity and sound level for all frequency bands (ANOVA: $4.42 \leq F_{1,49} \leq 114.08$; $p < 0.05$), except for 16 kHz. Discharge exhibited a significant effect on all frequency bands (ANOVA: $2.93 \leq F_{4,49} \leq 23.46$; $p < 0.05$). However, post-hoc tests showed that in our flume, a sound level created by discharge of 10 l s^{-1} differed from levels created by higher discharge rates. Moreover, variation in water velocity had a more pronounced influence (higher F-value) on sound level than variation in discharge, except for 8 and 16 kHz.

Increasing the water increased the sound level in a wide range of frequencies, except at a discharge of 10 l s^{-1} (Fig. 5). At 10 l s^{-1}the sound level of middle to high frequencies (500 Hz–2 and 8 kHz) decreased with increasing velocity (Table 2). At discharge rates ≥20 l s^{-1}, sound level increased with velocity (Fig. 5b–e). The increase was significant for all frequency bands, except for 63 Hz (for 40 and 50 l s^{-1}), 1 kHz (for 20 l s^{-1}), 8 kHz (for 20 and 30 l s^{-1}), and 16 kHz (for 20, 40 and 50 l s^{-1}) (Table 2).

Effect of relative submergence on sound level

An increase in relative submergence led to a significant increase in midrange frequency sound levels (125 Hz–2 kHz) (ANOVA: $7.93 \leq F_{1,6} \leq 10.01$; $p < 0.05$). At low relative submergence values, both low and high frequencies showed higher sound levels compared to midrange frequencies, where a "quiet" zone occurred (Figs. 6, 7). As relative submergence and turbulence increased (from 0 to 1 and from $Re = 5.50 \times 10^4$; $Fr = 0.17$ to $Re = 6.16 \times 10^4$; $Fr = 0.54$, respectively) (Table 1), sound levels increased in the midrange frequencies (125 Hz–2 kHz) more than in

Fig. 5 Relationship between sound level (dB, decibels; dB re 1 μPa) of 10 octave bands and flow velocity (cm s^{-1}) at five discharge conditions (10–50 l s^{-1}). *Closed symbols* and *solid regressions lines* show the octave bands from 31.5 to 500 Hz, *open symbols* and *dashed regression lines* show the octave bands from 1 to 16 kHz



the higher and lower frequencies (Figs. 6, 7). Moreover, an increase in relative submergence generally led to an increase in acoustic temporal variability (calculated as variance) across frequency bands and time. For example, at a relative submergence 1 the variance over time in the midrange frequencies 125 Hz, 250 Hz, 500 Hz, 1, and 2 kHz was 3.17, 5.39, 4.30, 4.26, and 11.33, respectively. At a relative submergence 0, the respective variances were 2.37, 0.5, 0.59, 1.52, and 0.46 respectively (Fig. 7).

Effect of bed structures on sound level

The sound level of most frequencies did not show major differences, except for 250 Hz, 1 and 2 kHz—which had very high variance—between the seven hydrophone positions (Fig. 8a). Flow turbulence remained relatively low at positions 1 and 7 located up- and downstream of the structures with minimum values ($Re = 5.28 \times 10^4$ and 3.52×10^4; $Fr = 0.16$ and 0.11, respectively) (Table 1). Turbulence was greatest in close proximity to flow obstruction structures, i.e. at position 3 ($Re = 10.56 \times 10^4$; $Fr = 0.33$), position 4 ($Re = 9.68 \times 10^4$; $Fr = 0.30$), and position 5 ($Re = 10.56 \times 10^4$; $Fr = 0.33$) (Table 1). However, decreasing flow depth (Fig. 8a, b), while keeping discharge constant, increased relative submergence and water velocity, and created enough turbulence to significantly change the sound signature. This resulted in different sound levels relative to frequency at different hydrophone

Table 2 Pearson moment correlation analysis to test direction and strength of the relationship (r) between water velocity and sound level (10 octave bands) at five discharge conditions (10–50 l s^{-1})

	r (10 l s^{-1})	r (20 l s^{-1})	r (30 l s^{-1})	r (40 l s^{-1})	r (50 l s^{-1})
31.5 Hz	0.096	**0.836****	**0.825****	**0.762****	**0.713***
63 Hz	−0.529	**0.934****	**0.908****	0.510	0.461
125 Hz	0.141	**0.897****	**0.880****	**0.811****	**0.828****
250 Hz	−0.524	**0.620***	**0.679***	**0.829****	**0.960****
500 Hz	**−0.947****	**0.815****	**0.880****	**0.981****	**0.957****
1 kHz	**−0.970****	0.406	**0.926****	**0.950****	**0.959****
2 kHz	**−0.830****	**0.747****	**0.960****	**0.980****	**0.914****
4 kHz	0.018	**0.731***	**0.970****	**0.991****	**0.847****
8 kHz	**−0.886****	−0.195	0.300	**0.822****	**0.722***
16 kHz	−0.634	0.052	**0.800****	0.496	0.599

Significant correlations are indicated in bold type

** $p < 0.01$; * $p < 0.05$

positions (Fig. 9b, c). Turbulence reached a maximum at position 3 ($Re = 11.52 \times 10^4$) and 4 ($Re = 14.40 \times 10^4$) (Figs. 8b, 9b; Table 1). Moreover, a transition from flow with low Froude number (Position 1, $Fr = 0.23$; Position 2, $Fr = 0.37$), to flow with larger Froude number (Position 3, $Fr = 0.57$; Position 4, $Fr = 0.72$), and again to flow with smaller Froude number (Position 5, $Fr = 0.50$; Position 6, $Fr = 0.42$) was generated in the flume (Table 1). The transition zone from flow with low to large Froude numbers generated turbulent vortexes. Thus, turbulence increased and the effect of the transition zone increased the level of sound generated in the mid frequency range (250 Hz–2 kHz) and a narrow band of low frequency between 31.5 and 63 Hz (Figs. 8b, 9b). Sound levels of midrange frequency bands (500 Hz–2 kHz) and the lowest frequency band (31.5 Hz) showed positive linear correlations with both Froude and Reynolds number (Table 3). Mid-frequency range sound levels quickly dissipated moving downstream from the sound source also becoming sporadic to semi-periodic at least over the sampling time frames. Low and high frequency sound did not diminish as much as the midrange frequencies (position 5 and 6, Figs. 8b and 9b, c). For midrange frequencies, the 3-D sound graph for position 7 (Figs. 8b, 9c) showed a similar pattern as position 6 but with a sharp

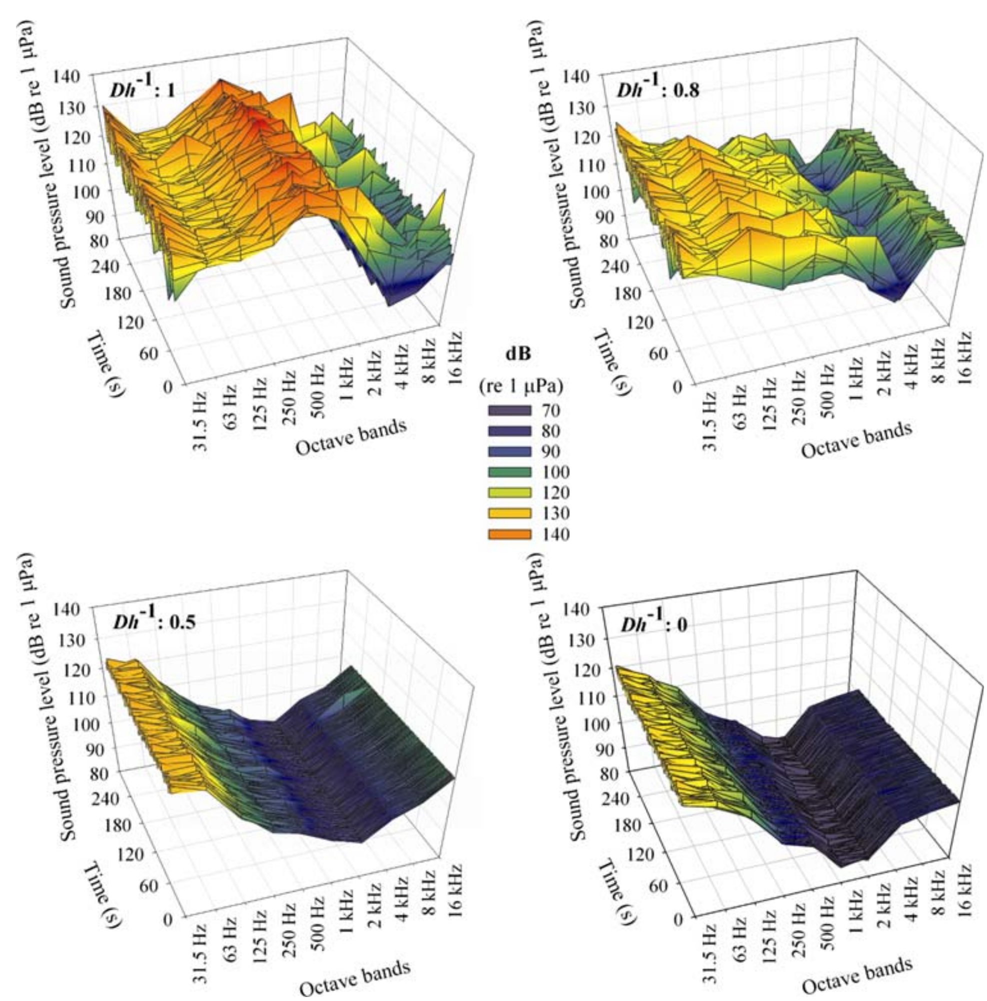


Fig. 6 3-D sound graphs (x-axis: 10 octave bands; y-axis: analyzed time, 300 s; z-axis: sound level expressed in decibels (dB re 1 µPa)) generated through four relative submergence levels ($D\,h^{-1}$: 1, 0.8, 0.5, 0; where D submerged object size (c-axis, height) and h flow depth) at a constant discharge of 20 l s^{-1}. Average cobbles size (c-axis, height): 11 cm

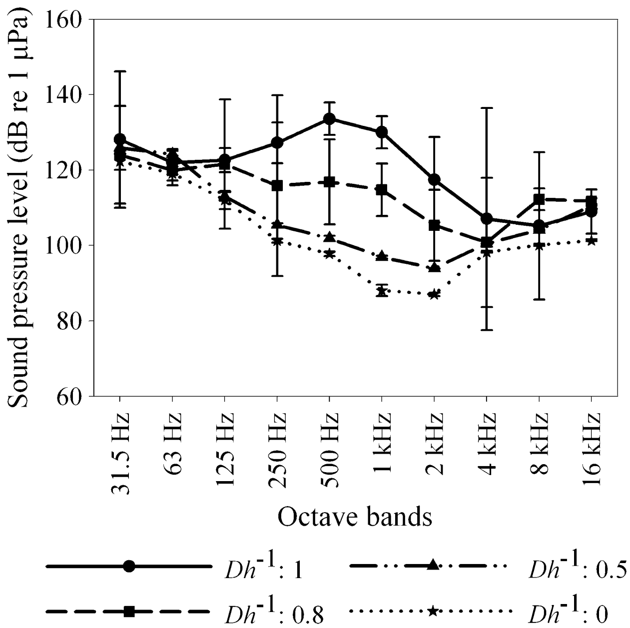


Fig. 7 Sound level (dB decibels, dB re 1 µPa; energetic average ± variance (as acoustic temporal variability); $n = 270$) for 10 octave bands at four relative submergence levels ($D\ h^{-1}$: 1, 0.8, 0.5, 0; where D submerged object size (c-axis, height) and h flow depth)) (3-D sound graphs see Fig. 6)

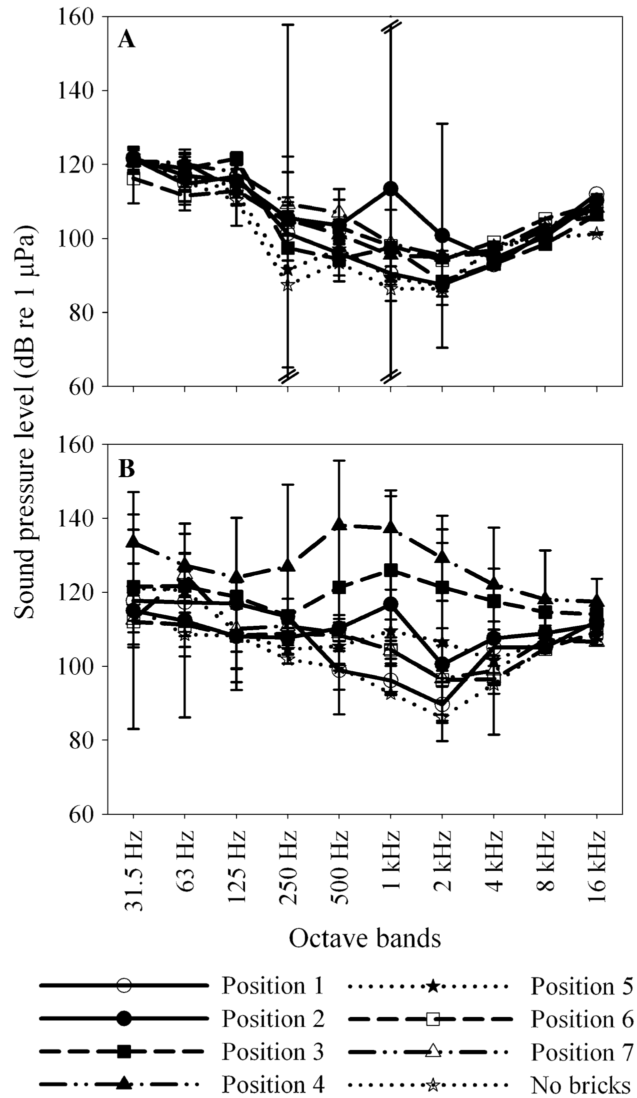


Fig. 8 Sound level (dB decibels; dB re 1 µPa; energetic average ± variance (as acoustic temporal variability); $n = 270$) for 10 octave bands at seven positions (see Fig. 9a). **a** Flow depth: 22 cm. **b** Flow depth: 16 cm. *Closed symbols* correspond to the 3-D sound graphs in **b**, *open symbols* to c in Fig. 9

peak in the low frequency range and lower sound level over the other frequencies. Position 1 (Figs. 8b, 9c) showed a small but noticeable sound level increase in low frequency sound for a position upstream of the source of turbulence (compared to no structures).

Discussion

Physical generated underwater sound is a strong signal in flowing waters and hence should be an ecologically important habitat attribute that organisms can use to sense energetic conditions of their environment. However, the underwater acoustic characteristics of aquatic habitats have only recently received attention (Amoser and Ladich 2005; Wysocki et al. 2007). In this study, we experimentally quantified the effects of water velocity, relative submergence, bed structures, and induced turbulence on physical sound generation. Based on flume experiments, we were able to identify characteristic “soundscapes” as well as to observe phenomena that generated these soundscapes.

We found that water velocity rather than discharge explained most of the variation in sound levels. The observed relationship between discharge (and the related water velocity) and generated sound is expected to also occur in rivers and streams. A discharge (i.e. turbulence) threshold seems to be necessary to influence the acoustic signature in the flume. Similarly, in a stream at low discharge and low turbulence level, one would expect low physical generated sound until discharge reaches a threshold level resulting in increased sound levels over a wide range of frequencies. Hence, we expect that the underwater sound level in streams and rivers may change as a consequence of the discharge (and the related water velocity) regime just as we measured in the flume. For example, some mountain rivers with discharge peak during the snow-melting period may have sound level change once a year with spring run-off and flooding. On the other hand, rainfall-dominated rivers (e.g. lowland temperate rivers) can undergo multiple high flow events of varying intensity and duration. The high rate of water level

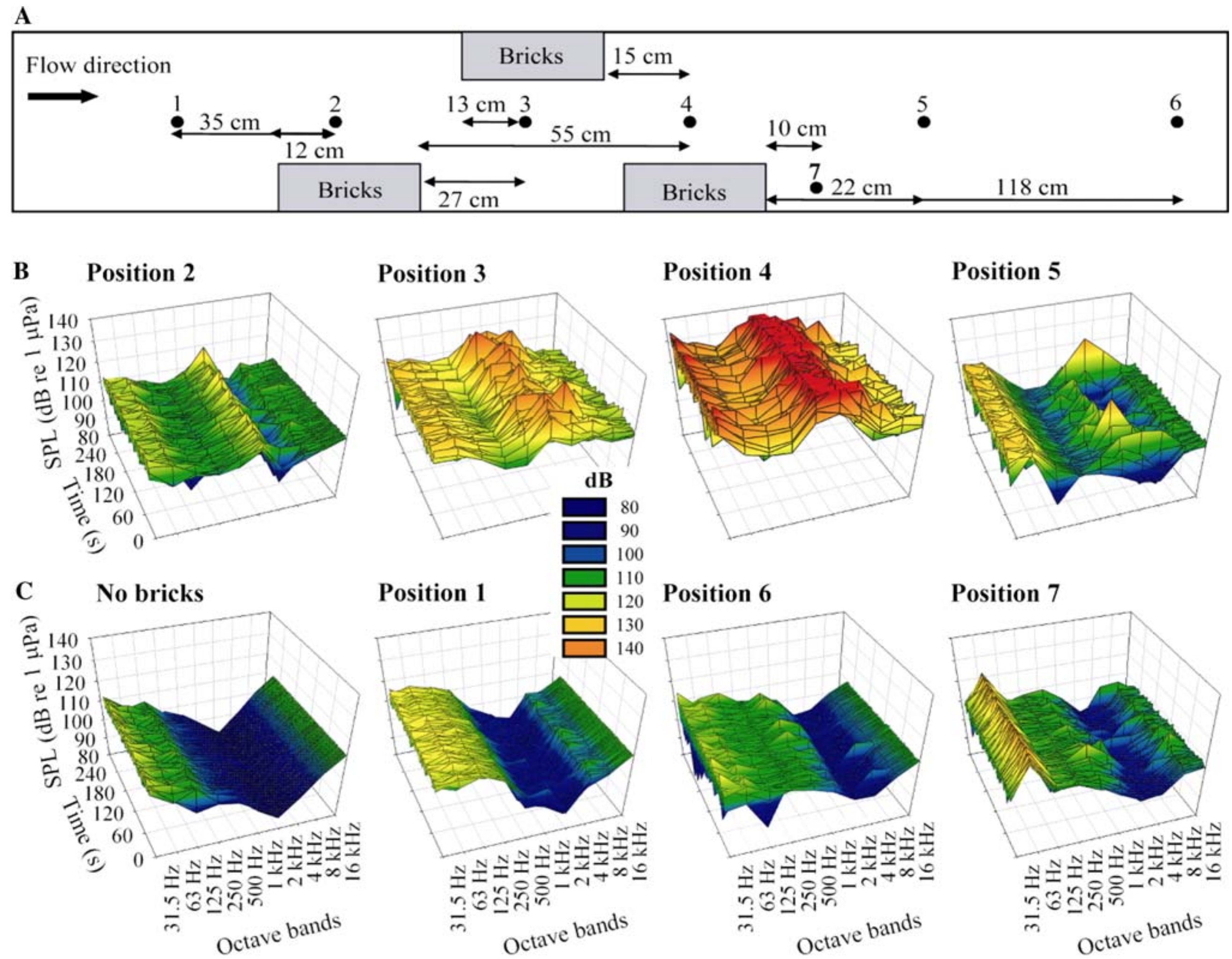


Fig. 9 The 3-D sound graphs in this figure correspond to b in Fig. 8. **a** Arrangement of multiple structures (bricks) from a single experimental run and multiple hydrophone positions (*black dots*) within the flume and relative to the flow of water, position and scale of turbulence. The series of 3-D sound graphs in **b** shows the recorded sound level per octave band in locations close to the source of turbulence and sound generation. The series of 3-D sound graphs in **c** shows the recorded sound level per octave band in the flume without structures (first panel) compared with 3-D sound graphs from above the structures (position 1), a distance below (position 6) and in the eddy of a structure (position 7). *x*-axis: 10 octave bands; *y*-axis: analyzed time (300 s); *z*-axis: sound level expressed in decibels (dB re 1 μPa)

increases and decreases (and the related water velocity) would result in rapid changes in the stream sound levels.

Such changes in underwater sound levels could affect the behavior of fish, as well as of other organisms, by triggering migration to new positions or habitats that have different sound levels. Moreover, organisms in such environments may have developed higher levels of sound perception and subsequent behavioral adaptations. Previous studies have shown that high sound levels can cause damage to inner organs and induce stress responses in many fishes. However, the impact of noise exposure is based on variation in auditory capabilities of different species and consequently do not affect all fishes equally (Scholik and Yan 2001, 2002a, b; Wysocki and Ladich 2005; Wysocki et al. 2006; Vasconcelos et al. 2007). Furthermore, acoustic communication distances in aquatic organisms are influenced by physical sound stimuli in their environment (Amoser and Ladich 2005; Wysocki et al. 2007). It is clear that past studies of aquatic organisms have, at least partially, neglected the potential effects of physical generated underwater sound and the role in evolutionary and behavioral outcomes and or adaptations.

The interaction between water velocity, relative submergence and flow obstructions can influence turbulence and bubble formation, as well as create transition zones, and therefore influence the underwater soundscape in streams. Flow obstructions created in the flume are comparable to boulders, outcrops, large trees, wood jams,

Table 3 Pearson moment correlation analysis to test direction and strength of the relationship (r) between Froude number (Fr), respectively Reynolds number (Re), and sound level (10 octave bands)

	r (Fr)	r (Re)
31.5 Hz	**0.802***	**0.798***
63 Hz	0.236	0.231
125 Hz	0.551	0.549
250 Hz	0.493	0.468
500 Hz	**0.763***	**0.756***
1 kHz	**0.831***	**0.825***
2 kHz	**0.869***	**0.865***
4 kHz	0.725	0.721
8 kHz	0.753	0.748
16 kHz	0.722	0.719

Flow depth was 16 cm (see Table 1). Significant correlations are indicated in bold type

* $p < 0.05$

bridges, and rip rap banks. Bed structures create local vortices that entrain air and release bubbles from breaking surface water. Changes in flow depth relative to stream-bed structures influence relative submergence, which again has a pronounced impact on the underwater soundscape. The effect of relative submergence on the acoustic signature should be particularly prominent in low-order streams with a moderate to low ratio between depth and sediment size. A riffle may shift from a soundscape dominated by middle frequencies at low discharge and flow depth to a soundscape characterized by low frequencies at higher discharge and greater flow depth.

Our results show that an increase in turbulence and bubble formation (due to submergence and flow obstructions) lead to a distinctive increase in midrange-frequency, as well as in a narrow band of low-frequency sound levels. This finding is confirmed by the work of Lugli and Fine (2003) who found that bubbles and turbulence increase sound levels in midrange frequencies and low frequencies, respectively. A predominance of sound levels at low frequencies (<1 kHz) is also known to be typical in underwater ambient sound, generally consisting of a combination of surf, wind and biological sound (Greene 1995). Further, the spatial heterogeneity of the underwater soundscape increased as the level of turbulence and bubble formation increased. This sound heterogeneity across middle frequency bands is probably related to pulsating sound produced by breaking and reforming turbulent waves on flow obstructions.

The physical generated underwater sound should travel in all directions independent of the flow direction because water velocity is very low compared with sound speed that can travel at about 1,463–1,524 m s^{-1} in water, depending on temperature, salinity and pressure (Officier 1958). Moreover, because of its extraordinarily low attenuation, physical generated sound should propagate over large distances (Hawkins and Myrberg 1983). However, our results suggested that physical generated sound in the lower frequency bands travelled short distances upstream and downstream, while sound at the midrange and high frequencies quickly attenuated over very short distances beyond the scale of the flow obstruction or scale of a turbulent flow structure. Indeed, position 7 located in the lee of one of the bricks had a much different sound regime than position 4 which showed the highest level of sound across all frequencies, yet it was <1 brick distance away (Fig. 9). We believe this is best explained by what is called the cutoff phenomenon (Officier 1958; Urick 1983), as well as to absorption and scattering processes.

We propose that the quick sound level attenuation over distance in the middle frequencies was mainly a consequence of the cutoff phenomenon. A frequency corresponding to $\lambda = 4$ h (where λ is the wavelength and h is flow depth) is termed the cutoff frequency where sound at frequencies below this cutoff level become quickly attenuated (Urick 1983). In the bed structures experiment of the present study, flow depth was relatively low (16–22 cm). This implicated a cutoff frequency between 2.3 and 1.7 kHz (by a rigid bottom and a sound velocity of 1,500 m s^{-1}). This means that frequencies lower than the cutoff frequency could not propagate as acoustic waves and quickly decay with distance from the sound source. One of the first studies to systematically measure sound propagation in shallow water was done to examine mating call propagation of the oyster toadfish, *Opsanus tau*, which commonly call in 1 m deep water (Fine and Lenhardt 1983). Those authors found that low frequency acoustic signals in water approximately 1 m deep (over a sandy bottom) attenuated rapidly, with absorption coefficients ranging from 3 to 9 dB m^{-1}. Therefore, fish communication was restricted within a range of several meters. Moreover, Lugli and Fine (2007) reported that a 200 Hz tone at a flow depth of 20 cm will be reduced by 20 dB every 15 cm in distance away from the source. Therefore, high dB sound levels in the mid-frequency range created at position 4 quickly decayed moving downstream from the sound source (position 5 and 6) (Fig. 9), mainly as consequence of the cutoff phenomenon. Because sound levels of the lower octave bands had high dB levels at all positions, which is in disagreement with the cutoff effect, we suggest that a very low frequency sound may be an artifact of the flume itself or internally generated by the recording equipment.

Sound at high frequencies has been shown to be absorbed more than low frequencies however, over short distances the effect of absorption is not a factor (UK

National Physical Laboratory). Hence, sound absorption should not affect the results of this study. However, sound attenuation was probably also influenced by scattering of physical generated sound due to bubbles created by the turbulence near flow obstructions. Plumes of bubbles have been found to absorb and scatter sound (Urick 1983; Norton and Novarini 2001). Scattering is responsible for the deflection of sound energy away from the main propagation direction. This can explain the 'quiet' zone (with low sound levels over most frequencies) behind the bricks at position 7 (Fig. 9). The high sound levels created at position 4 were quickly, and over a very short distance, scattered away from the flow direction. Therefore, most of the physical generated sound energy could not reach position 7 but some of this energy reached the position 6 placed more downstream (Fig. 9).

Ecological implications and conclusions

This study found that underwater soundscape in shallow running water is mainly shaped by the interaction between water velocity and relative submergence of flow obstructions and the related turbulence and bubble formation. Obstructions, which can create transition zones, are expected to generate unique acoustic signatures. In running-water habitats similar to those we created in the flume at positions 4 (e.g. riffle or cascade), 6 (e.g. run or glide) and 7 (e.g. backwater or eddy) are present at various discharges levels (Fig. 9). Riffles or cascades may generate high turbulence and plenty of air bubbles in the water column, such as we created at position 4 (Fig. 9). Therefore, the sound signature may be characterized by high sound levels in midrange frequencies. In contrast, pools or runs, in which turbulence is generated differently and air bubble formation is less pronounced, the 3-D sound graph should resemble the ones at position 5 and 6 in the flume (Fig. 9). Low-gradient streams may have lower ambient sound levels than rivers with steep channels. However, quiet zones such as eddies, backwaters, and glides may have similar 3-D sound graphs as the one at position 7 (Fig. 9).

We also expect that the specific physical generated sound recorded in the field remains a local phenomenon, especially in shallow waters, although very high frequency sound may travel over longer distances (because they are less affected by the cutoff phenomenon). The effect of sound absorption and scattering should also be more marked in riffles and cascades than in runs or pools because of a larger concentration of air bubbles in the water column and because of higher structural heterogeneity at the bottom. Therefore, physical generated sound provides a characteristic attribute of specific aquatic habitat types that organisms may use.

Organisms may obtain indirect information from the acoustic signals about the potential position of prey and predators, on how to find potential mates or competitors, and to communicate inter- and intra-specifically (Popper and Fay 1993; Lagardere et al. 1994; Myrberg and Lugli 2006). They can also receive abiotic information about waves, torrents, wind, currents or precipitation events (Popper and Fay 1993; Lagardere et al. 1994). Fish survival, for example, depends on their auditory system, which helps to accurately interpret information on the acoustic environment (Vasconcelos et al. 2007). The best hearing range and vocalization of most fish species is located below 1 kHz (Hawkins 1973; Amorim 2006). However, hearing specialists like carps can detect sound over a broader frequency range (up to several kHz), and at much lower sound level (Amoser and Ladich 2005). Fishes and most likely other aquatic organisms could use their auditory system to detect typical physical generated sounds or to find preferred feeding locations such as the downstream end of riffles. The present study showed that high sound levels in running waters can be generated by high water velocity as well as by the presence of submerged flow obstructions. Therefore, rivers and streams may show high sound levels, especially during high flow events. Thus, eddies, pools, backwaters and glides could serve as an important hydraulic refuge where aquatic organisms can attain a positive energetic balance as well as quiet zones, for example, for intraspecific communication.

On the other hand, human interventions may affect the acoustic signature. Canalization, for example, may decrease stream-bed heterogeneity and relative submergence, concurrently decrease flow depth and increase mean water velocity, and thereby reducing physical generated sound heterogeneity while increasing sound level and the effect of the cutoff phenomenon. Because different habitat types may have different acoustic signatures, their alteration may affect the soundscape of rivers and streams, and therefore may impact organism behavior. However, it remains an open question as to what extent physical generated sound, submerged flow obstructions, and velocity are used, independently or in concert, for positioning or movement.

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