HYDROLOGICAL PROCESSES
Hydrol. Process. (2010)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.7730

A field-based investigation to examine underwater soundscapes of five common river habitats†

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Abstract:

Aquatic river habitat types have been characterized and classified for over five decades based on hydrogeomorphic and ecological variables. However, few studies considered the generation of underwater sound as a unique property of aquatic habitats, and therefore as a potential information source for freshwater organisms. In this study, five common habitat types along 12 rivers in Switzerland (six replicates per habitat type) were acoustically compared. Acoustic signals were recorded by submerging two parallel hydrophones and were analysed by calculating the energetic mean as well as the temporal variance of ten octave bands (31·5 Hz–16 kHz). Concurrently, each habitat type was characterized by hydraulic and geomorphic variables, respectively. The average relative roughness, velocity-to-depth ratio, and Froude number explained most of the variance of the acoustic signals created in different habitat types. The average relative roughness predominantly affected middle frequencies (63 Hz–1 kHz), while streambed sediment transport increased high-frequency sound pressure levels (2–16 kHz) as well as the temporal variability of the recorded signal. Each aquatic habitat type exhibited a distinct acoustic signature or soundscape. These soundscapes may be a crucial information source for many freshwater organisms about their riverine environment.

KEY WORDS underwater soundscape; acoustic signature; hydrogeomorphology; hydrophone; sound pressure level; physical generated sound

Received 28 July 2009; Accepted 31 March 2010

INTRODUCTION

Aquatic river habitat types have traditionally been classified based on flow characteristics and geomorphic properties (Leopold and Maddock, 1953; Montgomery and Buffington, 1997; Wohl and Merritt, 2008). The structure and dynamics of these habitat types influence, among other stream ecosystem characteristics, the composition and distribution of fish (Stuart, 1953; Lamouroux *et al.*, 2002; Vlach *et al.*, 2005) and benthic invertebrates (Beisel *et al.*, 1998; Brooks *et al.*, 2005; Pastuchova *et al.*, 2008). However, little is known about the acoustic signature of aquatic habitat types. It is not known if all habitats simply have similar 'white-noise' signatures or if they have mixed or even unique signatures (e.g. do riffles and pools sound the same or different?).

Acoustically, freshwater ecosystems have been considered as large composite environments rather than as a mosaic of distinct habitat types (Amoser and Ladich, 2005; Wysocki *et al.*, 2007). Wysocki *et al.* (2007) noticed that physical sources of underwater sound generation depend on hydraulic conditions (flow depth and velocity, sediment transport), whereas biotic sources (e.g. created by aquatic insects) may only contribute to acoustic signals when water is stagnant or slowly flowing. Based on laboratory experiments, Tonolla *et al.* (2009) demonstrated that underwater sound in shallow waters may be created by turbulence resulting from the interaction of flow velocity, relative roughness (given as relative submergence), and flow obstructions. Furthermore, Tonolla *et al.* (2009) showed that different acoustic signatures exist at different positions in a flume course, pointing to a direct influence of morphological and hydraulic conditions on the acoustic signature, which may also be the case for different river habitat types.

Underwater sound exhibits a lower attenuation rate compared to light and chemical substances; at the same time, it is rapidly transmitted over long distances (4–5 times faster than in air; Hawkins and Myrberg, 1983; Rogers and Cox, 1988; Popper and Carlson, 1998). Therefore, acoustic signatures most likely provide important information sources about the underwater environment for aquatic organisms. Although few fish species actively use acoustic signals for communication, almost all fish species are able to detect sound and therefore may use it for positioning, navigation, refuge detection, and prey selection (Popper *et al.*, 2003). Therefore, underwater sound is expected to strongly influence the ecology and behaviour of many aquatic organisms.

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† This article was published online on 29 May 2010. An error was subsequently identified. This notice is included in the online version to indicate that this has been corrected on 26 July 2010.

The main goal of this study was to characterize hydrogeomorphologically and acoustically common aquatic habitat types including pools, runs (with and without streambed sediment transport), riffles, and step-pools. The specific objectives were (i) to characterize river habitat types based on acoustic signatures and (ii) to quantify the relationship between acoustic signatures and hydrogeomorphological characteristics. Specifically, we predict that (i) the five selected river habitat types can be clearly distinguished acoustically and (ii) that typical hydrogeomorphological characteristics influence single or a range of frequencies. Finally, the potential ecological relevance of different acoustic signatures for fishes is briefly discussed.

METHODS

Experimental design

Between April and December 2007, 30 aquatic habitats along 12 Swiss rivers were hydrogeomorphologically and acoustically investigated (Figure 1, Table I). Five common habitat types, with six replicates each, were empirically identified: pools, riffles, runs with (run sed.) and without (run) streambed sediment transport, and step-pools. Slow-flowing habitats with a smooth water surface were classified as pools; habitats with little surface agitation and no major flow obstruction as runs (runs with streambed sediment transport if this was visually clearly detectable); swiftly flowing turbulent waters with frequent surface waves as riffles, and habitats showing a single cascade of water into a boulder/cobble-forced pool as step-pools.

Data collection

Nine hydrogeomorphological variables were either directly measured in the field or calculated based on these measurements (Table II). Flow velocity (u), using a hand-held FlowTracker (Acoustic Doppler Velocimeter, SonTek, San Diego, USA), and flow depth (h), were measured in front of the hydrophone head. The average (D_{50}) and maximum ($D_{\max}$) particle size (c-axis; height) were calculated from 100 randomly selected substrate particles in an area of $\sim$10 m around the hydrophones (following a modified Wolman (1954) count). The average relative roughness ($D_{50}h^{-1}$), maximum relative roughness ($D_{\max}h^{-1}$), Froude number ($Fr = u\big/\sqrt{gh}$, where g is the acceleration due to gravity), velocity-to-depth ratio (uh^{-1}), and Reynolds number ($Re = uh\big/\nu$, where ν is kinematic viscosity of water) were calculated. Reynolds number is a dimensionless criterion describing the onset of turbulent flow from laminar flow conditions and Froude number indicates the energetic state of the flow (a value of 1 indicates the transition from subcritical to super-critical flow). In this study, all flow was turbulent, hence the Reynolds number was used to scale the level of turbulence rather than describe a change in flow from laminar to turbulent conditions.

Acoustic signals were recorded using two hydrophones (Type 8103, Brüel and Kjaer, Denmark). A metal rod was placed vertically in the sediment under the water surface and a supplementary metal rod ($\sim$40 cm length) was attached at the vertical one so that the hydrophones could be positioned parallel with the heads facing upstream at 60% flow depth. The 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^{-1}, was used to amplify the signal sent by the hydrophones. Finally, the signals were captured by a digital recorder (Type R-4, Edirol, Japan). The 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. The recording time was approximately 5·5 min per habitat.

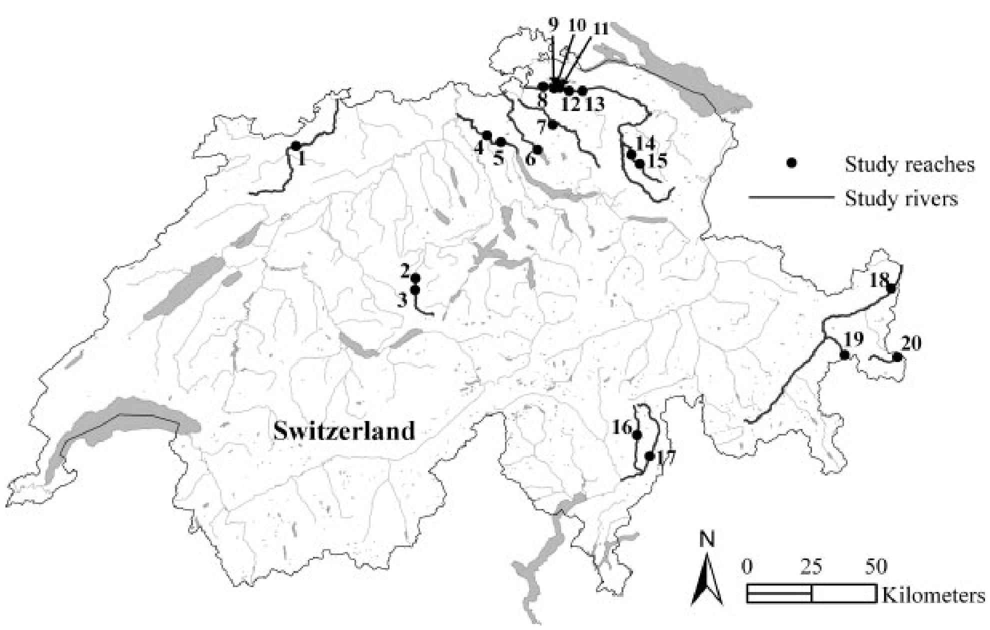

Figure 1. Location of the 20 study reaches along 12 Swiss rivers (see Table I for details)

Table I. Characterization of the study habitat types along 12 Swiss rivers

Study reach	River	Habitat type	Stream order (Strahler)	Discharge ($m^3\ s^{-1}$)
1	Birs	1 run sed.	6	33·1
2	Waldemme	1 pool, 1 step-pool	6	9·6
3	Waldemme	1 pool, 2 step-pools	6	9·6
4	Limmat	1 pool	7	53·7
5	Limmat	1 run	7	48·1
6	Glatt	1 run	6	3·5
7	Töss	1 riffle	6	8·1
8	Thur	1 run sed.	7	49·9
9	Thur	1 run sed.	7	58·6
10	Thur	1 run sed.	7	58·6
11	Thur	1 riffle[a], 1 run sed.	7	13·8
12	Thur	1 run	7	13·8
13	Thur	1 run	7	11·8
14	Necker	1 pool, 2 runs	6	2·3
15	Necker	1 step-pool	5	2·3
16	Calancasca	1 step-pool	4	5·4
17	Moesa	1 pool[a], 1 run sed.	5	30·2
18	Inn	1 riffle	6	52·7
19	Spöl	1 pool[a], 2 riffles, 1 step-pool	5	13·0
20	Rom	1 riffle	4	1·7

Study reaches are indicated in Figure 1. Daily average discharge at the time of measurement are from the nearest gauging station (FOEN, 2009).
[a] Not in the main channel.

Table II. Hydrogeomorphological variables (average ± standard deviation) of the five habitat types

	Pools ($N = 6$)	Runs ($N = 6$)	Runs Sed. ($N = 6$)	Riffles ($N = 6$)	Step-pools ($N = 6$)
u ($m\ s^{-1}$)	$0{\cdot}11 \pm 0{\cdot}06$	$0{\cdot}46 \pm 0{\cdot}10$	$0{\cdot}66 \pm 0{\cdot}22$	$1{\cdot}01 \pm 0{\cdot}22$	$0{\cdot}18 \pm 0{\cdot}13$
h (m)	$0{\cdot}80 \pm 0{\cdot}44$	$1{\cdot}01 \pm 0{\cdot}36$	$0{\cdot}74 \pm 0{\cdot}23$	$0{\cdot}30 \pm 0{\cdot}07$	$0{\cdot}41 \pm 0{\cdot}16$
D_{50} (m)	$0{\cdot}01 \pm 0{\cdot}01$	$0{\cdot}02 \pm 0{\cdot}02$	$0{\cdot}03 \pm 0{\cdot}02$	$0{\cdot}07 \pm 0{\cdot}05$	$0{\cdot}37 \pm 0{\cdot}20$
D_{max} (m)	$0{\cdot}18 \pm 0{\cdot}25$	$0{\cdot}09 \pm 0{\cdot}11$	$0{\cdot}09 \pm 0{\cdot}06$	$0{\cdot}20 \pm 0{\cdot}09$	$0{\cdot}55 \pm 0{\cdot}17$
$D_{50}h^{-1}$	$0{\cdot}01 \pm 0{\cdot}01$	$0{\cdot}03 \pm 0{\cdot}02$	$0{\cdot}04 \pm 0{\cdot}03$	$0{\cdot}21 \pm 0{\cdot}10$	$0{\cdot}90 \pm 0{\cdot}37$
$D_{max}h^{-1}$	$0{\cdot}19 \pm 0{\cdot}25$	$0{\cdot}10 \pm 0{\cdot}09$	$0{\cdot}14 \pm 0{\cdot}15$	$0{\cdot}66 \pm 0{\cdot}19$	$1{\cdot}37 \pm 0{\cdot}24$
Fr	$0{\cdot}04 \pm 0{\cdot}02$	$0{\cdot}16 \pm 0{\cdot}07$	$0{\cdot}25 \pm 0{\cdot}08$	$0{\cdot}62 \pm 0{\cdot}20$	$0{\cdot}09 \pm 0{\cdot}05$
uh^{-1}	$0{\cdot}16 \pm 0{\cdot}09$	$0{\cdot}58 \pm 0{\cdot}47$	$0{\cdot}93 \pm 0{\cdot}34$	$3{\cdot}73 \pm 1{\cdot}62$	$0{\cdot}41 \pm 0{\cdot}24$
Re ($\times 10^4$)	$9{\cdot}38 \pm 8{\cdot}10$	$45{\cdot}57 \pm 17{\cdot}04$	$50{\cdot}07 \pm 25{\cdot}90$	$28{\cdot}52 \pm 3{\cdot}40$	$8{\cdot}68 \pm 8{\cdot}66$

Flow velocity: u; flow depth: h; average substrate size (c-axis: height): D_{50}; maximum substrate size (max. c-axis: max. height): D_{max}; relative roughness: $D_{50}h^{-1}$; max. relative roughness: $D_{max}h^{-1}$; Froude number: Fr; velocity-to-depth ratio: uh^{-1}; Reynolds number: Re. Note that flow velocity and flow depth for step-pool habitats were measured in the pool under the step. Moreover, step height had also been considered in the measurement of substrate particle. Therefore, relative roughness values >1 in step-pools occurred.

Data analysis

Acoustic data reduction and analysis. The acoustic signals detected by the two hydrophones were analysed (5 min were randomly selected) by means of a signal-processing software package specifically developed and written for this specific purpose (K. Heutschi, unpublished). A cross-spectrum analysis was used to minimize the contribution of uncorrelated noise between the two hydrophones. The data analysis used in this study followed the one recently described in Tonolla *et al.* (2009); therefore, only a brief summary of the analysis is given here. In a first step, acoustic data were evaluated with a short-term third-octave band analysis over 31 frequency bands (20 Hz–20 kHz) and a temporal resolution of ∼1·1 s. In a second step, the third-octave bands were combined in ten octave bands. As the evaluation of a band-limited noise-like signal has uncertainty that depends reciprocally on the product of averaging time and bandwidth, the reduction of the spectral resolution from third-octave bands to octaves lowered the uncertainty significantly. One recording of approximately 5 min delivered a ∼270 octave band spectra. For each octave band, the temporal variation over the 5 min recording was evaluated by calculating the variance. Furthermore, the average signal energy (energetic mean) in each octave band was evaluated. In addition to this octave band specific inspection, the variance and the average energy were calculated for the broadband signal over the whole frequency spectrum (henceforth, broadband mean value and broadband mean variance, respectively). Supplementary to the broadband mean variance, a Shannon's diversity index (H) was calculated using a vector-based landscape analysis tool (V-LATE 1·1. extension for ArcGis 9·2, ESRI, Redlands, USA) to represent the acoustic variability of the data (variability over time and over all octave bands). In general, the Shannon's diversity index is measured on a set of classes differing in frequency ($\neq$ acoustic frequency; but occurrence). It increases with the evenness of the frequency of the classes and with the number of classes. In ecological studies, it is normally used to characterize species (classes) diversity in a community. The diversity analysis used in V-Late in this case focuses on acoustic classes rather than on species. The classes are sound pressure levels and their frequencies are the probability mass function of the amplitude envelope.

All data were expressed on a logarithmic scale as dB values relative to 1 μPa (dB re 1 μPa) as a reference. The calibration was performed with a Brüel and Kjaer calibrator (Type 4223, Brüel and Kjaer, Denmark), which generates a highly reproducible nominal sound pressure level of 166 dB at 250 Hz.

Sources of uncertainty. Potential uncertainty sources were considered when measuring and analysing acoustic data. These included the noise produced by the vibration of the hydrophone cable (induced by wind and/or water) and background noise produced by the suspension of the hydrophones in the water column. The metal rods placed under the water surface represented obstacles in the water flow and may have created some unwanted turbulence and vibrations, thus influencing the sound measurements. The most important external factor influencing sound measurements was wind, dominant at high frequencies. Moreover, Tonolla *et al.* (2009) found that, if sound is not affected by scattering and the 'cutoff phenomenon' (Officier, 1958; Urick, 1983; Rogers and Cox, 1988), some of the energy created upstream can reach positions placed more downstream, thus sound not directly produced at the individual habitat but at more distant locations could be detected. The effect of unwanted turbulence and vibrations due to flow obstruction was reduced by the use of two hydrophones, located close to each other. This instrument set-up has been shown to provide data that can be used to reduce the background noise caused by turbulent flow around the hydrophones and internal noise of sensors and amplifiers and therefore provides an elevated signal-to-noise ratio (Tonolla *et al.*, 2009). The advantage of this configuration is that by multiplying two signals instead of taking the square of just one sensor nullifies incoherent components between the two hydrophones (Norton, 1989). This reduces internal noise components and contributions of sound from turbulence around the hydrophones, resulting in a significantly improved signal-to-noise ratio (Tonolla *et al.*, 2009). The effect of vibration by flow was reduced by keeping the excess hydrophone cable out of the water column and securing in water cable to the metal rod. Moreover, acoustic measurements with feasible measurement artefacts such as energy peaks generated for short periods by, for example, cable movement, were identified and eliminated from the original data set.

Statistical analysis. Kolmogorov–Smirnov tests were initially used to test if variables clearly deviate from normality, and square-root-transformation applied if necessary. Principal component analyses (PCA) were performed based on hydrogeomorphological and acoustic variables. Factor loadings of the first and second principal component were extracted without rotation and used for further correlation analysis. A first PCA was used to generate habitat typology based on nine hydrogeomorphological variables (flow velocity, flow depth, average and maximum particle size, average and maximum relative roughness, Froude number, velocity-to-depth ratio, and Reynolds number). A second PCA was used to generate a habitat typology based on the sound pressure level (energetic mean) of the ten octave bands (31·5 Hz–16 kHz). Spearman's rank correlation analyses were used to identify the direction and strength of relationships between studied variables. Because variance of several octave bands was suspected to be inter-correlated, Spearman's rank correlation analysis was also used to determine these relationships. Analysis of variance between groups (one-way ANOVA) was performed to evaluate the effect of both habitat type and hydrogeomorphological variables on the acoustic signatures, and *post hoc* Tukey tests were performed for each pair-wise comparison to test for specific differences between habitat types. PCAs were performed with PRIMER 5 (version 5·2·9, Primer-E Ltd, Plymouth, UK), ANOVA's and *post hoc* Tukey tests were performed with SPSS (version 14·0, SPSS Inc., Chicago, USA).

RESULTS

Hydrogeomorphological characterization of river habitat types

Based on hydrogeomorphological variables, river habitat types could be separated into four distinct groups (Figure 2). Maximum relative roughness, maximum substrate size, and average relative roughness exhibited the best correlations with the factor scores of the first component of the PCA, while velocity-to-depth ratio, Froude number, and flow velocity showed the best correlation with the factor scores of the second component (Table III). Runs and runs with streambed sediment transport could not be clearly distinguished by the selected hydrogeomorphological variables. However, results from the present study suggest that runs with streambed sediment transport were associated with higher flow velocity, Froude number, velocity-to-depth ratio, as well as with higher Reynolds number (Table II).

To avoid redundancy and because of the good correlation with the factor scores, the variables average relative roughness, velocity-to-depth ratio, Froude number, and Reynolds number were used for further statistical analyses.

Acoustic characterization of river habitat types

Acoustically, except for one riffle outlier, river habitat types could be separated into four groups (Figure 3).

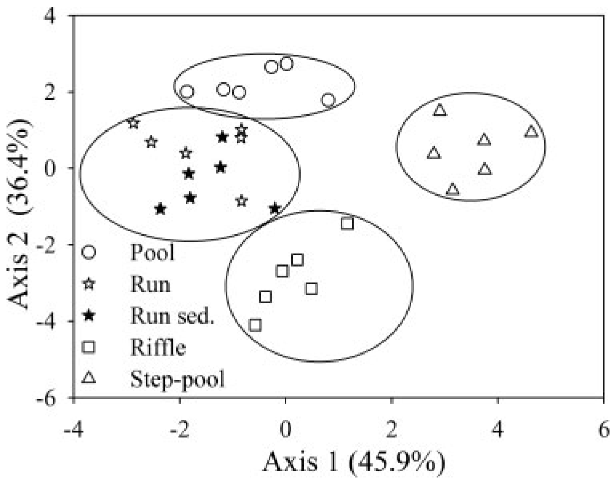

Figure 2. Principal components analysis (PCA) of the river habitats based on nine hydrogeomorphological variables ($N = 6$ per habitat type). The four groups separated by the PCA are indicated. Note that the percentage of explained information by each principal component is indicated in brackets

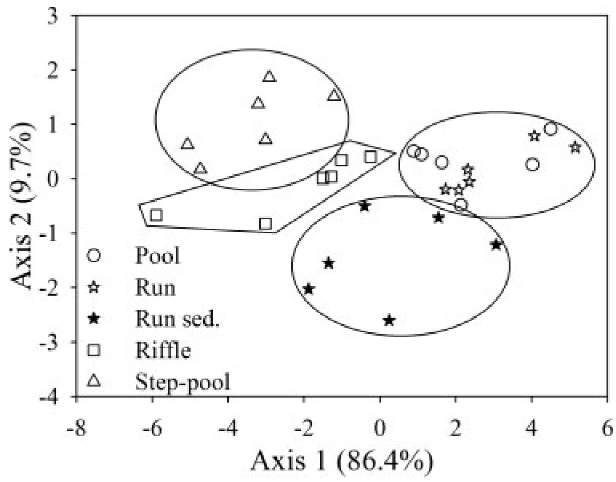

Figure 3. Principal components analysis (PCA) of the river habitats based on the sound pressure levels of ten octave bands ($N = 6$ per habitat type). The four groups separated by the PCA are indicated. Note that the percentage of explained information by each principal component is indicated in brackets

Table III. Spearman's rank correlation (r) between the nine hydrogeomorphological variables and the factor scores of the first (PCA1) and second (PCA2) components of the PCA

	PCA1 (r) ($N = 30$)	PCA2 (r) ($N = 30$)
u	−0·30	−0·89**
h	−0·52**	0·44*
D_{50}	0·80**	−0·38*
D_{max}	0·88**	−0·17
$D_{50}h^{-1}$	0·84**	−0·46*
$D_{max}h^{-1}$	0·93**	−0·34
Fr	−0·18	−0·94**
uh^{-1}	−0·01	−0·97**
Re	−0·63**	−0·48**

For abbreviations of the hydrogeomorphological variables see Table II.
* $P < 0·05$; ** $P < 0·01$.

Table IV. Spearman's rank correlation (r) between sound pressure levels of the ten octave bands and the factor scores of the first (PCA1) and second (PCA2) components of the PCA

	PCA1 (r) ($N = 30$)	PCA2 (r) ($N = 30$)
31·5 Hz	−0·93**	0·08
63 Hz	−0·94**	0·19
125 Hz	−0·94**	0·22
250 Hz	−0·91**	0·27
500 Hz	−0·93**	0·22
1 kHz	−0·96**	0·08
2 kHz	−0·96**	−0·16
4 kHz	−0·93**	−0·31
8 kHz	−0·90**	−0·40*
16 kHz	−0·84**	−0·42*

* $P < 0·05$; ** $P < 0·01$.

The riffle outlier was at a site with high discharge (Inn River; Table I), and had a two times higher average relative roughness than the other riffles. All ten octave bands exhibited a significant negative correlation with the factor scores of the first component but only a weak negative (2–16 kHz) and weak positive (31·5 Hz–1 kHz) correlation with the factor scores of the second component (Table IV). The Tukey pair-wise multiple comparisons test showed that the factor scores of the first and/or the second component significantly differed among habitat types ($P < 0·05$) except between pools and runs without streambed sediment transport.

The energetic mean of all octave bands, as well as of the broadband mean value, significantly differed among habitat types (one-way ANOVA: $n = 30$; $P < 0·01$). The octave bands 125, 250, and 500 Hz exhibited the most distinct differences ($26·72 \leq F_{4,29} \leq 26·97$; $P < 0·001$). Tukey pair-wise multiple comparisons showed that pools and runs without streambed sediment transport exhibited a similar energetic mean of all octave bands, and the broadband mean value. Pools and runs with streambed sediment transport significantly differed in the energetic mean from 2 to 8 kHz ($P < 0·05$). Runs and runs with streambed sediment transport differed in the energetic mean from 2 to 16 kHz as well as in the broadband mean value ($P < 0·05$). Step-pools and riffles significantly differed in the energetic mean of 125 and 250 Hz ($P < 0·01$). Runs with streambed sediment transport and step-pools did not significantly differ[§] in the energetic mean from 2 to 16 kHz, and runs with streambed sediment transport and riffles also did not differ[§] in the energetic mean of 125 Hz.

Each habitat type exhibited a distinct acoustic signature (Figure 4). Pools and runs showed similar acoustic signatures with low sound pressure levels over all octave bands and a main energy peak at the 31·5 Hz octave band. Runs with streambed sediment transport showed a distinct bimodal distribution (peaks between 2 and 16 kHz as well as at 31·5 and 63 Hz). Streambed sediment transport generated an energy peak in the high-frequency bands (2–16 kHz) with an increase of more than 10 dB in

[§] Correction made here after initial publication.

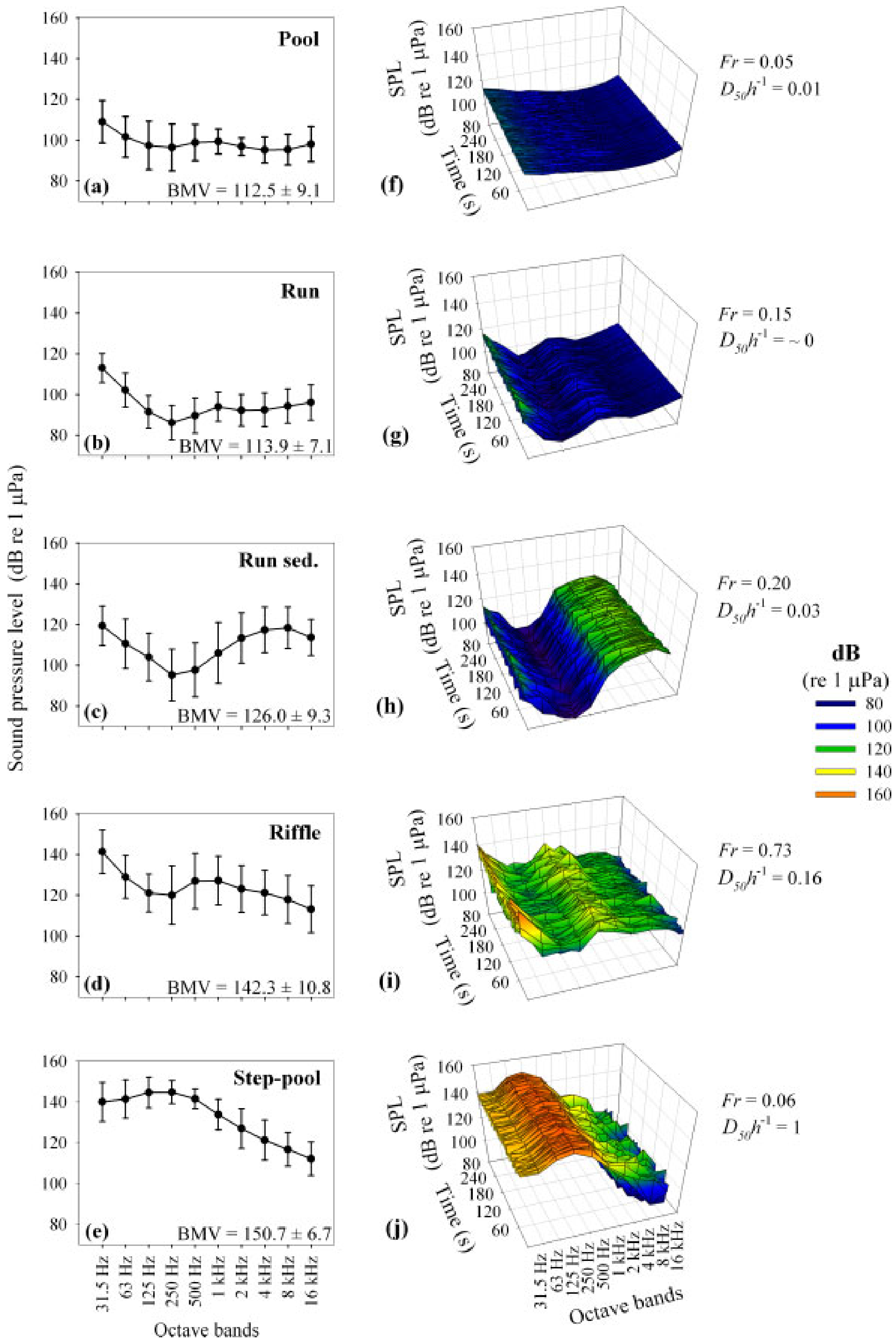

Figure 4. Acoustic signature of river habitats. Panels (a)–(e) showing sound pressure levels (average ± standard deviation) of ten octave bands in the five habitat types ($N = 6$ per each habitat type); BMV: broadband mean value (average ± standard deviation). Panels (f)–(j) showing examples of 3-D sound graphs (Soundscapes) for the five habitat types; SPL: sound pressure level; Fr: Froude number; $D_{50}h^{-1}$: relative roughness§

the broadband mean value compared to runs without sediment transport. Riffles showed a distinct bimodal sound distribution (peaks at 31·5 Hz and 500 Hz–2 kHz) and the sound pressure level was about 20–30 dB higher than that in pools, runs, and runs with streambed sediment transport. There is a mid-range depression (125 to 250–500 Hz), a 'silent' zone, in riffles, runs, runs with streambed sediment transport, and pools. However, step-pools exhibited sound pressure level peaks at these mid-range frequencies. Step-pool habitats showed by far the highest broadband mean value of all habitat types, reaching sound pressure levels of about 150§ dB (Figure 4).

The acoustic temporal variability (given as variance) of the ten octave bands could be separated into two distinct groups based on a PCA and Spearman's rank

§ Correction made here after initial publication.

Table V. ANOVA statistic (F, P) for assessing the effect of habitat type on the variance of the two selected octave bands (125 Hz and 2 kHz), the broadband mean variance (BMVa), and the Shannon's diversity index (H)

	$F_{4,29}$	P
125 Hz	4·16	0·010*
2 kHz	5·96	0·002**
BMVa	9·82	0·000**
H	10·53	0·000**

The statistical model considered habitat type as fixed factor and 125 Hz, 2 kHz, BMVa, and H as dependent variables.
* $P < 0.05$; ** $P < 0.01$.

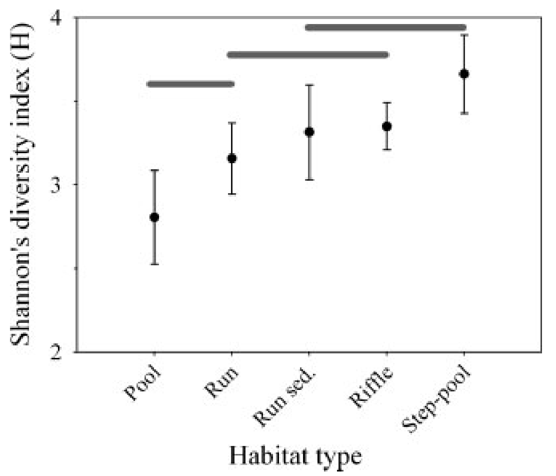

Figure 5. Shannon's diversity index (average ± standard deviation) of the five habitat types ($N = 6$ per habitat type). High Shannon's index values indicate high acoustic temporal and spatial (over all frequency bands) variability. Habitats plots not under the same horizontal bar are significantly different (based on Tukey pair-wise multiple comparisons test; $P < 0.01$)

correlation analyses among dependent variables. To avoid redundancy within each of these two groups, only the variance of an octave band per group (125 Hz and 2 kHz) was used for further statistical analysis. The five habitat types were significantly different based on the variance of the two selected octave bands, the broadband mean variance, as well as on the Shannon's diversity index (both variables corresponding to acoustic variability over octave bands and time). However, the Shannon's diversity index showed more pronounced differences among habitat types (Table V). Shannon's diversity decreased from step-pools, to riffles, runs with streambed sediment transport, runs, and pools (Figure 5).

Out of the selected hydrogeomorphological variables, the average relative roughness explained most of the difference of the acoustic signatures of all ten octave bands (in particular in the frequency range from 63 Hz to 1 kHz), as well as of the broadband mean value (Table VI). The velocity-to-depth ratio and Froude number showed weak albeit significant correlations with 4 and 8 kHz sound pressure levels; the velocity-to-depth ratio also showed weak significant correlations with 31·5 Hz and the broadband mean value. Reynolds number showed significant negative correlation only with 250 Hz (Table VI).

DISCUSSION

Aquatic river habitats have been studied and classified for decades. However, few studies considered the generation of underwater sound as an essential feature of aquatic habitats, and therefore as a potential information signal for freshwater organisms. This is one of the first studies that acoustically characterized aquatic river habitats, and identified the main flow and geomorphic features that best explain underwater acoustic signals. Moreover, this study confirmed with stationary field experiments data that had been recently created artificially in a flume (Tonolla *et al.*, 2009).

Based on acoustic signatures, it was possible to clearly differentiate the selected most common habitat types. Moreover, these acoustic signature groupings coincided with traditional hydrogeomorphological classifications that are typically used to distinguish habitat types. However, there was a high degree of variability within the habitat types that created a more continuous transition between habitats. Nevertheless, the common aquatic habitat types exhibited distinct acoustic signatures, although acoustic differences between pools and runs (without streambed sediment transport) were less pronounced than expected. Pools and runs exhibited low average relative roughness values due to a lack of flow obstructions, which are necessary for turbulence and air bubble formation and the subsequent sound generation (Tonolla *et al.*, 2009). However, both run habitat types had higher sound pressure levels than pools. Higher sound pressure levels can be attributed to a combination of higher velocities, as increasing flow velocity increased sound pressure levels in a wide frequency range (Tonolla *et al.*, 2009), and to particle collisions due to streambed sediment transport. The similarity of the acoustic signatures of step-pools and riffles might be due to the high average relative roughness that both habitat types have. High average relative roughness coupled to high flow velocity generates high turbulence and air bubbles (with related effects on sound absorption and scattering), which in turn causes broadband noise not always clearly distinguishable by the ten octave bands.

A common characteristic of all habitat types were high sound pressure levels in the low-frequency range (31·5 Hz), confirming previous results by Lugli and Fine (2003), Wysocki *et al.* (2007) and Tonolla *et al.* (2009). Low-frequency sound pressure levels have previously been attributed to large-scale turbulences (Lugli and Fine, 2003). Thus, the highest energy was found in high turbulence habitats such as riffles and step-pools. However, even pools showed maximum sound pressure levels in the low frequencies, and a pronounced decline in middle to high frequencies, similar to lakes and backwaters (Wysocki *et al.*, 2007). In contrast, high sound pressure levels in the mid to high frequencies

Table VI. Spearman's rank correlation (r) among the four selected hydrogeomorphological variables and the sound pressure level of the ten octave bands and the broadband mean value (BMV)

	$D_{50}h^{-1}$ (r) ($N = 30$)	Fr (r) ($N = 30$)	uh^{-1} (r) ($N = 30$)	Re (r) ($N = 30$)
31·5 Hz	0·79**	0·36	0·43*	−0·08
63 Hz	0·83**	0·21	0·32	−0·22
125 Hz	0·84**	0·16	0·28	−0·25
250 Hz	0·80**	0·05	0·16	−0·37*
500 Hz	0·84**	0·09	0·21	−0·32
1 kHz	0·82**	0·18	0·28	−0·20
2 kHz	0·74**	0·27	0·35	−0·06
4 kHz	0·68**	0·38*	0·45*	0·06
8 kHz	0·62**	0·43*	0·48**	0·15
16 kHz	0·47**	0·33	0·35	0·17
BMV	0·84**	0·27	0·37*	−0·12

For abbreviations of the hydrogeomorphological variables see Table II.
* $P < 0·05$; ** $P < 0·01$.

were typical for fast-flowing habitat types (riffles and runs with streambed sediment transport). This is in agreement with Wysocki *et al.* (2007), who also found high sound pressure level values in the high-frequency range above 1 kHz in fast-flowing habitat types.

Physical generated underwater sound is caused by specific hydraulic mechanisms including breaking waves, water plunging directly in the water column, and air bubbles that emerge from core regions of turbulent flow. In turn, turbulence is enhanced by high flow velocities, low flow depths (resulting in high velocity-to-depth ratio and Froude numbers), and high average relative roughness associated with coarse streambed particles. Therefore, differences in the acoustic signatures among habitat types were mainly determined by the average relative roughness, flow velocity, and flow depth. Similarly, Wysocki *et al.* (2007) attributed differences among habitat types to differences in flow velocity and type of bottom substrata. The average relative roughness influenced the acoustic signature in all frequency bands, in particular, in the 63 Hz–1 kHz range, as confirmed by flume experiments (Tonolla *et al.*, 2009). The effect of the average relative roughness was more pronounced in riffles and step-pools with sound pressure level peaks between 500 Hz and 2 kHz and between 125 and 500 Hz, respectively. Similar results were reported by Lugli and Fine (2003), who reported sound pressure level peaks between 200 and 500 Hz near waterfalls (equivalent to what is referred to here as step-pools) and rapids (equivalent to what is referred to here as riffles). This mid-range frequency sound is attributed to processes of water breaking the surface and entraining air. The loudest sound is generated by collapsing waves and plunging chutes of water that cause a violent and forceful air entrainment. Some sound is also caused by secondary splashes and bubbles (underwater air bubbles), which are then carried by turbulent sweeps or advected vortices of current beneath the surface, which creates shear within the flow and emerges at the surface as boils, seams, and other patches of water surface roughness as turbulence dissipates. The process of rapid entrainment of air and subsequent collapse of air bubbles due to turbulence is commonly called *cavitation* (Urick, 1983). Because of pressure changes, the bubbles of air dissolved in the water undergo dilatation and collapse after having reached a critical size, generating a short pulse of sound (Urick, 1983; Lurton, 2002). This process is thought to contribute to the physical underwater sound in the frequency range 0·1–1 kHz (Urick, 1983; Lurton, 2002). This frequency range corresponded to the sound pressure level peaks particularly found in riffles and step-pools.

High roughness coupled with high flow velocity induced breaking waves that collapsed in a rhythmic way, generating a distinct temporal sound variability. Therefore, differences in the average relative roughness were mainly responsible for differences in sound variability among habitat types. Similarly, Tonolla *et al.* (2009) reported that an increase in the average relative roughness (expressed as relative submergence), and an increase in the related level of turbulence, led to an increase in acoustic variability across frequency bands and in time. Thus, the lowest variability was observed in habitat types with low average relative roughness (due to low bed heterogeneity) such as pools and runs. The sound variability was also influenced by streambed sediment transport. Sound variability in the high frequencies due to streambed sediment transport was relatively low compared to the observed variability in turbulent habitat types such as riffles and step-pools (Figure 4). Indeed, streambed sediment transport had a relevant effect on the acoustic signature, mainly on the high frequencies between 2 and 16 kHz. Higher velocity-to-depth ratio, Froude number, and flow velocity, found in runs with streambed sediment transport in contrast to 'normal' runs, resulted from a higher gradient of energy across the runs, which in turn produced flow competent conditions for small particles composing the bed. Thus, the increase in the high-frequency energy was presumably caused by collisions and momentum exchange between particles in transport (mainly gravel and sand) and those resting on the bed, resulting in the production of sound and further entrainment of particle sizes larger than predicted by pure shears stress threshold conditions (Lorang and Hauer, 2003). The sound produced by streambed sediments moving on the river bottom has also been successfully used by Rickenmann and McArdell (2007, 2008) to estimate the volume of coarse streambed sediment transport in mountain streams. The acoustic device used by those authors registered vibrations from gravel particle impacts passing over a metal plate, and the number of impulses per unit time was then used as a measure of bedload transport activity.

Potential ecological relevance of underwater soundscapes

Is underwater sound just an attribute of river habitats or does it provide meaningful information for organisms? Several studies have shown that reef fish larvae can detect and localize underwater sound over large distances (Tolimieri *et al.*, 2000, 2004; Leis *et al.*, 2002) as well as use it to migrate towards the reef (Simpson *et al.*, 2005, 2008). Moreover, Popper *et al.* (2003) reported that fishes may detect and exploit complex acoustic signals. Acoustic signals in water are composed of particle motion and sound pressure components. However, certain fish taxa, the often-called hearing-generalist (e.g. salmonids, perches, eels), can only perceive the particle motion component of sound. Whereas, several group of unrelated taxa, the often-called hearing-specialists (e.g. carps, catfishes, herrings, and minnows), have additionally evolved the ability to perceive the pressure component of sound via accessory specialized anatomical structures (swim bladder or other gas-filled chambers) that transform sound pressure waves into particle displacements. This considerably enhances their hearing sensitivity and extends their detectable auditory bandwidth to higher frequencies, Thus, hearing specialists can detect sound at frequencies up to several kilohertz and at relatively low sound levels, whereas hearing generalists can only detect low-frequency sounds (<1 kHz) at a relatively high sound level (for reviews, e.g. Hawkins, 1981; Fay and Simmons, 1999; Ladich and Popper, 2004). As a consequence, the perception and use of the typical habitat soundscapes might differ between species. In this study, only sound pressure as a component of the soundscape was considered. However, this is an important sound component in natural environments like rivers, and the shape of the sound spectrum for particle motion and pressure at noisy sites is generally similar (Lugli and Fine, 2007).

Habitat types with fast-flowing water (riffles and runs with streambed sediment transport) or showing high turbulent zones (riffles and step-pools) can limit the detection of biological communication signals through high sound pressure levels. However, Lugli *et al.* (2003), Lugli and Fine (2003), and Wysocki *et al.* (2007) found a 'noise window' in the <1 kHz range in fast-flowing habitats, which corresponded to the communication range of many fishes (hearing-generalists). In this study, low sound pressure levels have been recorded around 125 to 250–500 Hz in all habitat types, except in step-pools, supporting the 'noise window' hypothesis. Moreover, Lugli and Fine (2007) found that a similar quiet zone is not only an attribute in pressure spectra but also in velocity spectra.

A major constraint in shallow waters is the limited propagation of sound. Low-frequency sounds, with long wavelengths, are relatively unaffected by scattering and absorption and may travel over great distances (Hawkins and Myrberg, 1983). However, propagation of wavelengths >4 times the flow depth cannot propagate as acoustic waves owing to the cut-off phenomenon (Officier, 1958; Urick, 1983; Rogers and Cox, 1988). Thus, sound propagation in shallow aquatic ecosystems is constrained by flow depth and the nature of the bottom material (Rogers and Cox, 1988). For example, in riffles, with flow depth typically $<0{\cdot}4$ m, low-frequency sound (<1 kHz), by a rigid bottom and a sound velocity of 1500 m s^{-1}, rapidly decays within short distances from their source. This phenomenon has implications in the propagation of low-to-middle-frequency sounds generated in an upstream habitat, which exponentially decays with distance from its source. Lugli and Fine (2003) demonstrated that low-frequency acoustic signals (<1 kHz) generated by a waterfall disappeared within only 2 m (because of decreasing turbulence). Similarly, Fine and Lenhardt (1983) 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, fishes that are able to detect sound pressure may probably detect these low-frequency sounds only from sources extremely close to them. On the other hand, the strong sound pressure levels increase in the high-frequency range (2–16 kHz), generated by streambed sediment transport, could aid in refugia location by some fish taxa. The complex soundscapes detected in this study may also be influenced by the high amount of air bubbles in the water column, which can absorb and scatter the generated sound (Urick, 1983; Norton and Novarini, 2001; Lurton, 2002), as well as by repeated reflections at the water surface and bottom, which may degrade or alter the signal quality (Hawkins and Myrberg, 1983; Urick, 1983; Lurton, 2002).

CONCLUSION

This study indicates that pools, runs, riffles, and step-pools can be clearly differentiated by their acoustic signatures, therefore supporting the first hypothesis. The average relative roughness, velocity-to-depth ratio, and Froude number were the main hydrogeomorphological variables that explained the differences in acoustic signals. However, acoustic signal differences were less clear between pools and runs because of similar average relative roughness values. Hydrogeomorphological variables such as average relative roughness showed the most pronounced effects on mid-range frequencies, while streambed sediment transport strongly increased sound pressure level in the high frequencies and the temporal sound variability of the recorded signal. Therefore, the second hypothesis could be partially supported.

Distinct underwater acoustic landscapes, so-called soundscapes, exist. Soundscape perception and interpretation are expected to be highly relevant for many freshwater organisms. In a recent study, Fay (2009) recommended to open our minds to the probable fact that fishes (and probably also other aquatic organisms like insects and crustaceans) listen to much more than simply communication signals. Therefore, physically generated underwater sound may contain important information about the environment; potentially influencing the behaviour and ecology of many freshwater organisms. Hence, a major future challenge is to design experiments that will allow for testing the importance of acoustic signals in fluvial ecosystems, in particular, their role as behavioural cues. Finally, in-depth research is required to understand the linkage between fluvial mechanics and physical underwater sound generation.

ACKNOWLEDGEMENTS

We are grateful to the three anonymous reviewers for their valuable comments and suggestions that helped in improving the paper. This study was supported by the MAVA foundation, the Swiss Federal Institute of Aquatic Science and Technology (EAWAG), the Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), and a Marie Curie Intra-European Fellowship to VA within the 6th European Community Framework Programme. Funding for MSL was provided by a grant from the Gordon and Betty Moore Foundation (Grant Award Letter Agreement 344·01), San Francisco, CA, USA.

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