Acoustic wave propagation in rivers: an experimental study

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Abstract. This research has been conducted to develop the use of Passive Acoustic Monitoring (PAM) in rivers, a surrogate method for bedload monitoring. PAM consists in measuring the underwater noise naturally generated by bedload particles when impacting the river bed. Monitored bedload acoustic signals depend on bedload characteristics (e.g. grain size

10 distribution, fluxes) but are also affected by the environment in which the acoustic waves are propagated. This study focuses on the determination of propagation effects in rivers. An experimental approach has been conducted in several streams to estimate acoustic propagation laws in field conditions. It is found that acoustic waves are differently propagated according to their frequency. As reported in other studies, acoustic waves are affected by the existence of a cutoff frequency in the kHz region. This cutoff frequency is inversely proportional to the water depth: larger water depth enables a better propagation of

15 the acoustic waves at low frequency. Above the cutoff frequency, attenuation coefficients are found to increase linearly with frequency. The power of bedload sounds is more attenuated at higher frequencies than at low frequencies which means that, above the cutoff frequency, sounds of big particles are better propagated than sounds of small particles. Finally, it is observed that attenuation coefficients are variable within 2 orders of magnitude from one river to another. Attenuation coefficients are compared to several characteristics of the river (e.g. bed slope, bed rugosity). It is found that acoustic waves are better

20 propagated in rivers characterised by smaller bed slopes. Bed rugosity and the presence of air bubbles in the water column are suspected to constrain the attenuation of acoustic wave in rivers.

1 Introduction

1.1 Context of this study

Bedload transport monitoring is a challenging issue for river management. Geomorphological changes may be driven by

25 anthropogenic uses of rivers (e.g. hydroelectricity, sediment dredging, embankment, mining, land use changes) or to changes in available sediment loads related to extreme events or climate changes. Bedload transport is a dominant factor governing fluvial morphology but monitoring bedload transport is a difficult task. Direct sampling of bedload flux requires intensive field work, is difficult to accomplish during flood conditions and cannot provide continuous measurements. This is why the development of surrogate (or indirect) methods has been studied in recent decades. The report of Gray et al. (2010) gives an

30 overview of available techniques. One of these methods concerns the use of bedload Self-Generated Noise (SGN). When

bedload particles impact the river bed, an acoustic noise is created that propagates in the water column. Bedload SGN can be measured using hydrophones that are deployed in the river. Theoretical and experimental studies shown that the acoustic power monitored by hydrophones can be related to bedload fluxes using power laws (Barton et al., 2010; Geay et al., 2017a; Johnson and Muir, 1969; Jonys, 1976; Marineau et al., 2016; Rigby et al., 2016a; Thorne, 2014). Some relations are also observed

5 between bedload granulometry and frequential characteristics of SGN signals (Geay et al., 2017a; Thorne, 2014).

However, monitored signals are not only dependent on bedload SGN but also on propagation effects (Geay et al., 2017b; Rigby et al., 2016a). When propagating in rivers, bedload SGN suffers from geometrical spreading losses (Medwin, 2005), multiple diffractions on rough boundaries (Wren et al., 2015) or from other attenuation processes, for example related to the occurrence of suspended load (Richards et al., 1996). Therefore, acoustic waves are modified by the environment along their propagation

10 paths, from noise sources to hydrophone measurements. It has been shown that the river could be modeled as an acoustic wave guide where acoustic waves are partially trapped between the water surface and the river bed (Geay et al., 2017b). The occurrence of a cutoff frequency (related to the Pekeris waveguide) has been observed in field experiments (Geay et al., 2017b; Lugli and Fine, 2007) and reported in a theoretical review (Rigby et al., 2016b). A laboratory study focused on the role of river bed roughness as a source of attenuation process (Wren et al., 2015): an increase of 4 dB with an increasing bed roughness of

15 20 mm has been observed. There is comparatively little literature in the range of frequencies of interest (i.e. 0.1 to 100 kHz) and none of these studies have done specific experiments to define acoustic propagation laws in field experiments. For this reason, we designed a new protocol enabling the determination of propagation laws in rivers. These experiments result in experimental laws that are useful for building direct or inverse models, which is necessary to analyze bedload SGN signals. For example, it could be used to better understand the measurement range of a hydrophone in a river, a question which remains

20 unknown.

The next section of the manuscript relates a simple theoretical framework that is used to analyze field data. The second part of this paper describes the protocol which is based on emitting a known signal with an active source (i.e. an underwater speaker) and on measuring this same signal at several distances from the source. The third part is related to the application of this protocol in a set of rivers that have different characteristics (e.g. water depth, slope, flow velocities, bed roughness). It is found

25 that attenuation coefficients are frequency dependent and variable according to the type of river. It is also found that longitudinal river slopes are well correlated to attenuation coefficients.

1.2 Theoretical framework

Acoustic measurements are in part determined by the ability of the environment to propagate sounds. In this section, an acoustic theory is proposed to model the loss of acoustic power with the distance of propagation. At a first stage, without attenuation

30 processes, the monitored power (P - µPa²) of a sound source decreases with distance from the point source as the energy is spreads in space:

$$P(r) = P_{@1m}\, G(r) \qquad (1)$$

Where r (m) is the distance from the source to the sensor, $P_{@1m}$ (μPa^2 @1m) is the initial power of the sound source monitored at 1 meter in a free field and G is a function depicting geometrical spreading. The geometry of the river is simplified as a rectangular channel with a uniform water depth, denoted h. For underwater acoustic waves propagating in a river, the medium

5 is bounded by the water surface and the river bed. The effect of river banks is not explicitly considered in this study. It is assumed that banks act as efficient sound absorbers. At the upper and lower interfaces, reflection coefficients are variables, depending on the geo-acoustic parameters of the river bed (Geay et al., 2017b) and on the roughness of the interfaces (Wren et al., 2015). Two extreme cases can be assumed. First, when the interfaces are perfectly reverberant, acoustic waves are totally trapped into the water column and acoustic waves propagate in a cylindrical way. For large distance of propagation (i.e. $r > h$):

$$G(r) = \frac{2}{rh} \tag{2}$$

Secondly, when the interfaces are totally transparent, acoustic waves propagate in a spherical mode as in a free space:

$$G(r) = \frac{1}{r^2} \tag{3}$$

In the following, both propagation laws (spherical or cylindrical) will be tested to fit field data.

Acoustic waves not only suffer from geometrical spreading but also from losses from other processes that attenuate sounds like absorption or scattering effects. As stated in ocean studies, it is not really possible to distinguish both effects in field

15 experiments (Jensen et al., 2011). In this study, we propose to quantify these effects in a single exponential term as written is the following equation:

$$P(r) = P_{@1m}\, G(r)\, e^{-2\alpha r} \tag{4}$$

Where α is a coefficient of attenuation (nepers/m), $\alpha>0$.

The attenuation of acoustic waves is a process which is frequency dependent. That is why it is common to express the coefficient of attenuation as a function of wavelength (Jensen et al., 2011), denoted here α_λ (nepers):

$$\alpha_\lambda = \alpha\lambda = \alpha\frac{c}{f} \tag{5}$$

20 where λ is the wavelength (m), c is the celerity of the acoustic waves in water (m/s).

The goal of this study is to experimentally determine the values of the attenuation coefficients for acoustic waves in rivers, for frequencies between 1 kHz-100 kHz. This range of frequency corresponds to the expected range of frequencies generated by bedload self-generated noise of particles size between 10^{-1} and 10^{-3} m (Thorne, 2014).

2 Experimental Setup

An experimental set-up was designed to measure the loss of acoustic power with distance of propagation in natural streams. A controlled sound source emits a known signal at a fixed position on the river bed and this same signal is monitored with a hydrophone, at several distances from the point of emission. The equipment and the protocol are described hereafter.

2.1 Sound source

The sound source is generated by an underwater loudspeaker (Lubell Labs, LL 916H) controlled by an electronic device designed by the RTSys Company. The generated sound is determined by a theoretical signal (i.e. a wave file) and reproduced with a bias linked to the transfer function of the loudspeaker. The theoretical signal, chosen for this study, is a logarithmic chirp varying from 0.2 kHz to 50 kHz in 1 second. This signal is continuously emitted by the loudspeaker in an endless loop.

In a preliminary study, several tests have been conducted in Lake Bourget (France) to characterize the response of the system. To measure the generated sound at different angles from the speaker, 4 hydrophones (HTI 96) were placed at a fixed distance of 0.7 m from the sound source (Figure 1a). The entire system was deployed in a lake with an aluminum structure to ensure the relative position of the sensors (Figure 1b). To minimize the effect of this structure, all the sensors were attached to the structure with free ropes of 10 cm length. Several measurements of the emitted sounds were made by varying the depth of the system from 0.5 to 3.5 m and by changing the orientation of the loudspeaker (horizontal or vertical). The Power Spectral Density (PSD) of each emitted chirp monitored by the 4 hydrophones have been computed and plotted all together (**Error! Reference source not found.**). It can be observed that the generated sounds have a spectral power between 10^{12} and 10^{14} $\mu Pa^2/Hz$ but do not have a flat frequency response due to the transfer function of the system. Overall, we observed that the monitored PSD was variable between the different tests that were conducted. The monitored power varied between +/- 3 dB between the quartiles 25 and 75, and between +/- 10 dB between the minimum and the maximum. The most important parameter influencing the emitted sounds was the directivity of the loudspeaker (horizontal or vertical positions). The emitted signals also did not vary when repeating the same signal in a fixed configuration of emission.

This preliminary study indicated that we would not be able to precisely predict the power emitted by the sound source during our experiments. The loudspeaker is deployed with a weighted rope from a bridge so that its orientation is uncertain when deployed on the river-bed. We therefore have an uncertainty concerning the initial power of the sound source ($P_{@1m}$) defined in the equation 1. This parameter will therefore be estimated for each experiment.

2.2 Hydrophone measurements at varying distances

Acoustic measurements were performed with HTI-96 hydrophones plugged to a EA-SDA14 recorder (RTSys company). Acoustic signals were stored in wav files at a sampling frequency of 156 kHz. The system is shared by a Carlson river board, drifting during the measurements (Figure 3). Lagrangian measurements were preferred to fix-position measurements to optimize the signal to noise ratio. The hydrophone was located under the river board at a constant depth from the water surface.

The underwater loudspeaker is deployed at a fixed position on the river bed and emits a logarithmic chirp with an infinite loop of 1 second. During this time, several drift trajectories were made with the river board along the cross-section. As a first step, acoustic measurements were positioned using a synchronized GPS. This GPS equipment was damaged during the first field experiments requiring another way to position the hydrophone during the drifts. The cross-sectional distance of the hydrophone

5 was monitored at start positions and considered as constant during the drift (i.e. drifts are considered parallel to the river banks). Secondly, longitudinal positions of the hydrophone during the drift were computed knowing the start position and by assuming a constant velocity of the river board:

$$x(t) = x_0$$
$$y(t) = y_0 + v_{drift} \, t \qquad (6)$$

Where x and y are respectively the cross-sectional and longitudinal positions of the hydrophone (m); x_0 and y_0 are the initial positions of the hydrophone monitored at the beginning of the drift; v_{drift} is the mean velocity of the river board during the drift

10 (m/s), computed as the travelled distance divided by the duration of the drift. The assumptions of parallel drifts at a constant velocity was supported by the fact that our field sites are straight reaches.

Finally, the position of the hydrophone is known over the time. The next section describes how are processed the hydrophone signals.

2.3 Signal Processing of the monitored acoustic waves

15 The use of a matched filter was chosen to detect the chirps in the hydrophone signals. When a chirp is detected, the position of the measurement is computed by matching the time of detection with the position of the hydrophone. Finally, knowing the position of the loudspeaker, the distance r, between the sound source and the measurement, is computed.

For each located chirp, a short-term spectrogram is computed using Hamming windows of 2^{12} points with 50% overlapping (Figure 4). Based on this spectrogram, several *PSDs* are computed. First, the PSD of the studied chirp (noted PSD_r) is computed

20 by using the signal contained inside the black lines. The black lines correspond to the upper and lower limits of the octave band centered around the instantaneous frequency of the chirp. Secondly, the 95 percentile of the monitored power is computed (Merchant et al., 2013) in each frequency band. This PSD is used to represent the power of the ambient noise (PSD_{95}). In this example (Figure 4), one can particularly observe the harmonics generated by the loudspeaker when reproducing the theoretical logarithmic chirp. The ambient noise depends on the sounds that are naturally generated in the river (e.g. bedload impacts). To

25 ensure that the chirp is not affected by ambient noise, we decided to keep only the chirps that are at least twice more powerful than the ambient noise (i.e. $PSD_r > 2 \, PSD_{95}$).

At this point, we can propose a protocol to monitor the *PSD* of an emitted chirp at varying distances from its point of emission.

2.4 Field sites

The protocol presented in the previous section was applied in 7 field sites located in the French Alps. Their characteristics are presented in the Table 1. The mean bed-slope of the studied reaches varies from 0.05 to 1 %, and the width of the cross-section from 8 to 60 m. The roughness (or the surface particle-size distribution) of the river bed is a difficult parameter to measure,

5 particularly in rivers that are not wadable. This aspect of bed roughness was approached by doing Wolman measurements on the closest emerged bars. The surface D_{84} of emerged bars varies from 20 to 150 mm. Hydraulic parameters (discharge, surface velocity and mean water depth) were obtained by using several methods (acoustic Doppler current profiler, SVR Radar Gun or existing gauging station) depending on the field sites. Finally, the measurement of suspended sediment load was achieved with a turbidimeter (Visoturb, WTW).

3 Results

3.1 The Leysse River

As an example, data from the Leysse River are presented in the Figure 5. It represents the acoustic power received by the hydrophone at different distances from the underwater loudspeaker. The plotted acoustic power is the integral of PSD_r in the

5 third-octave band centered on 1 kHz. This data set has been obtained with 27 drifts of the river board. The effect of source location has been tested by varying the source location in the river cross-section. It has been found that the result was insensitive to source location in this river. Spherical and cylindrical models of propagation losses have been fitted with a least square procedure on the logarithmic values of the acoustic power. Two parameters are obtained, the initial power of the sound source ($P_{@1m}$) and an attenuation coefficient (α). This procedure is repeated on each third-octave band to obtain the variation of these

10 parameters with frequency.

Results of the fits are shown in the Figure 6 for the Leysse river experiment. Logically, attenuation coefficients that are estimated with cylindrical spreading loss exhibit higher values than coefficients estimated with spherical spreading loss. However, they behave similarly with frequency variations. At low frequency, approximatively below 10^3 Hz, attenuation coefficient is higher. This result was expected because of the existence of a cutoff frequency (Geay et al., 2017b). Considering

15 a mean water depth of 0.95 m and a compressional speed of the acoustic waves of 1600 m/s in the sediment layer, we can estimate a cutoff frequency around $1.1\ 10^3$ Hz, which is consistent with our results. Above 10^3 Hz, attenuation coefficient increases with frequency: acoustic waves are more attenuated at higher frequencies. Considering the estimation of the sound source power, it is observed that the cylindrical model best reproduces the power monitored in the experiment made in the Bourget lake (the median value is represented in the Figure 6b). Using a spherical model, we overestimate the power of the

20 sound source by approximatively one order of magnitude. However, as we will see for other experiments, the best estimation of the sound source power is sometimes obtained with spherical spreading loss model.

In the Figure 6c, the residuals of the regression represent the dispersion of the data around the fit. It has been computed as the mean square difference between data and fits. In the Leysse river, we observed that the power of the reception fluctuates between 2 and 3 dB around the fits.

25 Finally, considering the correlation coefficients of the fitted laws (Figure 6d), we cannot make a distinction between spherical or cylindrical spreading loss models.

3.2 Propagation laws in several rivers

Propagation properties of several rivers were investigated. For some of the rivers, experiments were done at different hydrodynamic conditions (Table 1). As we did not notice any representative differences in the results for the discharges

30 investigated, we decided to gather data to propose a unique result for each river.

A first result concerns the estimated power of the sound source ($P_{@1m}$) emitted during the experiments (Figure 7). Compared with the measurements made in the Bourget lake, it can be observed that the estimation of the sound source power is

overestimated when using a spherical model and underestimated when using a cylindrical model of the geometric spreading loss. Considering the correlation coefficients of the data to the fits, we did not observe a significant difference between the models. Based on these observations, we are not able to argue that geometric spreading is cylindrical or spherical in these rivers. In the following, all the results are presented by assuming a cylindrical, spreading-loss model.

5 The attenuation coefficients obtained for each river are presented as a function of frequency (Figure 8). From the Isère to the Arve river, we can observe that the attenuation coefficient varies in more than one order of magnitude (Figure 8b). Looking at the linear representation (Figure 8a), we see that the variation of the attenuation coefficient with frequency is different from case to case. It increases faster for rivers having the largest attenuation coefficients. Note that minimal and maximum frequencies of the observations are variable from one river to another. At low frequency, observations are limited by the cutoff

10 frequency which is inversely proportional to the water depth (Geay et al., 2017b). At high frequencies, measurements are limited by too strong attenuation of the emitted acoustic waves.

The Table 2 contains, for each river, a summary of the results obtained by fitting a cylindrical propagation model to the data. All the parameters indicated in this table are an average of the values obtained over the monitored frequencies. It can be observed that the correlation coefficients vary from 0.4 to 0.8. We observed that the lowest correlation coefficients were

15 obtained for the largest rivers (Isère and Romanche rivers with section width of 60 and 33 m, respectively) and may be representative of cross-sectional variations that have not been considered in this study. The residuals vary from 2 to 6 dB. Rivers having largest attenuation coefficients seem to have larger residuals: the dispersion of the monitored acoustic power is larger when the attenuation is larger. Finally, the maximum distance of the monitored chirps represents the maximum distance from the hydrophone to the underwater speaker where we were able to record the chirps with a sufficient signal to noise ratio.

20 The smaller the attenuation coefficient, the larger the maximum distance of the observation. Note that the maximum distance is also dependent on operational issues.

4 Discussion

4.1 Attenuation processes in rivers

During our field campaign, it has been found that attenuation coefficients were variable from one river to another. In this

25 section, we wonder how propagation properties are related to typical characteristics of the rivers (e.g. slope, water depth). As shown in Figure 8 the dependency of the attenuation coefficient to frequency do not follow a simple law.

At low frequency, acoustic wave propagation should be affected by wave guide properties. The river could be considered as an acoustic wave guide where sounds are partly trapped between the water surface and the river bed (Geay et al., 2017b): this problem is known as the Pekeris waveguide. Theoretically, in a perfect medium without attenuation, it can be shown that

30 acoustic waves having frequencies lower than the cutoff frequency are exponentially decaying with horizontal distance (Jensen et al., 2011). The cutoff frequency f_{cutoff} (Hz) is dependent on the wave guide characteristics, water depth and sediment layer acoustic properties, as shown in the following equation:

$$f_{cutoff} = \frac{c_s c_w}{4h\sqrt{c_s^2 - c_w^2}} \qquad (7)$$

Where h is the water depth (m), c_s and c_w are sound celerity (m/s) in the sediment layer and in water, respectively. Cutoff frequencies have been estimated in each river, by assuming a fixed sound speed of 1600 m/s in the sediment layer and using the mean water depth monitored (Figure 8b). Estimated cutoff frequencies are approximatively located around the minimum of the observed attenuation coefficient. Our ability to precisely determine a cutoff frequency is limited. First, the acoustical

5 properties of river beds are unknown, depending on lithology, sizes, porosity and heterogeneity of the materials constituting the river bed. Secondly, the water depth is not constant over the investigated sections but vary from the banks to the middle of the river. For those reasons, cutoff frequencies are roughly estimated and do not perfectly correspond to the observed local minimum of attenuation coefficient.

The variation of attenuation coefficients at higher frequencies is here discussed. As attenuation properties are frequency

10 dependent, it is common to characterize the attenuation in mediums by giving a value of the attenuation coefficient per wavelength (eq. 5). Attenuation coefficients per wavelength (nepers) are presented in the Figure 9 for frequencies higher than the local minimum of α (nepers/m). Except for the Isère river, we can observe that α_λ is almost constant with frequency, which in turns means that α (nepers/m) varies almost linearly with frequency. Finally, each river is characterized by the average value of α_λ and is compared to river characteristics (Table 1; Figure 10). Looking at the relationship between α_λ and the slope

15 measured at the local reach (i.e. 100 meters downstream and upstream from the bridge where experiments were undertaken), we can observe that there is good correlation: higher attenuation coefficients were obtained for steeper rivers. As for slope, surficial granulometry of the emerged bars (D_{84}) are also well corelated to α_λ: larger roughness (i.e. larger D_{84}) induces larger attenuation of the acoustic waves. Surface velocity or water depth seems to be less robust explanatory variables of α_λ. The value of typical nondimensional numbers has also been tested. The ratio of the water depth over the D_{84} and the Froude number

20 were used by Tonolla et al. (Tonolla et al., 2009, 2010). They found that they were the main hydrogeomorphological variables explaining the differences in passive acoustic signals in field experiments. Small ratio of the relative submergence (i.e. small h/D_{84}) of bed roughness induce breaking waves or water plunging directly in the water column, entraining bubbles in the water column. These hydraulic mechanisms are sources of noise generated by oscillating air bubble in the water column as it is observed for breaking waves in marine environment (Deane, 1997; Norton and Novarini, 2001). In our study, entrained air

25 bubbles could explain the increase of attenuation coefficient in rivers having rough beds. It is indeed known that the presence of air bubbles increases the attenuation of acoustic waves (Deane, 1997; Norton and Novarini, 2001) because of the heterogeneity of the medium constituted of water and air which have very different acoustic impedances. Also, as observed in flume experiment (Wren et al., 2015), the bed roughness itself is a source of attenuation, larger roughness involving higher attenuation. Finally, both processes, rough boundaries and entrained air bubbles could explain our observations by causing

30 concomitantly higher attenuation of the acoustic wave. The river bed roughness should be the best characteristic enabling the prediction of acoustic wave propagation properties in river. However, this parameter is not easy to measure. It is sometimes

difficult to access to the riverbed and surface grain size distributions are known to be variable in space. The local slope of the reaches is easier to measure and, even if less meaningful, should be a more robust parameter to infer propagation properties of a river.

4.2 Recommendation for monitoring bedload with hydrophones

5 This study was done to improve our ability to better use the measurements of bedload self-generated noise in rivers. This section aims at giving an example on the use of attenuation coefficients in a simple case. Let us consider an infinite river bed with a homogeneous repartition of sound sources over the river bed. Bedload impacts generate a constant surficial spectral power noted PSD_s (μPa^2/Hz/m²). If sound sources are random and independent noise sources (Thorne, 2014), the acoustic power measured by a hydrophone can be written as a sum of the power of all sound sources:

$$PSD_h(f) = \int_d^\infty \frac{2PSD_s(f)}{rh} e^{-2\alpha(f)r} 2\pi r dr \qquad (8)$$

Where PSD_h is the spectral power monitored by a hydrophone in a fixed position (μPa^2/Hz), h is the water depth (m), d the distance of the hydrophone above the river bed (m) and r the horizontal distance from the hydrophone (m). From equation (8), it follows:

$$PSD_h(f) = \frac{2\pi PSD_s(f)}{h\alpha(f)} e^{-2\alpha(f)d} \qquad (9)$$

Considering that $0< \alpha \ll 1$, it follows that PSD_h is inversely proportional to the attenuation coefficient. This has several impacts on the use of bedload monitoring using passive acoustics. First, as the attenuation coefficient could be variable from one reach to another, the acoustic power of bedload SGN could be variable from one reach to another even if bedload fluxes are similar.

20 Secondly, as observed in Figure 8, attenuation coefficients are variable with frequency. It means that the frequency content of bedload SGN spectra is modified by propagation effects, which in turns means that the shape of monitored spectra are not only related to grain size distributions (Petrut et al., 2018; Thorne, 2014) but also to propagation properties. Therefore, in order to estimate grain size distribution, measured spectra should be corrected by propagation effects before any inversion procedure. For example, a better estimate of the sound generated by bedload transport could be done by multiplying the monitored sound

25 pressure levels by the attenuation coefficient ($\alpha > 0$):

$$PSD_s(f) \sim \alpha(f)PSD_h(f) \qquad (10)$$

This simple operation enables us to get an unbiased measurement of the sound generated by bedload impacts, and therefore a more robust proxy for bedload transport monitoring in rivers.

5 Conclusion

5   A simple model for acoustic wave propagation in rivers has been investigated in this study. It considers that the power of acoustic waves decreases with distance by spreading effects (cylindrical or spherical models) and with an additional exponential term including other propagation effects (e.g. volume attenuation, scatter by rough boundaries). The model was used to interpret the attenuation properties of a controlled sound source in several rivers having different hydrogeomorphic characteristics. Our tests were not able to distinguish whether spherical or cylindrical models should be used, both models

10   being valid. The exponential attenuation coefficient (α in nepers/m) has been found to vary with frequency and with the type of river considered. Two types of attenuation regimes have been observed. Below the cutoff frequency, which is inversely proportional to the average water depth, α decreases with increasing frequency until a local minimum is reached. Reaches with large water depth should therefore be selected for doing passive acoustic measurements. Above the local minimum (i.e. the cutoff frequency), attenuation coefficients increase almost linearly with frequency. The higher frequency regime has been

15   characterized by a constant attenuation coefficient per wavelength (α_λ in nepers). It has been found that α_λ was well correlated to the slope of the river-bed reaches, where α_λ is higher for higher bed slopes of the river. At high frequencies, attenuation properties seem dominated by processes related to the river-bed roughness, including the entrainment of air bubbles in the water column and scattering effects on rough boundaries. As shown in the discussion, the acoustic power monitored by a hydrophone, in a fixed position, is almost inversely proportional to the attenuation coefficient at a given frequency. As

20   consequences, the spectra of bedload SGN that are measured in rivers are modified by the variations of attenuation coefficients with frequency. As attenuation is higher at high frequencies, acoustic signals that are monitored by a hydrophone are shifted to lower frequencies compared to the sound really generated by bedload impacts. As shown for an idealized case with an infinite riverbed and homogeneous bedload sound sources, the real sounds generated by bedload can be estimated by correcting the hydrophone signal by the propagation laws of acoustic waves in rivers.

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Tables

Table 1 : Field site caracteristics

River	Local slope (%)	Width of the cross-section (m)	GSD of emerged bars $[D_{50}\text{-}D_{84}]$ (mm)	Date of field experiments	Water discharge (m^3/s)	mean water depth (m)	mean surface velocity (m/s)	suspended sediment concentration (g/L)
Arve	0.75	14	[70-120]	2017/06/27	38	1.25	2.3	0.35
				2017/06/29	29	1.1	1.95	-
Grand-Buëch	0.7	13	[30-66]	2017/04/12	5.5	0.35	1.5	<0.05
				2017/05/15	12.5	0.55	1.85	<0.05
Isère	0.05	60	[23.5-36.5]	2017/03/08	171	2.4	-	0.1
				2017/03/28	150	2.3	-	0.06
				2017/06/06	237	2.8	1.85	0.6
Leysse	0.1	18	[39-68]	2017/03/09	17	0.95	1.2	<0.05
Romanche	0.13	33	[20-39]	2017/06/14	55	1.2	1.85	0.14
Sarenne	0.13	8	[4-8]	2017/04/05	1.3	0.3	0.7	<0.05
Séveraisse	1.0	12.5	[32-75]	2017/04/25	5	0.4	1.8	<0.05

Table 2 : Average results over frequency of the parameters of the fit using cylindrical geometrical spreading

River	α (nepers/m)	Corr. coeff. of the fit (r^2)	Residuals (dB)	Maximum distance of the monitored chirps (m)
Arve	0.27	0.6	6	12
Grand-Buëch	0.15	0.7	4	25
Isère	0.009	0.4	3	77
Leysse	0.036	0.8	2	39
Romanche	0.022	0.5	4	55
Sarenne	0.082	0.8	5	57
Séveraisse	0.28	0.7	5	19

Figures
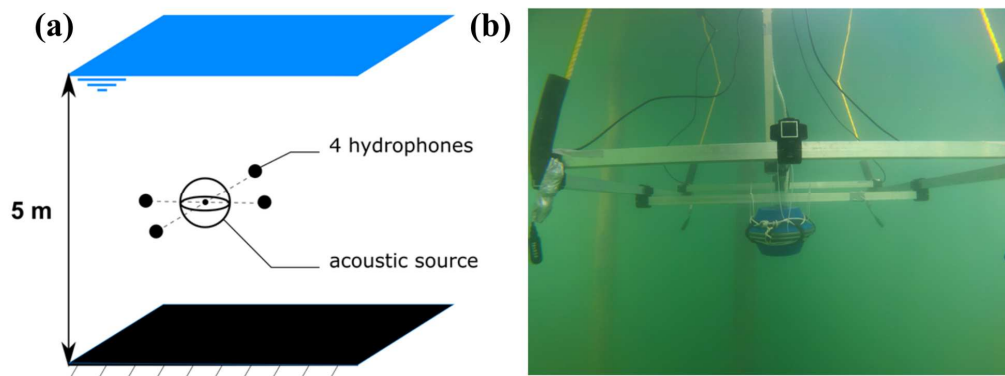
Figure 1: (a) schematic design of the test characterizing the system of emission; (b) photography of the immerged system in the lake
5 **of the Bourget (France).**
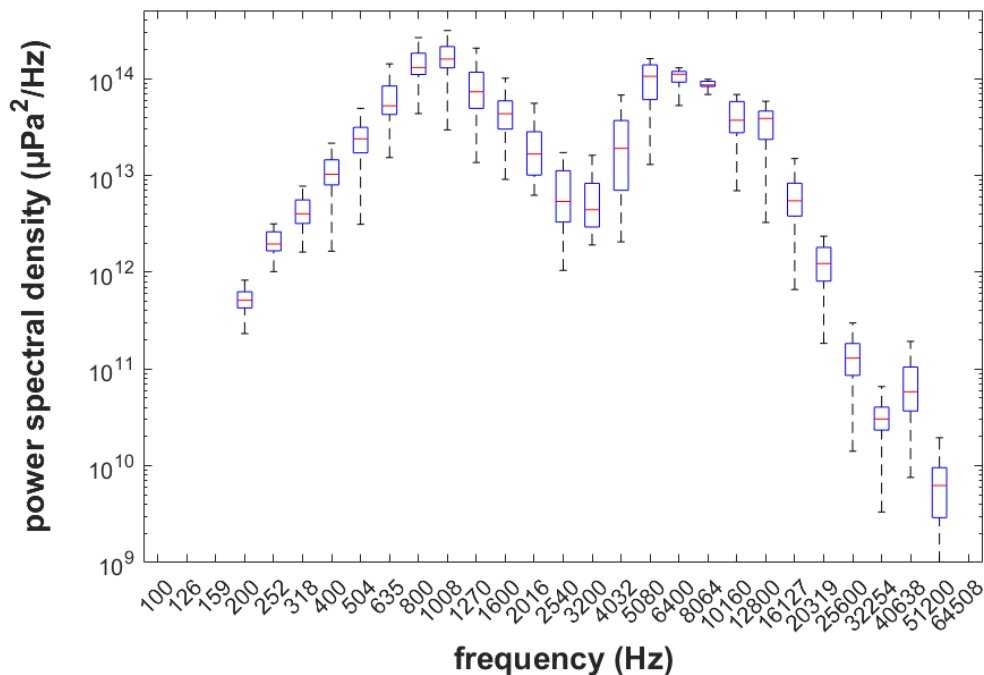
Figure 2: Power Spectral Densities (µPa^2/Hz) of the logarithmic chirps emitted by the loudspeaker.
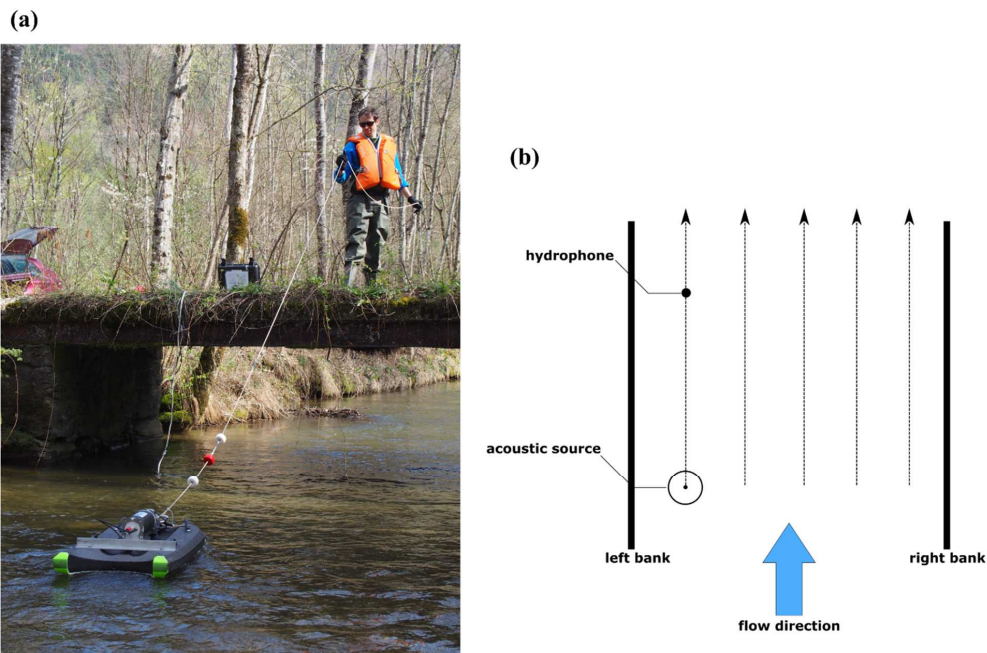
Figure 3: (a) Drifting board sharing the hydrophone and the acoustic recorder; (b) Drift trajectories of the recorder during the measurements.
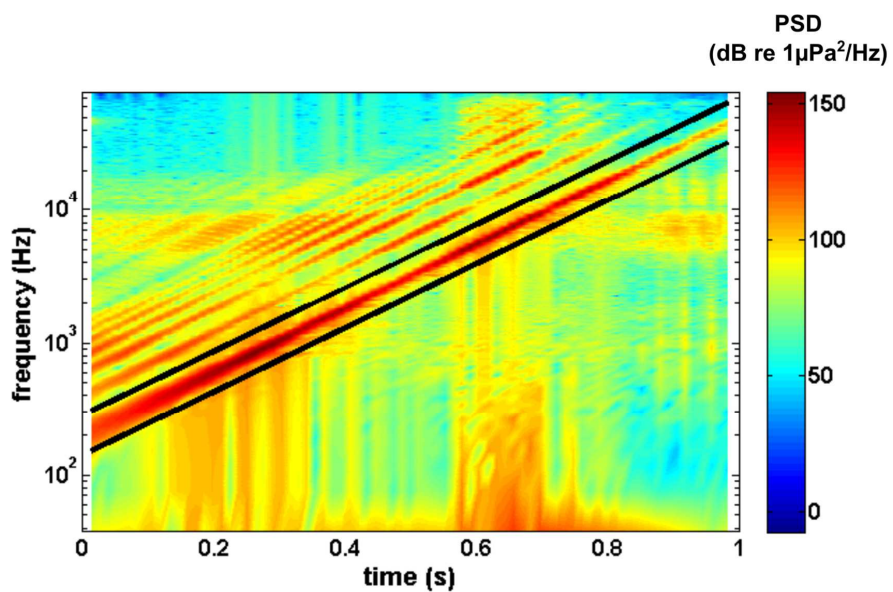
Figure 4: Short-term spectrogram of a chirp monitored by a hydrophone in the Leysse River. The black lines indicate the octave band centered around the instantaneous frequency of the theoretical logarithmic chirp.
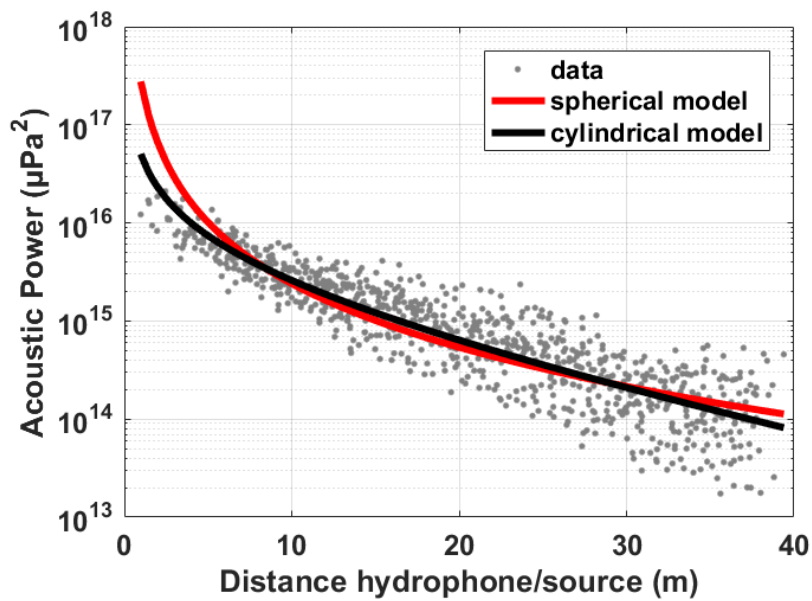
Figure 5: Measured acoustic power (µPa²) in function of the distance between the hydrophone and the active source. Results obtained in the third-Octave band centered on 1 kHz. Spherical and cylindrical fits are in thick lines.
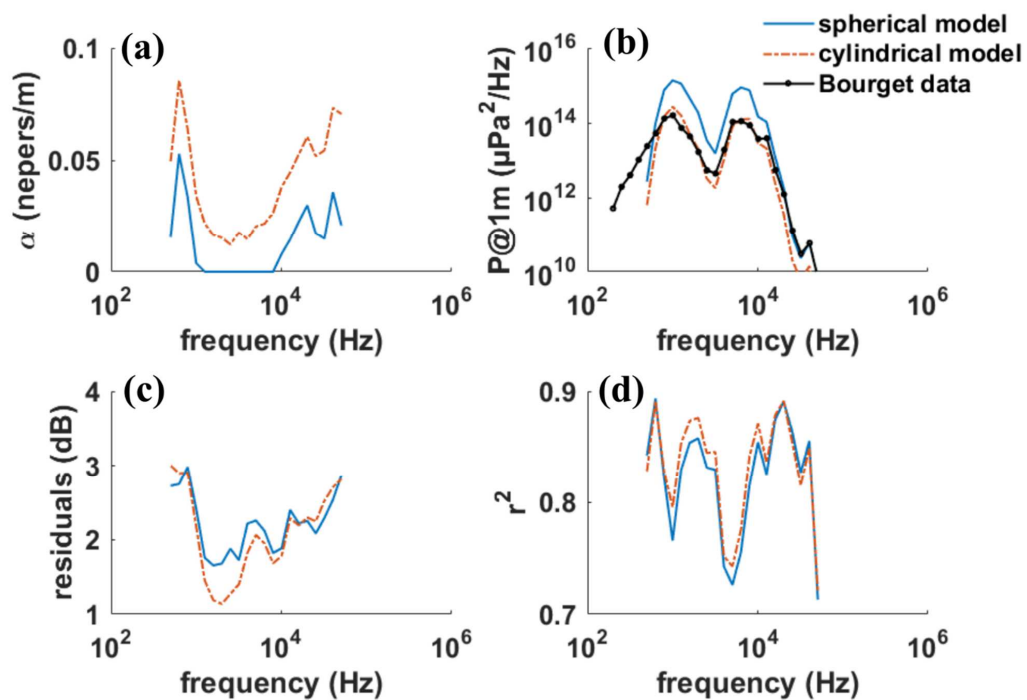
Figure 6: (a) Attenuation coefficient (nepers/m) ; (b) Sound source power spectral density (P@1m in μPa²/Hz) estimated with spherical/cylindrical models. Data from the Bourget lake are the median values of the measurement presented in Error! Reference source not found.**; (c) Residuals of the regression (dB); (c) Correlation coefficient of the fits.**
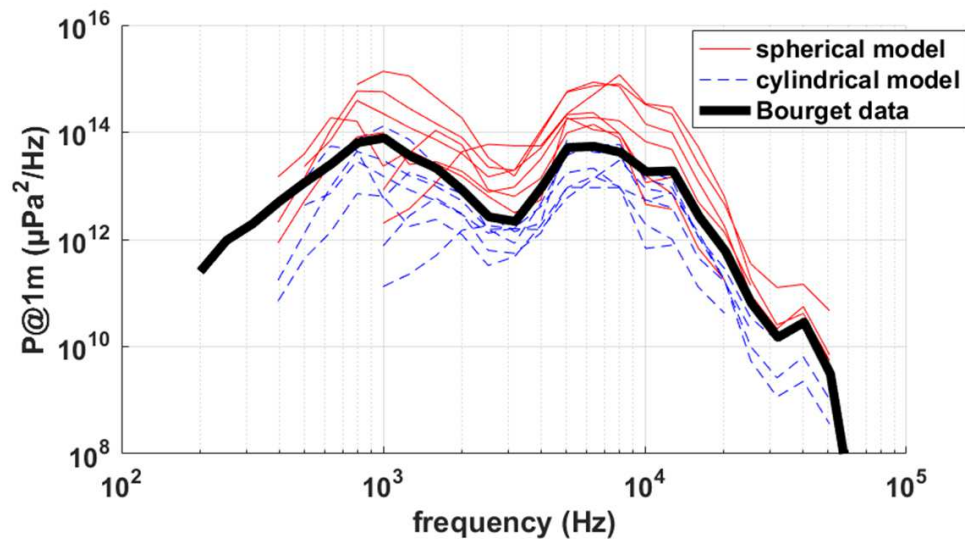
Figure 7: Power spectral density of the source power (P$_{@1m}$ in µPa^2/Hz) estimated with spherical and cylindrical models for all experiments made in rivers and measured in the Bourget lake.
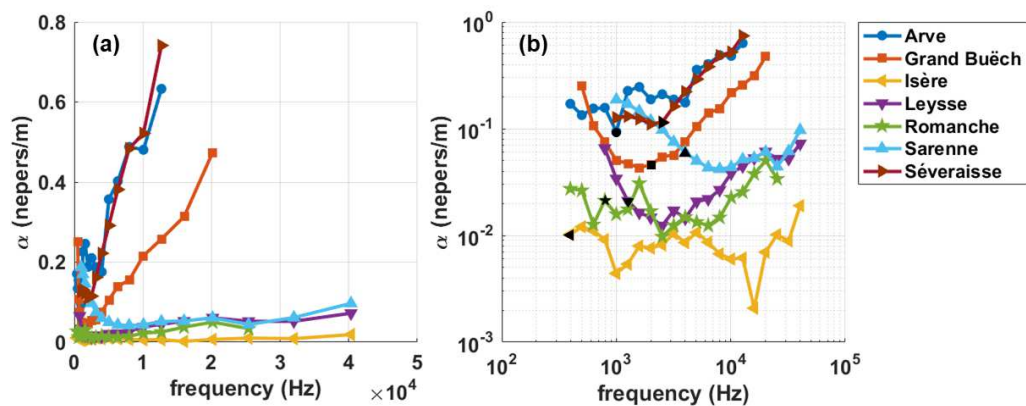
Figure 8: attenuation coefficient (α in nepers/m) obtained when using a cylindrical model of the geometrical spreading loss: (a) linear and (b) logarithmic scales. Black symbols indicate the cutoff frequency computed with eq. (7), sound speeds of 1500 m/s and 1600 m/s in the water and sediment layer, respectively.
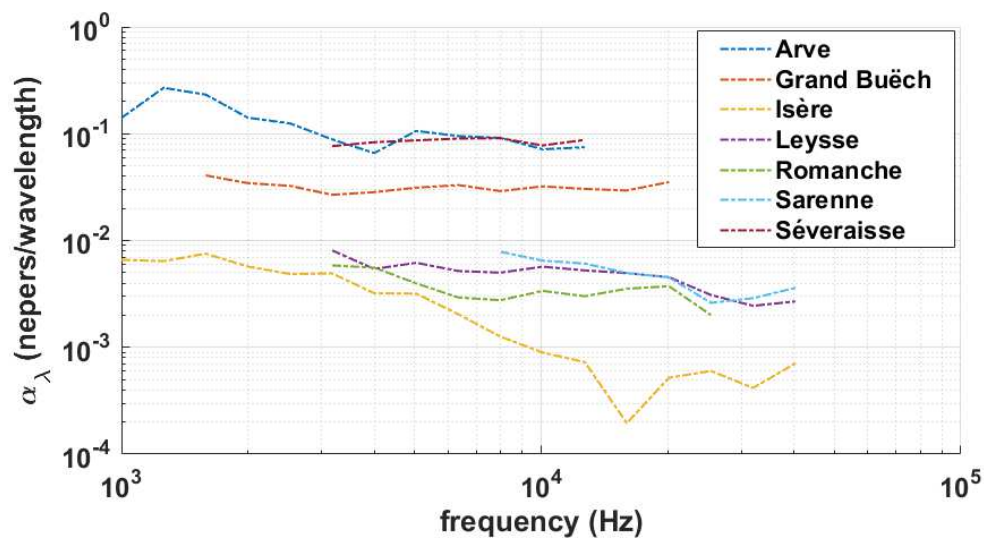
Figure 9: attenuation coefficient per wavelength (nepers) in function of frequency (Hz) above the cutoff frequency.
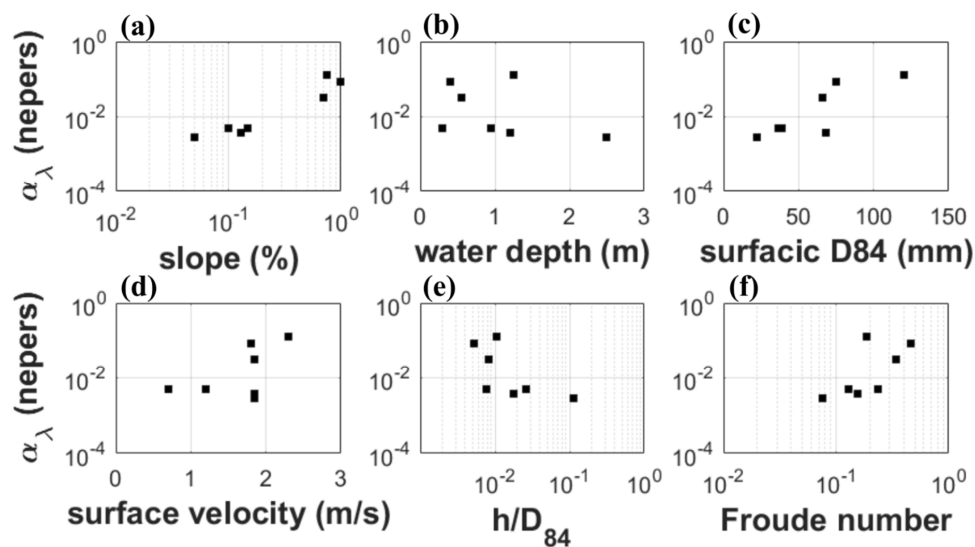
Figure 10: representation of the attenuation coefficient per wavelength (α_λ in nepers) in function of river characteristics: (a) local slope (%); (b) average water depth (m); (c) surfacic D_{84} (mm) of the closest emerged bars; (d) average surface velocity (m/s); (e) ratio of water depth (m) over surfacic D_{84} (m); (f) Froude number.