



Human-altered soundscapes in large European rivers: Widespread potential for masking by boats

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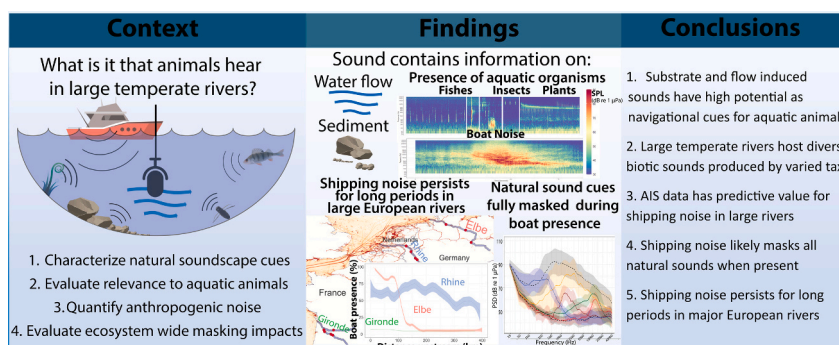
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HIGHLIGHTS

- Substrate and flow induced sounds have high potential as cues for aquatic animals.
- Large temperate rivers host diverse acoustic signals produced by varied taxa.
- AIS data are a good predictor for underwater shipping noise in large rivers.
- High levels of boat noise persist for long periods in major European rivers.
- Shipping noise likely severely limits aquatic animal sound perception in rivers.

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic noise is increasingly recognized as a stressor to marine animals, but is rarely considered as a pollutant in freshwater ecosystems. We therefore characterized underwater soundscapes in three major European rivers (Rhine, Elbe, Gironde). We evaluated how natural soundscapes are shaped by biotic sounds (biophony) and river hydro-geomorphology (geophony). Furthermore, we assessed level and duration of boat noise to provide insight into disturbance and masking potential. We (1) characterized biophony in 24-h recordings; (2) assessed relationships between hydro-geomorphological features and the soundscape using drifting hydrophone recordings (geophony); (3) quantified boat noise in 24-h recordings; (4) evaluated masking potential through sound spectrum comparisons between natural sounds and boat noise; and (5) assessed the value of Automatic Identification System (AIS)-based shipping density data to predict noise impact from commercial vessels in large rivers. River soundscapes contained biophony from diverse taxa. Water velocity and sediment hardness explained a significant proportion of the variation in background sound levels at frequencies above 350 Hz, and sound levels sharply increased above 1.4 m/s. In the presence of boat noise, most natural sounds have high potential to be masked. Boat noise occupied 42–86% of recording time in the Rhine, 2–38% in the Elbe, and 0–20% in the Gironde. We found a significant relationship between AIS boat density and recorded and extrapolated boat noise along each river. We conclude that: (a) river soundscapes reflect information on nearby physical river features

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and biota, providing environmental cues to aquatic animals, and (b) that boat noise is widespread and persisting for long periods, potentially disturbing aquatic fauna and masking natural auditory cues in large rivers.

1. Introduction

Underwater soundscapes have high potential to provide auditory cues to aquatic fauna about the ecological and geophysical environment. Underwater sounds may be generated by fish, aquatic invertebrates, amphibians, semi-aquatic mammals, reptiles, bubbles from plants, and decomposing bacteria (Aiken, 1985; Colley et al., 2013; Desjonqueres et al., 2024; Greenhalgh et al., 2025; Holt and Johnston, 2011; Kratochvil and Pollirer, 2017a; Marian et al., 2021; Rountree et al., 2020; te Velde et al., 2024; van der Lee et al., 2025). Sounds may also originate from physical disturbances of the water or substrate (Geay et al., 2017; Pijanowski et al., 2011; Tonolla et al., 2011). Furthermore, water depth-specific propagation of the habitat-specific variety in sources can provide critical information for soundscape orientation (Fay, 2009; Slabbekoorn and Bouton, 2008). Habitat associated soundscapes have already been shown to affect spatial behavior in aquatic animals from a diverse range of taxa and life stages, especially in marine systems (Gordon et al., 2019; Huijbers et al., 2012; Montgomery et al., 2006; Radford et al., 2011; Simpson et al., 2011; Vermeij et al., 2010). However, soundscape studies are still rare for freshwater systems, while the potentially disturbing and masking presence of anthropogenic noise is ever increasing.

However, habitat-associated soundscapes, attributed to hydro-geomorphological features (physical river characteristics, water flow, and the interaction between them) (Wysocki et al., 2007; Amoser and Ladich, 2010) or biotic sources (te Velde et al., 2024), may also affect freshwater fauna. Spatial heterogeneity of soundscapes can correlate strongly with flow speed, turbulence, depth and streambed sediment transport (Tonolla et al., 2010, 2011). Spectral soundscape variation in segments of a relatively slow-flowing river system was also shown to be determined by river size and flow velocities (te Velde et al., 2024). Furthermore, a study on fish distribution across specific micro-habitat types within a river revealed an association with variation in broadband sound pressure levels (Kacem et al., 2020). Acoustic responsiveness could be responsible for this pattern, as fish can be attracted to playback of substrate disturbance (Holt and Johnston, 2011), and flow and sediment transport sounds (Kowal et al., 2023). Consequently, gradually changing soundscapes in large river systems may be particularly relevant for migratory fish, when flow and olfactory cues do not provide adequate detail (Erman and Erman, 1984; Gore, 1978; Kemp et al., 2011; Molokwu et al., 2014; Rosenfeld, 2003).

Once high potential acoustic cues have been identified in rivers, it becomes important to understand to what extent they are still audible in the current state of human exploitation. This is particularly relevant due to extremely high biodiversity declines attributed to a wide range of anthropogenic stressors (Forseth et al., 2017; Tamarío et al., 2019; Deinet et al., 2024; Sánchez-Bayo and Wyckhuys, 2021). Freshwater fish are considered the most vulnerable group of all vertebrates, and migratory species are particularly threatened (Costa et al., 2021; Sayer et al., 2025; WWF, 2024). Boat noise (Marley et al., 2016; Smott et al., 2018; Vieira et al., 2021) and road traffic from urban areas (te Velde et al., 2024; te Velde and Slabbekoorn, 2024) may add a significant stressor (Popper et al., 2020; van Opzeeland and Slabbekoorn, 2012). While Automatic Identification System (AIS) data are applied to assess distribution and intensity of shipping noise at sea (Erbe et al., 2012; Sertlek et al., 2019; McKenna et al., 2024), this has not been exploited for rivers. Nevertheless, inland shipping traffic accounts for a significant proportion of total cargo transport in the industrialized parts of the world (Beyer, 2018), making it a potentially severe stressor in ecologically important freshwater systems (Dudgeon et al., 2006; Pracheil et al., 2013; van Puijenbroek et al., 2019).

Anthropogenic noise has been shown to affect behavior and physiology of aquatic animals in a multitude of ways. It can deter, attract, distract, affect activity patterns and reproductive success, and increase anxiety-related, or stress-induced physiological parameters in a wide range of taxa (Azarm-Karnagh et al., 2023; Nedelec et al., 2022; Neo et al., 2014; Rojas et al., 2021; Wysocki et al., 2006). Furthermore, anthropogenic noise can mask biologically relevant sounds, limiting availability of information critical for behavioral decisions of aquatic animals (Vasconcelos et al., 2007; Codarin et al., 2009; Erbe et al., 2016). Most, if not all aquatic animals can detect sound and use it for activities critical to their survival, such as habitat selection, navigation, predator avoidance, prey detection, and communication (Gordon et al., 2019; Jansson, 1973; Popper and Hawkins, 2019; Simpson et al., 2011; Wilson et al., 2014). To be able to understand how masking by anthropogenic noise can affect aquatic communities, we require more knowledge about the diversity and distribution of natural underwater soundscapes that are audible to aquatic animals.

When assessing acoustic masking, it is important to distinguish between sound pressure and particle motion. While all fishes and likely the majority of invertebrates and amphibians are sensitive to particle motion, the ability to detect sound pressure is restricted to species possessing specialized air-filled structures (Čokl and Theiss, 1987; Popper and Fay, 2011; Simmons, 2025). Specifically, sound pressure should be audible to most fishes with connections bringing the swim bladder closer to the ear or having a gas bubble near the ear (Popper and Fay, 2011; Alves et al., 2025), as well as aquatic insects and various anurans that utilize pressure-sensitive membranes, air bubbles, or internal cavities for signal detection (Čokl and Theiss, 1987; Simmons, 2025). While sound pressure and particle motion are related, their ratio can greatly vary in shallow water environments, especially near water-air or water-substrate boundaries and in the near or far field of the sound source (Larsen and Radford, 2018). Chapman and Johnstone (1974) demonstrated that in Atlantic cod (*Gadus morhua*), a species primarily sensitive to particle motion (Chapman and Hawkins, 1973), the masking effect of noise on a pure tone was reduced by approximately 7 dB when the angular separation between the masker and the signal exceeded 10° (Chapman and Hawkins, 1973; Chapman and Johnstone, 1974). However, the mechanisms underlying such directional hearing are complex; recent evidence suggests that fish may achieve sound source localization by integrating both particle motion and sound pressure cues (Sisneros and Rogers, 2016; Veith et al., 2024). Hence it is challenging to obtain exact estimates of the masking effects of natural sounds by boats. However, no studies addressed masking potential based on local sound pressure ratios between natural soundscapes and anthropogenic noise levels in large rivers used by both, migratory fish and commercial cargo vessels, which can provide rough estimates of masking impacts. There is a clear distinction between the terms sound and noise, where we define noise as a sound that is disruptive from an organism perspective. Because we aim to explore the potential masking effects of anthropogenic sounds in rivers from an organism perspective, we hereafter refer to anthropogenic sound and boat sound as anthropogenic noise and boat noise.

In the current study, we investigated three major European rivers; the Rhine (Netherlands, Germany), Elbe (Germany) and Gironde (France), to study natural soundscapes and the potential masking impact from boat traffic. We explored the presence of sounds made by aquatic animals (biophony) through 24-h stationary recordings at sites across the three rivers. We investigated natural background soundscapes (geophony) by analyzing the relationship between spatially replicated acoustic recordings from a drifting hydrophone, and hydro-geomorphological river features. Furthermore, we quantified the

percentage of time with boat noise present in our 24-h recordings using a threshold detection approach, and we investigated whether AIS boat density data have predictive value. Finally, we combined the results of these two analyses to evaluate the potential problem of masking of natural sounds by boat noise. We aimed to answer the following research questions: 1a) Do the three major European rivers vary among each other in amplitude and spectra of natural soundscapes? 1b) Do upstream and downstream river soundscapes vary consistently, taking water velocity, river size and bottom features into account? 2a) What proportion of the time are boats present in the Rhine, Elbe, and Gironde? 2b) To what extent could boat noise mask biophonic and geophonic sounds?

2. Methods

2.1. Research area

We collected underwater sound recordings in three large European river systems, the Elbe (Germany), Rhine (Netherlands & Germany), and Gironde (France) (Fig. 1A), to explore the potential for natural sound cues for aquatic animals and to assess whether and for how long these cues may be overpowered by boat noise. These rivers harbor important habitats to diverse European freshwater taxa, including aquatic invertebrates, birds, plants and fish and provide valuable ecosystem services to humans, including fisheries, transport, water supply, flood protection and recreation (Fenten and Dieperink, 2024; Fischer et al., 2019). Notably, the Elbe, Rhine and Gironde are especially important for several heavily threatened migratory fish species, some of which are also used as indicator species for good ecological status (Lasne et al., 2007; Schiemer, 2000). Between 7 and 9 anadromous species inhabit these rivers, which is relatively high compared to most other European rivers (van Puijenbroek et al., 2019), including Atlantic sturgeon (*A. sturio*), Allis shad (*A. alosa*), Twaite shad (*A. fallax*), Whitefish (*C. maraena*), Houting (*C. oxyrinchus*), River lamprey (*L. fluviatilis*), Sea lamprey (*P. marinus*), Atlantic salmon (*S. salar*) and Sea trout (*S. trutta*). From these 9 species, 8 are included in the IUCN red list. The Gironde contains the last surviving population of the critically endangered Atlantic sturgeon, while the feasibility of a restocking programme for this species is being evaluated for the Rhine and restocking is currently ongoing in the Elbe.

The fish and other taxa in these rivers and the ecosystem services they provide are threatened by multiple stressors including chemical and light pollution, reduced connectivity, channelization and invasive species (Fenten and Dieperink, 2024; Fischer et al., 2019; Leuven et al., 2009). In terms of boat traffic, the Rhine and Elbe are two of the most notable corridors for inland boat cargo transport in Europe, with the Rhine accounting for 58 billion t/km/yr, and the Elbe for 4.2 billion t/km/yr, while there is close to no inland cargo transport in the Gironde (Central Commission for the Navigation of the Rhine, 2024). Therefore, the Elbe, Rhine and Gironde provide us with three ecologically and societally important river systems affected by variable levels of boat traffic, suitable to compare in terms of shipping noise.

2.2. Data collection

2.2.1. Acoustic recordings

We made acoustic recordings in two different ways: (1) Stationary with deployed hydrophones fixed to the substrate or (2) canoe drift recordings passively drifting with the river current with a floating hydrophone attached behind the canoe. All acoustic recordings were made using calibrated SoundTrap 300STD hydrophones. Soundtraps were set to record with a sample rate of 96 kHz, high preAmp gain and high pass filter turned off. Below, we address the necessary details of the respective recording procedures and data processing.

2.2.2. Stationary acoustic recordings

To quantify boat noise, compare natural sound spectra of the three

rivers during boat absence and to characterize biophonic sounds in large temperate rivers, 24-h continuous stationary acoustic recordings were made by deploying hydrophones suspended between an anchor and sub-surface buoy at approximately 60 cm from the riverbed (c.f. te Velde et al., 2024). Hydrophones were placed several meters from the shore, at least at 2 m depth. In locations with tidal differences, hydrophones were deployed at low tide. Soundtraps were deployed in 3 locations in the Elbe, 4 in the Rhine, and 5 in the Gironde river system for a total of 12 recording locations (Table 1 & Fig. 1A).

2.2.3. Canoe drift recordings

To explore what local hydro-geomorphological river features are reflected in the soundscape, canoe drift recordings were made by deploying a weighted down soundtrap 50 cm below a floating surface buoy, at the end of a 5 m rope behind an inflatable canoe. To reduce the effects of flow noise artifacts, all recordings were made by drifting with the water current. The position of the canoe was recorded through gps tracking. Four drift recordings were made in the Gironde in France between 17 and 04-2023 and 21-04-2023 and 3 in the Rhine in Germany between 29 and 05-2023 and 31-05-2023. All useable drift recordings were made between 11:00 and 18:00. Total distance moved during each drift ranged from 8 to 27 km.

2.2.4. Hydro-geomorphological river features

To investigate the relationship between hydro-geomorphological river features and the natural soundscape, we used data from a 2019 echosounder and sediment survey in the Gironde river system conducted by the French National Research Institute for Agriculture, Food and the Environment (INRAE, unpublished data). In which sediment hardness and bathymetry maps were created using a Hummingbird Helix 9 echosounder, and collected substrate samples were passed through various square-mesh sieves after being dried in an oven to determine their composition based on 6 granulometric classes. Sediment hardness is a measure estimated from signal strength return of the echosounder, which has been shown to reflect sediment type, with lower grain size sediments such as silt having low signal strength, and higher grain size sediments such as gravel and bedrock having high signal return strength (Austin, 2012; Schooley and Neely, 2018; Winfield et al., 2015). The substrate size distribution at each site was used to explore the relationship between sediment hardness and substrate size and how the substrate changes with distance, from the river estuary to upstream locations.

At each 1-min mean gps location from the canoe recordings, sediment hardness and bathymetry maps were used to extract the sediment hardness, depth at recording location and maximum river depth (Fig. 1C). Furthermore, the water velocity was extracted from the mean distance moved in the canoe gps tracking data as the canoe was drifting with the water current this was indicative of the mean surface water velocity. River width at each location was determined from satellite images, and area of cross-section was calculated from the river width and max river depth.

2.2.5. AIS data

We used the internationally used tracking system of commercial vessels: Automatic Identification System (AIS) to compare potential noise pollution problems among the three rivers and to assess whether the AIS data have predictive value for boat noise in rivers. We obtained AIS boat density raster maps in hours/month/km² via the Global Maritime Traffic Density Service (GMTDS), retrieved from Global-MaritimeTraffic.org (a service of MapLarge 2021), using the 'Export' feature (GMTDS, 2024). Only data on non-loitering boats (spending less than 6 h in 1 km² area) were used in the analysis. It should be noted that AIS is only carried by commercial vessels. Therefore, AIS shipping density maps may underestimate boat noise in areas of high recreational activity (Hermannsen et al., 2019).

We extracted the specific boat densities in the month and year of

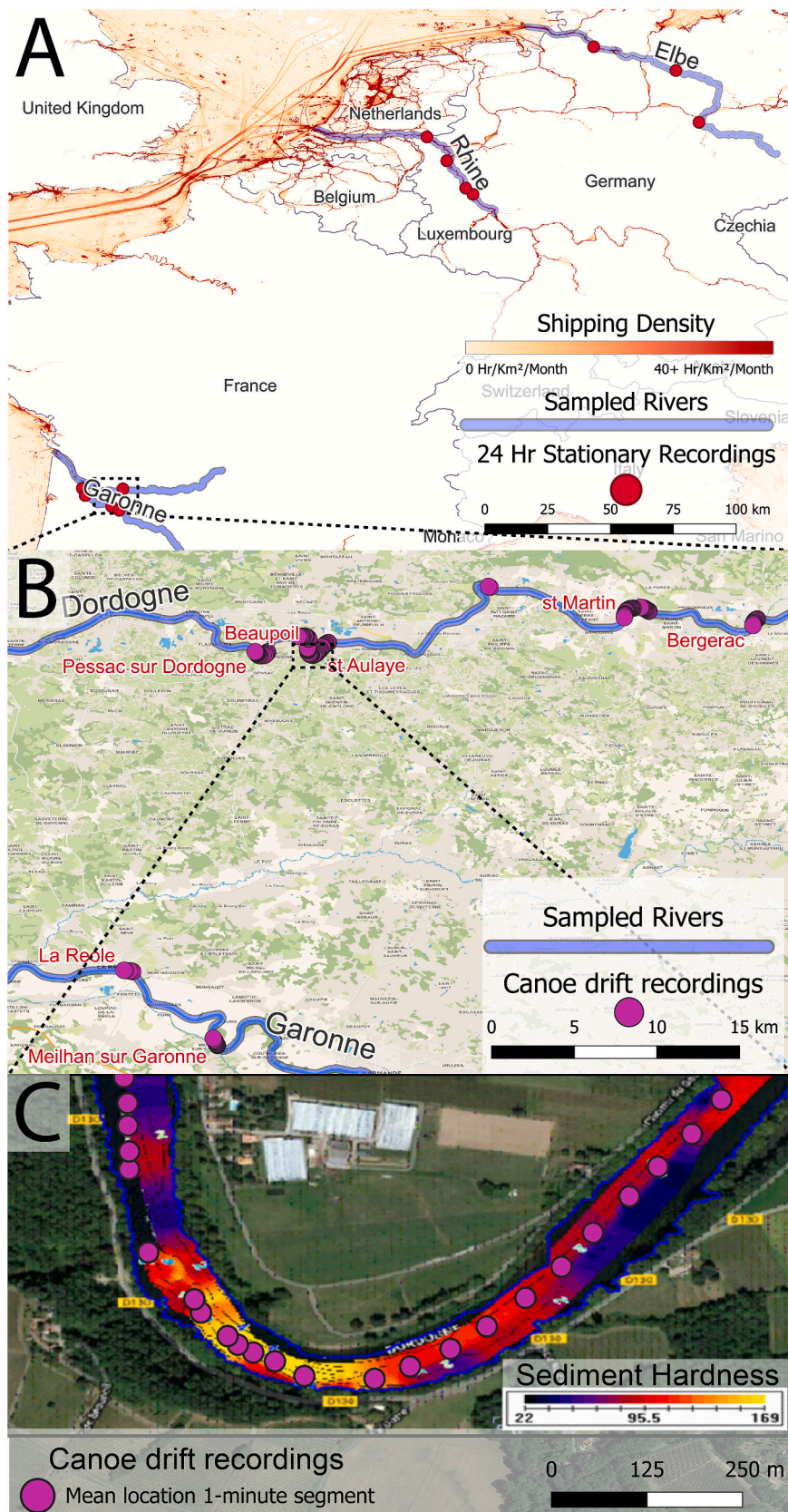


Fig. 1. Sample locations in three large European river systems; Elbe, Rhine and Gironde (A) 24-hour acoustic recording locations including an AIS shipping density background map. (B) Canoe drift recording locations in the Garonne and Dordogne, (C) Zoomed in example of sample points including a background map of the sediment hardness.

Table 1
24-Hour stationary recording locations.

Location	River system	Recording date	Coordinates	
			Lat	Long
Magdenburg	Elbe	07-06-2022	11.6410	52.1119
Damnatz	Elbe	07-06-2022	11.1836	53.1356
Hamburg	Elbe	09-06-2022	9.5604	53.6040
Quinsack	Gironde	13-04-2023	-0.4839	44.7374
Bordeaux	Gironde	13-04-2023	-0.5395	44.8794
Caumont	Gironde	15-04-2023	0.1895	44.4451
Meilhan	Gironde	16-04-2023	0.0399	44.5199
Le Fleix	Gironde	18-04-2023	0.2607	44.8676
Niederkassel	Rhine	28-05-2023	7.0314	50.8107
Köningswinter	Rhine	28-05-2023	7.1768	50.6891
Duisberg	Rhine	29-05-2023	6.6586	51.3519
Emmerick	Rhine	30-05-2023	6.2661	51.8229

each 24-h recording location to investigate the link between recorded acoustic boat presence and AIS shipping densities. The data do not include individual boat tracks, which prevents higher resolution analyses, but which would also be beyond the scale of interest of our current study. QGIS was used to extract the shipping density values from May 2023 at 1 km intervals along each river from the sea up to 400 km upstream, to assess and predict the distribution of shipping noise over the

entire river lengths. Fig. 1A shows this shipping density map from May 2023. To explore seasonal changes in shipping activity, the mean monthly shipping density across the whole length of each river was investigated from January–December 2023.

2.3. Acoustic data analysis

2.3.1. Acoustic boat detection

In order to allow analysis of natural soundscapes (without boat noise) and to quantify the percentage of time boat noise was present, we quantified acoustic boat presence in all our recordings using an adaptive threshold detection method adapted from Merchant et al., 2012. Any timepoint from both the stationary recordings and canoe drift recordings where no boats were detected (boat absent) could be used for further analysis of the natural soundscape (Biophony and Geophony).

First, long term spectral average (LTSA) spectrogram images were made of each recording using 1-min average temporal windows and a 1 Hz frequency resolution (Fig. 2). In Merchant et al., 2012, a relatively low-frequency band was used for threshold-based boat detection in a marine environment (10–1000 Hz), because of the high sound output of boats in that range, and because low frequencies carry further in deep water conditions. However, after viewing the LTSA spectrograms we noticed that the typical spectrum of boat noise is different in our recordings compared to the marine systems. This is likely caused by our

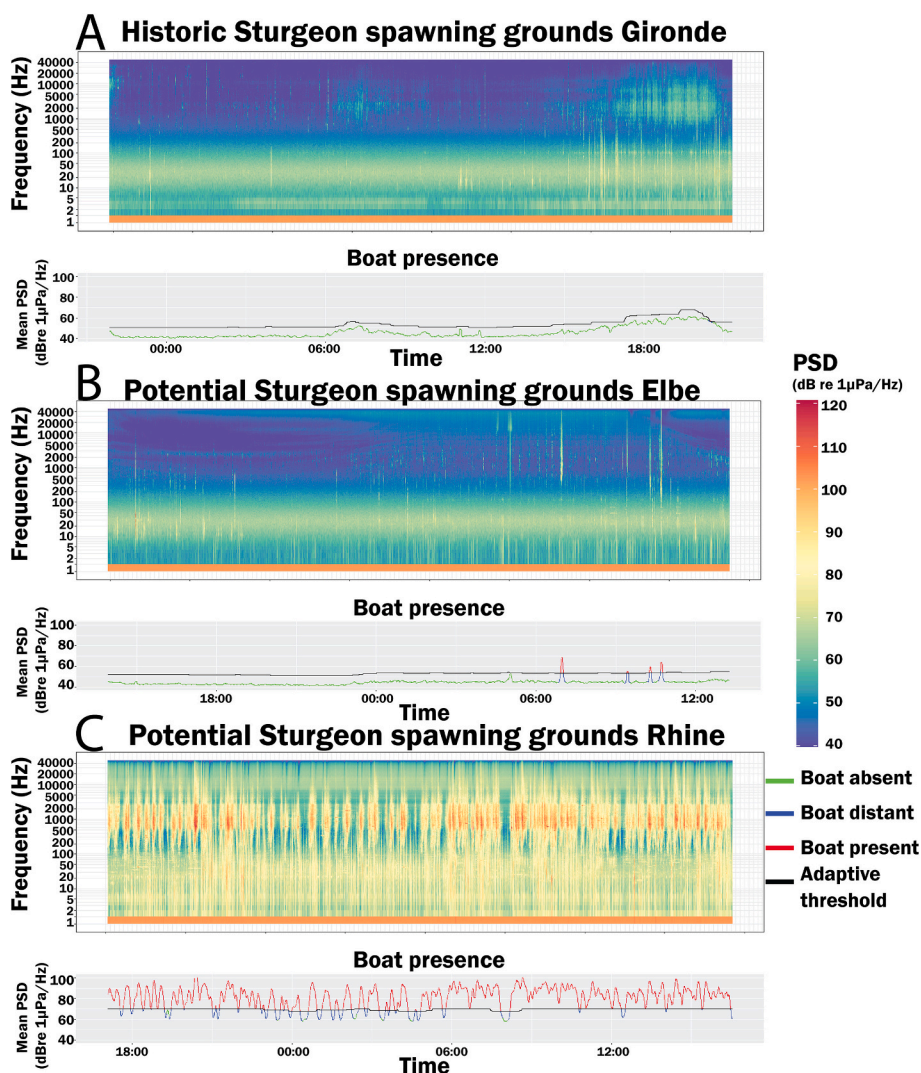


Fig. 2. Example 24-hour long term spectral average (LTSA) images, with average SPL at 1-minute timesteps and boat detection, at suitable spawning grounds for Atlantic sturgeon in the Rhine, Elbe and Gironde.

recording depth (2 m) and the shallow nature of rivers in general, resulting in a higher shallow water cut-off frequency, and boats are more likely to come close to the hydrophone in rivers, resulting in sound level elevations in higher frequencies.

After manual evaluation of the power spectrum levels of several representative boat passes from each recording location, we selected 1000–3000 Hz as the frequency band with the highest signal to noise ratio for boat detection. Then, acoustic boat presence was quantified from 5-min rolling average power spectral density levels (PSD) between 1000 and 3000 Hz. The adaptive threshold works on the assumption that the rolling minimum SPL of a given time window is representative for the natural background level. However, this assumption was violated in locations with close to 100% boat presence. Therefore, we introduced a 70 dB maximum threshold level: Any timepoint where the 5-min rolling mean exceeded 70 dB was classified as “Boat present”. For rolling means lower than 70 dB, the adaptive threshold level was used to correct for variation in the natural background level. Any timepoint where the 5-min rolling mean PSD between 1000 and 3000 Hz was >10 dB above the 1 h rolling minimum, was also classified as “Boat present”. To correct for the effect of sound propagation from boats at larger distances, any timepoint that was below the threshold level for at least 5 min in both directions was labelled as “Boat absent”. Any timepoint that was below the threshold, but still within 5 min before or after a Boat Presence detection, was classified as “Boat distant”. The percentage of time of boat noise presence was then calculated by dividing the summed duration of boat present in each recording by the total duration of the recording (24 h).

To evaluate the masking potential of boat noise on natural sounds, and to compare natural background spectra and levels with boat noise spectra and levels in each river, we selected 4 paired boat present, distant and absent recordings at each 24-h recording location, spread out across the day, at approximately 6 h apart. In some locations in the Gironde, fewer than 4 boat events were available. We calculated the power spectral density (PSD) of each of the selected boat present-, absent- and distant events using a Fourier transform in R, using Hann windows with 50% overlap, and a window length equal to the sample frequency (96 kHz). The mean and standard deviation was calculated and visualized to compare the mean boat noise and background spectra among rivers.

2.3.2. Natural soundscape analysis

To assess the presence and masking potential of underwater biophonic events, we visually screened spectrogram images in Audacity™ during boat absent time windows from the 24 h stationary recordings, for the presence of known and unknown biophony. Potentially biophonic events were saved and grouped into different classes after auditory and visual inspection. In order to select a sufficient number of representative biological sound types occurring across multiple locations, we applied the following selection criteria: 1. Confidence that the sound was of biological origin (based on availability of similar reference sounds), 2. A minimum of 5 sound events per type, 3. Occurrence at a minimum of two locations. These criteria resulted in the exclusion of less frequent biophonic sounds and potentially novel sound types present in the recordings, allowing us to retain a representative range of sound spectra and intensities for each selected sound type for the purpose of assessing masking potential. Example spectrograms were made of representative samples from the different sound types using a custom R script with a window size of 8192 and 90% overlap.

Canoe drift recordings were cut into 1-min segments and linked to the mean gps location during that 1-min timeframe. Any 1-min segment with artifacts from hydrophone collisions or paddling when repositioning the canoe were excluded from the analysis. Drift recordings were made along 4 drifts in the Rhine and 5 drifts in the Gironde. Only 1-min recordings with boat absence and from locations with available sediment data were further used in the analysis. Since all drift recordings in the Rhine contained 100% boat presence, these had to be excluded from

the analysis. This resulted in a total of 126 1-min samples, all used drift track segments are mapped in Fig. 1B.

2.4. Statistical analyses

2.4.1. Geophony

To explore the relationship between hydro-geomorphological river features and the natural river soundscape, we carried out a redundancy analysis (RDA) between the full octave band sound pressure level SPL and the hydro-geomorphological river features at each 1-min recording location (c.f. te Velde et al., 2024). Since this typically results in a grouping of cross-correlated high- and low-frequency octave bands, we calculated the mean SPL of all high-frequency octave bands (350–45,000 Hz), and low-frequency octave bands (11–350 Hz). We then selected the hydro-geomorphological features that showed the strongest association with either high- or low-frequency mean octave band SPL and carried out a multiple linear regression with SPL as dependent variable and hydro-geomorphological features as explanatory variables. To identify a potential threshold in the relationship between water velocity and high-frequency octave band SPL, we performed a segmented regression (hockey-stick model). The breakpoint identified by this model, was then used to carry out two separate multiple linear regression models for the relationship between high frequency octave band SPL and the selected hydro geomorphological features under high- and low-flow conditions.

2.4.2. Anthrophony

Acoustic boat presence detections as described above were converted into % time boat presence per 24-h at each site. To investigate the relationship between acoustic boat presence and AIS shipping density, we applied a quasibinomial Generalized Linear Model (GLM) with acoustic boat presence in % time per day as dependent variable and cumulative AIS boat presence in hours/day/km² as explanatory variable. The resulting model was then used to predict acoustic boat noise presence across the entire length of each river based on the AIS shipping density data.

2.4.3. Masking potential

To evaluate the masking potential of boat noise on biophony, we compared mean and standard deviation PSD spectra of biophonic events with the selected representative boat noise events. Because several biophonic events were shorter than 1 s, PSD spectra were calculated using a window length of 4096, using Hann windows with 50% overlap. To evaluate the masking potential of boat noise on geophony, we compared mean and standard deviation PSD spectra of 1-min recordings from locations within specific water velocity and sediment hardness bins, with the selected representative boat noise events. We calculated the PSD spectra using Hann windows with 50% overlap, and a window length equal to the sample frequency (96 kHz).

3. Results

3.1. Natural sounds

3.1.1. Biophony

Manual screening of the 24-h recordings yielded many sound events of potentially biological origin, including repeated occurrence of two sound types attributed to the Eurasian Perch (*Perca fluviatilis*) (Fig. 3A) (Tiepelt, 2005a, 2005b; te Velde et al., 2024; supplementary materials 1), and the lesser boatman (*Micronecta* sp.) (Fig. 3B) (Sueur et al., 2011; Desjonquères, 2016, supplementary materials 1). Perch sounds were detected in at least one location in all three rivers, for a total of 6 locations, while *Micronecta* was detected only at two locations in the Elbe, but if present, occurred for several hours throughout the night. We selected the following three common unknown sounds and, based on published and unpublished reference recordings (see supplementary

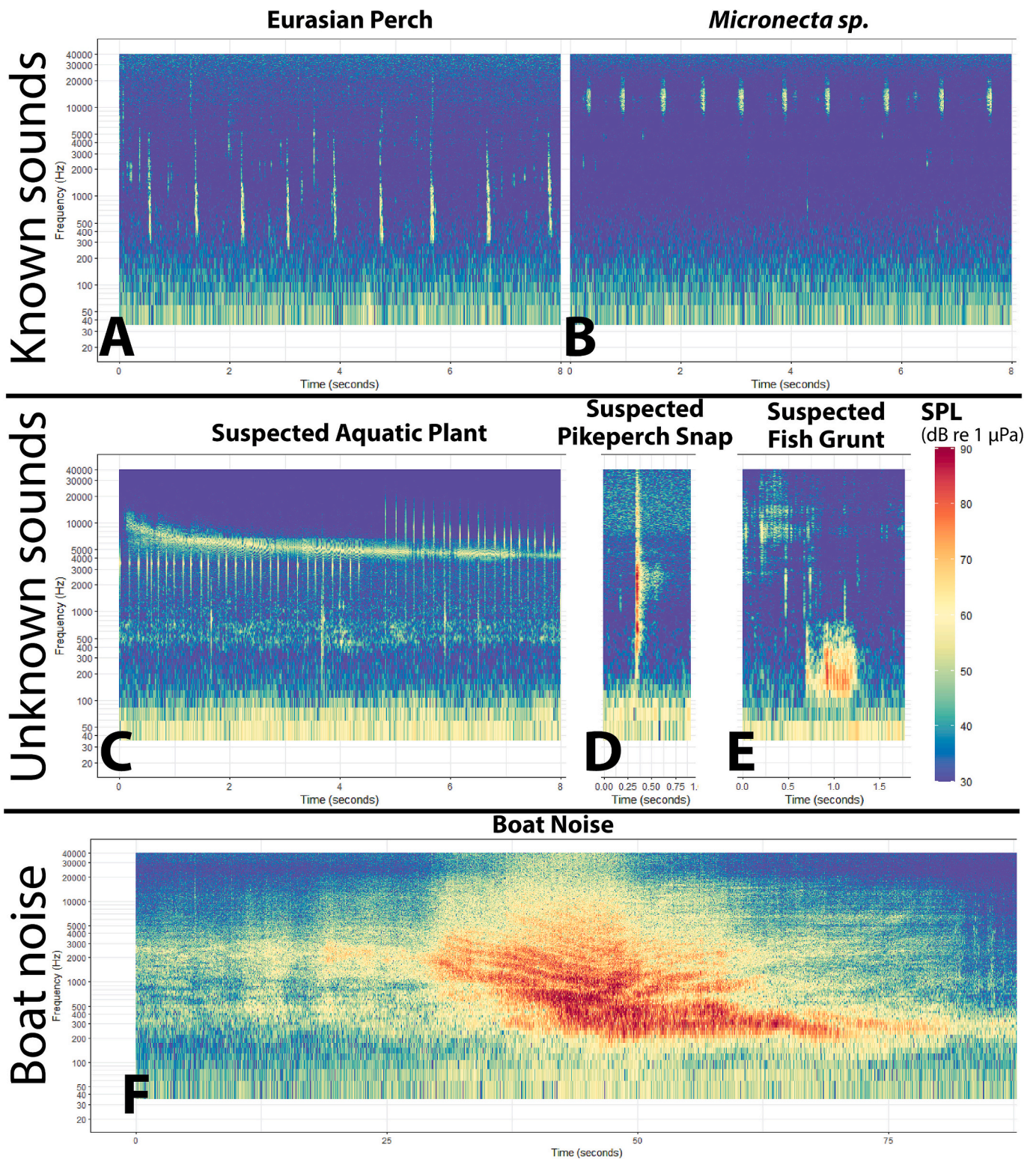


Fig. 3. Example spectrograms of biophonic sounds from known and unknown aquatic organisms. Frequency axis and sound pressure level (SPL) color scale are proportional in all spectrograms, time axis differs among some spectrograms. A; European perch (*Perca fluviatilis*), B; Aquatic insect species of genus *Micronecta*, C; likely produced by O₂ bubbles from an aquatic plant, D; Suspected Pikeperch (*Sander lucioperca*) snap, E; Suspected fish grunt (unknown species), F; Noise from a typical river boat.

materials 1), we suggested the following organisms responsible for production of the sounds: suspected aquatic plant (Fig. 3C) (Linke et al., 2018; van der Lee et al., 2025; supplementary materials 1), suspected pikeperch (*Sander lucioperca*) snap (Fig. 3D) (Kaschner, 2012; Tiepelt, 2005a, 2005b; supplementary materials 1), and suspected fish grunt

(Fig. 3E) (see similarity to painted goby *Pomatoschistus pictus* sounds in Amorim et al., 2013). The biophonic sounds had diverse frequency characteristics, ranging from low-frequency fish grunts to high-frequency aquatic insect stridulation and broad-band aquatic plant bubbles and pikeperch snaps, but all fall within the same frequency

spectrum as boat noise (Fig. 3F).

3.1.2. Geophony

To investigate the effect of hydro-geomorphological river features on the natural river soundscape, we carried out a redundancy analysis (RDA) between the full octave band sound pressure level (SPL) and the hydro-geomorphological river features at each 1-min recording location (Fig. 4A). A forward selection yielded a model with water velocity ($p = 0.005$) as significant variable, and Area of cross-section as non-significant trend ($p = 0.070$).

The RDA plot shows a grouping of high- (350–45,000 Hz) and low-frequency (11–350 Hz) octave bands. Water velocity, sediment hardness and distance from shore show the strongest association with higher frequency octave bands, while river width, depth recording and area of cross-section show the strongest associations with low-frequency octave bands. To further explore this relationship, we calculated the mean octave band SPL of the grouped low- and high-frequency octave bands.

Data visualization revealed a strong increase in the high-frequency octave band SPL at higher water velocities (Fig. 4B).

The multiple linear regression between mean SPL of the low-frequency octave bands (11–350 Hz) and depth, width, and area of cross-section yielded no significant predictors. When exploring correlations between mean low-frequency octave band SPL and the other hydro-geomorphological variables, only water velocity had a significant positive correlation with mean SPL of the low-frequency octave bands ($r = 0.39, p < 0.001$).

A segmented regression (hockey-stick model) identified a breakpoint in the relationship between high-frequency octave band SPL and water velocity at 1.40 m/s (± 0.03 SE), indicating a threshold beyond which SPL increases steeply with water velocity. Two separate multiple linear regression models in the low- (<1.4 m/s) and high-velocity (>1.4 m/s) range showed that both water velocity and sediment hardness were significant predictors of SPL below 1.4 m/s (Water velocity: $\beta = 1.51, p = 0.036$; Sediment Hardness: $\beta = -0.018, p = 0.025, R_{adj}^2 = 0.09$).

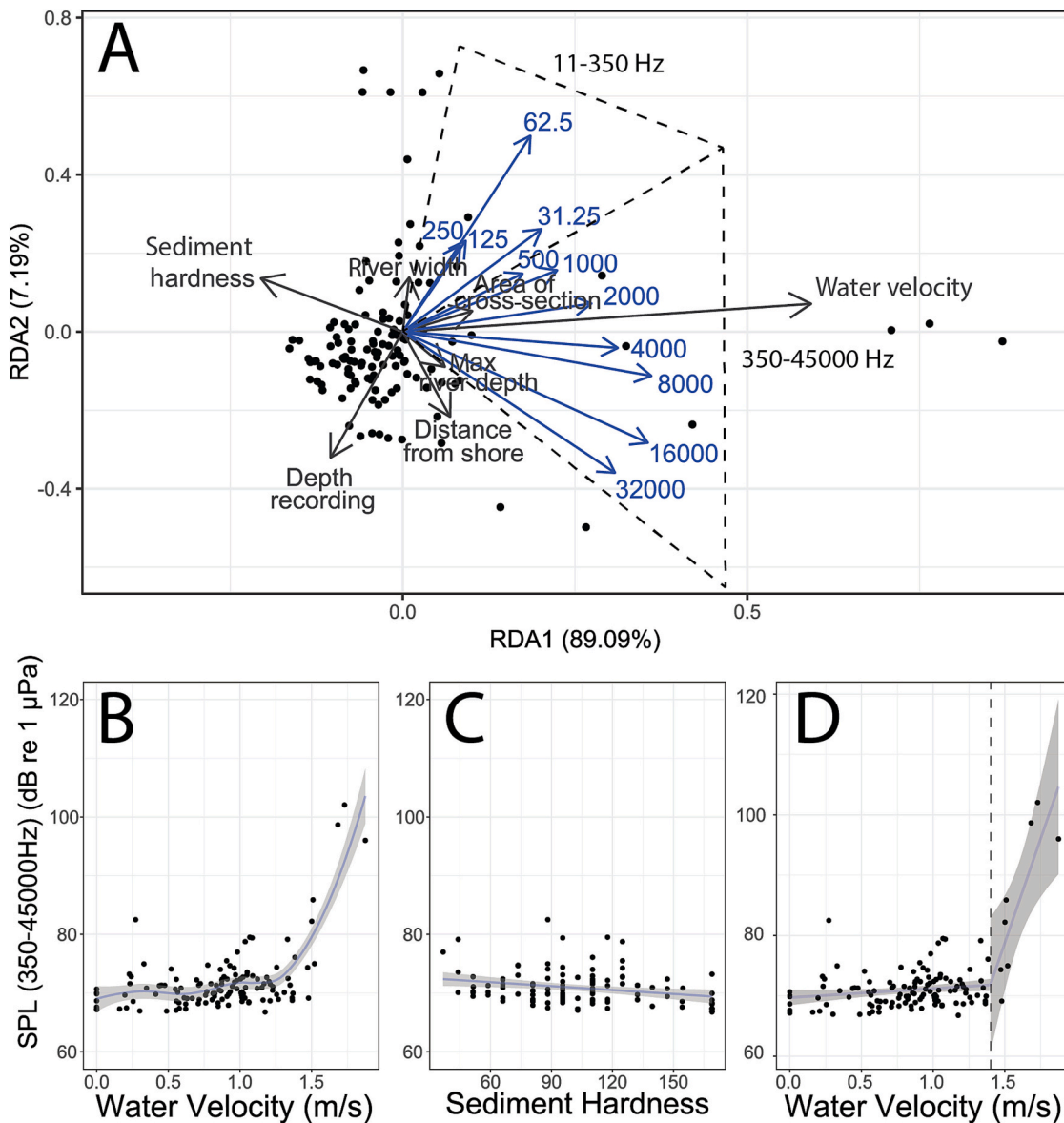


Fig. 4. Relationship between hydrogeomorphological variables and Sound Pressure Levels (SPL) at different frequencies in the canoe drift recordings. A; Redundancy Analysis of full octave band SPL against hydrogeomorphological variables, dotted lines highlight a directional grouping of low- and high- frequency octave bands, B; relationship between mean SPL of high frequency octave bands (350-45000 Hz) and Water velocity with a loess smoothing line, C; relationship between high frequency octaves mean SPL and Sediment hardness for samples with water velocities below 1.4 m/s, D; relationship between high frequency octaves mean SPL and Water velocity, with a segmented (hockeystick) model prediction and 95% confidence margins if sediment hardness is kept constant.

(Fig. 4C), and only water velocity was a significant predictor above 1.4 m/s ($\beta = 68.99, p = 0.010, R_{adj}^2 = 0.64$) (Fig. 4D).

$$High - frequency SPL = \begin{cases} 71.57 + 1.51 \cdot v - 0.018 \cdot h, & \text{if } v \leq 1.4 \\ -24.68 + 68.99 \cdot v, & \text{if } v > 1.4 \end{cases} \quad (1)$$

Where:

- High-frequency SPL = Mean high-frequency (350–45,000 Hz) octave Sound Pressure Level (dB re 1 μ Pa)
- v = Water Velocity (m/s)
- h = Sediment Hardness

To explore whether sediment associated soundscapes could inform fish about their position in the river, we examined how well sediment type distribution across river locations is reflected by the mean sediment hardness values at those locations as extracted from the echosounder data. There was a significant linear relationship between sediment hardness and the proportion of large grain size of substrate rocks & pebbles (>20 mm) ($\beta = 45.0, p = 0.002, R_{adj}^2 = 0.41$), with the opposite relationship between sediment hardness and the proportion of low grain size of substrate clay & gravel (<20 mm). Although strong statements on the relationship between sediment hardness and local grain size proportions would require more samples in locations with low grain size sediments, the general pattern found in this study is in line with expectations. Low sediment hardness is associated with small grain size

substrates, and high sediment hardness with large grain size substrates (Fig. 5A&B). Furthermore, we explored how sediment is distributed over the length of the river. A quasibinomial glm showed that the proportion of high grain size substrate rocks & pebbles increased significantly with distance upstream of the estuary ($\beta = 0.042, p < 0.001, pseudoR^2 = 0.69$), with the opposite relationship between the proportion of low grain size substrate particles and distance upstream. Showing a distribution from low grain size sediment particles downstream, towards higher grain size sediment particles upstream of the estuary (Fig. 5C&D).

3.2. Quantifying river boat noise

At our 24-h stationary recordings sites, the Rhine, Elbe and Gironde varied greatly in terms of boat noise, with daily boat presence in our recording locations ranging from 0 to 20% in the Gironde, 2–38% in the Elbe and 42–86% in the Rhine. The duration of detected boat presence varied greatly among single boat passes in all rivers, with boat pass durations ranging from 2 to 20 min.

3.2.1. Predictive value of AIS shipping density data

There was a significant positive relationship between the AIS boat density (in hours/km²/day) and acoustic boat noise presence (in % time per day), as assessed by a quasibinomial GLM ($\beta = 0.181 \pm 0.037, t = 4.89, p < 0.001$) including a significant intercept ($\beta = -2.974 \pm 0.592, t = -5.02, p < 0.001$) (Fig. 7A). This yielded the following model (with

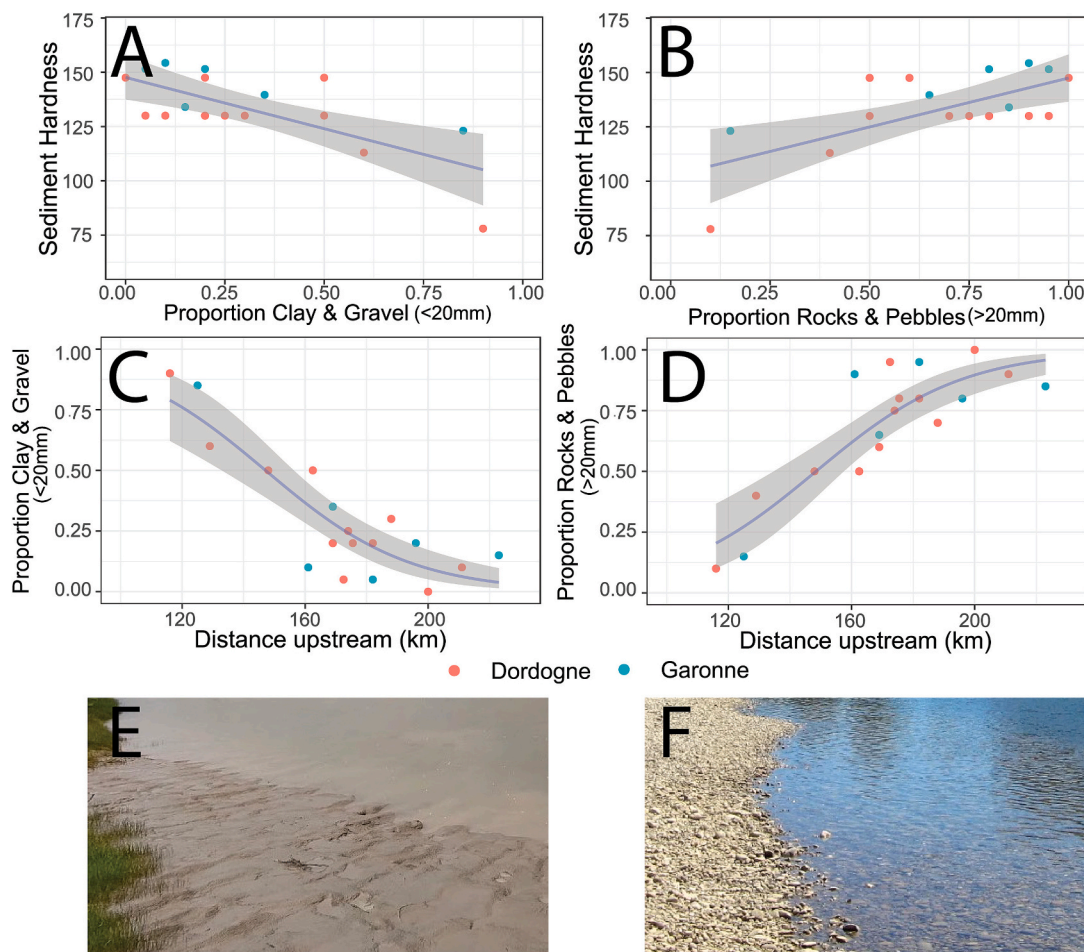


Fig. 5. Relationships between mean location sediment hardness and proportion of low- and high grain size substrates in the Garonne and Dordogne, sampled at different distances upstream of the Gironde estuary. A&B; Shows the linear relationship between Sediment hardness and proportion low- and high grain size substrates, C & D Shows the distribution of low- and high grain size substrates with distance upstream with a negative binomial generalized linear model prediction. Pictures on the bottom show the river bank along locations with small- (left) and large (right) grain size substrates.

Boat presence in %, and Boat Density in hours/km²/day):

$$\text{Boat Presence} = 100 \times \frac{e^{-2.97+0.181 \times \text{Boat Density}}}{1 + e^{-2.97+0.181 \times \text{Boat Density}}}$$

This model was used to predict the % boat presence based on data extracted from an AIS shipping density map (Fig. 1A) sampled along 400 km river length in each of the three rivers (Fig. 6B). Predicting 80–100% boat presence in the first 100 km of the Elbe, rapidly declining after Hamburg (at 100 km from the sea) towards 5–15%, in the Rhine 40–75% boat presence over the whole length, and in the Gironde 7% boat presence Bordeaux, declining to 5% after Bordeaux (Fig. 6B).

3.2.2. Differences among rivers

The sound spectra during boat absence in the Gironde and Elbe are relatively similar, while the Rhine has higher SPL above 500 Hz (Fig. 7). Boats in the Rhine had generally higher SPL across the whole spectrum compared to boats in the Elbe and Gironde (Fig. 7). Furthermore, above 50 Hz, boats in the Rhine have distinctly higher SPL compared to boat absence (Fig. 7A), while boats in the Elbe & Gironde start to show distinctly higher sound levels above 100 Hz (Fig. 7B&C). Boat distant spectra do not show distinctly elevated levels compared to boat absence, except for a slightly higher mean SPL between 400 Hz – 2000 Hz (Fig. 7). Indicating that boats may still be audible by some animals with sensitive hearing in those frequencies.

3.3. Masking potential of boat noise on natural sounds

To evaluate the masking potential of boat noise on natural sounds in rivers, we compared the mean boat noise spectra with mean spectrum levels of biophonic and geophonic sounds encountered in our recordings (Fig. 8). Only water velocities of 1.75 m/s produced sound spectra that exceeded boat noise below 75 Hz and above 1500 Hz (Fig. 8B) and the suspected fish grunt produced mean sound spectra that exceeded boat noise between 100 and 200 Hz (Fig. 8A). All other sounds had mean sound spectra below mean boat noise levels across the whole spectrum. Suspected aquatic plant, pikeperch, and *Micronecta* sp. have upper-level standard deviations that are above lower-level standard deviation of boat noise in some frequencies, indicating that these sounds can sometimes exceed the more quiet boat events. Still overall, most natural sounds have sound spectra below that of boat noise in most frequencies, indicating large potential for masking of natural sounds in the presence of boat noise.

4. Discussion

Our results have shown that 1a) The three major European rivers

vary among each other in amplitude and spectra of natural soundscapes; 1b) Upstream and downstream river soundscapes vary consistently, which can be attributed to water velocity, river size and bottom features; 2a) Boats are present at high proportions of the time in particular in the Rhine, in the downstream part of the Elbe, and to a lesser extent in the Gironde; and 2b) Boat noise is typically loud and broadband, overpowering biophonic and geophonic sounds, which likely yields to large-scale masking of environmental cues, when commercial vessels pass.

4.1. Biophony

In this study, we highlighted several putative biophonic sound examples, adding to the limited information on underwater sounds made by freshwater animals. We provided a qualitative analysis of biophonic sound events, showcasing some of the diversity of river biophony from distinct taxa. Some sounds are likely for communication purposes such as those from aquatic insects and fish, and others are not specifically linked to communication such as aquatic plant bubbles. Simply the presence of another species can tell an animal something about its surroundings, because the presence of an organism is typically associated with specific habitat features. Therefore, all these sounds can provide aquatic animals with information about their surroundings (Fay, 2009; Slabbekoom and Bouton, 2008; te Velde et al., 2024). However, most putative biophonic sounds encountered in this study still remain suspected and unidentified, as they lack high confident reference sounds from aquarium or mesocosm recordings (Looby et al., 2022), or combined video and hydrophone arrays recordings (Mouy et al., 2017). Furthermore, many potentially biophonic sounds in our recordings were excluded from the analysis because they did not meet our selection criteria, and longer recordings across seasons may yield many more biophonic sounds.

In order to gain a better understanding of the potential ecological effects of acoustic masking by anthropogenic noise, future studies should focus on describing novel biophonic sounds, and quantifying their spatial and temporal occurrence. Of the 7000 aquatic insect species that are predicted to produce sounds, less than 1% have been described (Desjonqueres et al., 2024; Greenhalgh et al., 2025). Furthermore, although currently almost 1000 fish species are known to produce sounds, 96% of all fish species remain to be investigated for sound production (Looby et al., 2022). Automated analysis of known and unknown sound events may provide more insights into the availability and spatial and temporal distribution of acoustic cues. Innovative techniques using machine learning for sound event detection and unsupervised clustering based on acoustic features can aid in identifying novel biophonic sounds (Alcocer et al., 2022; Barroso et al., 2023; Aslam et al., 2024; Parcerisas et al., 2024). Ultimately, applying machine learning to

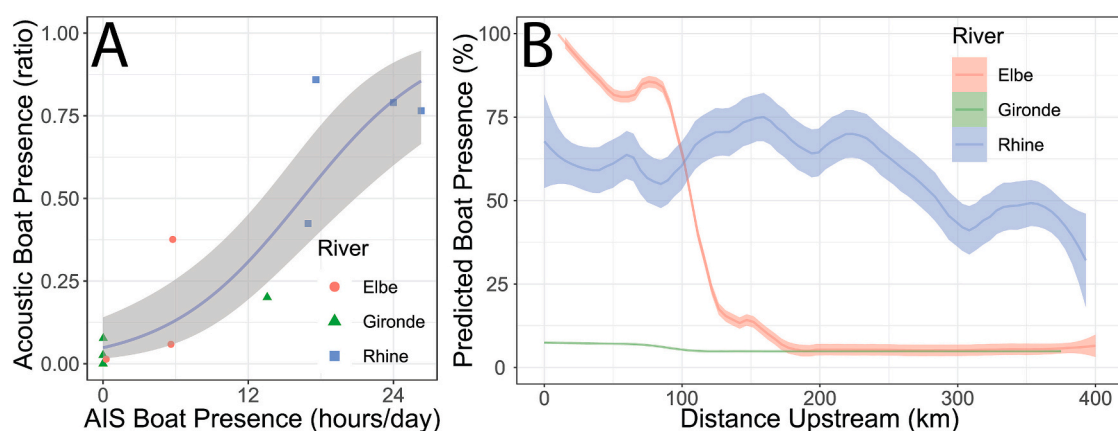


Fig. 6. A; Relationship between acoustic boat presence as measured in 24-hour recordings and the AIS boat presence extracted from monthly AIS density maps (GMTDS, 2024). The line indicates the negative binomial regression model with 95% confidence margins. B; Predicted acoustic boat presence from the sea to 400 km upstream in the Elbe, Rhine and Gironde rivers based on AIS shipping density maps.

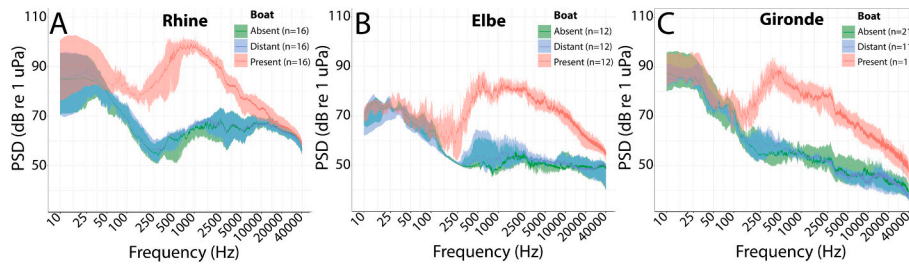


Fig. 7. Mean Power Spectral Density (PSD) values of boat absent, present and distant samples in the Rhine (A), Elbe (B) and Gironde (C). Error margins indicate standard deviation. Sample sizes refer to the number of boat passes analysed: Four boat passes with paired boat distant and absent sections were selected in each recording location, several locations in the Gironde had less than 4 boat passes, leading to fewer boat present and distant than absent samples.

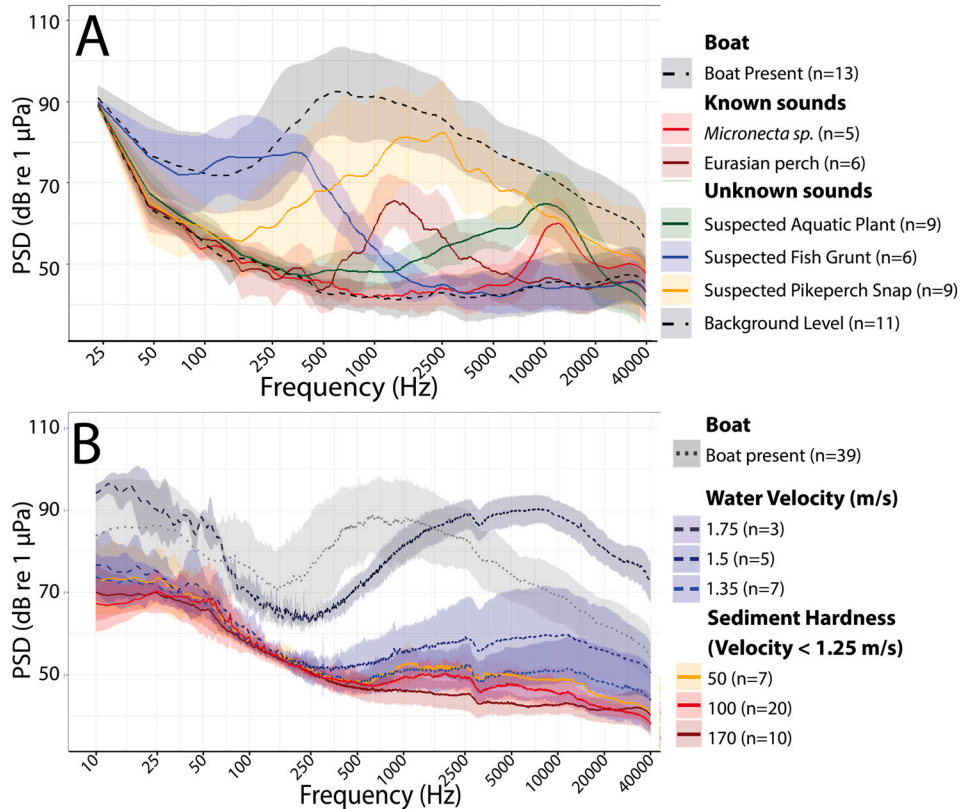


Fig. 8. Masking potential of natural sounds by boat noise in rivers, A; Biophonic sound spectra, B; Geophonic sound spectra. Note that PSD of biophonic sounds were calculated using a window length (wl) = 4096, and geophonic sounds wl equal to the sample frequency (96000), so dB values should be interpreted differently.

field recordings can help to accelerate the discovery of novel biophonic sounds, which will help to map the spatial and temporal distribution of biophony. However, in addition, we would also still require high-confidence ground-truthing from aquarium auditioning or combined audio-video recordings.

4.2. Geophony

Water velocity and sediment characteristics affect the generation of geophonic sound through turbulence and particle collisions, likely resulting in a condition-specific frequency spectrum, while river size characteristics mainly affect propagation of low-frequency sound. Our Redundancy Analysis (RDA) identified water velocity as the primary predictor of SPL across all octave bands, whereas river size (Area of cross-section) showed a non-significant trend. These findings are similar to reports from other river systems, which have also shown that water velocity and river size are reflected in the natural soundscape of rivers from a wide range of sizes and flow speed (Gu et al., 2022; te Velde et al.,

2024; Tonolla et al., 2010, 2011; Vračar and Mijić, 2011). River size related variables (river width, depth of recording, and area of cross-section) were most associated with low-frequency octave bands (11–350 Hz), likely due to physical propagation limits of shallow water (Forrest et al., 1993). However, water velocity proved the only significant predictor of low-frequency octave band SPL. This suggests that although there may be subtle effects of river size on low-frequency SPL, flow-induced sounds generated from nearby turbulence may overshadow this effect. Furthermore, we showed that sediment hardness and water velocity were significant predictors of high-frequency octave band (350–45,000 Hz) SPL below 1.4 m/s, but there is a steep increase in high-frequency SPL at velocities above 1.4 m/s where water velocity remains the only significant predictor. Our analysis therefore suggests that sediment characteristics primarily influence SPL under low-flow conditions, while high water velocities dominate SPL variation above this threshold.

The negative association between sediment hardness and mean SPL between 350 and 45,000 Hz in low-flow conditions was contrary to our

expectations, since higher hardness sediments such as gravel and rocks are expected to induce more sound from turbulent flow and particle collisions during bed load transfer (Geay et al., 2017). A possible explanation is that the low-flow conditions are not enough to cause sufficient bed load transfer of larger substrate particle sizes, while smaller substrate particles are more easily brought in motion. Nevertheless, whatever the causal factors are, our findings show that the underwater soundscape can reflect information on nearby substrate types, which may be audible and thereby available to aquatic animals (c.f. Slabbekoorn and Bouton, 2008; Fay, 2009; Febrina et al., 2015;). Furthermore, we showed that sediment is distributed from low grain size sediment particles downstream, towards higher grain size sediment particles upstream of the estuary. Consequently, we hypothesize that soundscapes dependent on local substrate type have potential to inform migratory fish about their position along the length of the river (Kacem et al., 2020; Kowal et al., 2023; Murchy et al., 2024).

4.3. Potential relevance of acoustic cues to aquatic animals

For potential relevance, it is important to consider whether the frequencies of potential cues fall within the hearing range of specific animal taxa. Fish typically have hearing ranges that are most sensitive in low frequencies with upper limits from 500 Hz up to 1000 Hz, some more specialized species have hearing capacity of detecting sound pressure, with limits up to 4000 Hz or 5000 Hz, while some clupeids can hear into the ultrasonic range (Popper and Fay, 2011; Popper et al., 2022). It should be noted that fish hearing ranges should always be considered with care. They are typically determined under artificial laboratory conditions, and threshold findings from the same species can vary greatly among studies (Popper and Hawkins, 2021). Not much is known about aquatic insect hearing, but they likely have a broad hearing range like terrestrial insects, with the highest sensitivity in frequencies of their own communication signals (Čokl and Theiss, 1987; Prager and Streng, 1982; Yack et al., 2020). Therefore, most sounds in this study up to 10,000–15,000 Hz are expected to fall within the hearing range of aquatic insects.

High flow rates affect a broadband range, including low frequencies, at high sound levels. Therefore, rapids and waterfalls can likely be detected by most aquatic animals. Sediment hardness is mostly reflected in frequencies above 500 Hz, making it less detectable by fish species such as salmon or sturgeon, but it should fall within the hearing range of more advanced hearing species such as shad and cyprinids (Harding et al., 2016; Hawkins and Johnstone, 1978; Mann et al., 1997; Popper et al., 2022; Popper and Calfee, 2023). Particle collisions from bed load transport may induce broadband peaks that have a low contribution to mean SPL, but could be detectable by fish species with low upper-frequency limits. Aquatic insects typically produce high-frequency sounds above 1000 Hz up to 10,000–15,000 Hz (Aiken, 1985; Desjonqueres et al., 2024; Greenhalgh et al., 2025), likely above the hearing range of most fish species. Aquatic plants can produce broadband pulses, potentially audible to most aquatic animals (van der Lee et al., 2025). Sounds attributed to fish vary from low- and mid-frequency grunts to broadband snaps, of which at least the lower parts are likely audible to all fish species (Amoser and Ladich, 2005).

The potential of underwater sounds as a cue for aquatic animals depends on quality and availability. The quality may be reflected by the association strength between occurrence and a relevant resource, such as food or suitable spawning habitat. The availability refers to the actual presence and audibility of the sound where and when required to serve a purpose. Flow-related geophonic sound sources are likely consistent, predictable and omnipresent (high quality and availability) (Geay et al., 2020; Johnson and Rice, 2014). They also vary with river discharge changes from meltwater and rain, thereby reflecting seasonal changes (Lumsdon et al., 2018). Detecting specific sediment and waterflow conditions can be of special importance to aquatic animals seeking a suitable place to deposit their eggs (Kemp et al., 2011; Rosenfeld, 2003).

Furthermore, many animals have different strategies to avoid predators through shelter between rocks or burrowing in sand, which may also be found through hearing variation in flow conditions. Gradually changing soundscapes, as you move upstream, probably allow rough orientation and navigation and, while more distinct local soundscape features such as waterfalls or rapids could act as landmarks during navigation (Murchy et al., 2024; Slabbekoorn and Bouton, 2008; Fay, 2009).

4.4. Boat noise potential for masking

Our findings show that boat noise is widespread in space and time and apparently overpowering most natural river sounds when commercial vessels pass by. Masking is a complex phenomenon, for example depending on the location of signal and noise sources relative to the receiver. However, the nature of rivers makes that vessels always pass by at relatively close distance, without acoustic hiding opportunities other than very shallow water areas with relatively high (> 500 Hz) cut-off frequencies. Only few natural sound events on our recordings exceeded boat noise spectra at some frequencies on some occasions. We believe that this is reflecting the typical situation for natural river soundscapes: likely fully masked during passage of commercial vessels, limiting any acoustic communication, and undermining any assessment of natural acoustic information by aquatic animals. Quantification of masking impact in more detail is difficult, as different taxa hear different spectra at different thresholds, and even among fish species there is large variation in hearing capacities, including unknown combinations in sensitivity for particle motion and sound pressure (Chapman & Johnstone, 1974; Popper and Fay, 2011; Alves et al., 2025).

Vessel passes can vary greatly in duration and intensity, depending on whether they go upstream or downstream and depending on their type, size, speed, and load. Boat noise spectra in the Rhine had higher average SPL and lower frequency cut-off compared to boat noise spectra in the Elbe and Gironde (Fig. 7). Vessel traffic may vary among these rivers, but these differences may also be explained by river features affecting sound propagation, and by locality-specific distance of the boat to the receiver (Jansen and De Jong, 2017; Macgillivray and de Jong, 2021). Due to the high shipping densities in the Rhine, there was often also more than one boat present. Furthermore, the AIS density data only include commercial boats, and this may underestimate boat noise at various places in particular seasons due to recreational activity (Hermanssen et al., 2019). Moreover, other anthropogenic activities may generate city noise, while land-based traffic noise from bridges and roads can also significantly affect the underwater soundscape (Holt and Johnston, 2015; Rountree et al., 2020; te Velde et al., 2024; te Velde and Slabbekoorn, 2024).

We showed that noise levels are high for long periods of time, especially for the Rhine, surpassing sound levels of most other underwater sounds at our hydrophones. This raises concerns about the effects of boat noise on freshwater animals and anadromous fish in rivers at a global scale. Within western Europe, the Rhine is exceptional in terms of the amount of shipping traffic. The amount of inland cargo transport is higher for the Rhine (58 billion t/km) than for any other of the large European rivers, such as the Danube (23 billion t/km), Elbe (4.2 billion t/km), Seine (3.1 billion t/km), Rhone (0.8 billion t/km) and Po (0.1 billion t/km) (Central Commission for the Navigation of the Rhine, 2024). However, similar values of acoustic boat presence may be found in rivers such as the Yangtze, Pearl, Grand Canal, and Mekong rivers in Asia, the Mississippi river in the United States of America and the Danube in eastern Europe (Lu et al., 2023). Research into designing more quiet ships, and management interventions, such as permanent or temporary, potentially seasonal, slow-downs, seem therefore vital, and relevant at a global scale. Even moderate source level reductions can significantly lessen the area impacted by anthropogenic noise at sea (Findlay et al., 2023). The longitudinal propagation situation of rivers will require translation, but seems interesting and worthwhile to explore, especially in the context of potential inclusion of noise pollution

into the European Water Framework Directive (c.f. Merchant et al., 2022).

5. Conclusions

We here reported on human-altered soundscapes in large European rivers and widespread potential for masking by boats. The three large rivers were similar in the presence of hydro-geomorphological determinants of specific parts of the underwater soundscapes. Biophony provided further potential to aquatic animals to acoustically assess the extent to which they find themselves upstream, away from the sea, above particular substrate, and in specific micro-habitat. The three rivers also varied in natural background sound levels, biophonic sound types, and especially the levels and duration of boat noise. Our analyses revealed that boat noise may severely limit access to acoustic information otherwise available to aquatic animals, particularly where and when important habitat or migratory routes overlap with heavy traffic corridors such as estuaries or the Rhine. AIS density maps have predictive value for the presence of underwater noise and may serve as a starting point to identify high impact areas in rivers. We believe that noise management is urgently needed in large rivers, and natural soundscapes should be integrated into conservation planning, particularly at migratory bottlenecks and vulnerable habitats. We argue that acoustic monitoring and mitigation measures are best included in international freshwater legislation such as the European Water Framework Directive.

CRedit authorship contribution statement

Kees te Velde: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rixt van der Horst:** Methodology, Investigation, Data curation. **Robin Neger:** Methodology, Investigation, Data curation. **Demi Pistor:** Methodology, Investigation, Data curation. **Bente Uiterwijk:** Methodology, Investigation, Data curation. **Christian Tudorache:** Writing – review & editing, Supervision, Conceptualization. **Hans Slabbekoorn:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hans Slabbekoorn reports financial support was provided by Horizon Europe. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2026.181798>.

Data availability

Data will be made available on request.

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