The Importance of Natural Soundscapes and Noise Pollution Threats to Freshwater Fauna in Quiet Waters

Kees te Velde and Hans Slabbekoorn

Contents

Introduction 2
Conceptual Framework to Study the Acoustic World of Migratory Fishes 3
Disentangling Natural Sound Sources 3
Potential Acoustic Cues 5
Quantifying Anthropogenic Noise 5
The Extent of Masking of Natural Sounds in Freshwater Systems 6
Responses to Sounds by Freshwater Animals 7
Conservation with Limited Knowledge 7
Conclusions 10
References 10

Abstract

Animals rely on limited sensory information to make behavioral decisions. Sounds are important underwater and especially relevant in quiet freshwater habitat. However, acoustic masking may also be severe in quiet waters and reduce signal efficiency for vital behaviors, such as mating, habitat selection, territory defense, foraging, and predator avoidance. There is growing support for noise mitigation measures in marine and terrestrial ecosystems, but policy is lagging behind for freshwater, which involves some of the most vulnerable ecosystems in

K. te Velde (✉)
Institute of Biology Leiden, Leiden University, Leiden, The Netherlands

Naturalis Biodiversity Center, Leiden, South-Holland, The Netherlands
e-mail: kees.tevelde@naturalis.nl

H. Slabbekoorn
Institute of Biology Leiden, Leiden University, Leiden, The Netherlands
e-mail: H.W.Slabbekoorn@biology.leidenuniv.nl

A. N. Popper et al. (eds.), *The Effects of Noise on Aquatic Life IV*,
https://doi.org/10.1007/978-3-031-94229-7_139-1

the world. Many of the fish species with the most sensitive hearing occupy freshwater habitats. Furthermore, acoustic communication by freshwater organisms, such as aquatic insects, amphibians, and fish, can be as diverse and abundant as in marine and terrestrial ecosystems. Local habitat characteristics, such as sediment type, flow speeds, and presence of aquatic plants and animals, may be audible, while river boat noise and traffic noise from cities, roads, and bridges can undermine the audibility. The authors therefore call for a rise in acoustic awareness and urge policymakers to implement measures for noise mitigation in vulnerable quiet waters with endangered species.

Keywords

Freshwater soundscapes · Masking · Fish behavior · Acoustic cues · Conservation · Noise policy, Deterrence, Attraction

Introduction

Freshwater biodiversity is not doing well: from 1970 to 2022, it declined globally with 87%, compared to 69% for terrestrial, and 56% for marine biodiversity (WWF 2024). One quarter of all freshwater species are threatened with extinction (Sayer et al. 2025). Freshwater fish are considered the most vulnerable group of all vertebrates, and migratory species are particularly threatened (Costa et al. 2021). This is caused by a wide range of stressors, including canalization and urbanization, migration barriers, habitat loss and degradation, invasive species, overfishing, chemical pollution, and climate change (Costa et al. 2021). However, a source of pollution that is rarely listed as a stressor in freshwater ecosystems but may have contributed to this decline is anthropogenic noise (Mickle and Higgs 2018).

In the past decades, human-made noise has been increasingly recognized as a stressor to both humans and animals (Slabbekoorn 2018). While the effects of noise on aquatic animals are relatively well studied in marine mammals, with also some insight from marine fish and invertebrates, studies on freshwater animals are still relatively scarce (Mickle and Higgs 2018). The acoustic landscapes of marine and freshwater systems differ considerably in terms of sound propagation, background levels, and types and distribution of sound sources (Wysocki et al. 2007). Therefore, freshwater ecosystems may also be affected differently by anthropogenic noise. To understand how anthropogenic noise may contribute to population-level effects of freshwater animals, it is necessary to understand how they use sound in their natural environment.

Most, if not all, aquatic animals can detect and respond to sound (Popper et al. 2019), and they have been shown to use sound for communication, predator- and prey detection, orientation, navigation, and habitat selection (Popper et al. 2019). There are animals that can detect but that are not known to actively produce sound, but many fish and invertebrates produce sound as a means of underwater communication (Greenhalgh et al. 2025; Looby et al. 2022). It is believed that the use of abiotic sounds, heterospecific calls, and unintended sounds may be important for

orientation and habitat selection (Slabbekoorn and Bouton 2008). However, only a few studies addressed the nature, diversity, and sources of natural freshwater soundscapes. Systematic underwater recordings are required to disentangle geophonic, biophonic, and anthropogenic sources to gain a better understanding of the acoustic world of aquatic animals.

Conceptual Framework to Study the Acoustic World of Migratory Fishes

The authors propose a conceptual framework to evaluate the importance of natural soundscapes and the potentially detrimental effects of anthropogenic noise for freshwater animals, in general, and migratory fishes in particular (Fig. 1). The first step in the framework is to make field recordings for identifying and quantifying natural sounds and anthropogenic noise sources. This can then already be used to make a precautionary impact assessment by comparing the intensity of anthropogenic noise with natural sounds and quantifying the extent of spatial and temporal overlap, which may be used to predict masking impact. Furthermore, it is important to identify natural sounds that have high potential to be used as acoustic cues for aquatic animals, which can then be used in controlled laboratory playback experiments, to verify whether they elicit behavioral changes in fish. If they do, this should be followed up with field experiments to investigate how they may affect free-swimming fish. Once the importance of acoustic cues is identified, the insights can contribute to mitigation measures, fish guidance, or biodiversity monitoring.

Disentangling Natural Sound Sources

Natural soundscapes can be studied through a combination of spatially replicated, short-term recordings and long-term, stationary deployments. Short-term recordings enable extensive spatial coverage, revealing heterogeneity across and within freshwater ecosystems. Long-term recordings capture temporal variability with diurnal, tidal, lunar, or seasonal cycles. Continuous sound sources (typically geophonic), such as water flow, wind, and sediment-induced sounds, can be distinguished from transient sound events (typically biophonic), such as animal vocalizations, bubbles, and splashes (Geay et al. 2020; Tonolla et al. 2010; Wysocki et al. 2007). Studies by te Velde et al. (2024, 2026a) showed that increases in water velocity result in increased sound levels over a wide range of frequencies and that obstructions in flowing water create turbulence and bubble formation, producing sound signatures most pronounced between 125 and 2000 Hz. A water-velocity threshold was also identified at which flow-induced sounds start to dominate the soundscape. Sediment transport generates sound from interparticle collisions, in particular above 1000 Hz (Geay et al. 2020), while spectra vary among sediment types (Greenberg et al. 2025). The local soundscape varies, in addition, with position across the river cross-section (te Velde et al. 2024).

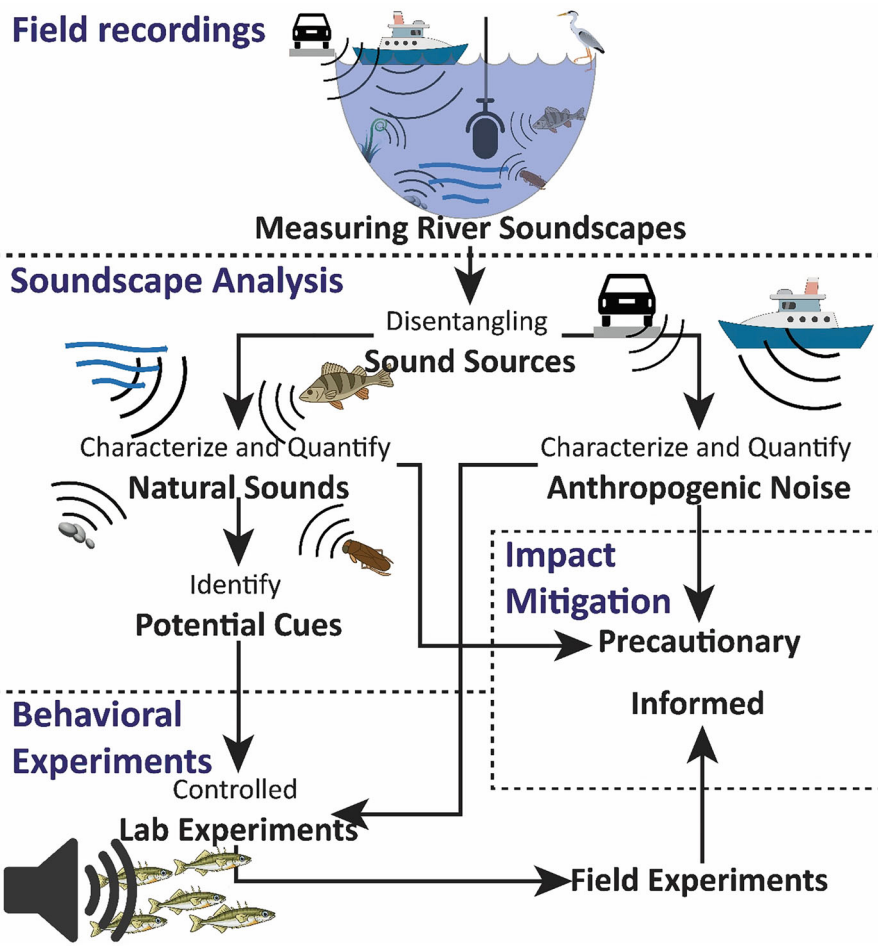

Fig. 1 Framework for investigating how natural acoustic information is used by aquatic animals, in general, and migratory fish, in particular, and evaluating the impacts of anthropogenic noise. (Icons used in this figure were made by the authors or adapted from public domain sources; car and heron by Wikimedia Commons, plant by Openclipart.org, boat image by Vectorportal.com)

Biophonic sounds are diverse and widespread in temperate river systems in Europe (te Velde et al. 2024, 2026a). Underwater sounds include calls from animals, such as amphibians, fish, and insects, and even from birds on, above, or next to the water. Animal sounds are highly variable in spectral and temporal characteristics and are often species-specific. Furthermore, there are many natural sound events not specifically linked to communication, such as gas bubbles from aquatic plants or bubbles escaping from the sediment (van der Lee et al. 2025). Still, most biotic sounds in freshwater have as yet not been described, and only a very limited number of species have been investigated for sound production (Looby et al. 2022; Greenhalgh et al. 2025). Innovative sound processing methods, including machine

learning algorithms, will likely accelerate progress in the study of transient biotic sounds (Stowell 2022; Parcerisas et al. 2024).

Potential Acoustic Cues

In marine systems, attraction to habitat-associated soundscapes has been shown in a wide range of taxa and life stages, including corals, bivalves, crustaceans, and fish (i.e., Lillis et al. 2013; Montgomery et al. 2006; Vermeij et al. 2010). The same may be true for freshwater fish. Soundscape orientation may be especially valuable to migratory fishes that have to navigate long distances in environments limited in terms of other sensory cues (Slabbekoorn and Bouton 2008). Playbacks of coral and oyster reef sounds typically concern a wide range of sounds, from fish calls to shrimp snaps and from geophysical forces, such as wind, waves, and waterflow, and have revealed experimental evidence for positive phonotaxis (Lillis et al. 2013; Montgomery et al. 2006).

Freshwater systems are less often tested experimentally, and soundscape components are rarely tested by themselves for their response triggering potential. However, the authors believe that habitat-specific river soundscapes can also be used by fish as navigational cues. Especially, sediment variation and water flow fluctuations have high potential to yield acoustic cues that have meaning, as many fish have specific sediment and flow condition requirements to deposit their eggs (Kemp et al. 2011). River size and sediment typically change gradually from upstream to downstream, offering reliable acoustic cues due to the predictable geophysical nature of rivers, and may therefore act as acoustic beacons for navigation. Although biophonic sound events are generally less abundant, they can provide high-quality information on habitat suitability, prey availability, potential mates, shelter, and predation risk. For example, bubbles produced by aquatic plants could inform fish about suitable spawning habitats or shelter. The presence of specific species is often linked to specific habitat features (Slabbekoorn and Bouton 2008).

Quantifying Anthropogenic Noise

In freshwater systems, there are two main sources of anthropogenic noise, namely, shipping noise and road traffic noise. Shipping noise is generally composed of a broadband component and a set of tonals, which are both generally high in amplitude compared to natural soundscapes (Jansen and de Jong 2017). Shipping noise in large European rivers can be predicted from AIS (Automatic Identification System) density data from commercial shipping. The density data closely match with higher noise levels near estuaries compared to more upstream locations (te Velde et al. 2026a; Smott et al. 2018). Boat sound presence occurred during 40–100% of the time throughout the Rhine and the Elbe estuary (Te Velde et al. 2026a), which is exceptionally high compared to other studies (Marley et al. 2016; Smott et al. 2018; Vieira et al. 2021). The Rhine is one of the busiest rivers in the world, and the Elbe is

the third busiest river in Europe (Central Commission for the Navigation of the Rhine 2024).

Noisy conditions vary with vessel activity in time and space. In 24-hour spectrograms, slightly lower boat presence was visible during the night. Strong temporal patterns in boat noise occurrence have been found before with higher boat noise during the day, weekends, and summer (Marley et al. 2016; Smott et al. 2018; Vieira et al. 2021). Commercial boat traffic may be more persistent across day, week, and season, while recreational boat traffic, not captured in AIS data, may have stronger diurnal, weekly, and seasonal patterns. There were elevated sound levels and clear diel noise patterns in cities and under bridges in the Netherlands. Even rural locations had diel patterns that are likely attributable to land-based traffic noise (te Velde et al. 2024; Te Velde et al. 2024). Weekends were slightly quieter under bridges compared to weekdays, which was also in line with earlier studies (Martin and Popper 2016). Still, it was rarely quiet under bridges, even at night. Noisy events from passing vehicles on bridges or in tunnels are generally low in frequency, up to 700 Hz, and sometimes up to 2000 Hz (Holt and Johnston 2015; Song et al. 2020).

The Extent of Masking of Natural Sounds in Freshwater Systems

If anthropogenic noise overlaps with biologically relevant sounds, it can lead to masking. Quantitative insights remain limited, but masking reduces the range and time over which suitable mates, predators, prey, and habitats can be detected (Voellmy et al. 2014). Communication is used by many freshwater animals in behaviors, such as mate attraction and alarm calls. Evaluating the masking impacts of noise on acoustic signals vital for survival and reproduction, requires the characterization and quantification of species-specific sounds. As indicated, non-communicative biotic sounds and geophonic sounds can also provide animals with valuable information on local resources, threats, and navigational landmarks. Efforts should be made to mitigate masking of natural sounds wherever possible.

Geophonic sounds can reflect physical aspects of the local river, but they can also produce noisy habitats that limit communication or other subtle sources of biophonic information. And animals are likely adapted to the acoustic environments they occupy. Some species are known to use frequencies that coincide with natural "quiet windows" in freshwater soundscapes for communication (Lugli 2010). Anthropogenic noise may not only mask signals but also fill these natural quiet windows, reducing opportunities for acoustic communication. It is important to quantify the intensity and spectrum of both natural and anthropogenic sounds to be able to predict masking impacts from anthropogenic noise sources. A noisy, high-flow, turbulent river environment is less likely to be impacted by noise than a quiet lake. Comparison of the spectral intensity of identified natural sound sources with that of boats recorded in large European rivers indicates that almost all natural sound sources in rivers are fully masked in the presence of boat noise (Te Velde et al. 2026a). Road traffic noise in and close to cities (te Velde et al. 2024; Te Velde et al. 2024) will likely mask low- and mid-frequency sounds, such as fish grunts.

Responses to Sounds by Freshwater Animals

Fish have been shown to respond to natural and anthropogenic sounds in a variety of ways, including spatial responses and activity level changes (Table 1; Slabbekoorn et al. 2025). Fish either swim toward the sound source (attraction) or away from the sound source (deterrence) (also referred to as positive and negative phonotaxis) (De Vincenzi et al. 2021; Matos et al. 2024; Shafiei Sabet et al. 2016a; Waddell and Širović 2023). Deterrence is typically interpreted as an auditory assessment of unfavorable conditions, such as predator presence, male competitors, or unsuitable habitat (Liu et al. 2019; Moynan et al. 2016; Parmentier et al. 2015; Qin et al. 2020). Attraction toward sounds is generally linked to beneficial conditions such as potential mates, food availability, or suitable habitat (De Vincenzi et al. 2021; Holt and Johnston 2011; Moynan et al. 2016; Wang et al. 2021). Sound can also increase (upregulate) or decrease (downregulate) the occurrence or intensity of certain behaviors, such as swimming speed or antipredator responses (De Vincenzi et al. 2021; Beach et al. 2025; Leduc et al. 2021; Matos et al. 2024; Shafiei Sabet et al. 2016a).

In freshwater, only a few studies have tested responses to natural soundscape cues (Table 1). Holt and Johnston (2011) showed the attraction of several freshwater fish species to acoustic playbacks of sediment disturbances in the field. Febrina et al. (2015) described how intensity-dependent sound preferences of adult and juvenile Ayu (*Plecoglossus altivelis*) varied for several pure tone frequencies and the sounds from an unpassable weir and a passable fish ladder. Three-spined sticklebacks (*Gasterosteus aculeatus*) swam closer to the speaker when natural flow sounds were played (te Velde et al. 2026b). Kowal et al. (2023) did show increased aggregation and changes in swimming patterns and longitudinal position of chub (*Squalius cephalus*) and brown trout (*Salmo trutta*) in response to acoustic playbacks of a high-flow and sediment transport environment. Future experiments should expand across species and contexts, use carefully controlled and well-replicated acoustic stimuli, and focus on behaviors that can be linked to fitness (Slabbekoorn and Bouton 2008; Slabbekoorn et al. 2019).

Conservation with Limited Knowledge

How animals use natural sound cues, how they are affected by noise in freshwater river systems, and how important natural sounds are to their survival and fitness vary among species, life stages, and contexts (Shafiei Sabet et al. 2016b) and can only be determined through experiments. However, experiments take time, and given the current threats to freshwater ecosystems, immediate conservation measures are required to prevent further degradation. A precautionary approach to noise pollution in freshwater is recommended. Given that all natural sounds may serve as important information for aquatic animals, masking of natural sounds should be limited wherever possible, especially in vulnerable habitats and for endangered species.

Unlike the EU Marine Strategy Framework Directive (MSFD), which has included underwater noise as a pollutant since 2008 and requires Member States to

Table 1 Summary of behavioral responses of fishes to natural and anthropogenic sounds. Spatial responses describe movement relative to the sound source. Up- and downregulated behaviors indicate increased or decreased behavioral expression. N.T. = not tested or not reported; empty cells indicate no reported effect

Spatial response	Upregulated behaviors	Downregulated Behaviors	Sound type	Captive/ free swimming	System	Species	Reference
Natural							
Both	*N.T.*	*N.T.*	Vocalizations	Captive	Freshwater	Round Goby	Moynan et al. (2016)
Deterrence		*Swimming speed*	Predator sound	Captive	Freshwater	Flower fish	Liu et al. (2019)
Deterrence	*Swimming speed*		Predator sound	Captive	Freshwater	Tu-fish	Qin et al. (2020)
	Activity		Vocalizations	Captive	Freshwater	Lake Victoria cichlid	Estramil et al. (2014)
Displacement	*Directional changes, acceleration, group cohesion*		Flow sound	Captive	Freshwater	Chub & brown trout	Kowal et al. (2023)
Attraction	*Swimming speed*		Feeding sound	Captive	Freshwater	Flower fish	Wang et al. (2021)
Attraction	*N.T.*	*N.T.*	Rock shuffling	Free swimming	Freshwater	Several	Holt and Johnston (2011)
Both	*N.T.*	*N.T.*	Reef soundscapes	Captive	Marine	Several	Parmentier et al. (2015)
Both							
Deterrence & No-response	*N.T.*	*N.T.*	Boat noise & estuary sound	Captive	Estuary	Several	Waddell and Širović (2023)

Deterrence & attraction and diving down	*Activity & no response*		Boat noise & biophony	Captive	Marine	*Small-spotted catshark*	De Vincenzi et al. (2021)
Deterrence & attraction	*Group cohesion*		Boat noise & flow sound	Captive	Freshwater	Three-spined Stickleback	Te Velde et al. (2026b)
Anthropogenic							
Deterrence	*Activity & Swimming speed*		Boat noise	Captive	Freshwater	Brook trout	Beach et al. (2025)
N.T.	*Startle responses*	*Feeding*	White noise	Captive	Freshwater	Three-spined stickleback	Purser and Radford (2011)
N.T.	*Antipredator response*		Boat noise	Captive	Freshwater	Three-spined stickleback & European minnow	Voellmy et al. (2014)
Displacement		*Vocal activity*	Boat noise	Free swimming	Estuary	Meagre & weakfish	Matos et al. (2024)
Deterrence		*Swimming speed*	Intermittend	Captive	Freshwater	Zebrafish	Shafiei Sabet et al. (2016a)
N.T.	*Swimming speed & group cohesion*		Intermittend & continuous	Captive	Freshwater	European minnow	Currie et al. (2020)
		Feeding, antipredator response	Carnaval noise	Free swimming	Marine	Brazilian damsels	Leduc et al. (2021)
N.T.	*Antipredator response*		Boat noise	Free-swimming	Marine	Brown meagre	La Manna et al. (2016)

monitor and set thresholds for it, the Water Framework Directive (WFD) incorporates no legislative protection for freshwater ecosystems against anthropogenic noise (Bolgan et al. 2016). However, freshwater ecosystems over a large geographic range experience noise pollution from various sources for long periods of time. Associated problems can be counteracted, for example, by limiting sound transmission through material choices when constructing roads and bridges or through modifications to ship propellers, but also with speed limits, rerouting shipping lanes, requiring ships to travel in convoy, incentivizing fewer boats with larger transport capacity (Merchant 2019), or by enforcing closed seasons or times for boat traffic in important seasons or habitats (Findlay et al. 2023).

Conclusions

Soundscape recordings reveal that the most prominent sounds in freshwater habitats include continuous geophonic sounds from water flow, wind, and sediment transport. Furthermore, transient biophonic sounds from amphibians, fish, and insects appear diverse and widespread. These natural sounds stand out as promising acoustic cues for migratory fish. Although transient biophonic sounds, such as animal communication signals or aquatic plant bubbles, have lower temporal availability, they may provide high-quality cues by reflecting nearby resources or dangers, such as conspecifics, predators, shelter, or food. The dominant anthropogenic noise sources in freshwater systems are inland shipping and land-based traffic noise. Commercial shipping produces continuous high-amplitude broadband noise in large rivers and estuaries, while road noise produces persistent low-frequency noise near roads, cities, and under bridges, with clear temporal patterns characteristic of human activity. Hence, acoustic masking of natural sounds by anthropogenic noise may be widespread in freshwater systems. Future research should prioritize experimental validation of potential acoustic cues in the field, effects of anthropogenic noise sources on fish migration, the use of passive acoustic monitoring using machine learning, and the development of predictive noise maps to assess masking impacts. A precautionary approach to noise management is urgently needed, and soundscapes should be integrated into conservation planning, particularly at migratory bottlenecks and vulnerable habitats for migratory fishes. Noise monitoring and mitigation measures should be incorporated into international freshwater legislation, such as the European Water Framework Directive.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

References

Beach RK et al (2025) No trout about it: behavioural and transcriptional effects of long-term noise exposure in brook trout (Salvelinus fontinalis). Can J Fish Aquat Sci 82:1–16

Bolgan M et al (2016) First observations of anthropogenic underwater noise in a large multi-use lake. J Limnol 75(3):644–651

Central Commission for the Navigation of the Rhine (2024) Annual Report

Costa MJ et al (2021) Major threats to European freshwater fish species. Sci Total Environ 797:149105
Currie HAL et al (2020) Group behavior and tolerance of Eurasian minnow (*Phoxinus phoxinus*) in response to tones of differing pulse repetition rate. J Acoust Soc Am 147(3):1709–1718
De Vincenzi G et al (2021) Biological sound vs. anthropogenic noise: assessment of behavioural changes in *Scyliorhinus canicula* exposed to boats noise. Animals 11(1):174
Estramil N et al (2014) Cichlids respond to conspecific sounds but females exhibit no phonotaxis without the presence of live males. Ecol Freshw Fish 23(3):305–312
Febrina R et al (2015) Modeling the preference of ayu (*Plecoglossus altivelis*) for underwater sounds to determine the migration path in a river. Ecol Model 299:102–113
Findlay CR et al (2023) Small reductions in cargo vessel speed substantially reduce noise impacts to marine mammals. Sci Adv 9(25):eadf2987
Geay T et al (2020) Passive acoustic measurement of bedload transport: toward a global calibration curve? J Geophys Res: Earth Surf 125(8):e2019JF005242
Greenberg M, Kushnir U, Frid V (2025) Frequency-dependent acoustic reflection for soil classification in a controlled aquatic environment. Appl Sci 15(9):4870
Greenhalgh JA et al (2025) The freshwater sounds archive. bioRxiv:2025–2005
Holt DE, Johnston CE (2011) Can you hear the dinner bell? Response of cyprinid fishes to environmental acoustic cues. Anim Behav 82(3):529–534
Holt DE, Johnston CE (2015) Traffic noise masks acoustic signals of freshwater stream fish. Biol Conserv 187:27–33
Jansen E, de Jong C (2017) Experimental assessment of underwater acoustic source levels of different ship types. IEEE J Ocean Eng 42(2):439–448
Kemp P et al (2011) The impacts of fine sediment on riverine fish. Hydrol Process 25(11): 1800–1821
Kowal JL et al (2023) Does soundpeaking affect the behavior of chub (*Squalius cephalus*) and brown trout (*Salmo trutta*)? An experimental approach. Fishes 8(12):581
La Manna G et al (2016) Behavioral response of brown meagre (*Sciaena umbra*) to boat noise. Mar Pollut Bull 110(1):324–334
Leduc AOHC et al (2021) Land-based noise pollution impairs reef fish behavior: a case study with a Brazilian carnival. Biol Conserv 253:108910
Lillis A, Eggleston DB, Bohnenstiehl DWR (2013) Oyster larvae settle in response to habitat-associated underwater sounds. PLoS One 8(10):e79337
Liu G et al (2019) Laboratory experiments demonstrate that the hissing of the Chinese alligator can effectively inhibit movement of flower fish *Ptychobarbus kaznakovi*. Hydrobiologia 836(1): 97–108
Looby A et al (2022) A quantitative inventory of global soniferous fish diversity. Rev Fish Biol Fish 32(2):581–595
Lugli M (2010) Sounds of shallow water fishes pitch within the quiet window of the habitat ambient noise. J Comp Physiol A 196:439–451
Marley SA, Erbe C, Salgado-Kent CP (2016) Underwater sound in an urban estuarine river: sound sources, soundscape contribution, and temporal variability. Acoustics Australia 44(1):171–186
Martin SB, Popper AN (2016) Short-and long-term monitoring of underwater sound levels in the Hudson River (New York, USA). J Acoust Soc Am 139(4):1886–1897
Matos AB et al (2024) Reaction of two sciaenid species to passing boats: insights from passive acoustic localisation. Estuar Coast Shelf Sci 311:109012
Merchant ND (2019) Underwater noise abatement: economic factors and policy options. Environ Sci Pol 92:116–123
Mickle MF, Higgs DM (2018) Integrating techniques: a review of the effects of anthropogenic noise on freshwater fish. Can J Fish Aquat Sci 75(9):1534–1541
Montgomery JC et al (2006) Sound as an orientation cue for the pelagic larvae of reef fishes and decapod crustaceans. Adv Mar Biol 51:143–196
Moynan CR, Neumann CE, Welsh CA (2016) The effect of gender, tone, and sound location on the response behavior of *Neogobius melanostomus* (Round Goby) and the possibility of future trapping of this invasive species in lake superior. Zebrafish 13(4):287–292

Parcerisas C et al (2024) Machine learning for efficient segregation and labeling of potential biological sounds in long-term underwater recordings. Front Remote Sensing 5:1390687
Parmentier E et al (2015) The influence of various reef sounds on coral-fish larvae behaviour. J Fish Biol 86(5):1507–1518
Popper AN et al (2019) Examining the hearing abilities of fishes. J Acoust Soc Am 146(2):948–955
Purser J, Radford AN (2011) Acoustic noise induces attention shifts and reduces foraging performance in three-spined sticklebacks (*Gasterosteus aculeatus*). PLoS One 6(2):e17478
Qin XH et al (2020) Spatial avoidance of tu-fish *Schizopygopsis younghusbandi* for different sounds may inform behavioural deterrence strategies. Fish Manag Ecol 27(1):10–19
Sayer CA et al (2025) One-quarter of freshwater fauna threatened with extinction. Nature 638(8049):138–145
Shafiei Sabet S, Van Dooren D, Slabbekoorn H (2016a) Son et lumière: sound and light effects on spatial distribution and swimming behavior in captive zebrafish. Environ Pollut 212:480–488
Shafiei Sabet S et al (2016b) Behavioural responses to sound exposure in captivity by two fish species with different hearing ability. Anim Behav 116:1–11
Slabbekoorn H (2018) Soundscape ecology of the Anthropocene. Acoustics Today 14(1):42–49
Slabbekoorn H, Bouton N (2008) Soundscape orientation: a new field in need of sound investigation. Anim Behav 76(4):e5–e8
Slabbekoorn H et al (2019) Population-level consequences of seismic surveys on fishes: an interdisciplinary challenge. Fish Fish 20(4):653–685
Slabbekoorn H et al (2025) Anthropogenic noise and artificial light at night: additive and interactive effects on activity level and spatial behaviour. In: Proceedings of Forum Acusticum/EuroNoise 2025, European Acoustics Association, 23–26 June 2025, Málaga, Spain. Forum Acusticum, pp 249–256. https://doi.org/10.61782/fa.2025.0139
Smott S et al (2018) Boat noise in an estuarine soundscape–a potential risk on the acoustic communication and reproduction of soniferous fish in the May River, South Carolina. Mar Pollut Bull 133:246–260
Song X et al (2020) Experimental and numerical study on underwater noise radiation from an underwater tunnel. Environ Pollut 267:115536
Stowell D (2022) Computational bioacoustics with deep learning: a review and roadmap. PeerJ 10: e13152
Te Velde K, Slabbekoorn H (2024) Acoustic profiles of underwater soundscapes affected by road traffic. In: The effects of noise on aquatic life: principles and practical considerations. Springer International Publishing, Cham, pp 365–378
Te Velde K et al (2024) Natural soundscapes of lowland river habitats and the potential threat of urban noise pollution to migratory fish. Environ Pollut 359:124517
Te Velde K et al (2026a) Human-altered Soundscapes in Large European Rivers: widespread potential for masking by boats. Under review
Te Velde K et al (2026b) Spatial response to playbacks of natural flow sound and ship noise in wild-caught sticklebacks. Under review
Tonolla D et al (2010) A field-based investigation to examine underwater soundscapes of five common river habitats. Hydrol Process 24(22):3146–3156
van der Lee GH et al (2025) Underwater plant sounds: diel acoustic patterns of four submerged aquatic macrophytes. Sci Total Environ 993:179967
Vermeij MJA et al (2010) Coral larvae move toward reef sounds. PLoS One 5(5):e10660
Vieira M, Fonseca PJ, Amorim MCP (2021) Fish sounds and boat noise are prominent soundscape contributors in an urban European estuary. Mar Pollut Bull 172:112845
Voellmy IK et al (2014) Acoustic noise reduces foraging success in two sympatric fish species via different mechanisms. Anim Behav 89:191–198
Waddell EE, Širović A (2023) Effects of anthropogenic noise and natural soundscape on larval fish behavior in four estuarine species. J Acoust Soc Am 154(2):863–873

Wang M et al (2021) Can feeding sound attract flower fish (*Ptychobarbus kaznakovi*)? J Comp Physiol A 207(5):617–627
WWF (2024) Living planet report 2024 – a system in peril. WWF, Gland
Wysocki LE, Amoser S, Ladich F (2007) Diversity in ambient noise in European freshwater habitats: noise levels, spectral profiles, and impact on fishes. J Acoust Soc Am 121(5): 2559–2566