Fish Models in Noise Pollution Research: A Comparative Perspective on Freshwater and Marine Species

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Abstract

Anthropogenic underwater noise has emerged as a growing stressor in aquatic ecosystems, with negative impact on fish physiology, sensory adaptation, behavior, and survival. This chapter reviews current knowledge on the fish species most commonly used to investigate the effects of noise pollution, highlighting the

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advantages and limitations of freshwater versus marine models, while also proposing guidelines for species selection. While zebrafish has been widely used as a freshwater model, the marine medaka is presented as a promising model species for ecotoxicology and noise pollution research.

Furthermore, studies indicate that molecular and physiological alterations, such as transcriptomic changes and endocrine disruption, can occur even in the absence of evident behavioral changes, highlighting the need for integrative approaches. By integrating behavioral, physiological, and molecular approaches with model organisms that allow high-throughput screening of ecotoxicology effects, this chapter outlines strategies for improving noise pollution research.

Keywords

Anthropogenic noise · Model organism · Freshwater fish · Marine fish

Introduction

Sound is a fundamental source of information for fish, providing essential cues about their environment, including the presence of conspecifics, predators, and prey, and serving multiple vital functions such as spatial orientation, habitat selection, and social interactions (reviewed in Popper and Hawkins 2019). Unlike other sensory cues, which attenuate quickly underwater, sound travels efficiently and over long distances, making it an especially reliable information source in aquatic habitats. However, both physical and chemical factors significantly influence sound propagation in freshwater and marine environments. While water depth strongly affects transmission through interactions with the bottom and surface, temperature variation and stratification can alter how sound travels in both ecosystems (Possenti et al. 2023). Water density related to salinity is another important factor increasing sound speed in the ocean, as well as the composition of the seabed or lakebed (such as rocks, sand, silt, clay, aquatic vegetation), which can influence sound absorption and reflection in both ecosystems (e.g., Lagrois et al. 2025). As such, fish have evolved diverse and highly sensitive auditory systems to detect acoustic signals and perform auditory scene analysis in these highly variable acoustic environments (Ladich and Schulz-Mirbach 2016). Aquatic soundscapes can be extremely rich in information, composed by biotic sounds, such as fish vocalizations and snapping shrimp clicks (e.g., Rountree et al. 2020), and abiotic geophysical sounds, including those from wind, rain, hydraulic turbulence (waves) or sediment transport.

However, the last few decades have seen an unprecedented increase in anthropogenic underwater noise, which now dominates many freshwater and marine environments, particularly in coastal regions where human activity is typically concentrated. While marine environments are mostly affected by noise generated from various sources, including shipping activities, industrial operations, construction, seismic exploration, and fishing sonar, freshwater environments are typically affected by noise from boating, ferry traffic, road bridges, and nearby industrial activities (Duarte et al. 2021).

Numerous studies have documented that exposure to anthropogenic noise can disrupt various aspects of fish behavior in both marine and freshwater ecosystems, affecting proximate individual responses (aggression, communication, foraging, parental care, prey detection) and ultimate social responses (e.g., group cohesion, social bonds) (Kunc et al. 2016). Altered swimming activity, reduced foraging efficiency, impaired social interactions, and changes in risk-taking behavior are among the commonly reported outcomes (Kunc et al. 2016; Popper and Hawkins 2019). These behavioral disruptions may, in turn, compromise survival and fitness, particularly when they interfere with predator avoidance or reproductive success. Anthropogenic noise is also known to induce physiological stress, impair acoustic communication, affect spawning interactions and egg production, and even cause mortality (e.g., Blom et al. 2019; Faria et al. 2022; Lara and Vasconcelos 2021; Lara et al. 2022). These effects have been reported for both marine and freshwater species, despite their ecological differences and distinct threats.

Given the substantial research conducted using both marine and freshwater species, an overview of the advantages and limitations of the most used organisms is needed to help guide researchers in selecting the most appropriate study species for future research.

The goal of this chapter is to synthesize current knowledge on the most used freshwater and marine fish species for studying the impact of noise pollution and identify specific knowledge gaps that warrant further investigation.

Freshwater Versus Marine Fish Models in Bioacoustics

Freshwater fish species offer key advantages for noise pollution research, including easier maintenance and breeding in laboratory settings, well-established genetic and molecular tools, and high relevance to inland aquatic ecosystems, which are increasingly exposed to anthropogenic acoustic disturbances such as boating, hydropower, and aquaculture (Rountree et al. 2020, Table 1). Moreover, the most hearing-sensitive fish are almost exclusively freshwater species found in rivers, lakes, and floodplains and include both otophysans and anabantoids (Ladich and Schulz-Mirbach 2016). Otophysans, a diverse group including carps, minnows, catfish, and characins, possess a Weberian apparatus that enhances auditory sensitivity and extends the detectable frequency range. Anabantoids, such as the Siamese fighting fish and gouramis, have a highly folded, vascularized labyrinth organ supported by the epibranchial bone, enabling aerial respiration and enhancing their hearing abilities (Ramos et al. 2025).

On the other hand, marine fish models also offer research advantages since they inhabit environments dominated by anthropogenic noise sources (shipping, drilling, and construction). Many species rely on acoustic communication, experience long-range sound masking effects, and frequently represent species of commercial or ecological importance. Besides, marine fish models are particularly valuable for research on climate change, as they inhabit environments where global-scale stressors such as warming, acidification, and deoxygenation co-occur and interact,

Table 1 Comparative features of freshwater and marine fish studies for bioacoustics and underwater noise research (partially based on Risch and Parks 2017; Popper and Hawkins 2019)

Research topic	Freshwater fish	Marine fish
Hearing	High variation in auditory sensitivity across species. Several species with specialized auditory structures, higher sensitivity and wider detectable frequency bandwidth (otophysans and anabantoids).	More information on auditory-vocal systems, and acoustic preferences (phonotaxis).
Acoustic communication	Less studied or vocal species reported.	Many examples of vocal communication systems used for mating, nest signaling, and agonistic interactions.
Anthropogenic noise sources	Studies focus mainly on boat noise.	Studies cover a wide range of anthropogenic noise sources like shipping, pile driving, construction, seismic airguns, fishing and military sonars.
Behavioral responses	Changes in swimming patterns, anxiety-like responses, social interactions and feeding.	Changes in swimming patterns, social interactions, feeding, and orientation.
Research location	Less in situ research; mostly lab or small enclosure studies.	Both lab and field studies; more realistic noise exposure experiments.
Ecoacoustic tools	Emerging but with many knowledge gaps.	More established with advanced monitoring and analytical methods.
Conservation implications	More research needed to inform conservation strategies.	More informed but generally lacking noise mitigation efforts.
Genetic and molecular tools	Well-developed for species like zebrafish, enabling mechanistic studies.	Very limited; possible expansion for some model species used in ecotoxicology (e.g., marine medaka).

providing a realistic context for assessing combined impacts, including with noise pollution (Possenti et al. 2023). Their relevance is further enhanced by environmental conservation policies, with international frameworks (e.g., IPCC 2023) often prioritizing marine ecosystems.

Table 1 provides a comparative perspective on the use of freshwater and marine fish species in bioacoustics and underwater noise research. Overall, freshwater models provide advanced genetic tools and valuable insights into auditory specialization, while marine models offer greater ecological value and more established ecoacoustic methodologies. This comparison supports the need to integrate both fish groups in future research when addressing noise pollution at a global scale, while also highlighting specific knowledge gaps that require further investigation, such as field-based studies in freshwater ecosystems and the establishment of marine models that enable integrative approaches to assess behavioral, physiological, neural, and molecular responses to acoustic stress.

Diversity of Fish Models in Noise Pollution Research

A wide range of fish species has been used to investigate the impacts of anthropogenic noise, reflecting both the availability of laboratory models and their ecological relevance of species (see Table 2). These studies have revealed consistent effects of noise on auditory sensitivity, behavior, physiology, and reproduction, though

Table 2 Examples of freshwater and marine fish species used in noise pollution research

Freshwater species	Main research focus	Marine species	Main research focus
Zebrafish (*Danio rerio*)	Hearing loss, inner ear, physiological and behavioral stress, developmental effects, gene expression (e.g., Schuck et al. 2011; Lara and Vasconcelos 2021; Wong et al. 2022)	**Lusitanian toadfish** (*Halobatrachus didactylus*)	Vocal behavior disruption, auditory masking, physiological stress, developmental effects (e.g., Vasconcelos et al. 2007; Faria et al. 2022)
Goldfish (*Carassius auratus*)	Hearing loss, inner ear damage (e.g., Smith et al. 2004; Wysocki and Ladich 2005)	**Meagre** (*Argyrosomus regius*)	Vocal behavior disruption, auditory masking, developmental effects (e.g., Vieira et al. 2021; Trabulo et al. 2023)
Common carp (*Cyprinus carpio*)	Behavioral and physiological responses, auditory masking (e.g., Wysocki et al. 2006; Ladich and Schulz-Mirbach 2013; Zielinski and Sorensen 2017; Currie et al. 2025)	**Atlantic cod** (*Gadus morhua*)	Growth, behavior, development, physiology, hearing (e.g., Hawkins and Popper 2020; Davidsen et al. 2019; McQueen et al. 2023)
Rainbow trout (*Oncorhynchus mykiss*)	Reproduction, growth, behavioral effects, auditory sensitivity (e.g., Scholik et al. 2004; Hasan et al. 2018)	**European seabass** (*Dicentrarchus labrax*)	Stress physiology, hearing thresholds, growth impacts (e.g., Radford et al. 2016; Neo et al. 2018)
Minnows (e.g., *Pimephales promelas*)	Hearing loss, behavioral effects (e.g., Scholik et al. 2004; Hasan et al. 2018)	**Gilthead seabream** (*Sparus aurata*)	Behavioral disruption and physiological stress (e.g., Celi et al. 2016)
African Cichlids (e.g., *Astatotilapia burtoni, Maylandia zebra*)	Growth, behavior, reproduction, developmental and transcriptomic effects (e.g., Butler and Maruska 2021; Wang et al. 2025)	**Gobies** (e.g., *Pomatoschistus pictus, Pomatoschistus microps, Gobiusculus flavescens*)	Vocal behavior disruption, spawning, antipredator behavior (e.g., de Jong et al. 2018; Blom et al. 2019; Kok et al. 2021)

findings are difficult to compare since studies focused on distinct noise sources, exposure regimes, treatment conditions, and methodological approaches.

Freshwater models such as zebrafish, goldfish, carp, trout, minnows, and cichlids have been particularly important in advancing understanding of noise effects on hearing, physiological stress, and behavioral responses.

Zebrafish (*Danio rerio*) is a key model species in ecotoxicology, and research on noise pollution has primarily examined hearing loss, physiological stress, and behavioral responses. Studies by Breitzler et al. (2020) and Wong et al. (2022) demonstrated that 24-hour exposure to continuous and intermittent white noise (130–150 dB re 1 μPa) leads to hearing loss (up to 14 dB) and increased auditory response latency, as well as saccular hair cell loss and reduced presynaptic activity (Ribeye b protein levels) at the highest sound level tested (150 dB) in zebrafish. Temporary threshold shifts (TTS) and recovery time, including both saccular hair cells and sensitivity, revealed a noise level-dependent relationship (Breitzler et al. 2020). Behavioral assays also indicated heightened anxiety-like responses in noise-treated zebrafish, as they spent more time near the bottom when introduced in a novel environment (Vasconcelos et al. 2023). Moreover, chronic exposure to continuous white noise at the larval stage (150 dB re 1 μPa) also elevated auditory thresholds and reduced saccular hair cell number (Lara et al. 2022), while causing physiological stress, shown by increased cardiac rate, yolk sac consumption, and cortisol levels (Lara and Vasconcelos 2021).

Goldfish (*Carassius auratus*) has also been widely used in auditory neurophysiology, serving as a reference species for investigating noise impacts on the auditory system and behavioral stress. For instance, when goldfish were exposed to 24 hours of white noise (158 dB re 1 μPa), they revealed a 21 dB reduction in hearing sensitivity, with recovery times ranging from 3 days to 2 weeks (Wysocki and Ladich 2005). Another study by Smith et al. (2004) found that noise exposure (to white noise, 160–170 dB re 1 μPa) was correlated with increased cortisol levels, but not glucose, after 10 min treatment.

An additional freshwater fish that has been mostly studied at the behavioral level is the common carp (*Cyprinus carpio*). A recent study by Currie et al. (2025) demonstrated that in this species, the ability to discriminate 170 Hz tones across different signal-to-noise ratios was reduced under masking noise conditions. Startle responses were absent, and swimming speed, group cohesion, and alignment were suppressed, although these behaviors improved with higher signal-to-noise ratios. Another example was the study conducted by Zielinski and Sorensen (2017) that showed that the carp displayed negative phonotaxis to complex broadband sounds, although this avoidance behavior diminished after repeated exposures.

The rainbow trout (Oncorhynchus mykiss) has also been considered in research related to noise in aquaculture environments. Evidence showed no effects on auditory sensitivity of chronic noise exposure (115–150 dB re 1 μPa) from housing facilities (Wysocki et al. 2007). In addition, Long-term exposure up to five months to elevated noise levels (149 dB vs. 117 dB) showed no lasting differences in growth rate, body condition, feed conversion efficiency, or survival. Trout initially experienced slower growth within the first month at the highest noise level, but they acclimated thereafter, equalizing growth rates with quieter conditions (Davidson et al. 2009).

Examples of small freshwater fish used in aquatic toxicology and noise pollution research are the minnows, such as the fathead minnow *Pimephales promelas*. For instance, a previous study showed that motorboat noise disrupted antipredator behavior by eliminating fright responses to conspecific alarm cues (Hasan et al. 2018). Interestingly, fathead minnows retained the ability to learn new sound–predator associations when acoustic cues were paired with chemical alarm signals, indicating adaptive learning in response to altered acoustic environments (Wisenden et al. 2008).

Finally, the African cichlids have been widely used to study animal behavior, evolutionary speciation, and noise-induced behavioral changes. For example, research with *Astatotilapia burtoni* showed that noise exposure (~140 dB, pure tones) induced over 50% of brooding females to cannibalize their young or prematurely release them, compared to 90% of control females that maintained normal maternal behaviors (Butler and Maruska 2021). RNA-seq analysis revealed that genes related to feeding and parental care were differentially expressed in the brains of noise-exposed females and that noise-exposed juveniles had lower body condition factors, higher mortality, and altered head transcriptomes compared to controls. Recently, a recent study by Wang et al. (2025) on another cichlid species (*Maylandia zebra*) found that juveniles exposed to boat noise exhibited increased foraging activity and swimming distance, stayed closer to the surface, and showed reduced digging, shelter use, and group cohesion. Although such changes disappeared with time, suggesting habituation, the authors suggested they may pose unpredictable risks at early developmental stages in the wild.

Among marine species, the Lusitanian toadfish (*Halobatrachus didactylus*) and the meagre (*Argyrosomus regius)* have been studied in the context of noise pollution due to their high dependence on acoustic communication and susceptibility to acoustic disturbance. Both species experienced auditory masking due to boat noise, which impaired their ability to discriminate conspecific calls, potentially affecting reproductive communication and sensory adaptation (e.g., Vasconcelos et al. 2007; Vieira et al. 2021).

Another important reference is the Atlantic cod (*Gadus morhua*), which is a commercially important species and an ideal model for noise research due to the available acoustic monitoring techniques, such as fixed-station passive acoustic recorders or mobile gliders to map their spatial distribution and movement, especially during the spawning season. This species show weak behavioral responses to seismic airguns, such as minor depth changes without significant alterations in activity or space use (McQueen et al. 2023), physiological effects, including bradycardia, and increased variability in depth and horizontal movements (Davidsen et al. 2019). European seabass (*Dicentrarchus labrax*), a valuable commercial species, reacts strongly to impulsive noise, exhibiting elevated ventilation rates. However, the response to continuous ship noise is less pronounced and long-term exposure suggests some habituation (Radford et al. 2016).

Gilthead seabream (*Sparus aurata*), another important model, exhibited noise frequency-dependent behavioral changes—low-frequency sounds causing short-term dispersion with partial habituation, while higher frequencies trigger persistent responses (Mauro et al. 2020). Prolonged exposure to boat noise also elevated multiple stress biomarkers, including ACTH, cortisol, glucose, lactate, and Hsp70, demonstrating a strong physiological stress response (Celi et al. 2016).

Moreover gobies have been used as marine species in bioacoustics studies, including noise pollution. For instance, the common goby (*Pomatoschistus microps*) reduced spawning probability and increased latency in nest inspection under continuous noise (Blom et al. 2019).

Finally, preliminary findings (Ramos et al., unpublished) suggest that marine medaka (*Oryzias melastigma*) are behaviorally sensitive to boat noise, affecting their anxiety-like behavior in a novel environment, as well as hearing and egg production. Given that this species is already established as a promising model in marine ecotoxicology, the authors suggest that future research should prioritize its use to investigate the molecular mechanisms underlying the impacts of noise pollution.

Conclusion and Future Perspectives

In summary, research on both freshwater and marine fishes demonstrates that anthropogenic noise affects multiple biological levels, ranging from auditory sensitivity and inner ear structure (e.g., hearing loss, hair cell damage), extending to whole-organism physiological stress responses (elevated cortisol and cardiac rates), and ultimately impacting higher-level processes such as behavior, communication, and reproductive success. These effects can compromise individual survival, alter population dynamics, and ultimately reshape community structure in aquatic ecosystems.

Deciding whether to work with freshwater or marine species is important because the two groups offer complementary advantages that shape both the scope and applicability of research outcomes. Freshwater species, such as zebrafish, are well-established model organisms with powerful genetic and molecular tools, transparent larvae, and short generation times. This makes them ideal for controlled laboratory experiments and for uncovering mechanistic insights into how noise affects hearing, physiology, and behavior. Other freshwater fishes, including goldfish, carps, cichlids, minnows, and trouts, have also been used in noise studies, providing diverse perspectives on auditory physiology, stress responses, reproductive behavior, and predator–prey interactions. However, much less information and molecular tools are available for these species, which limits the depth of mechanistic understanding they can provide. More research on alternative freshwater models is therefore needed to better understand how animals navigate their highly variable natural environments, understand their distinct sensory ecology and stress coping mechanisms, and to gain greater ecological relevance in laboratory-based studies.

On the other hand, studies on marine species provide greater ecological relevance, as many fishes have been investigated in relation to their acoustic communication systems and navigation based on acoustic cues within their natural habitats. Studying marine fishes such as cod, toadfish, seabass, or gobies has revealed how anthropogenic noise interacts with life-history strategies and ecological contexts, making it possible to assess the broader consequences for populations and ecosystems. Future studies should focus on expanding the range of marine species studied, integrating multilevel assessments (from molecular to ecological) using model species such as marine medaka, and conducting long-term field-based experiments to better predict the consequences of chronic noise pollution on marine biodiversity.

The choice of fish models in noise pollution research should be guided by the specific research goals and practical considerations. For mechanistic and physiological studies, small species such as the freshwater zebrafish or the marine medaka are ideal due to their well-established genetic, molecular, and electrophysiological tools, as well as their suitability for controlled laboratory experiments. For studies emphasizing ecological relevance or conservation, marine models such as toadfish, meagre, cod, or gobies, and freshwater species, such as catfish and cichlids, provide greater choice, especially when investigating natural soundscapes, acoustic communication, and the impacts of anthropogenic noise in the wild. In applied aquaculture research, species like sole, turbot, seabass, and seabream are most appropriate given their economic importance and relevance production practices and animal welfare. Practical considerations are also critical, namely species availability, ease of maintenance and breeding, ethical or regulatory restrictions, hearing range, and whether the species exhibits vocal behavior or hearing specializations should all inform the choice.

Finally, integrating both freshwater and marine models, where feasible, offers the most comprehensive approach by bridging mechanistic insights with ecological and applied outcomes, offering a broad perspective across ecosystems. The use of model organisms, namely fish species that are widely studied and for which extensive scientific knowledge, standardized protocols, and technical tools are available, can be advantageous due to their established research frameworks and comparability across studies.

Moreover, a major challenge in evaluating the impacts of underwater noise is the complexity and variability of biological responses, which are influenced by various intrinsic and extrinsic factors. Factors such as sex, age, developmental stage, species-specific traits, and environmental context can significantly affect how individuals respond to acoustic disturbances. To address this variability, robust multifactorial experimental designs are needed that account for biological diversity within species and their ecological context. Such approaches are essential for identifying vulnerability periods and resilience mechanisms to noise exposure.

Additionally, comparative approaches should consider evolutionary adaptations and life-history traits that may affect sensitivity to noise exposure. Also, Laboratory-based studies often suffer from unrealistic sound fields, lack of particle motion measurements, and inconsistencies in noise exposure protocols (Popper and Hawkins 2018). Differences in sound sources, levels, durations, and frequency content make cross-study comparisons difficult. Moreover, most behavioral research focuses on adults, despite evidence that early developmental periods and later life stages may be more vulnerable to acoustic disturbances.

Another critical gap is the limited integration of behavioral endpoints with physiological, neural, and molecular data. Without this, the mechanisms by which noise alters behavior, whether through direct sensory interference, stress-axis activation, or energy trade-offs, remain unclear. The molecular mechanisms driving noise-induced changes are poorly explored. Evidence indicates that noise can disrupt endocrine regulation, activate chronic stress pathways, induce oxidative stress, alter neurotransmitter levels and impair sensory function (e.g., Butler and Maruska 2021; Faria et al. 2022). These disruptions can lead to deficits in development, locomotion, cognition, social behavior, and reproduction. For instance, transcriptomic studies on species such as brook trout, and farmed salmon have revealed significant changes in the expression of genes related to neuroplasticity, metabolism, protein folding, and stress responses. These molecular changes often correlate with behavioral impairments (Zhang et al. 2024). In some cases, these alterations occurred before or independently of observable behavioral changes, emphasizing the importance of integrating molecular insights with detailed behavioral assessments. Also, Increasing the use of multiomics approaches alongside hormonal, neurophysiological, and behavioral data will enable more robust causal inferences.

Overall, Future research should adopt standardized, biologically informed, and ecologically relevant protocols, apply multiomics analyses, and address chronic and transgenerational impacts. Linking molecular alterations to ecological processes will provide the mechanistic framework needed for predictive models of noise vulnerability and guide mitigation strategies.

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