

Bioacoustics disruption in marine environments: Reviewing the impact of anthropogenic noise on marine organisms

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Abstract

Anthropogenic underwater noise is increasingly recognized as a pervasive stressor in marine ecosystems, with significant implications for biodiversity and ecological health. This review synthesizes findings from the literature and studies conducted between 1992 and 2024, focusing on the impacts of anthropogenic noise on marine mammals, fishes, and sea turtles. Key sources of underwater noise include offshore seismic surveys, sonar systems, shipping activities, and oil and gas exploration. These sounds vary in intensity, frequency, and duration, resulting in a range of biological responses across taxa. The review identifies consistent evidence of behavioral disruptions, such as altered communication, foraging, mating, and migratory patterns. Physiological effects include hearing loss, tissue damage, endocrine disruption, and elevated stress hormone levels. Developmental impacts, particularly in early life stages, include growth abnormalities and sensory impairment. Species-specific variability in sensitivity to sound presents challenges for standardized assessments but underscores the need for targeted research. Mitigation strategies are also discussed, including passive acoustic monitoring, exclusion zones, soft-start procedures, and engineering controls such as bubble curtains and hydro sound dampers. These measures, while promising, require further evaluation for effectiveness across varying marine conditions. Given the rapid expansion of offshore industrial activity within Guyana's Exclusive Economic Zone, this review highlights the urgent need for context-specific research and stronger regulatory frameworks. Raising awareness among stakeholders and informing conservation policy are essential to reducing acoustic impacts and preserving marine biodiversity.

Keywords: Anthropogenic noise; Marine organisms; Marine environments; Bioacoustics disruption; Impact.

1. Introduction

Marine ecosystems encompass a wide range of organisms living in saltwater, including macroscopic plants and animals, as well as microorganisms such as bacteria and archaea [12, 17]. These systems contribute significantly to global ecological processes, including biogeochemical cycling, oxygen production, and carbon sequestration. In addition to supporting biodiversity, marine life provides essential ecosystem services such as food, medicine, and raw materials for billions of people. Furthermore, marine environments support coastal economies among other activities through fisheries, tourism, and recreation [24].

The Exclusive Economic Zone (EEZ), as defined by the United Nations Convention on the Law of the Sea (1982), grants coastal states sovereign rights over marine resources within 200 nautical miles of their coastline [12]. Guyana's EEZ spans approximately 135,900 km² [13], and in recent years, it has become the focus of accelerated offshore industrial

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activity, particularly oil and gas exploration. While such activities present economic opportunities, they also raise concerns regarding their potential ecological impacts, particularly from anthropogenic underwater noise.

1.1. Characteristics of Underwater Sound

Sound can be defined as a mechanical disruption that passes through a medium, such as water [16, 21, 32]. To clarify, one may conclude that when an external force displaces particles in a medium (in this case water) and begins to oscillate around their original location and also sets off their neighboring particles into motion as the disturbance moves through the medium (water) sound is said to be created. Sound waves are longitudinal and, as pressure fluctuations, disperse or migrate across the interior of materials. The change rate of these pressure fluctuations determines the frequency of the sound given and is measured in hertz (Hz). Hertz measures the number of complete cycles of vibration per second. Sounds outside the human hearing range are referred to as infrasound which is around 20Hz and ultrasound which is around 20kHz respectively.

The pressure between particles is higher during temporary compression in acoustic waves and lower in rarefaction. The magnitude of the variations between these pressures determines the sound amplitude. Amplitude is commonly measured as the difference between equilibrium and maximum positive pressure (peak) or as the difference between maximum positive and maximum negative pressure (peak to peak) of the waveform while the wavelength of a sound is the distance a wave travels during a cycle. Particle motion is the vibrations of the molecules around an equilibrium state and can be calculated by measuring either velocity or acceleration of the particles. The relation between these particle velocities and pressure excursions depends on the medium properties and is described by the acoustic impedance. For a medium like sea water this impedance is approximately 3560 times larger than for air [12].

The Sound Exposure Level (SEL) is a measure of the energy of a sound and depends on amplitude and duration. SEL is the time-integral of the instantaneous squared sound pressure normalized to a squared reference pressure over a 1-second period and are especially convenient when making predictions about the physiological impact of noise [12]. To know the equivalent of sound pressure in water from that of an airborne sound level of the same magnitude then 61 decibels (dB) must be added to the airborne sound level to get the result of what in sounds like in water [34].

A sound spectrum is usually a short sample of a sound in terms of the amount of vibration at each individual frequency. Because the spectrum can display the measured sound pressure power within different frequency intervals it is important to know the spectrum of a sound in order to predict impact of noise on marine animals, as species have different hearing sensitivity at different frequencies [12, 16]. Hearing sensitivity is typically measured by determining the quietest possible sound perceptible by an animal either by a behavioral response or by quantifying an electrical response [39].

Hearing threshold is the average sound pressure level that is just audible to an individual under conditions with little or no noise. When the hearing threshold is plotted as a function of frequency it is called an audiogram [25]. Audiograms of various species would vary with respect to their frequency range of hearing and with respect to their sensitivity. When the sound pressure level in dB by which a stimulus exceeds the hearing threshold at a given frequency of interest is called the sensation level [46]. The term "noise" has many meanings, however, in this case we can say that any unwanted sound with an amplitude exceeding a certain hearing threshold, above which it is known to adversely affect the behavior or physiology of an organism would be termed as noise [12, 21].

1.2. Anthropogenic sources of underwater noise

Anthropogenic underwater noise, defined as human-generated sound introduced into marine environments, has increasingly disrupted natural soundscapes and is considered a significant threat to marine biodiversity [3, 9, 30]. This noise can be classified as either acute (e.g., short-duration, high-intensity pulses from sonar or seismic surveys) or chronic (e.g., continuous, low-intensity noise from shipping or drilling) [3, 16]. The most common yet most impactful sources of anthropogenic sounds worldwide are sonars, seismic air guns, offshore drilling vessels example drill ships, and sounds from shipping vessels [3, 34].

1.3. Off-Shore Seismic Surveys

Off-shore seismic surveys are carried out by a ship pulling multiple compressed air guns; that fires pressurized air bubbles at regular intervals that produces the sound waves, and a large range of sound sensors or hydrophones that records the period of time that the sound waves would take to bounce back from the layers of rocks on the seafloor [3, 34]. These air guns generate low frequency impulses below 250Hz with the strongest energy ranging from 10-120Hz and its peak energy ranging from 30-50Hz. These air guns also emit low amplitude high frequency sounds measured

with an average of 100kHz but with technology growing rapidly on a daily basis so does the power of air guns which can reach up to 260-262 dB (p-p) re 1 μ Pa @ 1m [3, 12]. The data produced provides a 3D image of the Earth's layers allowing the engineers to pinpoint areas with oil and gas and allows them to generate a plan to extract the oil and gas [3]. While for some, air-guns may seem not so ruinous, seismic surveys are not limited to air guns but have a wide range of sound sources that would depend on the depth of penetration required, among other factors. Some of the other sources would be "sparkers", "boomers", "pingers" and "chirp sonars" [3, 12].

1.4. Off-shore drilling

Offshore drilling is a process where a borehole is drilled through the seabed [3]. There are of two main types: floating and bottom-supported unit. The floating unit includes: semisubmersibles (bottle-type, column stabilized), barge rigs and drill ships. The bottom-supported unit includes: submersibles (posted barges, bottle-type submersibles, arctic submersibles), jack-ups and platforms [3].

1.5. Sonars

The first anthropogenic sound to be intentionally incorporated on a large scale into the oceans was sonar. Active sonar is defined as the use of acoustic energy for locating and surveying. They may use all sound frequencies and are classified into low (<1 kHz), mid (1 to 10 kHz) and high frequency (>10 kHz) for convenience in this paper. Military mid-frequency sonars are used to survey areas with a range of tens of kilometers and are used to locate and monitor targets underwater. Military high-frequency sonars are either used in attacking or defending systems and are designed to work over hundreds of meters to a few kilometers [3, 12].

1.6. Shipping

Ships travel the oceans for numerous purposes; for example, cruise ships are for recreation/tourism while commercial ships are for transporting cargo. Numerous factors, including ship type, size, hull shape, propulsion system, speed, load, and sea conditions, would all contribute to the level of anthropogenic sound introduced into the ocean. Underwater noise is created by ships' propulsion systems and other machinery. An especially important source of noise is cavitation that occurs at the propeller blade tips. This occurs when the spinning blades cause the local pressure in the water to fall below a critical value and bubbles to form. In addition, the water flow past the ship's hull generates broadband sound, particularly with ship moving at high speed [3, 14].

After reviewing some of the impacts that anthropogenic sounds had on marine life in other countries and with Guyana advancing in development in its exclusive economic zone, a paper summarizing the sources of anthropogenic sounds and their impacts was needed to spread awareness that it may have upon marine biodiversity, for example, the strandings of Greece 1996, Bahamas 2000, Madeira 2000, Canary Islands 2002 and Canary Islands 2004, where the strandings and deaths of these animals were a mystery until researchers started conducting necropsy and came to the realization of the negative impacts anthropogenic sounds were having on marine species.

In Greece 1996, twelve Cuvier's beaked whales were stranded. The strandings were linked with a nearby military exercise using sonars at frequencies of 450-700 Hz and 2.8-3.3 kHz [3]. In Bahamas 2000, fourteen beaked whales, one spotted dolphin, and two minke whales were reported stranded [3]. The strandings occurred within a 36-hour period following the passage of five U.S. Navy ships taking part in an exercise that also used mid-frequency (1-10 kHz) sonars [3]. Blood deposits were found in and around the ears in several of the animals [3, 18, 19]. In Madeira 2000, three Cuvier's beaked whales stranded with a fourth reported floating in the water by a fisherman, but it did not come ashore. A naval exercise was done a day prior to the stranding. A head of one the animals was examined and it was found to have blood in and around the eyes, ears, and brain. This animal and another that were also examined on site were also found to have lung hemorrhaging [3, 18, 19]. Canary Islands 2002, 14 beaked whales washed ashore bleeding from the ears. All eventually died. A post-mortem examination revealed that the whales showed signs of decompression sickness [3]. Canary Islands 2004, four Cuvier's beaked whales were found stranded and floating ashore [3]. These strandings occurred one week after a military exercise using several warships that used mid-frequency sonar (2-10 kHz) [3].

Research based on the impacts of anthropogenic noise on marine organisms are very limited because every species would respond differently to different sound frequencies. Hence, it is very costly and complex to undertake experiments to assess the impacts on every species. This is because the impacts of anthropogenic noise on marine organisms varies depending on the species, since each species would respond differently to different sound frequencies. In addition, scientists have not yet discovered an accurate way in assessing the damage done to marine organisms in their natural habitat [3].

2. Material and Method

The topic of “bioacoustics disruption and anthropogenic noise on the marine environment and marine organisms” is the subject of a systematic review using “Google Scholar,” a web-based search engine which provides a quick and easy way to search and access published literature from articles, journals and books. Several thematic key terminologies such as ‘anthropogenic noise, marine life and sounds, how does sound affect marine life, anthropogenic noise on marine life, effects oil and gas company have on marine life, why do sounds affect marine life, how do sounds affect marine life, how to prevent anthropogenic noise in the ocean, how to monitor marine life, monitoring marine mammals, monitoring fishes, monitoring sea turtles, parts of marine mammals ear, parts of fishes ear, parts of sea turtles ear, ideal sound frequency preferred by marine mammals, ideal sound frequency preferred by fishes, ideal sound frequency preferred by sea turtles, effects of sound on juvenile turtles, sound effect on fishes and fish eggs, sound effect on marine mammals, sound effect on sea turtles’.

Articles from the period 1990-2024 were identified, collected and reviewed by the researchers. While articles older than the year 1990 were also collected and studied however, more emphasis was placed on articles from years 1990-2024. After reviewing the articles, the researcher compiled a report, on the potential effects of anthropogenic noise on marine species. Eight-seven (87) research articles were retrieved and included in this review and literature from forty-one (41) papers published between the years 1992-2024 were presented in this paper.

The search yielded different results: Some articles had all the thematic keywords and some were obtained that were specific to legislation measures and management approaches to protect marine species against anthropogenic sound, while others were specific to anthropogenic sound affecting a specific targeted group of marine organisms e.g. marine mammals or fishes, marine organisms threatened with oil spills and marine organisms’ responses to environmental stressors and climate change.

3. Results

When searching “Google Scholar” for information on bioacoustics disruption in marine environments and the impact of anthropogenic noise on marine organisms, a total of 8,520 articles were retrieved. Among the results obtained from the search, a total of 1910 were published within the years 2000-2024, 2050 were published between the years 2010-2024 and 2050 were published within the years 2015-2024. A total of 1870 publications between 2020-2024 addressed bioacoustics disruption in marine environments and impact of anthropogenic noise on marine organisms.

However, while not all the results retrieved for this research focused on bioacoustics disruption in marine environments and the impact of anthropogenic noise on marine organisms, some focused solely on anthropogenic sound impact on marine mammals. Some examined legislation measures and management approaches to protect marine organisms from the impact of anthropogenic sound and some were specific to anthropogenic sound affecting fishes, marine organisms’ threatened with oil spills and marine organisms’ responses to environmental stressors and climate change. Further, some papers focused on checklist sources of various anthropogenic sounds affecting specific species of marine organisms.

4. Discussion

4.1. Impacts of anthropogenic sounds on marine species

Although seismic surveys, offshore drilling, and commercial shipping are widely regarded as effective and technologically advanced methods for resource exploration and transportation, these activities have increasingly been associated with detrimental impacts on marine life.

Numerous studies have documented the negative consequences of anthropogenic underwater noise on marine ecosystems. For instance, Götz, *et al.* (2009) [12] and Peng *et al.* (2015) [29] have reported that areas exposed to persistent anthropogenic stress often exhibit degraded marine biodiversity and poor ecological conditions.

Research findings suggest that intense underwater sound waves can cause direct physical harm to marine organisms. High-intensity noise has been shown to damage or destroy fish eggs, impair auditory functions, and induce stress responses in fishes, sea turtles, and marine mammals [30]. These disruptions may lead to changes in reproductive success, increased susceptibility to predation, and long-term population declines.

Anthropogenic sound sources can be broadly categorized into two types: incidental and deliberate. Incidental sounds are by products of routine human activities such as commercial shipping and industrial operations. In contrast, deliberate sounds are intentionally generated, for example, during military sonar use or geophysical seismic surveys. These categories and associated sound sources are summarized in Table 1 while Table 2 addresses the general effects of anthropogenic noise on marine organisms

Understanding the extent and mechanisms by which anthropogenic noise affects marine organisms is crucial for developing effective conservation strategies and informing policy decisions. The continued expansion of industrial activities in marine environments, including Guyana's EEZ, underscores the urgency of addressing this growing environmental challenge.

Table 1 Examples of anthropogenic noise activities within the two main categories

Incidental	Deliberate
Commercial vessel traffic	Defense-related tactical sonar systems
Ice breakers	Air-guns associated with oil and gas seismic surveys
Oil and gas drilling activities	Navigational sonars
Marine construction	Imaging echo sounders.

(Taken from Chou *et al.*, 2021 [7])

Table 2 General effects of anthropogenic noise on marine organisms

Development	Physiology	Behavioral
-Damage to single cells and/or entire organs -Damage to ears and/or swim bladders in fishes -Damage to auditory organs in marine mammals -Negatively affect perception and orientation -Negatively affects buoyancy control which can lead to mass strandings -May cause developmental instability -May cause canalization	-Changes hearing capabilities -Influence loss of sensory hair bundles -Affects endocrine system, causes release of stress hormones -Causes developmental delays and growth abnormalities -Affects reproduction - Affects metabolism	-Overlapping with the hearing range of species -Masking acoustic behavior -Causes distraction -Disrupts acoustic information needed for navigation -Causes difficulties in locating indispensable resources -Affects predator-prey interactions -Impacts foraging and feeding efficiency -Causes short term avoidance behavior -Causes long term habitat abandonment -Affects social structures such as pair or group interactions -Increases aggression -Reduces ability to maintain territories -Negatively impacts mate choice, courtship and parental care

(Taken from Johansson, 2011 [16]; Kunc *et al.*, 2016 [21]; Bhagarathi *et al.*, 2024 [3])

4.2. Marine Mammals

4.2.1. How Marine Mammals Process Sounds

Each ear's components work together to provide its hearing capacity. An outer ear and an air-filled middle ear with bone levers and membranes are present in all mammalian ears, as are fluid-filled inner ears that include mechanical resonators, sensory cells and other components. The outer ear is a sound-collecting mechanism. It converts auditory components into mechanical ones that can be detected by the inner ear through the middle ear. The inner ear functions as a band-pass filter as well as a mechanochemical converter of sound into neural impulses [3, 18, 19].

In response to atmospheric pressure dynamics in ocean environments, cetaceans have adapted their hearing systems by reducing certain bony, air-filled holes and losing external pinnae [3]. Furthermore, the ears of cetaceans are nearly completely separated from the cranium, reducing the possibility of acoustic vibrations being transmitted through bone [3]. With the highest degree of alteration of any vertebrate, cetacean cranial anatomy allows for the development of acoustically significant structures, soft tissues and sinuses necessary for sound generation and reception underwater [3]. As the size and scale of mysticete (baleen whale) ears change, so do their morphological adaptations. However, the auditory apparatus of odontocetes (toothed whales) show major changes in the sound reception mechanical pathway. Unlike mammals, who hear sound through external auditory canals, odontocetes receive sound predominantly through their lower jaws, according to research [3]. Mandibles of toothed whales have thin, flexible walls and thick pads of specific acoustic lipids at their posterior ends. It is thought that these lipid structures include wax esters and long straight-chain fatty acids, which allow sound to travel quicker, and that they enhance and channel the acoustic vibrations directly into the inner ear [3]. The melon of odontocetes also contains special lipids that serve as the foundation for the animal's echolocation abilities. Its auditory bullae are larger and denser than those of any other animal, and it lacks any bone connections with the skull, which further isolates it from external acoustic waves and allows it to carry sound more effectively [3, 11, 18, 19].

Mysticetes, Type I odontocetes, and Type II odontocetes are the three auditory categories of modern cetaceans [3]. The acoustic divisions correspond to three cochlear forms, which differ primarily in the design and support of the basilar membrane. With an unusually thin basilar membrane, large spiral ganglion cell densities, and an enormous bony outer spiral lamina, the odontocete cochlea is well suited for ultrasonic perception [3]. The cross-sectional dimensions of the basilar membrane interact with its composition and support to determine resonance characteristics. The basal turn of odontocetes has the highest membrane thickness-to-width ratios of any animal studied so far [3]. Mysticete basilar membranes are very broad and thin, indicating that they are specialized for encoding extremely low frequencies; however, there is insufficient evidence to establish whether low frequency specializations exist in mysticete cochlear ducts (Figure 1) [3, 18, 19].

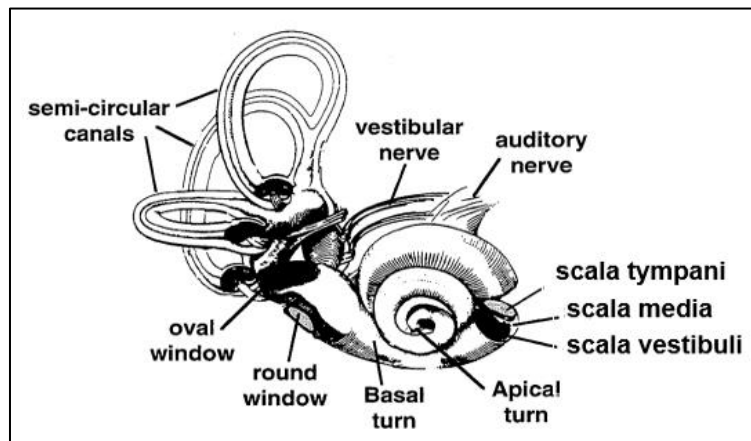


Figure 1 Fundamental structure of a mammalian inner ear (Source: Wartzok & Ketten, 1992 [45])

Hearing in mysticetes is approximated using different methods like as vocalizations, anatomy, behavioral reactions to sound, and notional natural background noise levels in the expected hearing frequency ranges [3]. The evidence gathered from sources states that mysticetes are most sensitive to sound frequencies ranging from tens of hertz to tens of kHz. However, humpback whales (*Megaptera novaeangliae*) make noises with harmonics over 24 kHz, and certain mysticetes might detect frequencies up to 30 kHz, according to anatomical evidence. Mysticetes operate primarily in the very low and low frequency ranges [3, 7, 12, 35].

Because odontocete cetaceans have specific high-frequency biosonar and lower-frequency communication systems, it's extremely probable that they can hear throughout a large frequency range, maybe up to 12 octaves in certain species. Southall *et al.* (2007) reviewed the literature and identified two functional hearing groups within the odontocetes, which they dubbed mid-frequency cetaceans (functional hearing estimated between 150 Hz and 160 kHz) and high-frequency specialists (functional hearing estimated between 200 Hz and 180 kHz). They have the ability to process sounds quickly, compensating for both the faster underwater sound speed and the more complex echolocation requirements [3, 7, 12, 35].

4.2.2. How Anthropogenic Noise Affects Marine Mammals

Marine mammals are especially sensitive to sound waves and use echolocation for their survival; echolocation being a sound wave that can sometimes extend above 100kHz that is emitted commonly as clicks or short sound pulses from the animal that bounces off distant objects including other marine life then returns back to its emitter [3, 29, 39, 44]. Echolocation is used by solitary individuals as well as groups for a number of purposes such as means of obtaining food, socializing with other marine mammals, aiding the animal with orientation, avoiding confrontation with predators, group cohesion, helping the animal to find its way back home, attracting mates, exploring depths of waters and helping mothers to locate their young [3, 7, 10, 39, 42, 44]. For this adaptation to be efficient for the organisms the oceans and rivers must be calm and quiet with only ambient sounds. However, over half of a century the oceans and rivers worldwide have only gotten more ear splitting with all of the anthropogenic sounds that man rains from the surface of the waters without taking into consideration the effects that it has on the marine ecosystems below.

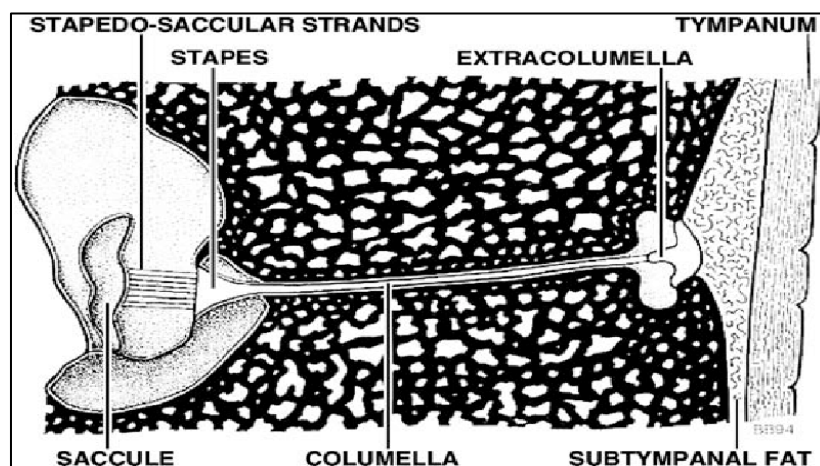
In the case of marine mammals, anthropogenic noise can cause threshold shifts which can be temporary (TTS) or permanent (PTS). TTS is relatively short-term reversible hearing lost caused from cellular fatigue and metabolic changes, on the other hand PTS is an irreversible loss of hearing that is caused from inner ear hair cell loss and/or severe damage or other structural damage to auditory tissues [3]. Permanent loss of hearing is a factor that can lead to beaching of marine mammals followed by their death. Some more minor behavior changes that loud noise can affect would include breeding, calving, feeding, changes in diving behaviors, swimming speed, prolonged time at the surface of the water and habitat displacement [3, 7, 16, 29, 31, 37, 39, 42]. Echolocation in marine mammals is also affected by loss of hearing, and, because of this, the animals may become disoriented, lost, unable to detect predators and unable to detect ships. When this happens, the animal may collide with ships and die [3, 31].

They may also die of decompression sickness common called “the bends” this happens when the mammal ascends to the surface too quickly causing nitrogen gas bubbles to clog their blood vessels [3, 7, 10]. Some other effects noise pollution may have on these marine mammals includes hormone level changes often affecting their immune systems, restlessness, lack of sleep, aggressiveness, alertness and very often masking; this occurs when the noise frequency is the same of other important sound frequencies to the mammal such as mating calls [3, 10, 21, 37, 39]. When masking occurs the animals try to shift the frequency of their calls and increase the length of their calls in presence of loud noise in hope of trying to overcome the anthropogenic noise [3, 7, 39, 42].

4.3. Sea Turtles

4.3.1. How Sea Turtles Process Sounds

The outer ear, external pinnae, and ear canal are absent in sea turtles. The tympanum, a facial tissue projection, covers the sea turtle's ear, and both the middle and inner ears are bone-encased. Acoustic energy is transferred to the columella, or stapes, in an air-filled middle ear, via the tympanum and a thick layer of sub-tympanal fatty tissue. The thin columella extends throughout the oval window, forming a cone-shaped footplate. Only seen in turtles, stapedo-saccular threads connect the oval window and stapes to the saccule and are thought to transfer vibrational energy to the saccule (Figure 2). The stapes moves inward and outward, causing fluid to flow in the pericapsular recess and activating hair cells on the basilar membrane and cochlea's limbus (Figure 2) [30].



(Source: Bartol & Musick, 2002 [2])

Figure 2 Middle ear anatomy of the juvenile loggerhead sea turtle

4.3.2. How anthropogenic noise affects sea turtles

As previously mentioned, marine mammals are the most affected when compared to the fishes and turtles however, more studies are now being done on fishes and turtles to assess the impacts caused by anthropogenic noise and it was concluded that marine sound has the potential to impact sea turtles physically and behaviorally [30]. Impacts observed could be minor or severe, depending on the type and frequency of the sound. It is believed that sea turtles use both acoustic and vibratory stimuli to monitor their environment [30] and use sound to aid in orientation as well [39]. In *Marine turtle management plan* by BHP Billiton, adult turtles were said to have physical injury and/or instantaneous permanent hearing damage at 240 dB re 1 μ Pa and behavioral and masking changes are likely to occur at levels above 120 dB re 1 μ Pa. Activities that are not within those sound ranges, such as dredging, were stated unlikely to cause any injury or hearing loss in turtles but may have an effect on their behavioral responses such as avoiding the area but also sometimes adapt to the sound and stay within the habitat.

Few studies have been conducted on hair cell damage in reptiles, and it is still unknown whether sea turtles can regenerate hair cells. Because there is practically little evidence on the impact of strong noises on sea turtles, predicting the amount of damage to hearing structures is challenging. Clear avoidance reactions to seismic sounds at levels ranging from 166 to 179 dB re 1 Pa have been recorded; however, these experiments were conducted in a confined environment, making it impossible to evaluate the amount of avoidance. Moein *et al.* (1995) observed a habituation effect with the airguns; after three exposures, the animals ceased reacting to the signal. This lack of behavioral reaction may be caused by TTS or PTS [30]. In *Underwater hearing sensitivity of the coriacea: Assessing the potential effect of anthropogenic noise* by Piniak *et al.*, 2012 [30] however, stated a research done by Bartol & Musick, 2002 [2] on two juvenile and six sub-adult green sea turtles, and two juvenile Kemp's Ridley sea turtles and the results stated that the subadult Pacific green turtles reacted to stimuli at frequencies of 100 to 500 Hz, with greatest sensitivity between 200 and 400 Hz, whereas juvenile Atlantic green turtles responded at frequencies of 100 to 800 Hz, with maximum sensitivity between 600 and 700 Hz. Kemp's Ridelys had a maximal sensitivity between 100 and 200 Hz and reacted to stimuli between 100 and 500 Hz.

After Piniak *et al.*, 2012 [30] used the AEP technique to show that juvenile green sea turtles respond to stimuli between 50 and 1600 Hz in water and 50 and 800 Hz in air, with maximum sensitivity ranges between 50 and 400 Hz in water and 300 and 400 Hz in air, this information was found to be somewhat inaccurate. A research done by Martin *et al.*, 2012 in which a similar approach was performed on an adult loggerhead and recorded responses to frequencies between 100 to 1131 Hz with highest sensitivity between 200 and 400 Hz was mentioned in the article by Piniak *et al.*, 2012 [30] also. Because sea turtles are migratory, sound events in one location might affect not just the turtles who utilize that area to breed and feed, but also those that are merely "passing through", but because of a paucity of data on hearing capacities and behavioral reactions to sound, the effects of noise on sea turtles are mainly uncertain [30].

4.4. Fishes

From the articles reviewed, it was found that experiments conducted for research on the impacts of anthropogenic sounds on marine life were done mainly ex-situ rather than in-situ. This was mainly because of the fact hearing threshold are species specific so noise would affect various species differently. So, it would have not only been difficult to study these species in their natural environment, but also very costly and complex. Data collected on species in captivity, especially their behavioral responses, may be different from the same species of organism that live in their natural free habitat because to some extent the ones living in captivity are subjected to human influences so they may not show the full range of their natural behavior. For example, in the scientific journal "*An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes*" it was stated that because of the many nuanced elements that affect their behavior in a natural context, findings from research employing free-living fishes are exceedingly likely to differ from those using fishes in captivity.

In addition, when research is conducted in tanks and other enclosures, the sound fields may differ significantly from those experienced by fish in the wild, particularly in terms of the amplitude of particle motion compared to sound pressure [33]. In the end, the authors found that it was very difficult if not next to impossible to set sound exposure criteria for every potential sound source, kind of response to the sound, or conduct an investigation for every fish species. Instead, they devised a method that focused on fish groupings based on the anatomy of auditory apparatus on key sound sources such as shipping as shown in Table 3 below [33]. This concept also applies to marine mammals and sea turtles as well as every other species in a marine ecosystem and because researches done on the impacts of anthropogenic noise are species specific there were very limited published resources on the topic.

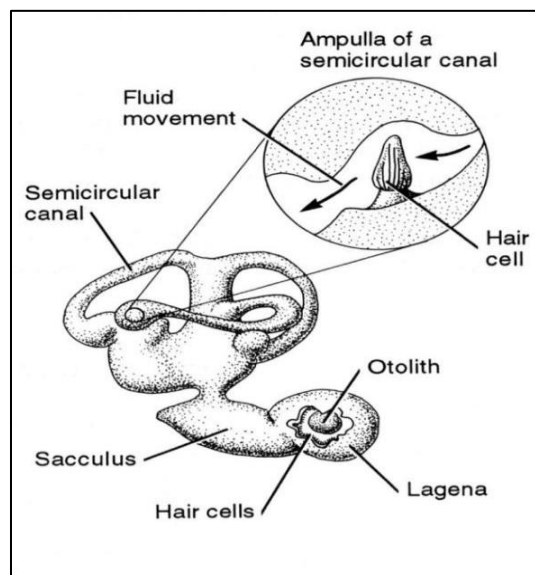
Table 3 Grouping of fishes as per 2014 guidelines

Group	Characteristics
1	Fishes lacking swim bladders that are sensitive only to sound particle motion and show sensitivity to only a narrow band of frequencies (e.g., flatfishes, Pleuronectiformes; sharks skates and rays, Chondrichthyes).
2	Fishes with a swim bladder where that organ does not appear to play a role in hearing. These fish are sensitive only to particle motion and show sensitivity to only a narrow band of frequencies. This group includes salmonids (Salmonidae) and some tunas and mackerels (Scombridae), but many other species are likely to fit into this category as well
3	Fishes with swim bladders that are close, but not intimately connected, to the ear. These fishes are sensitive to both particle motion and sound pressure, and show a more extended frequency range than groups 1 or 2, extending up to about 500 Hz. This group includes cod fishes (Gadidae), eels (Anguillidae), some drums and croakers (Sciaenidae), and perhaps other fishes
4	Fishes that have special structures mechanically linking the swim bladder to the ear. These fishes are primarily sensitive to sound pressure, although they also detect particle motion. They have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in groups 1, 2, or 3. The group includes some of the squirrelfishes (Holocentridae), drums and croakers (Sciaenidae), herrings (Clupeidae) and the large group of otophysan fishes.
5	Eggs and larvae represent the earliest and most vulnerable developmental stages in a fish's life cycle. These stages are critical for population recruitment and are highly sensitive to environmental conditions such as temperature, salinity, and pollution. Effective monitoring and protection of eggs and larvae are therefore essential for sustainable fisheries and ecosystem management.

(Taken from Popper & Hawkins, 2019 [33])

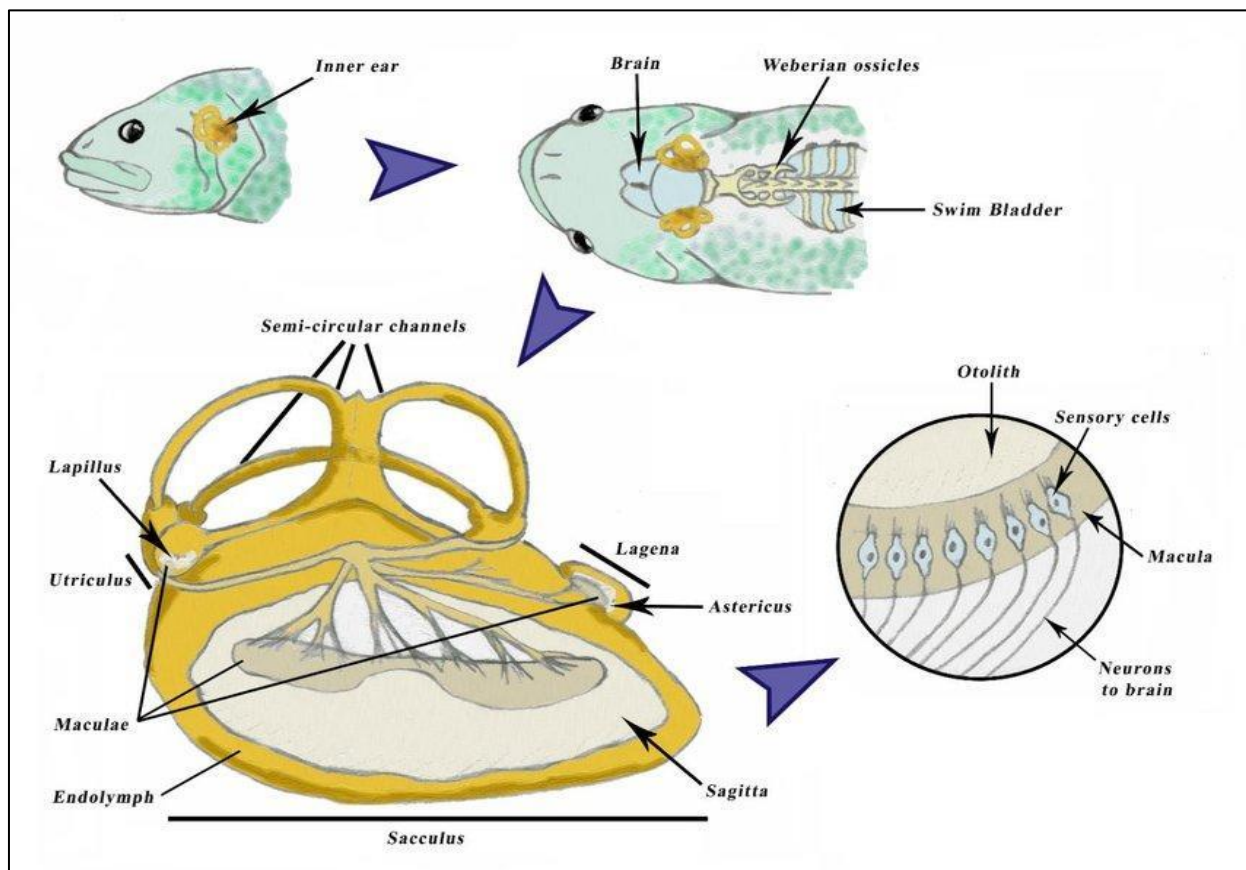
4.4.1. How Fishes Process Sounds

The body of a fish is the same density as its habitat [16], because of this, fishes do not have external or middle ear as compared to humans. They have a pair of inner ears in their cranial cavity that is lateral to their brains and at the same level of their medulla. In fishes three semi-circular canals and related sensory regions (ampullae) are responsible for detecting angular acceleration, while three otolith organs (saccul, lagena, and utricle) are responsible for the hearing and positioning perceptions [16, 33]. Each of the otolith organs has a sensory epithelium that is in close contact with the otolith i.e., a thick calcium carbonate structure. Many sensory hair cells of the sensory epithelium, commonly referred to as a macula, or seventh sense organ, are remarkably similar to those present in the human ear [32, 33]. Fishes also have lateral lines that aids in the detection of vibrational sounds. Their ear and lateral line together make up their octavolateralis system (Figure 3) [32].

**Figure 3** The inner ear of a fish (Source: University of Hawaii, 2016)

Most fishes can detect sounds over 3000Hz but hear best between 500Hz to 1000Hz by sensing particle acceleration/motion with their inner ear [9, 34]. When a fish is subjected to particle motion, its body move with the water, while the denser otoliths move at a different amplitude and phase. This causes the cilia on the sensory cell's apical surface to flex, releasing a neurotransmitter and transmitting a signal to the brain through an afferent neuron, this is known as direct sound stimulation [32, 33]. By perceiving pressure changes in their swim bladder, especially if it is linked to the inner ear, certain fishes can hear higher frequencies, including ultrasound. Lower frequency hearing may also be aided by the lateral line [16]. These are both known as indirect sound stimulation [9, 16, 32].

The lateral line hair cells are arranged into sensory structures termed neuromasts, which can be found in canals (as canal neuromasts) or on the skin's surface (free neuromasts). Each neuromast has tens to hundreds of hair cells, all of which are connected to the water by a gelatinous cupula. The displacement of the cilia of hair cells in the neuromasts is caused by the movement of water particles against the cupulae, which triggers the innervating lateral line neurons. The lateral line can pick up mostly low frequencies from less than 1Hz to several hundred hertz (Figure 4). It usually detects signals close to the fish and differentiates between the motion of the fish from motion of the fish's surrounding [32]. Sound source directions without doubt play a huge part in the hearing process of fishes. Individual sensory hair cells are morphologically polarized, and their responses alter whenever they bend in different directions. As a result, each cell is sensitive to its surroundings (Figure 4) [33].



(Source: Ashworth, 2016 [1])

Figure 4 Parts of a fish's ear

Sensory cells in fishes can be repaired so it believed that fishes do not suffer from permanent hearing loss (PTS) but they can suffer from temporary hearing loss (TTS). TTS is a temporary loss of hearing sensitivity caused by exposure to loud noises or sounds that last a long time. Following the sound's cessation, normal hearing ability recovers over a period of minutes to days, depending on a variety of circumstances, including the strength and length of exposure [33].

4.5. How Anthropogenic Noise Affects Fishes

Sound is thought to be used by fishes to obtain a broad "sense" of their surroundings similar to echolocation in marine mammals. Fishes use sounds to detect the existence and position of objects that make up the overall structure of their environment [16, 29, 32, 34, 35, 39]. Continuous sounds are likely to cause masking and hearing loss in fishes [9, 34],

while continuous sounds with irregular amplitude or frequency are likely to cause stress [9]. Fishes when exposed to loud noise show changes in behavior; moving away from their migration route, leave habitats in which they breed or feed and often end up with damages to their ear [7, 16, 29, 34].

Fishes also use sound as means of communication, so being exposed to loud sounds also interferes with their communication. Lack in communication leads to less spawning which sound is often used to attract males hence, an overall change in reproductive behavior of fishes [16, 29, 33]. These responses can be grouped in three categories of stress; primary, secondary and tertiary. For primary these responses happen within seconds and it is a neurological and hormonal response to prepare the animal for either a flight-fight response or to freeze in place. Secondary is the activation of the hypothalamo-pituitary-interrenal axis which controls concentration changes in hormones and tertiary is when the animal is unable to adapt to its new environment, this happens if stress is prolonged. Stress can also cause physiological changes such as body conditions, growth reduction and hampered immune system [7, 9, 16]. Table 4 shows the main mechanisms and the potential effects of anthropogenic noise on fishes.

Table 4 Three main mechanisms and the potential effects of anthropogenic noise on fishes

Stress	Masking	Hearing-loss
1. Affects growth 2. Affects maturation 3. Affects reproduction 4. Affects signaling 5. Trigger avoidance behavior	1. Impacts communication 2. Impacts feeding rate 3. Impacts predation	1. Elevated hearing thresholds 2. Reduced temporal resolutions causing similar masking effects but prolonged

(Source: de Jong *et al.*, 2020 [9])

High intensity sounds also disable lateral line functions in fishes by damaging sensory hair cells in the lateral line. This can disrupt schooling behavior in some species and affect predator-prey relationships since fishes will be unable to detect predators within a close range [16, 32]. Table 5 shows the detrimental impact of anthropogenic sounds on the behavior of fishes.

Table 5 Anthropogenic sounds and their impact on fishes' behavior

How The Types Of Anthropogenic Sounds Generally Impact Fishes			
Continuous	Reference	Impulsive	Reference
Interferes with foraging behavior either by masking the relevant sounds or by resembling the sounds that the prey may generate	(Purser & Radford, 2011)	Change in both horizontal and vertical distributions	(Løkkeborg <i>et al.</i> , 2012)
Elevated sound levels, including intermittent or pulsed sounds, may affect predator prey interactions	(Luczkovich & Keusenkothen, 2008; Ramage-Healey & Bass, 2006)		
High level sounds may result in avoidance responses, deflecting fish away from their migration routes.	(Radford <i>et al.</i> , 2010; Stanley <i>et al.</i> , 2012)		
Interference with detection of spawning sounds can have a significant effect on reproductive success of a population.	(de Jong <i>et al.</i> , 2020)		

Some of the studies reviewed have concluded that anthropogenic sounds may not be as harmful as projected by other studies. For example, in the article "*Shipping noise impacts on marine life*" by Douglas H. Cato, it was mentioned that noise from close shipping was not as fatal as ship strikes but there were assumptions that the noise of shipping did influence whales mainly to get hit by a moving ship due to the reason that they may just adapt to the ships' noise and this often results in failure to move or respond to the ships especially those close to the surface. Traffic noise was said to mask the natural background noise in the oceans at low frequencies and it has notably reduced the ability for marine

animals who uses low frequencies to communicate, examples that were listed was the baleen whales and some species of fishes. He also stressed that there was little to no experimental studies done on the effects of shipping on marine animals but he did speak of a study done along the east coast of Australia, one of the busiest shipping areas next to Australia, on humpback whale population migration. It was thought that since the humpback was one of the most vocal baleen whales then their vocal frequencies would overlap with the noise from ships which would eventually lead to a decrease in their population. However, that was not the case since the population increase 10.5% indicating that the noise from the ships did not affect the humpbacks [5].

Most of the literature reviewed reported that (i) hearing damage, including permanent threshold shifts and other non-auditory tissue damage from exposure to very loud sounds, (ii) temporary threshold shifts from acoustic overexposure, (iii) masking of sounds hindering the perception of acoustic information, and (iv) changing hormone levels, are all examples of how anthropogenic noise can affect an individual's anatomy, physiology, and/or behavior. So, we can probably say that anthropogenic noise may cause minor, short-term behavioral alterations to significant, long-term behavioral or physiological abnormalities that end in mortality.

4.6. Mitigation of anthropogenic sounds in marine environment to reduce impacts on marine life

The first step in taking mitigation measures would be data collection based on the ecological and biological aspects of the area such as presence, density, distribution and hearing sensitivity of the targeted species. After data collection, mitigative methods can then be put into place to protect and conserve vulnerable species [22, 31].

A method used is conducting visual and acoustic watches for marine mammals and/or other vulnerable species. This is usually done by well trained and dedicated Passive Acoustic/PAM Operators and/or Marine Mammal Observers/MMOs [7, 22, 35, 37]. Their job is to ensure that vulnerable species are not within immediate vicinity of the noise source but sometimes it is difficult to monitor the waters in unfavorable conditions. So, to aid in the detection of these marine mammals in unfavorable conditions, other technologies can be coupled with PAM, which is done by use of hydrophones to identify an animal's vocalizations. These include active acoustic monitoring (AAM), thermal imaging (thermal IR) and radio detection and ranging (RADAR).

Active acoustic monitoring is a technique in which sound pulses are broadcast into the water and acoustic reflections from animals are picked up by hydrophones. Thermal IR detects temperature differences between the body or exhalation of a warm-blooded marine mammal and the surrounding environment using an electro-optical imaging sensor. Radio or micro-waves are emitted into the air in RADAR, and echoes from the animal's body, exhalation, or disturbance on the sea surface are picked up by an array of receivers [44].

Some other techniques that can aid in mitigating the effects of noise on marine life would be to have pre-watches and exclusive/safety zones [22, 37]. An exclusive zone is usually 500m to 1000m radius to the sound source that must be cleared before the activation of any anthropogenic sound, but these zones can sometimes be larger in some countries. The sound source is always in the middle of an exclusive zone and these zones are often divided into smaller, more specific zones but varies with country, for example Brazil has two zones: safety (500m) and warning (1km) while Australia has three zones: Observation (3km), low power (1 or 2 km) and shut down (500m) zones. A pre-watch is the length of time taken for the exclusive zone to stay clear of vulnerable species before the activation of noise. This usually lasts for about 30-60mins but may differ in locations and depth of water.

Another way impacts of noise may be reduced in marine ecosystems is by conducting soft starts before carrying out the project. This gives the organisms time to move out of the area to a much safer place [7, 22, 37]. In addition, impacts of noise can be mitigated by careful project planning. Guidelines should be established for projects that will be introducing anthropogenic sounds into marine environment. Some of these guidelines could be to avoid sensitive times and areas such as breeding and feeding grounds [7, 22, 37], avoiding "peak seasons" meaning seasons that these vulnerable species are plentiful or are taking a known migratory route and finally better operational procedures for the project. Better operational procedures allow the project to be executed in a way that minimizes the impacts of noise on marine life, for example for use of seismic surveys the lowest practicable power equipment could be used for data collection or for underwater explosions the smallest charge can be used.

The use of acoustic isolating material or bubble curtains, as they are commonly known, is another noise reduction method [7]. They are usually installed at the source which would reduce the output of sound, or they are sometimes placed along propagation paths to reduce the intensity of the sound. Experiments were done and reviewed by Lucke *et al.*, 2011, Spence & Dreyer, 2012 and Lee *et al.*, 2012 to test the efficiency of these bubble curtains and it was found to be useful in noise reduction, but they can also be greatly affected by strong ocean currents and other environmental

factors [7]. Hydro Sound Dampers (HSD) are now slowly replacing bubble curtains [7]. HSDs are gas filled envelopes, like balloons, which are attached to, and surround the pile in various ways. The theory is primarily the same as bubble curtains, but by containing gas within a structure, more control can be exerted. They are less affected by currents and tides, and performance is thus improved.

Use of air-filled cofferdams, isolation casing and vibro-piling were listed in article *International policy, recommendations, actions and mitigation efforts of anthropogenic underwater noise* by [7] as ways to help reduce noise from offshore wind related construction activities. This article also mentioned various noise reduction techniques that can be used in the detection of oil and gas and seismic surveys. These techniques were higher sensitivity hydrophones, benthic stationary fiber-optic receivers, parabolic reflectors, sound baffling and extremely low frequency marine vibroseis. The marine vibroseis technology is a controlled sound source for oil and gas exploration that may reduce peak pressure by distributing acoustic energy across time, eliminating the rapid increase time, and reduce noise production over 100 Hz [37].

Use of Acoustic mitigation devices (AMD or ADD) can also be used in noise related projects to divert species away from loud noise [7]. Pingers are a common acoustic harassment device that can be used. They emit sounds within the hearing range of targeted species and cause them to divert or move away into another direction. However, the pingers themselves may be a threat to marine life over sometime, so should only be used in certain circumstances and simultaneously with marine mammal observers or passive acoustic monitoring only when absolutely necessary. Because it was observed that they may influence non-targeted species within the ecosystem to permanently move away [7, 16, 21].

For shipping, engine noise vibrating through the hull adds to ship noise, propeller cavitation, which occurs when huge numbers of vacuum bubbles generated by propeller motion collapse, is the most significant contributor to vessel noise. Propellers should be built and chosen with cavitation in mind, such as by minimizing propeller load, ensuring as uniform water flow as possible into propellers which can be impacted by hull design, and carefully selecting propeller characteristics. Hence, ships can be redesigned to mitigate noise impacts on species [7, 31]. In addition to the design of the propellers and hull components, vessel speed influences overall noise output. Slowing down allows vessels to drastically minimize the amount of noise they make, but slowing down with a lower frequency would mean continuous sound over a longer period of time, hence, this method needs more research. Having protected areas are also a way to keep marine life safer from anthropogenic noise [7, 37].

5. Conclusion

Anthropogenic noise is becoming increasingly common in aquatic ecosystems. Extensive evidence was uncovered after reviewing the articles, that noise has an impact on an individuals' development, physiology, and/or behavior. According to most literature that was reviewed, it was observed that (i) hearing damage, including permanent threshold shifts and other non-auditory tissue damage from exposure to very loud sounds, (ii) habitat displacement, (iii) masking of sounds hindering the perception of acoustic information, and (iv) changing hormone levels, are some examples of how anthropogenic noise can affect an individual's anatomy, physiology, and/or behavior. So, we can say that anthropogenic noise can cause minor, short-term behavioral alterations or long-term behavioral or physiological abnormalities that end in mortality.

Because sound propagation characteristics differ between aquatic and terrestrial environments, since sound in water travels faster and further and attenuates less than sound in air, noise pollution in aquatic ecosystems may be more widespread than in terrestrial ecosystems because it covers a broader region. The interaction with other environmental stressors may create difficulties for animals living in noise-polluted aquatic environments. Some common anthropogenic sounds that were identified with a mitigative measure would be: Seismic survey- Soft starts, High Power Sonar- Power down in animal detected, Marine traffic noise- Speed and route management, Coastal and Offshore Development- Use of Low powered equipment.

To date, no formal assessment has been conducted on the potential impacts of anthropogenic sound on marine life within Guyana's marine territory. This review aimed to begin the process to addressing this existing knowledge gap by examining common anthropogenic noise sources and their known effects on marine mammals, fishes, and sea turtles. The findings are intended to increase awareness and inform policy decisions among key national stakeholders, including the Guyana Marine Conservation Society, Environmental Protection Agency, World Wildlife Fund, Maritime Administration Department Guyana, and Global Wildlife Conservation and others to safeguard Guyana's marine biodiversity from acoustic disturbance. Much of the information reviewed appear to be based on studies that have been conducted on captive animals in laboratories rather than on free-living species in the wild. There is definitely a need for

more research on species in their natural habitats and for research in Guyana and this geographic region on this particular topic, since there appears to be a dearth of data relating to this biodiversity rich region.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors certify that this submission is original work and is not under review at any other publication. The authors hereby declare that this manuscript does not have any conflict of interest.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Data will be made available on request.

Statement of informed consent

The author declare that informed consent was obtained from all individual participants included in the study. All work utilized in this study was fully cited and referenced so authors of prior researches are given their due credentials for their work.

Credit authorship contribution statement

Rathnawali Basedeo - Conceptualization, methodology, data collection, data analysis, draft preparation, and revision; Maria A. Fraser - Conceptualization, methodology, data analysis, draft preparation, revision and editing; Phillip N. B. Da Silva - Conceptualization, methodology, data analysis, revision and editing; Lakhnarayan Kumar Bhagarathi - Methodology, data analysis, draft preparation, revision and editing; Ferial Pestano - Conceptualization, methodology, data analysis and revision.

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