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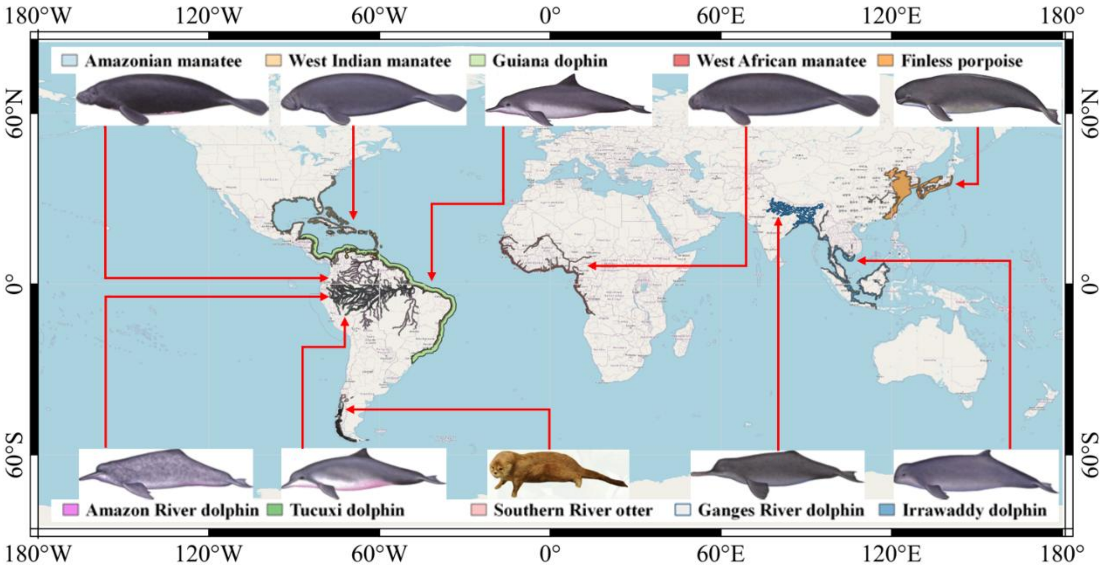
ANTHROPOGENIC UNDERWATER NOISE IMPACTS AND MITIGATION STRATEGIES FOR CMS-LISTED FRESHWATER MAMMALS (CETACEANS, SIRENIANS, OTTERS) AND THEIR PREY SPECIES

(Prepared by the Secretariat)

Summary:

This document contains the report *Anthropogenic Underwater Noise Impacts and Mitigation Strategies for CMS-Listed Freshwater Mammals (Cetaceans, Sirenians, Otters) and Their Prey Species* that was written in accordance with Decision 14.45 (c).

Anthropogenic Underwater Noise Impacts and Mitigation Strategies for CMS-Listed Freshwater Mammals (Cetaceans, Sirenians, Otters) and Their Prey Species



Anthropogenic Underwater Noise Impacts and Mitigation Strategies for CMS-Listed Freshwater Mammals (Cetaceans, Sirenians, Otters) and Their Prey Species

Prepared by the Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals (CMS).

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Abstract

There has been a marked increase in anthropogenic underwater noise levels since the mid-1900s. Given the fundamental role of sound in aquatic ecosystems and the demonstrated and potential adverse effects of anthropogenic noise, underwater noise pollution is increasingly being recognized as a critical global conservation challenge. While oceanic soundscapes have garnered significant scientific concern, anthropogenic noise pollution in freshwater ecosystems has received comparatively little attention. A concise report with appropriate references and recommendations was drafted by compiling and analysing available information relevant for all freshwater mammals (cetaceans, sirenians, otters) listed by the Convention on the Conservation of Migratory Species of Wild Animals (CMS).

This report covers the following four parts:

1) The state of knowledge of underwater noise impacts on CMS-listed freshwater mammals and their prey
2) The state of knowledge of underwater noise mitigation measures that take into account the specific requirements and properties in habitats such as estuaries, rivers and lakes
3) An assessment of whether existing guidance on underwater noise mitigation sufficiently covers the needs of CMS-listed freshwater mammal species and their prey
4) A recommendation as to whether specific underwater noise mitigation guidance for freshwater habitats is required

This report highlights the urgent need to address underwater noise impacts on CMS-listed freshwater mammals and their prey species, providing critical evidence to guide effective noise mitigation strategies for their conservation.

Although the report is focused on CMS-listed freshwater mammals, its findings and recommendations are also useful to other freshwater mammal species, including resident, non-migratory, and/or endemic populations.

1. Underwater noise impacts on CMS-listed freshwater mammals and their prey species

Sound is among the most effective signal carriers in aquatic environments, because acoustic waves travel nearly five times faster in water than in air and undergo less attenuation compared to chemical signals and light. Additionally, sound is capable of propagating over long distances and in low-light conditions (Au and Hastings, 2008). Anthropogenic underwater noise has magnified since the mid-1900s (Ellison et al., 2012; Hildebrand, 2009).

In freshwater systems, dominant anthropogenic activities include:

1. Vessel traffic, which produce intense and continues underwater noise pollution, such as the heavy vessel navigation in the Yangtze River (Wang et al., 2020a; Wang et al., 2021a).
2. Blasting during the construction of ports, jetties and bridges (Liang et al., 2024).
3. Pile-driving during the construction of ports, jetties and bridges (Shi et al., 2015).
4. Seismic surveys employ airguns to investigate subterranean structures, primarily for exploring petroleum, natural gas, and mineral deposits. This method generates intense, broadband, and impulsive sounds that can propagate tens to hundreds of kilometers from the source (Carroll et al., 2017).
5. Sand and gravel extraction processes in river ecosystems, such as the mechanical diggers operation (Tripathi et al., 2025).
6. Waterway regulation projects, which typically involve extensive operations such as sediment dredging, revetment construction, and rock dumping (Fu et al., 2025).
7. Traffic-induced vibration noise in bridges and underwater tunnels (Song et al., 2020).

While underwater noise has been extensively documented in marine ecosystems (Haver et al., 2018; Menze et al., 2017; Miksis-Olds and Nichols, 2016; Staaterman et al., 2014), research on acoustic environments in inland shallow water systems - particularly rivers - remains limited (Wang et al., 2021b). To date, peer-reviewed literature only reports on underwater noise measurements in the following major rivers: the Danube, Sava, and Tisa in Eastern-Europe (Vracar and Mijic, 2011), the Valleikanaal-Eem river system in the Netherlands (Velde et al., 2024), the Hudson River in the United States (Martin and Popper, 2016), and the Yangtze River in China (Wang et al., 2020a; Wang et al., 2021a). This research gap is particularly concerning given the ecological importance of these habitats for acoustically specialized species.

Many aquatic animals are highly dependent on their auditory system and rely on acoustic signals for survival, communication, prey location, predator avoidance and navigation purposes (Gannon et al., 2005; King and Janik, 2013; Simpson et al., 2016). The vocalization and hearing ranges of aquatic animals exhibit substantial interspecies variation (Fig. 1). Aquatic invertebrates, fishes, and reptiles primarily detect low-frequency sounds (typically <5 kHz), whereas cetaceans are capable of perceiving high-frequency sounds up to 200 kHz (Fig. 1). Aquatic species produce sounds across a broad frequency spectrum, from infrasonic (<20 Hz) to ultrasonic (>20 kHz), with most vocalizations occurring between 20 Hz and 20 kHz—a range audible to many taxa (Fig. 1). Since the Industrial Revolution, increasing anthropogenic noise has significantly elevated aquatic sound levels. The pronounced spectral overlap between human-generated noise and the auditory/vocalization ranges of aquatic fauna highlights the critical threat posed by underwater noise pollution (Duarte et al., 2021; Wang et al., 2025a; Wang et al., 2025b). Specifically, underwater noise pollution may interfere or impair the successful accomplishment of above mentioned critical life functions and imposes detrimental effects on aquatic animals (Codarin et al., 2009; Putland et al., 2018).

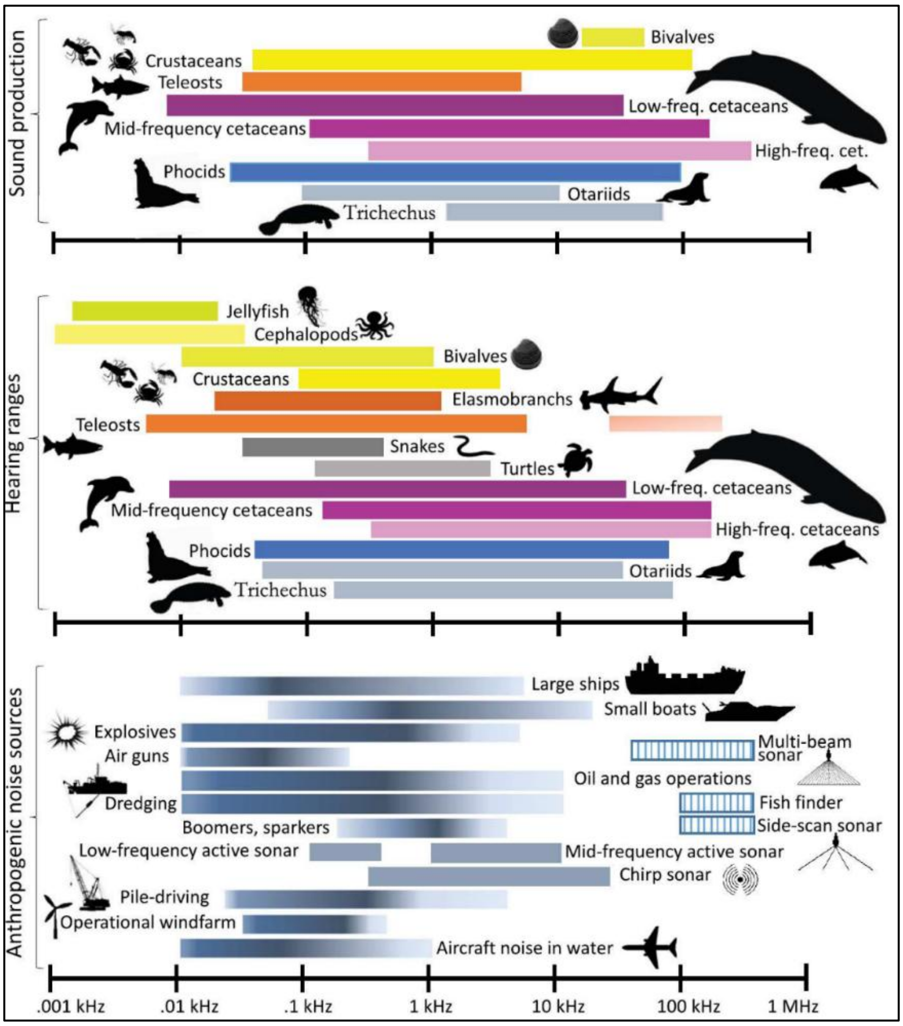

Fig.1 Approximate hearing and sound production ranges of aquatic taxa, compared with the frequency ranges of selected anthropogenic noise sources. Figure was revised from Duarte and colleagues (Duarte et al., 2021). The vocalization frequency range of Trichechus, which range from 1.87 to 88.3 kHz, was derived from studies by Brady and its colleagues (Brady et al., 2022) and Nowacek and its colleagues (Nowacek et al., 2003). The hearing frequency range of Trichechus, which range from 0.25 to 90.5 kHz, was derived from studies by Gaspard and its colleagues (Gaspard et al., 2012) and Gerstein and its colleagues (Gerstein et al., 1999).

The major effects of sound on aquatic animals include:

1. Behavioural changes, such as impacts on breeding, migration, anti-predator behaviours and group cohesion (Balazik et al., 2020; Cox et al., 2018; Nedelec et al., 2017; Radford et al., 2016; Simpson et al., 2015; van Oosterom et al., 2016; Wright et al., 2020);
2. Masking affects or suppresses the ability of animals to detect biologically important sounds, such as communication, echolocation and predator signals (Putland et al., 2018; Wang et al., 2014b);
3. Temporary threshold shift (TTS) caused by sound exposure, i.e., a recoverable temporary reduction in hearing sensitivity (McCauley et al., 2003; NMFS, 2016; Popov et al., 2011);
4. Permanent threshold shift (PTS), i.e., the unrecoverable or partially recoverable loss of hearing in marine mammals (McCauley et al., 2003; NMFS, 2016);
5. Physiological effects, such as increased levels of stress hormones (Mills et al., 2020) and immunophysiological responses (Lin et al., 2019);
6. Injuries, such as barotrauma, which damage organs and impairs their function (Casper et al., 2013; Halvorsen et al., 2012; McCauley et al., 2003) and can even be lethal (Nedelec et al., 2017; Simpson et al., 2016), may occur.
7. Shifts in distribution (Rako et al., 2013) or moving away from the sound (Hao et al., 2024).

While oceanic soundscapes have garnered significant scientific concern, anthropogenic underwater noise pollution in freshwater ecosystems has received comparatively little attention. Freshwater mammals have been established as bioindicators of ecosystem health in major tropical river systems across Asia and South America (Gomez-Salazar et al., 2012). Moreover, around 1.6 billion people live in river systems inhabited by freshwater dolphins, representing around 20% of the planet’s total population (Koncagül et al., 2020). Human population growth in these rivers has had a major impact on these ecosystems, with vessel traffic and engine noise increasing exponentially over the last 20 years. However, effective conservation of freshwater cetaceans as well as other mammals faces significant challenges (Campbell et al., 2022; IWC, 2001).

The Convention on the Conservation of Migratory Species of Wild Animals (CMS) is the only global convention specializing in the conservation of migratory species, their habitats and migration routes. Migratory species threatened with extinction are listed on Appendix I of the Convention, whereas migratory species that need or would significantly benefit from international co-operation are listed in Appendix II of the Convention. Currently, 10 freshwater mammal species are listed on CMS Appendix I and II (Table 1), which are distributed across different regions (Fig. 2). This report was developed in response to CMS COP14 Decision 14.45 (c), which requested the preparation of a report on the state of knowledge of noise impacts and noise mitigation measures for CMS-listed freshwater mammal species, and assess the need for specific guidance for freshwater habitats.

In Chapter 1, the state of knowledge of underwater noise impacts on each CMS-listed freshwater mammals and their prey is addressed. Chapter 2 covers the state of knowledge on underwater noise mitigation measures in freshwater habitats. In Chapter 3, currently available guidelines on underwater noise mitigation in freshwater habitats are outlined and key gaps identified. Subsequently, Chapter 4 contains recommendations to support the development of science-based underwater noise mitigation guidance for freshwater habitats.

Although this report was developed for CMS-listed freshwater species and their prey, the recommendations can be more broadly applicable to other freshwater mammal species, including non-migratory or endemic populations. An overview of other freshwater mammals can, for example, be found in the manuscript by Sanders and his colleagues (Sanders et al., 2024).

Table 1. All CMS-listed freshwater mammal species.

	Scientific Name	Common Name	Order	Family	Appendix I	Appendix II
1	*Trichechus inunguis*	Amazonian Manatee	Sirenia	Trichechidae		2002
2	*Trichechus manatus*	West Indian Manatee	Sirenia	Trichechidae	1999	1999
3	*Trichechus senegalensis*	West African Manatee	Sirenia	Trichechidae	2009	2009
4	*Lontra provocax*	Southern River Otter	Carnivora	Mustelidae	1979	
5	*Sotalia fluviatilis*	Tucuxi	Cetacea	Delphinidae		1979
6	*Sotalia guianensis*	Guiana Dolphin[1]	Cetacea	Delphinidae		1979
7	*Orcaella brevirostris*	Irrawaddy Dolphin	Cetacea	Delphinidae	2009	1991
8	*Neophocaena asiaeorientalis*	Narrow-ridged Finless Porpoise	Cetacea	Phocoenidae		1979
9	*Platanista gangetica*	Ganges River Dolphin	Cetacea	Platanistidae	2002	1991
10	*Inia geoffrensis*	Amazon River Dolphin	Cetacea	Iniidae		1991

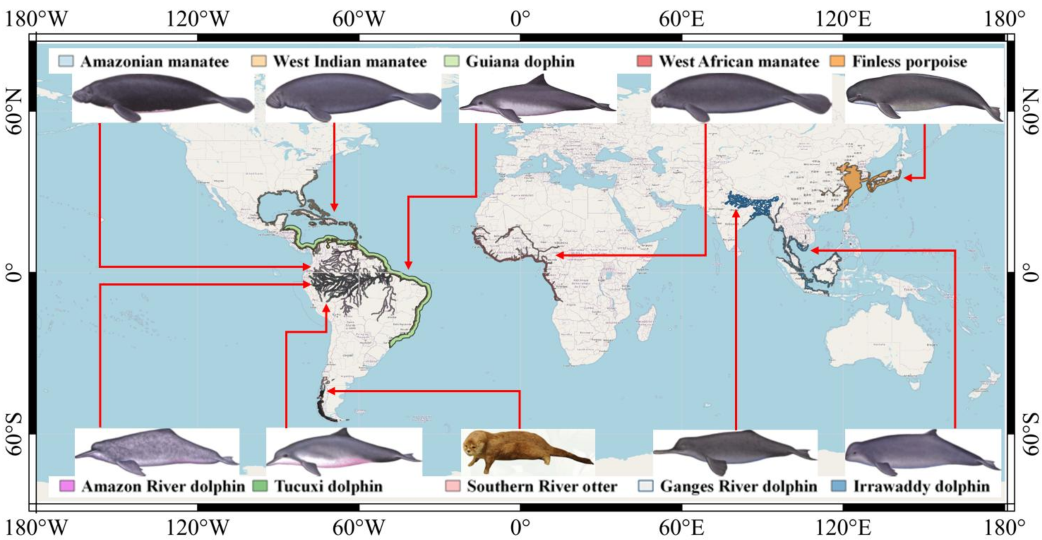

Fig.2 Distribution map of all CMS-listed freshwater mammals (distribution range of each species cited from IUCN Red List).

[1] Habitat of the Guiana Dolphin includes both oceanic and freshwater habitat.

1.1 Underwater noise impacts on CMS-listed freshwater mammals

1.1.1 Amazonian Manatee (*Trichechus inunguis*)

Amazonian Manatees (*Trichechus inunguis*) are found exclusively in northern South America, inhabiting freshwater systems across the Amazon Basin. Their range spans the entire Amazon River drainage, including rivers and lakes, from the headwaters in Colombia, Ecuador, and Peru downstream to the river's mouth near Marajó Island in Brazil (Fig. 3) (Marmontel et al., 2016). The Amazonian Manatee is listed on the IUCN Red List as Vulnerable; Threats include habitat loss and degradation associated with fisheries and river traffic (Marmontel et al., 2016).

In Amanã SDR (Brazil), manatees are believed to have moved away due to habitat alterations and increasing noise levels (Calvimontes, 2009). Seventy-three percent of interviewees in the Belém region (near the mouth of the Amazon) perceived a decline in the manatee population, attributing it to hunting, pollution, boat traffic, and noise disturbances (Miranda et al., 2014). Brazil has developed extensive navigation plans, including proposed dams on the Tapajós River to establish a waterway for soybean transport. This infrastructure would facilitate access to the Amazon River and the Atlantic Ocean (Marmontel et al., 2016). However, these planned projects involve significant construction activities and are expected to increase noise levels, potentially affecting the Amazonian manatee.

Oil exploitation has been authorized in critical habitats of the Amazonian Manatee (Utreras et al., 2013). This species exhibits high sensitivity to noise pollution, and increased boat traffic associated with oil exploitation in Amazonian rivers may disrupt its behavioural patterns and habitat utilization (Marmontel et al., 2016).

The use of dynamite for fishing and the growing prevalence of motorized boats in the Cuyabeno and Jatuncocha river systems to support nature-based tourism pose significant emerging threats to Ecuador's Amazonian Manatee (Marmontel et al., 2016; Utreras et al., 2011).

In the coastal waters surrounding Belém and the Amazon River estuary, dense marine traffic – including commercial ferries and cargo vessels – has been documented to potentially disrupt manatee migratory patterns and local movement ecology (Miranda et al., 2014).

Fig.3 Distribution map of the Amazonian Manatee (*Trichechus inunguis*) (Marmontel et al., 2016).

1.1.2 West Indian Manatee (*Trichechus manatus*)

The West Indian Manatee (*Trichechus manatus*) is currently divided into two subspecies: the Florida Manatee (*T. m. latirostris*) and the Antillean Manatee (*T. m. manatus*) (Deutsch and Morales-Vela, 2024). The West Indian Manatee is listed on the IUCN Red List as Vulnerable (Deutsch and Morales-Vela, 2024). The Florida Manatee subspecies is also listed as Vulnerable on the IUCN Red List (Deutsch and Valade, 2024), whereas the Antillean Manatee subspecies, recently proposed to be called the Greater Caribbean Manatee, has been classified as Endangered on the IUCN Red List (Morales-Vela et al., 2024). In addition to coastal areas, the West Indian Manatee inhabits numerous freshwater bodies throughout its range, which extends from the southeastern United States to Brazil and includes the Greater Antilles (Fig. 4) (Deutsch and Morales-Vela, 2024). These habitats include major rivers, lakes, and lagoons, such as those along the coast of Honduras (Gonzalez-Socoloske et al., 2011). In the Gulf of Mexico, freshwater systems constitute a significant portion of the West Indian Manatee's habitat (Fig. 4) (Jiménez-

Domínguez and Olivera-Gómez, 2014).

Manatees occupy habitats in the same coastal zone and inland waterways where humans carry out recreational and other activities, a fact that contributes to manatee vulnerability to human pressures. In Sarasota Bay, FL, background noise can impact the vocal communication space and may limit the ability of vocal-mediated mother-calf cohesion in Florida Manatees (Rycyk et al., 2022). Manatees primarily feed on a wide variety of aquatic vegetation, including seagrasses and algae (Allen et al., 2022) and can spend four to eight hours per day feeding (Etheridge et al., 1985). Vessel traffic and recreational activities that disturb manatees can displace them from preferred habitats and disrupt biologically critical behaviours, including feeding, nursing, and resting (Gerstein et al., 2005; O'Shea, 1995; Wright et al., 1995). Furthermore, manatees exhibit a stronger preference for seagrass habitats over dredged areas, particularly when ambient noise levels – especially low-frequency (<1 kHz) noise – are reduced. Grass bed usage was negatively correlated with high boat traffic in the morning, suggesting that vessel activity and associated noise may influence daily foraging habitat selection (Miksis-Olds et al., 2007). Additionally, for the Florida Manatee, vessel strikes have accounted for an average of 21.1% (min-max = 8.8-31.1% across years) of all reported manatee deaths (Deutsch and Reynolds III, 2012). Advances in vessel hull and engine design have enabled boats to achieve higher speeds in shallower waters (Wright et al., 1995), damaging seagrass beds and increasing risk of vessel strikes with manatees. Faster boats are more likely to collide with manatees than slower vessels, as manatees have insufficient time to react to boats traveling at planning speeds (Rycyk et al., 2018). Dredging of canals and channels to promote vessel traffic and shipping for industrial or tourism activities may have significant consequences on habitat connectivity and ecological structure (Rasheed and Balchand, 2001).

The Greater Caribbean Manatee is closely associated with freshwater ecosystems, relying on freshwater sources and coastal marine estuaries throughout its range from Mexico through Central America to South America (Morales-Vela et al., 2024). Dredging canals and channels to facilitate vessel traffic – whether for industrial or tourism purposes – can generate noise pollution and significantly disrupt habitat connectivity and ecological integrity impacting the Greater Caribbean Manatee. Manatees inhabiting or migrating through nearshore zones now encounter higher vessel densities than previously documented (Cloyed et al., 2021). In Puerto Rico, watercraft-related manatee mortalities – primarily caused by propeller strikes and jet-ski strikes – are frequently attributed to high-speed vessel activity (Bonde et al., 2012).

In conclusion, anthropogenic underwater noise pollution has a wide-ranging disruptive impact on both subspecies of the West Indian Manatee, primarily from noise generated by shipping and other watercrafts. Vessel traffic is also related to the largest cause of manatee death: vessel strikes, confirmed by the many living manatees that bear scars or wounds from vessel strikes (Bassett et al., 2020).

Fig.4 Distribution map of the West Indian Manatee (*Trichechus manatus*) (Deutsch and Morales-Vela, 2024).

1.1.3 West African Manatee (*Trichechus senegalensis*)

The West African Manatee (*Trichechus senegalensis*) occurs in most of the coastal marine waters, brackish estuaries, and adjacent rivers along the coast of western Africa from southern Mauritania (16°N) to the Cuanza and Longa Rivers, Angola (9°S) (Fig. 5). The West African Manatee is listed on the IUCN Red List as Vulnerable (Keith Diagne, 2015).

The West African Manatee is one of the least understood marine mammals globally and has been identified as the least studied large mammal in Africa (Trimble and Van Aarde, 2010). Although there is a lack of research, the increase in motorized boats and large vessel traffic in some of the rivers and lagoons is thought to pose a threat to this species, both from the noise pollution generated by the vessel traffic, but also from strikes with these vessels, which is the most prevalent known cause of death in Florida and Belizean Manatee populations (Keith Diagne, 2015).

Fig.5 Distribution map of the West African Manatee (*Trichechus senegalensis*) (Keith Diagne, 2015).

1.1.4 Southern River Otter (*Lontra provocax*)

The Southern River Otter (*Lontra provocax*) occurs in Chile and Argentina in freshwater and marine environments (Fig. 6). The Southern River Otter is listed on the IUCN Red List as Endangered (Sepúlveda et al., 2021). The habitat of the Southern River Otter is very sensitive to anthropogenic impacts (Valenzuela et al., 2013). The population of the Southern River Otter has declined dramatically due to multiple threats, including habitat destruction, river and stream canalization, and extensive dredging (Medina-Vogel et al., 2003). Rapid habitat destruction and degradation across the Southern River Otter's range pose the most significant threat to the species. Based on current trends, these pressures are projected to cause a future population decline of ≥50% over the next three generations (30 years). This applies to both freshwater-dependent subpopulations (inhabiting rivers and lakes) and marine-adapted subpopulations (occupying southern fjords and islands) (Sepúlveda et al., 2021). In freshwater habitats, the Southern River Otter is associated with the presence of macro-crustaceans from the genus *Aegla spp.* and *Sammastacus spp.* (Franco et al., 2013; Medina-Vogel and Gonzalez-Lagos, 2008; Sepúlveda et al., 2009). All these crustacean species are noise-sensitive and may be adversely affected by anthropogenic sound disturbances (see 1.2 Noise impacts on prey of CMS-listed freshwater mammals). In several parts of the otter's distribution range, hydroelectric dams are installed or are planned to be built in the near future (Sepúlveda et al., 2021). Though there are few studies on underwater noise impacts on the Southern River Otter, studies on other otter species suggest that underwater noise pollution from these projects may adversely impact the species (Garcês and Pires, 2024; Stepien et al., 2024), both directly and indirectly.

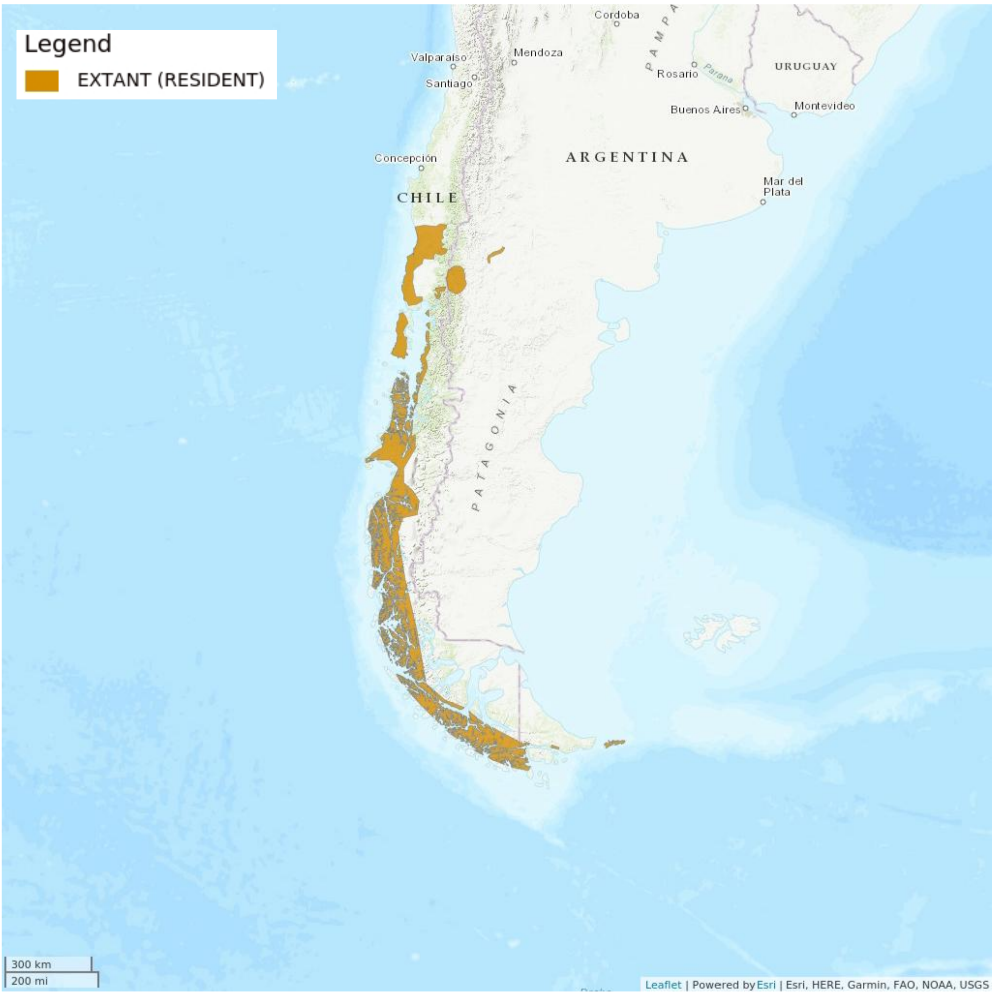

Fig.6 Distribution map of the Southern River Otter (*Lontra provocax*) (Sepúlveda et al., 2021).

1.1.5 Tucuxi (*Sotalia fluviatilis*)

Tucuxi (*Sotalia fluviatilis*) are found in the Amazon drainage as far inland as southern Peru, eastern Ecuador and southeastern Colombia (Fig. 7). The tucuxi is listed on the IUCN

Red List as Endangered (da Silva et al., 2020). Its habitat has been modified and degraded by various human activities including fishing, dam construction, mining, ship traffic and oil exploitation (da Silva et al., 2020). Fishing with explosives has been common in some areas of the Amazon basin (Goulding, 1983; Smith, 1985) and threatens Tucuxis due to concussive effects. Recent interviews with fisherman from Manacapuru area (Brazil), revealed that explosives are still being used in the jaraqui (*Semaprochilodus sp*) fishery (da Silva et al., 2020). Hydraulic infrastructure development (e.g., dams and river diversions) represents a growing and significant threat to Tucuxi dolphins in the Amazon River basin (da Silva et al., 2015). In terms of underwater noise pollution, hydraulic infrastructure development and increased boat navigation may adversely impact the Tucuxi. Additionally, the proliferation of dams, including expanding commercial exploitation networks, enhancing river navigation, and expanding terrestrial access routes, will inevitably constrain dolphin mobility, exacerbate population fragmentation, and further degrade critical habitats (Pavanato et al., 2016).

Fig.7 Distribution map of the Tucuxi (*Sotalia fluviatilis*) (da Silva et al., 2020).

1.1.6 Guiana Dolphin (*Sotalia guianensis*)

The Guiana Dolphin (*Sotalia guianensis*) is distributed primarily throughout shallow coastal waters and estuarine systems along the Atlantic coast of northern and eastern South America, extending from Florianópolis, Santa Catarina State (southern Brazil) northward through the Caribbean Sea to La Mosquitia, Honduras (Fig. 8) (Secchi et al., 2018). It is classified as Near Threatened on the IUCN Red List of Threatened Species (Secchi et al., 2018). This small cetacean species exhibits two ecotypes: a coastal marine form and a freshwater-adapted form.

Fig.8 Distribution map of the Guiana Dolphin (*Sotalia guianensis*) (Secchi et al., 2018).

In freshwater systems, the Guiana Dolphin demonstrates an extensive distribution, with confirmed populations in the Orinoco River basin including regular sightings at Ciudad Bolívar (~300 km upstream) (da Silva et al., 2010; Flores and Da Silva, 2009; Secchi et al., 2018) and records extending to Estado Bolívar and Apure near the Suapure River confluence (~800 km upstream) (da Silva et al., 2010). The species is particularly abundant in the Amazon River estuary, where its habitat extends hundreds of kilometres seaward through the river's extensive freshwater plume (Secchi et al., 2018). Additional freshwater populations inhabit the southern basin of Lake Maracaibo and are frequently observed in the Marowijne River (Suriname-French Guiana border region) and major river estuaries throughout Suriname (Secchi et al., 2018). In Guyana, the dolphins predominantly occupy the estuarine zones of the Demerara, Cuyuni, Mazaruni, and Essequibo rivers (Secchi et al., 2018), with peripheral populations documented in Nicaragua's Wauhta Lagoon within the Cayos Miskito Reserve (Fig. 9) (Edwards and Schnell, 2001a; Edwards and Schnell, 2001b).

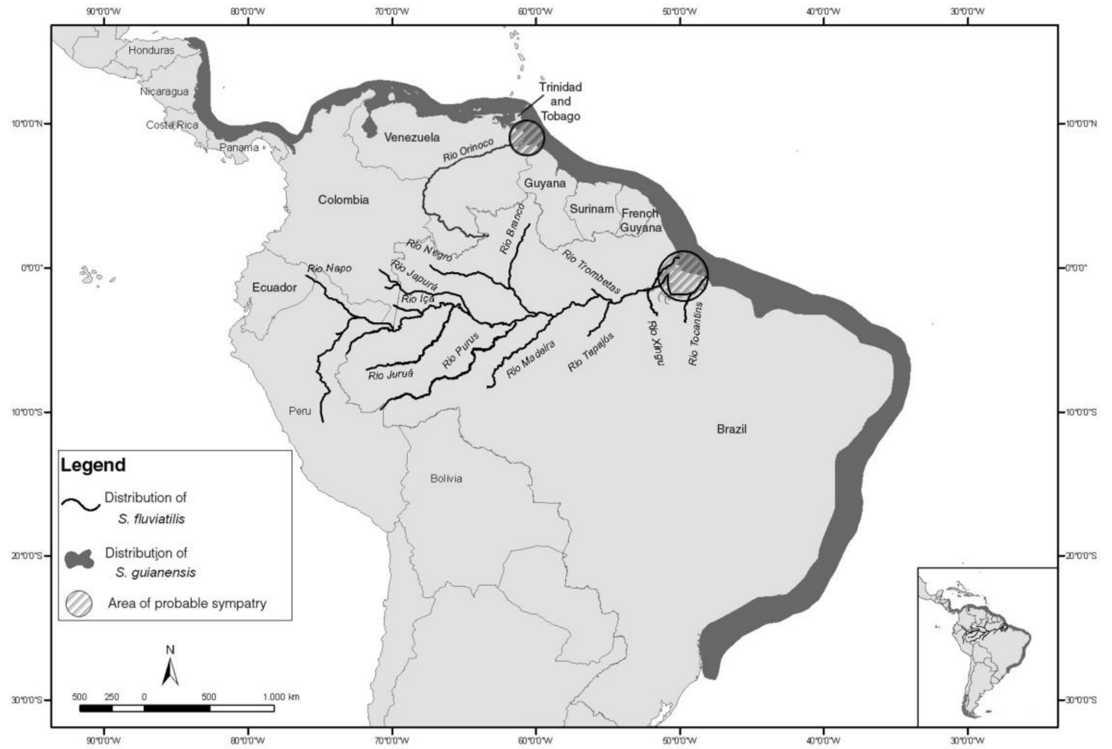

Fig.9 Geographic distribution of the Guiana Dolphin (*Sotalia guianensis*) (dark grey shading) and Tucuxi (*Sotalia fluviatilis*) (black line). The area of potential overlap between the two species in the Amazon and Orinoco estuaries is also shown (crosshatching) (da Silva et al., 2010).

The Guiana Dolphins' preference for coastal and estuarine habitats, which overlaps extensively with human activities, makes them particularly vulnerable to anthropogenic pressures, including fisheries bycatch, intense boat traffic and associated high noise levels, hydrocarbon exploration, and coastal urbanization (da Silva et al., 2010).

Underwater noise pollution is considered to be an important threat to Guiana dolphins (Domit et al., 2021). In a study by Maciel and colleagues (Maciel et al., 2023), Guiana dolphins communicated mainly in less noisy areas and noise levels were the most important variable to explain the reduction in whistle rates. The whistling rate decreased by up to 79% during the high-noise period, suggesting reduced social communication or masking effects (Marcondes et al., 2025). Anthropogenic noise can also affect the whistle parameters of Guiana dolphins, resulting in higher initial and ending frequencies as well as shorter durations (Bittencourt et al., 2017; Leão Martins et al., 2018; Marcondes et al., 2025).

Furthermore, Lake Maracaibo contains over 15,000 active oil wells, and the lake floor is latticed with oil pipelines. Oil well operations generate substantial underwater noise pollution that can adversely affect these dolphins (Torres, 2016; Villasmil et al., 2003). Furthermore, the pipeline infrastructure may create physical barriers for dolphins to move between areas and populations.

1.1.7 Irrawaddy Dolphin (*Orcaella brevirostris*)

Irrawaddy dolphins (*Orcaella brevirostris*) occur in south and southeast Asia where coastal populations are limited to shallow coastal waters (usually associated with freshwater inputs) as well as three brackish lagoons or inlets (Fig. 10) (Minton et al., 2017). Entirely freshwater populations are well known from three large river systems (Minton et al., 2017). The species is classified as Endangered on the IUCN Red List of Threatened Species (Minton et al., 2017), and the isolated populations that occur in the Mahakam River (Indonesia), Ayeyarwady River (Myanmar), Mekong River (Cambodia and Laos), Iloilo-Guimaras and Malampaya Sound (Philippines), and Songkhla Lake (Thailand) are listed as Critically Endangered (Minton et al., 2017; Wang et al., 2020b).

Noise from high-speed boats and container vessels – especially large coal barges operating in narrow tributaries – poses a significant threat to the Irrawaddy dolphin and observations indicate that dolphins have been displaced from core areas in response to the presence of these vessels. In addition to elevated underwater noise levels, there is also an increased risk of vessel strike, which could cause death or injury (Jefferson et al., 2008; Kreb, 2014).

Compared with coastal Irrawaddy dolphins, freshwater Irrawaddy dolphins in Indonesia's Mahakam River, locally referred to as pesut, showed a hypersensitivity to intensive boat traffic. During one study, it was documented that dolphins in the Mahakam River surfaced significantly less often in the presence of motorized canoes (< 40 hp), speedboats (40-200 hp), and container tugboats (> 1,000 hp) (Kreb and Rahadi, 2004). Pesuts were also observed responding to speedboats at distances of up to 250 m before passage and 300 m following passage (Kreb and Rahadi, 2004). Besides surfacing changes, pesut dolphins actively avoided container tugboats by changing direction or surfacing more often at close range as if to obtain visual clues to the boat's position, which possibly could be due to the loud underwater noise from these boats in narrow tributaries may make them unable to accurately locate the ships' position through echolocation, especially in narrow tributaries (Kreb and Rahadi, 2004), which may be due to (partial) acoustic masking of dolphins' sonar reflections (Au and Penner, 1981). This may cause disorientation, and inaccurate distance estimation, which is very dangerous in narrow rivers with many river bends while the distance between ships in convoy is also often only 50 m. This also leads to potential vessel strikes, with at least two known strikes on record (Danielle Kreb, personal communication). In one study, when coal barge-tug boats approached pesut dolphins to a distance of 100 m, all dolphins stopped vocalizing and echolocation was not detected (Kreb and Rahadi, 2004). For this reason, barge traffic at night increases the risk of vessel strikes further, as they are unable to detect boats visually at night (Kreb and Budiono., 2025a). The Irrawaddy dolphin prefers areas of confluence that are also important as fishing grounds, therefore core habitats for this species tend to overlap with intense vessel traffic (Kreb and Budiono, 2005).

Two out of four major tributaries of the Mahakam River, with an average width of 100 m, representing important dolphin habitat, have become intensive shipping lanes for coal barges (55-90 metres in size with a draught of 3-5 meters) (Kreb and Budiono., 2025a). In the main river, shipping has increased tremendously in frequency since 2024 with, at some points, 6-8 coal ships passing by per hour (Danielle Kreb, personal communication). Not only do these vessels generate chemical pollution, but also noise pollution. Furthermore, coal barge transports in the Mahakam often do not travel in the centre of the river, in violation of prevailing regulations, and so often collide with river shores, changing the river's natural geophysical shape by increasing canalization. It also alters the micro habitat by increasing currents near the shore, affecting both dolphins and their prey and disturbing dolphins who spend the majority of their time near the shores (Kreb and Budiono., 2025a, b).

Studies indicate that Irrawaddy dolphins in the Mahakam River exhibit disturbance behaviour for approximately five minutes every time a vessel comes within close proximity (Kreb and Budiono., 2024). Dolphin behaviour and/or position changed from feeding/playing/resting (initial behaviour) to other behaviours, including longer dives upon large vessel approach (100m-300m) as well as after passing, more frequent surfacing at close range (<50 m), and changing initial locations or swimming directions, as well as changes in groups' spatial patterns (Kreb and Rahadi, 2004). Studies on other dolphin species' behaviour and ship disturbances, such as the bottlenose dolphin (*Tursiops truncatus*) in the Bay of Islands, New Zealand have shown that with increasing boat numbers, even minimal (wake) speed and noise levels can lead to a reduction in resting behaviour, a vital behaviour for dolphins to remain healthy (Constantine et al., 2004).

There are currently no regulations governing the distance between large ships or the maximum frequency of ships per day/night in the Mahakam River. To protect the dolphins' resting behaviour and not affect their activity budgets, it is necessary to set a maximum limit on the number of ships in dolphin habitat on the Mahakam River. The Indonesian government is fostering cooperation among relevant stakeholders to implement protections for the Irrawaddy dolphin in the Mahakam River. It is crucial that these protections include science-based limits on shipping activity. The objective is to prevent disruption of critical behaviors like resting and feeding, thereby avoiding negative population-level impacts, such as reduced survival rates.

Gold mining operations on the geomorphology of deep pools, where Irrawaddy dolphins in the Ayeyarwady River generally concentrate, produce underwater noise with harmful effects (Smith et al., 2007; Wang et al., 2020b).

Fig.10 Distribution map of Irrawaddy Dolphins (*Orcaella brevirostris*) (Minton et al., 2017).

1.1.8 Narrow-ridged Finless Porpoise (*Neophocaena asiaeorientalis*)

The Narrow-ridged Finless Porpoise (*Neophocaena asiaeorientalis*) occurs in a narrow strip of shallow coastal water around the western Pacific Ocean from the Taiwan Strait to the waters of northern China, Korea and northern Honshu, Japan (Fig. 11) (Wang and Reeves, 2017). It is classified as Endangered on the IUCN Red List of Threatened Species (Wang and Reeves, 2017). *N. asiaeorientalis* is recognized to have two subspecies (*N. a. asiaeorientalis* and *N. a. sunameri*). The Yangtze Finless Porpoise (*N. a. asiaeorientalis*) is endemic to the middle-lower Yangtze River drainage basin in eastern China, from Yichang downstream to the estuary near Shanghai. It is now almost completely restricted to the main river channel and its two largest appended lakes: Poyang and Dongting (Fig. 12) (Wang et al., 2013). The Yangtze Finless Porpoise represents the sole freshwater subspecies of the Narrow-ridged Finless Porpoise. It has been classified as Critically Endangered on the IUCN Red List of Threatened Species (Wang et al., 2013). It faces a high risk of extinction, much like the Yangtze River Dolphin (*Lipotes vexillifer*), which once shared the same habitat and threats and is believed to have been driven to extinction by human activities (Turvey et al., 2007). The Yangtze River has been the world's busiest inland river in terms of shipping since 2005. The annual cargo throughput of the Yangtze River trunk line reached 0.3 million tons in 2002 and steadily increased at an annual rate of 12%, amounting to 4.02 million tons in 2024 (Yangtze River Yearbook Editorial Committee, 2024). Evidence for boat avoidance behaviour in Yangtze finless porpoise has been demonstrated through both indirect and direct observation methods (Wang et al., 2015; Wei et al., 2002). Initial indirect evidence was obtained through visual line transect surveys (Zhao et al., 2008) and towed acoustic monitoring (Li et al., 2008). Subsequently, stationary acoustic surveys have provided direct observational confirmation of this avoidance behaviour (Wang et al., 2015).

Research on local sites revealed that when vessels passed by, the vocalization frequency of the Yangtze Finless Porpoises decreased significantly (Dong et al., 2012). Navigation noise of large vessels in the Hechangzhou region of the Yangtze River may cause significant auditory damage to the Yangtze Finless Porpoise (Zhang et al., 2018).

Range-wide surveys confirm that noise pollution threatens the Yangtze Finless Porpoise. In 2012, the underwater noise levels (sound pressure level (SPL) and unweighted sound exposure level (SEL)) in 25 sites along the middle and lower sections of the Yangtze River were measured. A broadband SPL in Root Mean Square (SPL_{rms}) of 120 dB re 1μPa is proposed as the threshold of noise causing responsiveness in cetaceans (Richardson et al., 1995). In this study, 88% of the locations (22 out of 25 sites) had SPL_{rms} of over 120 dB (SPL and SEL ranged between 105 ± 2.4 (median ± quartile deviation) and 150 ± 5.5 dB at each site). The majority of the sites had an averaged cumulative unweighted SEL (72%) and cumulative weighted SEL (68%) that surpassed the underwater acoustic thresholds for onset of temporal threshold shifts (TTS)[2] for Yangtze Finless Porpoise. In 8% of the sites, the averaged cumulative weighted SEL exceeded that of underwater acoustic thresholds causing non-recoverable permanent threshold shifts of the Yangtze Finless Porpoises' auditory system, whereas it was less than 1 dB below the underwater acoustic thresholds in another 8% of the sites (Wang et al., 2020a). In 2017, the underwater noise level in 25 riverside locations along the middle and lower reaches of the Yangtze River were investigated again by using passive acoustic monitoring method. At approximately 88% of the locations (22 out of 25 sites), SPL_{rms} was higher than the responsiveness threshold of cetaceans (120 dB) (Richardson et al., 1995). Approximately 40% of the sampled sites exhibited noise levels exceeding the underwater acoustic thresholds of causing temporary threshold shift in the Yangtze Finless Porpoise (Wang et al., 2021a).

[2] Temporal threshold shifts are temporary decreases in hearing sensitivity due to exposure to noise.

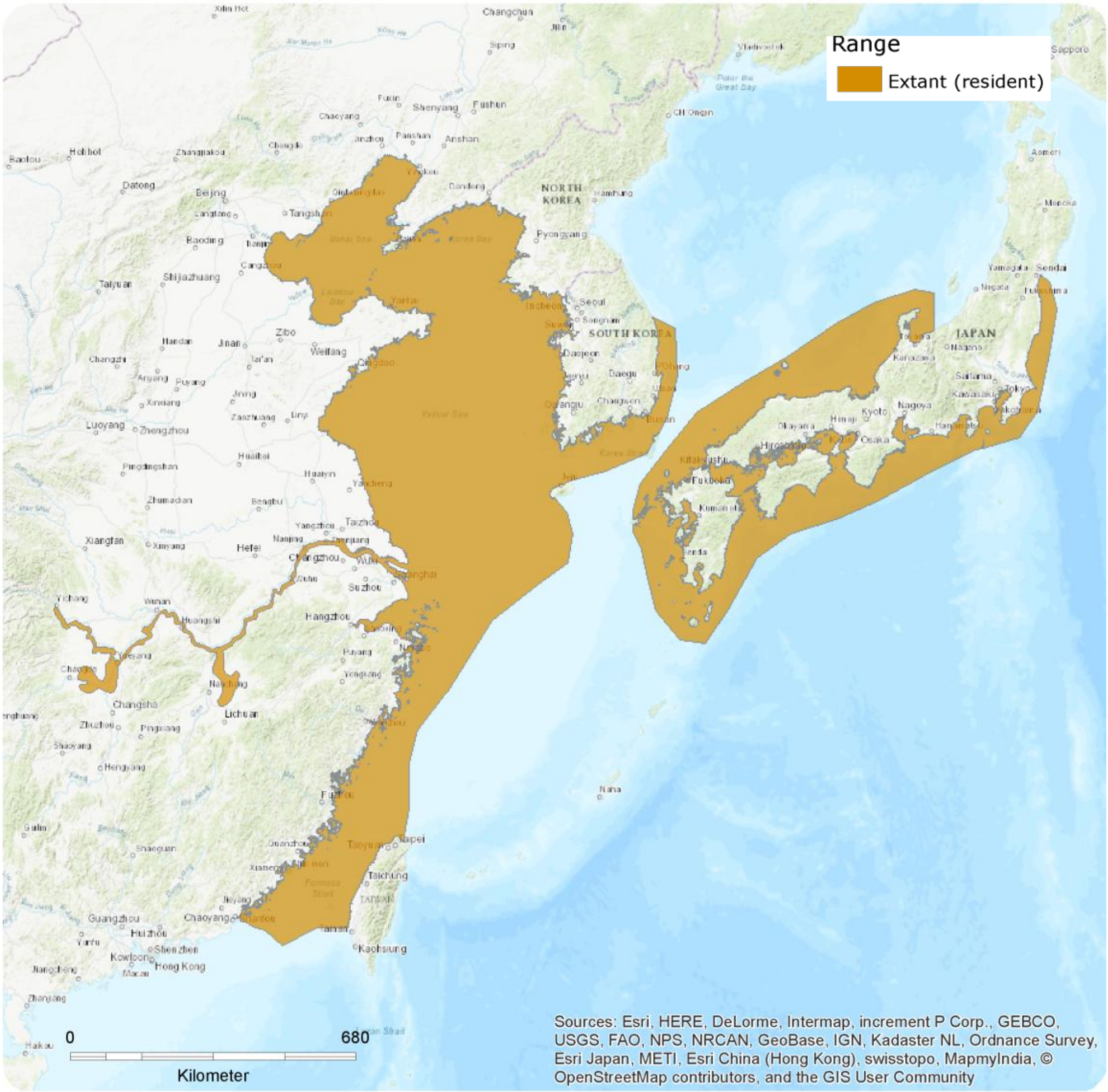

Fig.11 Distribution map of the Narrow-ridged Finless Porpoise (*Neophocaena asiaeorientalis*) (Wang and Reeves, 2017). *N. a. asiaeorientalis* is endemic to the middle-lower Yangtze River drainage basin in eastern China, and *N. a. sunameri* is distributed in shallow coastal water around the western Pacific Ocean from the Taiwan Strait to the waters of northern China, Korea and northern Honshu, Japan.

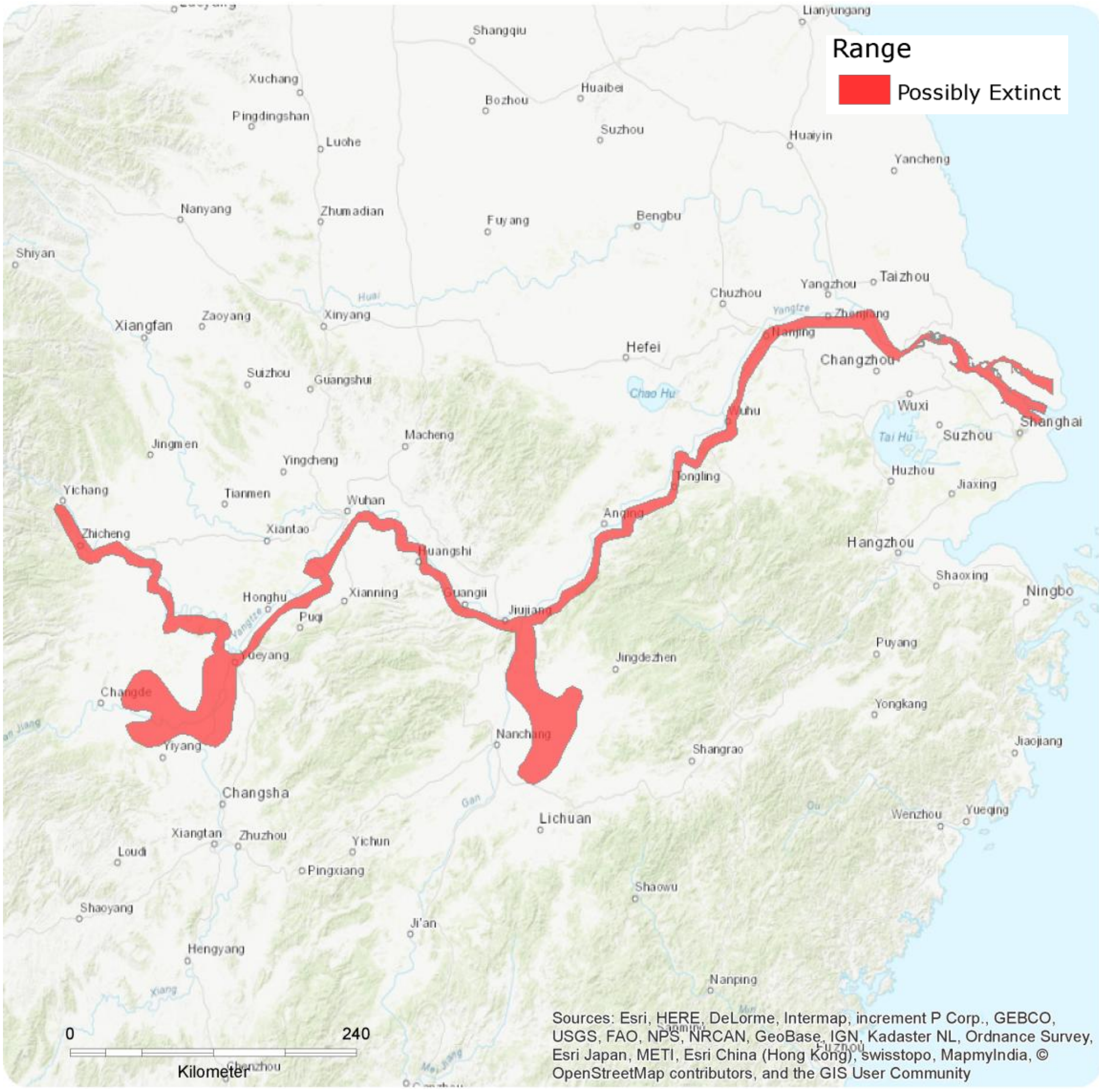

Fig.12 Distribution map of the Yangtze Finless Porpoise (*Neophocaena asiaeorientalis asiaeorientalis*) (revised from Wang et al., 2013).

1.1.9 Ganges River Dolphin (*Platanista gangetica*)

Ganges River Dolphins (*Platanista gangetica*) historically occurred throughout the Ganges-Brahmaputra-Meghna (GBM) and Karnaphuli-Sangu (KS) river basins from their tidal deltas in India and Bangladesh, to the plains at the Himalayan foothills, where rocky barriers, shallow water, and fast currents prevented upstream movement (Fig. 13) (Kelkar et al., 2022). The species is classified as Endangered on the IUCN Red List of Threatened Species (Kelkar et al., 2022).

Disturbance from human activities related to boat traffic, underwater noise, and shoreline/riverfront development is one of the major threats to Ganges River Dolphins (Kelkar et al., 2022). Ganges River Dolphins produce high-frequency echolocation clicks at relatively low source levels compared to marine dolphins, making them particularly vulnerable to anthropogenic noise impacts (Kelkar et al., 2022). Ganges River Dolphins are continuous click emitters (Dey et al., 2019) and rely almost entirely on high-frequency echolocation clicks (55-75 kHz peak frequency) (Jensen et al., 2013). Furthermore, Ganges River Dolphins have been observed to avoid motorized boats (Smith, 1993).

In 2016, the Indian Government enacted the National Waterways Act, designating 111 rivers for development as commercial and industrial waterways to facilitate cargo transport (including industrial machinery and coal), shipping, and passenger travel (Dey et al., 2019). This planned expansion of inland navigation – targeting over 3,600 km of waterways – overlaps with approximately 90% of the Ganges River Dolphin's habitat in India (Kelkar, 2017). The further expansion of industrial transportation and recreational waterways in the Ganga-Brahmaputra river basins might expose Ganges River Dolphins to increasing underwater noise from vessels and river-bottom dredging (Dey et al., 2019). Increase in underwater noise due to motorised vessels resulted in major alterations to acoustic responses, strong masking of echolocation clicks, and high metabolic costs to river dolphins in the Ganges River. Vessel noise impacts were the strongest at low water depth in the dry-season (Dey et al., 2019). Dolphins showed enhanced activity during acute noise exposure and suppressed activity during chronic exposure. With the expansion, the impacts on Ganges River Dolphins from dredging and high vessel traffic are likely to increase. Its sister species, the Indus River dolphin (*Platanista minor*) – previously classified as a subspecies *P. gangetica minor* (Braulik et al., 2022) –faces similar threats from motorised vessel traffic (Perveen et al., 2011). It is the only freshwater species of cetacean not listed on CMS Appendices.

The diversion of water for irrigation – through dams, barrages, and groundwater/surface water extraction via tube wells and surface pumps – has reduced dry-season river flows in all Range States, significantly degrading river dolphin habitat in many regions (Lapworth et al., 2021). Additionally, in 2020, an oil well blowout at the Baghjan oil field in Assam, India – located near the Lohit-Dibru tributaries of the Brahmaputra River – caused temporary habitat loss for Ganges River Dolphins (Wildlife Institute of India, 2020). Extensive extraction of sand and gravel for construction occurs from riverbeds throughout India, Nepal and Bangladesh and causes considerable noise and ecological disturbance (Das et al., 2025).

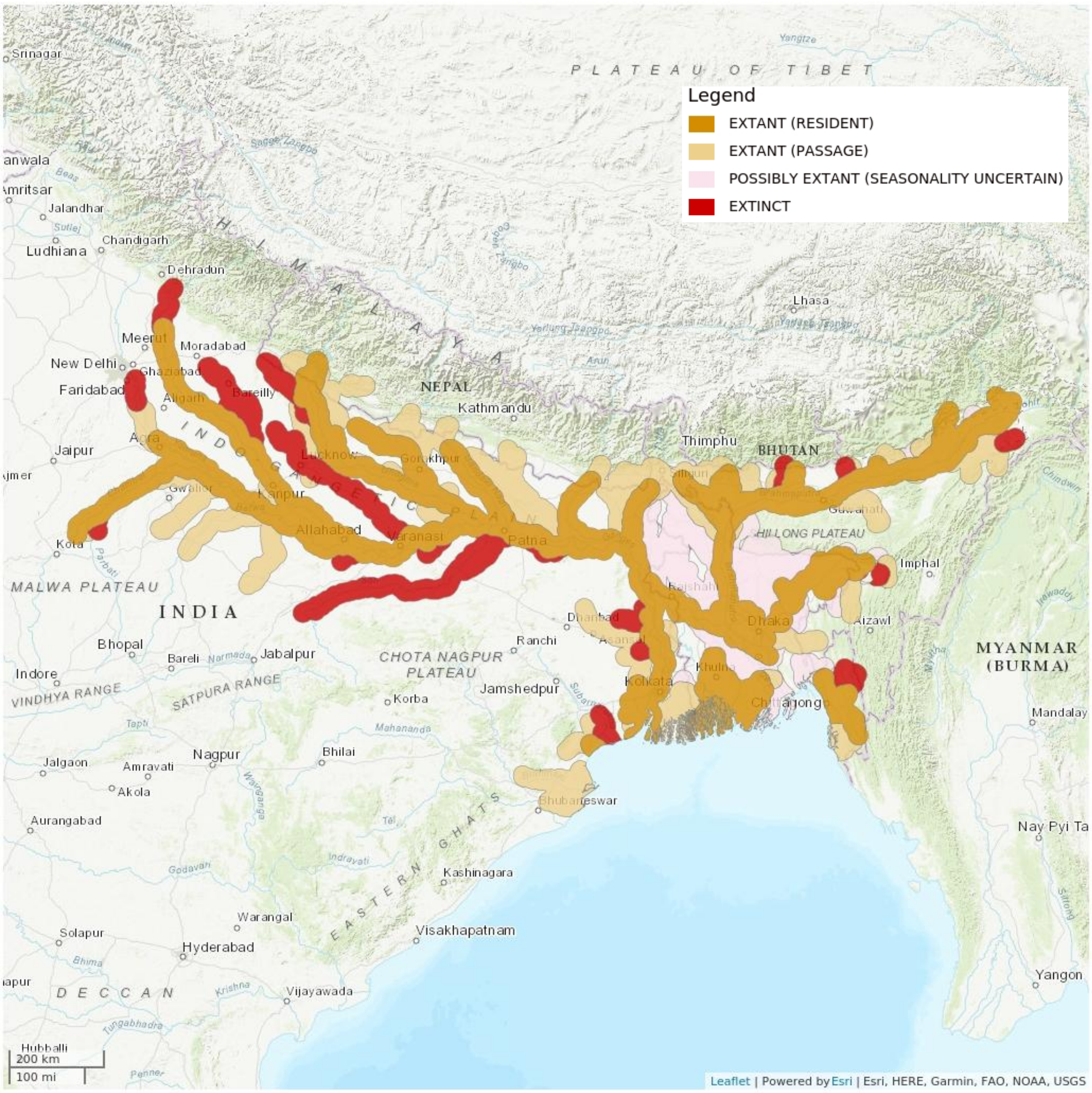

Fig.13 Distribution map of the Ganges River Dolphin (*Platanista gangetica*) (Kelkar et al., 2022).

1.1.10 Amazon River Dolphin (*Inia geoffrensis*)

The Amazon River Dolphin (*Inia geoffrensis*) occurs throughout the Amazon and Orinoco river basins in Brazil, Bolivia, Colombia, Ecuador, Peru, and Venezuela, from the deltas upstream to where impassable rapids, waterfalls, lack of water, and low temperatures block their movement (Fig. 14) (da Silva et al., 2018). There is a single species in the genus *Inia geoffrensis*, with two subspecies: *I. g. boliviensis*, the Bolivian Bufeo, and *I. g. geoffrensis*, the Common Boto. The Amazon River Dolphin is listed on the IUCN Red List as Endangered (da Silva et al., 2018).

An increasing number of people depend on the Amazon River and its major tributaries for subsistence and transportation, while their activities simultaneously degrade water quality through sewage discharge, underwater noise pollution, and chemical or physical waste contamination (Martin and da Silva, 2022). Although it has long been recognized that Amazon River Dolphins die from entanglement (bycatch) in fishing gear across much of their range, their habitat has also been modified and degraded in many places by human activities other than fishing, such as dam construction, port development, mining, and ship traffic, all of which contribute to underwater noise pollution (da Silva et al., 2018). Blast fishing, though illegal in most countries, was historically prevalent in certain regions of the Amazon Basin. In Venezuela, this practice persists and has been documented as a threat to the Amazon River Dolphin due to the lethal concussive effects of underwater explosions (Aya, 2010).

The Amazon Basin currently has 434 barriers (dams or other obstructions) that are either built or under construction, with an additional 463 proposed projects in early planning phases (Caldas et al., 2023). Dams are bound to restrict dolphin movements, contribute to increased population fragmentation, and continue to alter and degrade their habitat by opening commercialization networks, improving navigability, and increasing road access (Williams et al., 2016a). The Tocantins-Araguaia Basin has undergone significant ecological transformations in recent decades due to dam construction, deforestation for cattle ranching, logging activities, and road development (Siciliano et al., 2016). Furthermore, near Mocajuba along the lower Tocantins River, unregulated interactions between humans and wild dolphins – including feeding and physical contact by both tourists and local residents – may elevate the dolphins' vulnerability (Melo-Santos et al., 2014). The lower reaches of the Guamá and Tocantins Rivers represent one of the most densely populated areas in the Amazon region. This area faces intense anthropogenic pressures, including heavy boat traffic, the presence of ports accommodating large vessels, mineral extraction activities, and gravel dredging from riverbeds (Goulding et al., 2003), raising concerns about the increasing underwater noise impacts on Amazon River Dolphins.

Fig.14 Distribution map of the Amazon River Dolphin (*Inia geoffrensis*) (da Silva et al., 2018).

1.2 Noise impacts on prey of CMS-listed freshwater mammals

Freshwater mammals are known to have varying diets, from herbivores such as the West African manatee, West Indian manatee and the Amazonian manatee, to carnivores such as river dolphins and otters. Many freshwater mammals feed primarily on fish, invertebrates, or zooplankton (Trites, 2009). Small odontocetes are widely recognized as opportunistic predators (Spitz et al., 2010; Spitz et al., 2012). This ecological trait is exemplified by the Yangtze Finless Porpoise, which demonstrates opportunistic foraging behaviour by consuming prey in proportion to availability rather than selectively targeting specific taxa (Yang et al., 2019; Yang et al., 2021). The interaction between freshwater mammals and their prey influences the structure and dynamics of freshwater ecosystems. Noise pollution not only affects freshwater mammals themselves, but also, the prey species of the mammals discussed in this report.

Most fish and invertebrates use sound for vital life functions (Weilgart, 2018). The impact of noise on fish and invertebrates has gained increasing attention. Examples of the non-lethal impacts of underwater noise pollution on fish and invertebrates are distraction, decreased foraging efficiency, greater vulnerability to predation, and less feeding (Davies et al., 2024; Thomsen et al., 2006; Wahlberg and Westerberg, 2005).

1.2.1 Fish

A variety of fish species are part of the diets of freshwater mammals. CMS-listed freshwater mammals that prey on fish include the Tucuxi, Guiana Dolphin, Irrawaddy Dolphin, Narrow-ridged Finless Porpoise, Ganges River Dolphin, Amazon River Dolphin, and Southern River Otter. There are approximately 18,000 species of freshwater fish (van der Sleen and Albert, 2022). All fish species studied to date have demonstrated auditory capabilities (Slabbekoorn et al., 2010). Fish produce sounds for feeding, avoidance of predators, communication, group cohesion and other vital functions. Approximately 800 fish species from over 100 families are known to produce sound (Ladich, 2005; Tavolga, 1964; Wang et al., 2017). Anthropogenic noise that masks these acoustic signals poses a significant ecological concern. The linear threshold shift phenomenon – characterized by a linear relationship between noise-induced temporary threshold shift and the sound pressure level difference between baseline hearing thresholds and noise exposure levels – has been observed in multiple fish species (Smith et al., 2004; Smith and Monroe, 2016).

Compared to fish species without swim bladders (e.g., Chondrichthyes), those with swim bladders are more susceptible to noise interference (Popper et al., 2014). When exposed to intense sound waves, the swim bladder can vibrate like an air bubble, potentially damaging itself and adjacent organs (Casper et al., 2013). Additionally, noise-induced injuries may depend on swim bladder type (physoclistous or physostomous) (Fänge, 1983). Physostomous swim bladders (e.g., in Cyprinidae) connect to the oesophagus via a pneumatic duct, enabling rapid air volume adjustment (inflation/deflation) by expelling or taking in gas (Dumbarton et al., 2010). Physoclistous swim bladders (e.g., in Acipenseriformes) rely on a gas gland, which permits only slow, inefficient gas exchange with the bloodstream (Smith and Monroe, 2016). Furthermore, Cyprinomorpha species possess Weberian ossicles, specialized structures linking the swim bladder to the inner ear. These ossicles transmit sound-induced vibrations, enhancing hearing sensitivity and broadening detectable frequency ranges (Liu and Zheng, 1997). Consequently, species with Weberian ossicles may be at higher risk from noise impacts.

Subway-induced vibration and noise significantly affect the food intake, gastric evacuation rate, and growth performance of grass carp (*Ctenopharyngodon idella*) (Yu and Yi, 2014). Oil drilling noise and vibration has been shown to significantly affect all components of the energy budget in common carp, including feeding, growth, metabolism, and excretion (Sun et al., 2008).

The Yangtze River, with a total length of 6300 km, is the longest river in Asia and the third longest river in the world. It has been reported that more than 416 fish species and subspecies occur in the Yangtze River, 178 of which are endemic species (Ye et al., 2011). The Amazon Basin spans over 6 million square kilometers, accounting for approximately 16% of global freshwater discharge (Latrubesse et al., 2017) and harboring the Earth's most diverse freshwater ecosystems (Tisseuil et al., 2013). Current records (www.amazon-fish.com) document 2,257 fish species in the basin, including 1,248 endemic species, representing roughly 15% of all described freshwater fish species worldwide (Tedesco et al., 2017). India has a rich diversity of aquatic species, including over 1045 freshwater fish species (Froese, 2022). The total number of freshwater fish species recorded in Pakistan varies across studies, ranging from a minimum of 160 species (Mirza, 1994) to a maximum of 193 species (Navid et al., 2017).

Underwater noise pollution in the Yangtze River may impose a high impact on fish with physostomous swim bladders and Weberian ossicles, such as silver carp (*Hypopthalmichthys molitrix*) (Lovell et al., 2006), bighead carp (*Aristichthys nobilis*) (Lovell et al., 2006), goldfish (*Carassius auratus*) (Kenyon et al., 1998) and common carp (*Cyprinus carpio*) (Amoser and Ladich, 2005). It may also affect fish with physoclistous swim bladders and without Weberian ossicles, such as lake sturgeon (*Acipenser fulvescens*) (Lovell et al., 2005), paddlefish (*Polyodon spathula*) (Lovell et al., 2005), but to a lesser extent (Wang et al., 2021a). Nedwell and colleagues classified avoidance reactions in fish to sounds in water ranging from 75 dB (moderate), 90 dB (significant) and 100 dB (strong) (Nedwell et al., 2003).

In the Yangtze River, the median noise 1-octave-band power spectrum was approximately 50 dB higher than the most sensitive region of the audiograms of the Chinese sucker, goldfish, and common carp at 88% of the monitoring locations and 20 dB higher at the other 12%. This suggests that the noise in the Yangtze River may significantly impact these three fish species (Wang et al., 2021a), with potential cascading effects on the Yangtze Finless Porpoise. Amazon river dolphins primarily prey on sciaenids, cichlids, and characins, listed in descending order of dietary importance (Kastelein et al., 1999). Sciaenids, commonly known as croakers or drums, are notable for their vocalizations (Mok et al., 2020). In most species, males produce choruses of croaking or drumming sounds—particularly during reproductive seasons—making them more vulnerable to noise interference (Mok et al., 2020).

For other major river systems that are home to CMS-listed freshwater mammals and their prey, such as the Ayeyarwady (Irrawaddy) River, Indus and the Amazon, there is no literature on underwater noise pollution. This shows that there is a crucial gap in the knowledge about noise impacts on freshwater mammals in these habitats.

Noise exposure can lead to auditory hair bundle loss and hair cell death in fish. However, unlike mammals, they possess a unique regenerative capacity: damaged or lost sensory hair cells can be continuously replaced, even after intense or prolonged acoustic exposure (Popper and Hoxter, 1984; Smith et al., 2006; Smith and Monroe, 2016). Consequently, the effects of noise-induced hair cell damage in fish are often temporary, as regeneration mitigates long-term impairment (Smith et al., 2011). Thus, compared to marine mammals, fish may be less vulnerable to permanent auditory injury from underwater noise due to their capacity for sensory hair cell regeneration.

1.2.2 Invertebrates

There are approximately 107,000 known species of freshwater invertebrates (Balian et al., 2008; Simpson et al., 2011) and a growing body of evidence shows that many invertebrates can detect sound and/or vibrations, with many exhibiting behavioural responses to acoustic cues (Simpson et al., 2011). More than 40 invertebrate species have been recorded in the Yangtze River Estuary (Xu et al., 2014) and 54 invertebrate families were found in the Andean-Amazon basin (Lessmann et al., 2016). Invertebrates play key roles in the ecology of aquatic ecosystems and have an important influence on nutrient cycles and play an important role in the energy flow of ecosystems.

Most CMS-listed cetaceans are generalist feeders, such as Amazon River Dolphin (Kastelein et al., 1999), the Yangtze Finless Porpoise (Yang et al., 2019; Yang et al., 2021) and the Ganges and Indus River dolphins (Kelkar et al., 2018). Several invertebrate species – primarily crustaceans and cephalopods – are found in the diets of the Southern river otter (Medina-Vogel and Gonzalez-Lagos, 2008; Medina, 1997), Tucuxi, Guiana dolphin (Rodrigues et al., 2020), Irrawaddy dolphin, Narrow-ridged Finless Porpoise (Amano, 2018), Ganges River Dolphin, and Amazon River Dolphin (Würsig et al., 2018).

Sound is important to many invertebrates and is used in a variety of ways, for orientation, feeding, parental care or prey detection (Popper et al., 2001). Because of this, underwater noise pollution can impact the development of invertebrates, leading to physical deformities, increased egg or juvenile mortality, developmental delays, slower growth rates, and disruptions in metamorphosis and settlement (Weilgart, 2018). Underwater noise pollution has also been shown to negatively affect specific behaviours, such as foraging and anti-predator behaviour in shore crabs (Wale et al., 2013). Crustacean species, such as *Aegla spp.* and *Sammastacus spp.*, important prey of the Southern River Otter, are noise-sensitive and risk being negatively affected by noise pollution. For crustaceans, impacts of underwater noise can lead to a variety of biological and ecological impacts, ranging from increase in locomotion and stress, reduced and slower antipredator behaviour, changes in foraging, suppressed behaviours with an ecological function such as bioirrigation, and changes to intraspecific behaviour such as agonistic encounters (Tidau and Briffa, 2016).

Underwater noise can also damage single cells or whole organs. Invertebrates use organs called statocysts for balance, orientation, and body positional information. When exposed to low-frequency sounds, tested cephalopod specimens exhibited consistent lesion patterns and progressive deterioration over time. These pathological findings align with severe acoustic trauma observed in other species exposed to significantly higher sound intensities (André et al., 2011b; Solé et al., 2013). Research demonstrates that cuttlefish are sensitive to underwater noise pollution in their natural environment, with impacts occurring at both physiological and pathological levels. This exposure likely disrupts their sound perception mechanisms, potentially compromising their survival in the wild (Solé et al., 2017). As a whole, information about the impact of underwater noise on invertebrates is still scarce and further research is necessary (Hawkins et al., 2015).

2. The state of knowledge on underwater noise mitigation measures in freshwater habitats

For marine cetaceans, noise avoidance is not constrained by space availability (Forney et al., 2017). This differs from freshwater mammals inhabiting spatially restricted, depth-limited environments such as rivers, lakes, and estuaries (Dey et al., 2019). River-dwelling freshwater mammals are thus particularly vulnerable to anthropogenic pressures due to their limited ability to escape threats (Martin and da Silva, 2022).

In marine ecosystems, the most effective strategy to mitigate the impacts of shipping on aquatic life is to alter shipping routes, avoiding critical habitats and migration corridors of aquatic species. Unlike the marine environment, riverine ecosystems are constricted areas that often face inevitable competition with humans. Certain tropical river systems harbour obligate freshwater mammals (e.g., freshwater cetaceans), whose restricted dispersal capacity makes them particularly vulnerable to both direct exploitation and cumulative habitat degradation throughout their range. This is exacerbated where human structures such as dams and barrages fragment habitat and freshwater mammal populations as their ability to disperse away from human threats is further impeded (Araújo and Wang, 2015; Braulik et al., 2014).

Sound is attenuated less than chemical substances and light, so it may propagate over long distances. In shallow environments, the greater the depth and the density of the substrate, the greater the sound propagation (Au and Hastings, 2008). Shallow, acoustically complex freshwater habitats are characterized by high reverberation and acoustic clutter (Jensen et al., 2013). In shallow water environments, sound propagation often follows a cylindrical spreading pattern rather than spherical spreading. This results in reduced acoustic attenuation, allowing sound to travel significantly farther distances compared to deep water scenarios (Urick, 1983). Additionally, the underwater noise impacts in shallower channel conditions are greater due to higher reverberation and persistence of noise in the water column (Dey et al., 2019).

Key threats to the CMS-listed freshwater mammals in habitats such as estuaries, rivers and lakes include: vessel navigation, habitat fragmentation due to waterway modifications, prey depletion from overfishing, pollution, construction of dams, bridges and underwater tunnels (Reeves and Martin, 2009), sand and gravel mining, seismic surveys employing airguns, occasional use of explosives for construction purposes, pile-driving activities and excessive anthropogenic underwater noise generated by all of these activities.

In reverberation or clutter limited conditions, the backscattered echo from clutter, the river bed, or the water surface will be just as much or greater as the echo from potential targets (Jensen et al., 2013; Urick, 1983). In addition, forward masking of the outgoing click may play an increasingly important role for toothed whales echolocating at very close range. Consequently, the acoustic properties of shallow-water habitats might have favoured the use of clicks with relatively low source levels, such as observed with Irrawaddy and Ganges River Dolphins (Jensen et al., 2013).

In shallow waters, low-frequency sounds (with longer wavelengths) are reflected at the water surface and absorbed by the substrate. Due to anti-phase reflections from the water surface, low-frequency sounds with wavelengths exceeding the water depth experience significant attenuation, limiting their propagation range (Akamatsu et al., 2002). In practice, acoustic attenuation is determined by both sound frequency and local bathymetry. In very shallow waters (<5 m depth), low-frequency components (several tens of Hz) typically propagate poorly. Conversely, in moderately shallow waters (several tens of meters depth) with flat bottoms, sound may propagate farther than would occur through spherical spreading in deep water. These findings highlight the importance of assessing sound propagation characteristics within the critical habitats of endangered aquatic species. The high-frequency sounds, due to their shorter wavelengths, can propagate through water with minimal interference from the water surface or substrate. Therefore, in cluttered shallow environments, animals typically emit echolocation clicks at higher frequencies. However, simultaneously increasing the SPL to compensate for masking at high peak frequencies could have detrimental effects on river dolphins. In shallow water environments, the proximity between anthropogenic sound sources (e.g., echosounders or depth profilers) and aquatic animals is typically reduced due to limited spatial separation. This constrained habitat geometry inherently decreases the potential avoidance distance available to aquatic organisms. Higher SPL implies greater sound wave amplitude, which increases the likelihood of high-frequency sounds interacting with suspended sediments and other clutter in shallow water. These interactions would generate stronger backscatter and reverberation, thereby reducing the effectiveness of high-frequency clicks in such environments (Dey et al., 2019). Thus, dolphins may be unable to effectively cope with increased noise interference in shallow waters in estuaries, rivers and lakes.

Optimal spatio-temporal mitigation requires restricting noise-generating operations in ecologically vulnerable areas and during biologically significant periods. Critical habitats like breeding grounds and feeding aggregations, including Important Marine Mammal Areas (IMMAs), should especially be considered at times animals are most vulnerable (Chou et al., 2021). Underwater noise impacts on CMS-listed freshwater mammals often follow temporal patterns, with effects further exacerbated during dry-season river depth reduction. Maintaining ecological flows could help mitigate noise impacts on river dolphins (Dey et al., 2019).

The methods described below summarise the state of knowledge regarding underwater noise mitigation measures taking into account the specific requirements and properties in habitats such as estuaries, rivers and lakes.

2.1 Spatial management approaches

Spatial management approaches to mitigate underwater noise impacts include Noise Buffer Zones and Speed Reduction Zones. Noise Buffer Zones are designated quiet areas in critical habitats (e.g., spawning grounds, aquatic animal reserves) where anthropogenic noise-generating activities, such as vessel traffic and other infrastructure development, are regulated or restricted. An example of such Noise Buffer Zones can be found in China, where the government has established four national-level and four provincial-level nature reserves[3] in the middle and lower reaches of the Yangtze River to protect the baiji (Yangtze River Dolphin) and the Yangtze Finless Porpoise (Wang, 2009). The establishment of appropriate buffer zones requires comprehensive noise mapping of the target area combined with detailed analysis of sound propagation characteristics.

Speed Reduction Zones enforce lower vessel speeds in noise-sensitive regions, as lower speeds typically reduce underwater noise levels. For example, in the core and buffer zones of the Tongling Freshwater Dolphin National Nature Reserve (Yangtze River) maximum vessel speeds were reduced to 12 km/h (upstream) and 20 km/h (downstream) starting 1 October 2017. These limits were later revised to 15 km/h (upstream) and 25 km/h (downstream) and have been in effect since 2 November 2018 (Wang et al., 2021a), although the reason for the speed limit adjustment remains unclear.

2.2 Temporal management approaches

Underwater noise impacts can also be mitigated through temporal management approaches. Seasonal restrictions are noise regulations implemented during biologically critical periods (e.g., breeding or migration seasons) to minimize disturbance. Extreme droughts in regions such as the Amazon can exacerbate the impact of noise generated by vessels, necessitating temporary measures to further reduce pressure on freshwater mammals. Similarly in the Ganges-Brahmaputra and Indus River systems the lowest flows occur in the winter months and avoiding these times when habitat volume is severally restricted is important to reduce noise impacts.

In the Yangtze River an annual three-month spring moratorium (from 1 April to 30 June) on fishing has been fully implemented in the middle and lower reaches of the Yangtze River from the Gezhouba Dam to the Yangtze Estuary since 2003. Since 2016, the no-fishing period has been adjusted and extended to five months (from 1 March to 30 July) to cover the main spawning and breeding period of most aquatic organisms in the Yangtze River basin. Since 2020, a comprehensive year-round ban on productive fishing was started in all 332 nature reserves and aquatic germplasm resource reserves in the Yangtze River basin. Additionally, since 2021, a permanent ban on fishing over a provisional period of 10 years has been implemented in the main stream and important tributaries of the Yangtze River and large lakes such as Poyang and Dongting Lake (Wang et al., 2021a). The fishing ban period can significantly reduce underwater noise pollution caused by fishing activities.

On July 3, 2023, Brazil extended the moratorium on fishing the catfish Piracatinga (*Calophysus macropterus*) in the Amazon for the third time since its implementation in 2014. While the ban now has no expiration date, the Ministries of Environment and Fisheries must reevaluate it every three years (Gonçalves da Silva et al., 2025). Additionally, to

[3] National-level nature reserves: Anhui Tongling Freshwater Dolphin National Nature Reserve; East Dongting Lake National Nature Reserve; Hubei Yangtze Swan Oxbow Baiji National Nature Reserve; Yangtze Xinluo Baiji National Nature Reserve. Provincial-level nature reserves: Poyang Lake Yangtze Finless Porpoise Provincial Nature Reserve; Anqing Finless Porpoise Provincial Nature Reserve; Nanjing Yangtze Finless Porpoise Provincial Nature Reserve; Zhenjiang Yangtze Cetacean Provincial Nature Reserve.

prevent the collapse of Amazon fisheries, Prestes and colleagues (Prestes et al., 2022) proposed managing fishing pressure through enforced market regulations, such as imposing size limits and closed seasons on fish sold in urban markets or to refrigeration companies. These proposals may further reduce fishing intensity and the resulting underwater noise pollution.

2.3 Best available technology and best environmental practice for mitigating shipping noise

The most intense underwater noise pollution in habitats such as estuaries, rivers, and lakes comes from vessel traffic. Vessel noise is too disruptive for cetaceans to adapt to through natural selection (Parks et al., 2011; Putland et al., 2018). Additionally, many cetaceans are long-lived, which results in long generation times. This means that adaptation through natural selection occurs too slowly to keep pace with rapid environmental changes. Even a moderate level of anthropogenic disturbance can cause serious fitness consequences at individual and population levels (Wisniewska et al., 2016).

As stated in the CMS Technical Series No. 46 Best Available Technology (BAT) and Best Environmental Practice (BEP) for Shipping, Seismic Airgun Surveys and Pile Driving, the BAT and BEP for mitigating shipping noise generally include minimizing cavitation by various techniques such as better maintenance, optimizing propeller design, focusing quieting on the 10-15% of the noisiest container and cargo ships, as well as slow steaming – reducing ship speed from an average of 16 kts to 14 kts – , which was done in the Mediterranean and probably reduced the overall broadband acoustic footprint by over 50% (Weilgart, 2023). Although this CMS Technical Guideline was primarily developed for marine species, its provisions are also applicable to freshwater habitats, including estuaries, rivers, and lakes.

The ISO 17208-1 standard specifies methods for measuring underwater shipping noise, while ISO 17208-3 provides specific protocols for shallow-water environments. However, in very shallow waters (<10 m depth), source-level measurements and sound propagation modelling become particularly challenging due to complex boundary interactions. Numerical methods may yield unreliable results when high-resolution bathymetric data and sediment impedance properties are unavailable. Under such conditions, direct in situ noise measurements remain the most practical approach for accurate assessment.

Additionally, the green development approach in shipping – such as the construction of green shipping lanes, ports, ships, and transport systems in the Yangtze River Economic Belt – has been implemented to help mitigate underwater noise pollution (Wang et al., 2021a). Noise level reductions of approximately 10 dB in the middle reaches of the Yangtze River and 20 dB in the lower reaches were observed in 2017 compared to the 2012 level. The emphasis on “green shipping” in the Yangtze River Economic Belt may account for the alleviated underwater noise pollution (Wang et al., 2021a). These underwater noise mitigation methods are also applicable to freshwater habitats, including estuaries, rivers, and lakes.

2.4 Best available technology and best environmental practice for mitigating pile driving noise

Pile driving is widely used in dam, bridge and underwater tunnel construction. The German Federal Maritime and Hydrographic Agency established noise control standards specifying 160 dB re 1 μPa^2·s (SEL) for single-strike sound exposure and 190 dB re 1 μPa (peak) as maximum permissible levels, measured at 750 m from the source (Weilgart, 2023). As outlined in the CMS Technical Series No. 46 on BAT/BEP for Shipping, Seismic Airgun Surveys and Pile Driving, the most effective BAT and BEP for pile driving noise mitigation typically include: noise mitigation and abatement systems, vibration pile-driving (vibro-piling) as a lower-impact alternative to conventional impact driving methods, blue piling, adaptation of hydraulic hammers, smart pile driving, bucket foundations, gravity-based foundations, drilling, push-in and helical piles, floating wind turbines and other secondary noise mitigation, such as a big bubble curtains, noise mitigation screens and hydro sound dampers (Weilgart, 2023).

3. Existing guidelines for mitigation of underwater noise-generating activities and key deficiencies for CMS-listed freshwater mammal species

There is increasing global acknowledgment that underwater noise is a major source of pollution, posing significant threats to aquatic ecosystems, particularly aquatic mammals. This Chapter covers existing guidelines from CMS, Parties and non-Parties and identifies key deficiencies for the mitigation of noise impacts for CMS-listed freshwater mammals.

3.1 Existing guidelines on environmental impact assessments and mitigation measures for underwater noise-generating activities

3.1.1 Existing CMS guidelines

Recognizing the adverse impacts of anthropogenic marine noise on cetaceans and other marine biota, the Parties to the CMS adopted several Resolutions calling for effective measures to mitigate and minimize the impact of underwater noise pollution on marine life. Important to note is that all existing CMS guidance has been developed for the marine environment only, without specific consideration of freshwater habitats such as rivers, estuaries or lakes.

CMS COP14 adopted Resolution 12.14 Adverse impacts of anthropogenic noise on cetaceans and other migratory species (CMS, 2017a). Amongst other measures, Resolution 12.4 emphasizes the need for ongoing and internationally coordinated research on the impact of underwater noise on CMS-listed marine species and their prey, their migration routes and ecological coherence, as well as the need for international, national and regional limitation of harmful anthropogenic marine noise. The Resolution stresses the importance for Parties to consult with any stakeholder conducting activities known to produce anthropogenic marine noise with the potential to cause adverse effects on CMS-listed marine species and their prey. It invites the private sector and other stakeholders to make use of the existing guidelines and assist in developing further mitigation measures. It also recommends that Parties establish national noise registries to collect and display data on noise-generating activities in the marine area to help assess exposure levels and the likely impacts on the marine environment (CMS, 2017a).

Existing CMS guidance that addresses environmental impact assessments and mitigation for noise generating activities include:

(1) Annex to Resolution 12.14: CMS Family Guidelines on Environmental Impact Assessments for Marine Noise-Generating Activities (CMS, 2017b).

These Guidelines are designed to provide regulators with tailored advice to apply in domestic jurisdictions to create appropriate EIA standards for managing marine noise-generating activities. They cover the necessary detail for meaningful EIAs for Military and Civil High-powered Sonar, Shipping and Vessels Traffic, Seismic Surveys (Air Gun and Alternative Technologies), Construction Works, Offshore Platforms, Playback and Sound Exposure Experiments, Pingers (Acoustic Deterrent/ Harassment Devices, Navigation), and other Noise-generating Activities (Acoustic Data Transmission, Wind, Tidal and Wave Turbines and Future Technologies).

(2) Technical Support Information to the CMS Family Guidelines on Environmental Impact Assessment for Marine Noise-Generating Activities (Prideaux, 2017) & Advisory Note: Further guidance on independent, scientific modelling of noise propagation (module added by COP13).

The Technical Support Information and Advisory Note present the Best Available Techniques (BAT) and Best Environmental Practice (BEP) for assessment of underwater noise impacts and marine noise-generating activities, outlining the basic understanding needed of the characteristics of underwater noise and the specific vulnerabilities of the different taxonomic groups covered by CMS and its daughter agreements. The species groups covered are: Inshore Odontocetes, Offshore Odontocetes, Beaked Whales, Mysticetes, Pinnipeds, Polar Bears, Sirenians, Marine and Sea Otters, Marine Turtles, Fin-fish, Elasmobranchs, and Marine Invertebrates.

(3) CMS Technical Series No. 46: Best Available Technology (BAT) and Best Environmental Practice (BEP) for Mitigating Three Noise Sources: Shipping, Seismic Airgun Surveys, and Pile Driving (Weilgart, 2023).

In this technical report, the Best Available Technology (BAT) and Best Environmental Practice (BEP) for mitigating three different underwater noise sources – shipping, seismic airgun surveys, and pile driving – are addressed. For shipping noise, this generally includes minimizing cavitation by various techniques such as better maintenance and optimizing the propeller design. Focusing quieting on the 10-15% of the noisiest container and cargo ships is proposed for furthest reduction in overall shipping noise. Slow steaming, or reducing ship speed from an average of 16 kts to 14 kts can probably reduce the overall broadband acoustic footprint by over 50% (Weilgart, 2023).

3.1.2 Existing guidance of the European Union

The Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC) is the world's first legislation to explicitly address underwater noise pollution, through Descriptor 11. It mandates that underwater noise levels must not adversely affect marine ecosystems, prompting a coordinated European research effort to establish noise monitoring programmes and define threshold values for Good Environmental Status (GES) regarding underwater noise (Merchant et al., 2022). The MFSD is not primarily applicable to freshwater habitats such as lakes, rivers, or inland waters. However, it does apply to certain transitional waters, such as estuaries, under specific conditions. If part of an estuary is open to marine influence and meets the definition of coastal waters under the Water Framework Directive, it can fall under the MSFD's remit for marine descriptors, including Descriptor 11 on underwater noise. There are currently no EU Directives or guidelines that regulate underwater noise pollution in freshwater habitats.

Specifically, the MSFD established ambient noise indicators for marine environments, stipulating that annual averaged 1/3 octave band levels (centre frequency at 63 and 125 Hz) should not exceed 100 dB re 1μPa for low-frequency continuous sound (Tasker et al., 2010). The EU Commission established the following two criteria to achieve Descriptor 11 'Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment':

Anthropogenic impulsive sound: "The spatial distribution, temporal extent, and levels of anthropogenic impulsive sound sources do not exceed levels that adversely affect populations of marine animals".

Anthropogenic continuous low-frequency sound: The spatial distribution, temporal extent and levels of anthropogenic continuous low-frequency sound do not exceed levels that adversely affect populations of marine animals".

In an EU Commission Notice (C/2024/2078) in 2024, the threshold values for impulsive and continuous noise set under the MFSD 2008/56/EC and EU Commission Decision 2017/848 were established. The threshold for impulsive sound (DC11C1) is defined as:

> "For short-term exposure (1 day, i.e., daily exposure), the maximum proportion of an assessment/habitat area utilised by a species of interest that is accepted to be exposed to impulsive noise levels higher than the Level of Onset of Biologically adverse Effects (LOBE), over 1 day, is 20 % or lower (≤ 20 %). For long-term exposure (1 year), the average exposure is calculated. The maximum proportion of an assessment/habitat area utilised by a species of interest that is accepted to be exposed to impulsive noise levels higher than LOBE, over 1 year on average, is 10 % or lower (≤ 10 %)."

The threshold for continuous noise (DC11C2) is defined as:

> "20 % of the target species habitat having noise levels above LOBE not to be exceeded in any month of the assessment year, in agreement with the conservation objective of the 80 % of the carrying capacity/habitat size."

Member States are not allowed to use different national threshold values, only threshold values set at EU, regional or subregional level. The Commission will check whether Member States have used the threshold values to determine GES when evaluating the Member States' updated marine strategies.

3.1.3 Existing national guidance

Provisions on noise exposure and mitigation exist in many countries, however, regarding guidance specifically for freshwater species and habitats, nothing could be found. Important to note is that this report only included English-language resources, excluding any guidance that may have been written in other languages. As a result, some regions, particularly those with English-Speaking countries are better represented than others. Although the US is not a CMS Party, the guidance on underwater noise is considered a representative example of what was found for most countries.

The existing guidelines on noise exposure for marine animals from the US include:

(1) 2024 Update to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 3.0): Underwater and In-Air Criteria for Onset of Auditory Injury and Temporary Threshold Shifts (National Marine Fisheries Service, 2024).

This updated technical guidance is to be used for assessing the effects of underwater and in-air anthropogenic sound on the hearing of marine mammal species under the jurisdiction of the National Marine Fisheries Service. Specifically, the criteria provided include: 1) the classification of five marine mammal hearing groups (Low-frequency cetaceans, High-frequency cetaceans, Very High-frequency cetaceans, Phocid pinnipeds, and Otariid pinnipeds); 2) marine mammal auditory weighting functions; and 3) onset thresholds for auditory injury and temporary threshold shifts.

(2) Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report Prepared by American National Standards Institute (ANSI) (Popper et al., 2014).

These guidelines account for the biological diversity of fish and sea turtles by establishing criteria for functional groups defined by their sound detection mechanisms, which includes several species of freshwater fish. For each sound source category, it also evaluates the relevant acoustic parameters and specified appropriate metrics for quantifying received sound levels (Popper et al., 2014).

3.1.4 Guidance contained in scientific literature

Aside from nationally developed or internationally agreed guidelines, scientific literature is also available that is of relevance. An example:

Marine Mammal Noise Exposure Criteria: Assessing the Severity of Marine Mammal Behavioural Responses to Human Noise (Southall et al., 2021).

The accumulated evidence strongly indicates that attempts to establish binary thresholds for individual noise exposure parameters (e.g., received sound pressure levels) to predict behavioural responses across diverse taxa and sound types may produce substantial prediction errors, as they fail to account for the inherently probabilistic nature of these responses. Significant variability in response probability and magnitude arises from interspecies differences, individual variation, contextual factors, and the spatiotemporal characteristics of exposure events. Accordingly, this document presents several novel methodologies for assessing response severity under both controlled and natural conditions, such as the revised behavioural response severity scale for discrete exposures, with particular emphasis on impacts to biologically significant vital rates (Southall et al., 2021). However, these guidelines were developed for marine species, not freshwater species. Development of similar guidelines specific to freshwater species would be beneficial to inform improved mitigation measures.

3.2 Key gaps in existing guidance related to CMS-listed freshwater mammals and their prey

Despite the above mentioned recent resolutions and guidelines adopted across regional, national, and international fora (Chou et al., 2021), current legal frameworks continue to prove insufficient for effectively governing the growing environmental threat of underwater noise pollution in freshwater systems (Chou et al., 2021; Yi, 2022). The establishment and application of biologically meaningful impact thresholds for aquatic animals remain at a nascent stage of scientific development (Hawkins and Popper, 2016a).

The MSFD frequency bands (63 Hz and 125 Hz) may insufficiently capture acoustic masking risks. Furthermore, while MSFD recommends RMS level as the metric, this approach is inherently sensitive to distribution outliers. Transient high-amplitude events – though statistically unrepresentative – can disproportionately skew RMS values, thereby distorting the overall noise level trend interpretation (Merchant et al., 2016).

There is currently also no targeted underwater noise mitigation for prey of CMS-listed freshwater mammals, despite the poor conservation status of many fish stocks that form part of freshwater mammal diets, and for which underwater noise is an additional pressure (Wang et al., 2021a; Zhang et al., 2020). However, extrapolating guidelines designed for marine mammals and fish to CMS-listed freshwater mammals and their prey is not sufficient, as organisms as well as ecosystems in freshwater function differently than those in salt water. Furthermore, underwater noise sources and propagation, as well as impacts differ, and tailored/adjusted mitigation measures may be required. Targeted guidance on underwater noise mitigation for CMS-listed freshwater mammals is currently lacking.

Because the existing guidance on underwater noise mitigation as outlined above does not sufficiently cover the needs of freshwater mammals and their prey, there is therefore an urgent need to strengthen international legal provisions addressing underwater noise pollution with tailored, freshwater specific guidelines. Some key gaps in the existing guidance are explained in more depth below.

3.2.1 Recognition as priority species in regulation

Underwater noise regulation focused on freshwater mammals is currently lacking. There are currently no defined allowable harm thresholds for freshwater habitats to trigger underwater noise mitigation measures (Williams et al., 2016b). Even a moderate level of anthropogenic disturbance can cause serious fitness consequences at individual and population levels (Wisniewska et al., 2016). As an example, Canada's West Coast is home to the Southern Resident Killer Whale (*Orcinus orca*). However, this population faces three critical threats: 1) physical and acoustic disturbances, including underwater noise pollution; 2) declining prey availability; and 3) exposure to environmental contaminants. Canada has taken a leading role in this regard, using the Southern Resident Killer Whale as a focal species for noise regulation (Joy et al., 2019; Williams et al., 2014a; Williams et al., 2014b; Williams et al., 2016b). Further research is needed to determine whether the biological traits of CMS-listed freshwater mammals could similarly inform the establishment of harm limits. Such studies should account for species-specific requirements and habitat characteristics – including estuaries, rivers, and lakes – and employ a "reverse-engineering" approach to derive science-based regulatory guidelines.

3.2.2 Insufficient baseline data on habitat noise levels

Baseline data on soundscape, and anthropogenic underwater noise pollution in the habitat of the majority of CMS-listed freshwater mammals is lacking and needs to be investigated in the near future. To the author's knowledge, soundscape assessments have only been conducted in the Yangtze River to date (Wang et al., 2020a; Wang et al., 2021a), while baseline background underwater noise levels in the habitats of other CMS-listed freshwater mammals have yet to be investigated.

3.2.3 Missing data on the effects of underwater noise on disruption of behaviour for most freshwater mammals

Currently, there is a significant lack of data regarding the impacts of anthropogenic underwater noise on the behavioural disruption of most freshwater mammals (Duan et al., 2023; Wang et al., 2015; Wang et al., 2014a; Wang et al., 2024a, b). This knowledge gap hinders a comprehensive understanding of how activities such as shipping, construction, and sonar operations affect species like river dolphins, manatees, and otters. Without detailed studies on species-specific auditory thresholds and behavioural responses, it is difficult to assess the full extent of noise-induced stress, communication masking, or foraging interruptions. Filling this research void is essential for developing effective mitigation strategies, informing regulatory policies, and ensuring the conservation of vulnerable freshwater species in increasingly noisy environments.

Given the significant biological differences among, for example, freshwater dolphin species, baseline data on hearing and acoustic effects are needed for each species and population; findings from one cannot be extrapolated to all. Information on the hearing sensitivity variability within a species obtained in a biologically relevant wild context is fundamental to evaluating potential underwater noise impact and population-relevant management. To date, hearing audiograms have been collected only for the Yangtze finless porpoise among CMS-listed freshwater mammals, with studies conducted on both wild and captive individuals (Popov et al., 2005; Wang et al., 2025b; Wang et al., 2020c). Audiograms and data on the effects of underwater noise on hearing for other CMS-listed freshwater mammals are currently lacking and have yet to be investigated.

4. Recommendation of specific noise mitigation guidance for freshwater habitats

Given the distinct ecological characteristics of freshwater ecosystems, precautionary conservation strategies and targeted mitigation measures must be implemented to safeguard CMS-listed freshwater mammals. This report concludes that tailored underwater noise mitigation guidelines are needed for freshwater habitats, as existing frameworks were not intended to address the requirements of freshwater mammals or their prey. In this chapter, we recommend several mitigation measures and several research requirements so that freshwater noise mitigation guidelines can be developed.

4.1 Implementing restrictions on noise-generating activities

Implementation and enforcement of spatial noise mitigation areas and/or time periods that restrict, prohibit and/or reduce high-intensity anthropogenic activities. Temporal restrictions that are applied during biologically critical periods (e.g., peak breeding, calving, and foraging seasons) in designated core habitats of CMS-listed freshwater mammals could be an effective measure. Similarly temporal restrictions applied during periods of low flow during the dry season when habitat is more restricted is another measure that is important to highlight. Designating specific areas and/or time periods where noise-generating activities—such as vessel traffic and construction—are restricted or prohibited is essential for protecting freshwater mammal habitats. Effective measures already in practice include fishing bans, speed reduction zones, and vessel size restrictions in areas inhabited by otters, manatees, and cetaceans. Furthermore, regulating vessel dimensions relative to river morphology can significantly reduce acoustic disturbance. For example, under the Regulation of the Ministry of Transportation of the Republic of Indonesia No. PM. 52 of 2012 concerning River and Lake Shipping Routes, vessels operating in river conservation areas such as the Mahakam must adhere to strict criteria: the draught must not exceed half of the river depth, and the vessel width must be no more than one-sixth of the river width. In addition, ships larger than seven gross tonnage are required to navigate within the central deepest part of the channel, maintaining a clearance of at least 15 meters below the draught. Such spatially explicit regulations serve as valuable models for mitigating noise impacts in sensitive aquatic environments.

Speedboats appearing after a river bend can cause startle responses and immediate dives in Irrawaddy Dolphins. To protect Irrawaddy Dolphins, it is proposed to install speed reduction signs in key dolphin habitats, in close cooperation with local residents and speedboat operators. Boat owners are urged to slow down in the marked areas (Kreb and Rahadi, 2004). Furthermore, it has been proposed to prohibit large boat dredges and hydraulic land blasting operations in and surrounding (particularly upstream of) the core areas of Irrawaddy Dolphin distribution (Smith et al., 2007)

The peak calving period and early maternal care phase of Amazon River Dolphins (September-November) coincides with low water levels, when the dolphins are largely confined to river margins. This temporal overlap occurs precisely when high densities of large-mesh gillnets are deployed in river margins for fishing operations (Martin and da Silva, 2018). Spatiotemporal noise mitigation zones could be an effective measure to reduce or prevent the temporal overlap and thus reduce or prevent harmful effects of underwater noise pollution.

Regarding construction operation, there is an opportunity to coordinate with the World Bank, which developed a protocol for use in Environmental and Social Impact Assessments for infrastructure projects focused on the Ganges River Dolphin in the Ganges-Brahmaputra-Meghna river basin (World Bank, 2024). The protocol provides guidance on the most suitable survey methods, data collection, equipment needs, data analysis, reporting and stakeholder engagement. However, it does not adequately address noise mitigation during surveys or methods for assessing the impact of underwater noise on river dolphins—aspects that should be included.

4.2 Applying vessel-quieting technologies and vessel-type restrictions

The acoustic signature of individual vessels is determined by vessel class/type, size, power plant configuration, propulsion system design, hull form characteristics, and operating speed (Prideaux, 2017).

The noise mitigation methods listed in the CMS Technical Series No. 46 primarily focus on protecting marine mammals, including through the following measures: improved maintenance practices and optimized propeller design to reduce cavitation noise, slow streaming, improving the wake flow around the hull ahead of the propeller, improved vessel hull design – particularly at the aft end – , well-constructed and optimally designed propellers, design an integrated system for the propeller and hull, vibration isolation, noise insulation, and damping treatments (Weilgart, 2023). Propellers should be kept clean, free of fouling, polished, and well-maintained, with no nicks or surface imperfections, particularly on the leading edge (Leaper and Renilson, 2012). This suggested shipping noise mitigation method should also be applied to the conservation of CMS-listed freshwater mammals.

Adoption of vessel-quieting technologies, such as through implementation of the revised IMO guidelines, during both vessel design (Spence and Fischer, 2017) and retrofitting should be encouraged. This may include: propulsion systems that reduce cavitation (e.g., propeller and hull modifications, air injection through propeller blades) (IMO, 2014); quieter onboard machinery (e.g., vibration isolation, optimized placement of power machinery within the hull) (Merchant, 2019); and retrofit design modifications to enhance energy efficiency (Gassmann et al., 2017). Priority should be given to design improvements for the noisiest vessels in the fleet (Veirs et al., 2018). Standardizing vessel designs and promoting the construction and retrofitting of eco-friendly, fuel-efficient vessels – such as Liquified Natural Gas (LNG)-powered ships – can help reduce underwater noise pollution. LNG engines generally produce less noise compared to traditional diesel engines (Shipuniverse, 2024). LNG-powered vessels are also found to be quieter than an older generation with similar specifications (Johansson et al., 2024). By prioritizing LNG energy use, enhancing construction standards, and improving operational and policy support for LNG-powered vessels, underwater noise pollution can be mitigated.

Technological improvement of vessel engines is challenging, however, since in most rivers the most commonly used equipment are simple diesel motors (the “peque-peque”, or long-tail) that also produce the most underwater noise. Collaboration with large manufacturers of these engines could provide an opportunity to further mitigate underwater noise.

Vessel-type standardization in the Yangtze River began in 2003, initially targeting the Chuanjiang River and Three Gorges Reservoir Region. In 2009, the Ministry of Transport of the People's Republic of China accelerated this process by releasing an executive plan for the main channel, introducing measures such as restricting nonstandard vessel construction, promoting standard vessel types, adjusting freight capacity structures, and subsidizing the phase-out of small-tonnage and obsolete vessels. As a result, vessels under 600 tons were banned from the Three Gorges ship lock after 2013. Between 2014 and 2017, 43,500 transport vessels were dismantled or remodelled (Editorial committee of the Yangtze river yearbook, 2018), reducing the number of commercial vessels in the Yangtze River Economic Zone from 133,000 in 2012 to 101,000 in 2017 (Editorial committee of the Yangtze river yearbook, 2013, 2018). Standardization also drove vessel upscaling and specialization: the average cargo vessel tonnage rose from 450 tons in 2005 to 1,007 tons in 2011 (Editorial committee of the Yangtze river yearbook, 2012), then continued climbing to 1,080 tons in 2012 and 1,630 tons in 2017. Although larger industrial vessels generate less cavitation noise, their deeper draft requirements increase dredging needs and physical injury risks, while introducing persistent active sonar exposure for river dolphins. Therefore, though vessel standardization in busy rivers such as the Yangtze can mitigate underwater noise pollution, a comprehensive trade-off analysis must evaluate: (1) transport efficiency and vessel design improvements against (2) habitat maintenance costs (e.g., dredging impacts), to effectively mitigate threats to CMS-listed freshwater mammals (Dey et al., 2019). However, current mitigation measures are not adequate. In addition, governments can consider offering subsidies or tax incentives to replace or retrofit noisy vessels with quieter ones (Veirs et al., 2018). Vessel standardization should also be considered for areas with little current shipping traffic but aspirations for future growth.

4.3 Reducing vessel traffic intensity

Underwater noise pollution in river systems has been correlated with the number of vessels and their navigation speed (McKenna et al., 2013). Most vessels can reduce their broadband source level by 2 dB by slowing down by 1 m/s (Veirs et al., 2016). Underwater noise radiating from surface vessels is a significant contributor to low-frequency ambient noise (<100 Hz) (Hildebrand, 2009). The primary sources of vessel noise are propeller cavitation, propeller singing, and propulsion machinery, with fundamental peaks occurring in the frequency ranges of 50-150 Hz, 100-1000 Hz, and below 50 Hz, respectively (Hildebrand, 2009; Richardson et al., 1995). Commercial vessels radiate underwater noise with peak spectral power between 20-200 Hz (Ross, 1976). Underwater noise from merchant vessels elevates the natural ambient level by 20-30 dB in many locations (Arveson and Vendittis, 2000). Prompted by research showing strong adverse reactions of Mahakam River dolphins to large (100-foot) barges (Kreb and Budiono., 2025a; Kreb and Rahadi, 2004), the Ministry of Environment in Indonesia, building on a local NGO's proposal, requested the Ministry of Transportation in August 2025 to implement preliminary measures for future regulation. These measures include limiting barge traffic to a maximum of 3 vessels per hour with 3 km spacing, confining operations to 06:00-18:00, and prohibiting coal barges in tributaries.

Vessel speed regulations need further investigation. In the middle and lower regions of the Yangtze River, only certain vessel speed regulations are in effect in the Jiangsu and Anhui regions (Wang et al., 2021a). In the Mahakam, at several confluence areas and tributary segments, a maximum speed of 15 km/hour was regulated under the Decree of the Director General of PKRL/ No. 61, 2023 related to conservation area management. The extension of vessel speed restriction and the determination of the optimal navigation speed in an extended range of the habitat of CMS-listed freshwater mammals deserves consideration, and is recommended to take into account studies on thresholds of elevated background noise and exposure leading to chronic stress, physical damage, or behavioural changes.

A reduction in sound source levels was observed for vessels transiting at low speeds. Specifically, for ships equipped with fixed-pitch propellers, both SPLs and SELs decrease significantly as vessel speed is reduced. Even a modest reduction in ship speed can therefore lead to substantially quieter noise emissions (Findlay et al., 2023; Leaper, 2019). In addition to setting traffic limits and lowering navigation speeds, ensuring vessels are fully loaded, thereby reducing the number of vessels required, can balance ecological protection with transport efficiency.

Studies on dolphin behavioural responses in marine habitats to vessel disturbances within 300 meters have shown reduced resting behaviour (Constantine et al., 2004), a vital activity for maintaining dolphin health. Impacts from vessel noise in confined water bodies like rivers, where animals have less ability to avoid the noise are likely to be more severe (Dey et al., 2019). Therefore, it is recommended to set a maximum limit on the number of transportation routes for vessels in river dolphin habitat and reduce vessel disturbance within a 300 m range to a maximum time that will not impact dolphin's resting behaviour. This needs to be determined through studies for each freshwater mammal species.

Further research is needed to determine the underwater noise levels and exposure durations that lead to chronic stress, physical harm, or behavioural changes in freshwater mammal species and populations, such as exclusion from important habitats. This research will inform the development of science-based guidelines for underwater noise management.

4.4 Implementing reductions in sonar use

In a study on the impact of underwater vessel noise, including vessel sonar, Dey and colleagues (Dey et al., 2019) found that Ganges River Dolphins showed increased activity during acute exposure to underwater noise and sonar from ships and suppressed activity during chronic exposure. Additionally, they concluded that increasing underwater noise levels altered dolphins' acoustic responses and echolocation, as well as exposed them to more than double the metabolic stress, especially in the dry season when river depth decreases. As sonar use can severely disrupt echolocation, limiting or prohibiting it in key habitats helps reduce metabolic stress and behavioural disturbance. However, in proposals for sonar use reduction, the transportation and trade needs of the local communities must be taken into consideration, such as through analysis of overlap between key areas for river dolphins and urban centres along rivers.

4.5 Reducing vessel traffic at times animals are most vulnerable

A broad range of organisms exhibit diel foraging habits shaped by the trade-off between foraging efficiency and predation risk (Payne et al., 2013). Vessel activity at times when animals are most vulnerable, e.g. spending more time near the surface as part of their diurnal pattern, may increase vessel strikes risk for some freshwater mammals. Both indirect and direct evidence of vessel avoiding behaviour has been documented, such as for the Yangtze finless porpoise (Li et al., 2008; Wang et al., 2015; Wang et al., 2014a). Limiting or prohibiting traffic at times when animals are most vulnerable in key habitats, and/or lowering vessel speed, helps reduce metabolic stress and behavioural disturbance. This is particularly important during dry seasons when river depth is low. The extreme droughts in regions such as the Amazon, Yangtze, Indus and Ganges can further exacerbate the impact of noise generated by boats and limiting vessel traffic and sonar use during these times of environmental stress would be beneficial to the animals.

Mahakam River dolphins have been observed surfacing near large coal barges (Kreb and Budiono., 2025a; Kreb and Rahadi, 2004). This behaviour is potentially due to acoustic masking caused by the barges' loud underwater noise, which can interfere with the dolphins' echolocation (Au and Penner, 1981). This creates a particularly severe threat at night when visibility is low, making dolphins unable to avoid these vessels. Therefore, a restriction on nighttime traffic is strongly recommended for this population to mitigate this danger. Implementation of this recommendation has been requested by the Ministry of Environment to the Ministry of Transportation in July 2025 but is not yet regulatory.

In some rivers, the most sensitive aquatic habitats are located near river shores, such as in the Yangtze, Amazon and Mahakam Rivers. Regulations in these areas should mandate that vessels stay in the central channel (thalweg) of the river. This would prevent them from seeking fuel-efficient but damaging paths along the banks. Furthermore, establishing designated shipping lanes in these central, navigable areas would minimize disturbance to these critical ecosystems. Different guidelines may apply for other rivers such as the Ganges and Indus with different river structures and with different preferred or important habitats of freshwater mammals. National regulations need to be based on the specific situation in each river system.

4.6 Establishing slow-down zones

Speed zones can be quite effective at reducing underwater noise levels and the risk of lethal vessel strikes (Udell et al., 2018). Compliant vessels could be offered subsidies or reduced berthing fees, while non-compliant vessels could be subjected to sanctions.

A voluntary commercial vessel slowdown trial benefited the conservation of endangered Southern Resident Killer Whales by reducing underwater noise and the ‘potential lost foraging time’ for the killer whales (Joy et al., 2019). In 2008, NOAA established a mandatory vessel speed rule to mitigate the impact of vessel strikes on North Atlantic Right Whales. The rule requires that vessels longer than 65 feet (19.8 m) slow their speed in seasonal management areas along the East Coast at certain times of year (National Oceanic and Atmospheric Administration, 2021). But because vessels of all sizes can strike a whale, NOAA Fisheries also encourages vessels less than 65 feet long (19.8 m) to slow to 10 knots or less in Right Whale speed reduction zones. Most vessels 35 feet (10.7 m) or longer would be required to transit at 10 knots or less within active proposed Seasonal Speed Zones (National Oceanic and Atmospheric Administration, 2022; Office of Protected Resources, 2024). In a new development, the National Marine Fisheries Service is withdrawing this proposed rule as of January 16, 2025 (National Oceanic and Atmospheric Administration, 2025).

As voluntary slow-down zones have proven effective in marine contexts, it is recommended that consideration be given to establishing such zones in habitats of CMS-listed freshwater mammals where required.

Furthermore, the establishment of non-passable zones is critical. This is particularly evident in the case of the Mahakam River dolphins, where narrow tributaries—some as narrow as 100 meters—are entered by 300-foot-long coal barges. This creates a high risk of dangerous encounters, as evidenced by a confirmed vessel strike with a calf (Kreb and Budiono., 2025a). The danger is exacerbated by sharp river bends, which cause vessels to appear suddenly, and by intense engine noise that may (partially) mask the dolphins' sonar echoes (Au and Penner, 1981). This acoustic interference is especially detrimental as these dolphins tend to surface frequently when boats are near (Kreb and Budiono., 2025a).

4.7 Maintaining ecological flow regimes

Anthropogenic activities – particularly dam construction – have altered flow regimes in many freshwater systems, exacerbating drought conditions. The multitude of ways rivers are managed including via high dams, diversion dams and embankments may reduce flows, fragment habitats and make it difficult to move away from threats. Maintaining ecological flow regimes in the habitats of CMS-listed freshwater mammals is critical to prevent their displacement into high-traffic main river channels, where intense vessel noise – particularly during dry seasons – poses significant threats. Additionally, maintaining natural depth profiles that reduce reverberation via ecological flow regimes is essential, as demonstrated in the Ganges River system (Dey et al., 2019). Maintaining ecological flows thus helps keep freshwater mammals in quieter, safer areas and supports healthy habitat conditions.

4.8 Maintaining the non-navigable status of ecologically important river branches

Vessel traffic noise resulting in communication space reductions might be beyond the evolutionary adaptation process of cetacean species (Parks et al., 2011; Putland et al., 2018). While rerouting shipping lanes in the mainstem is often unfeasible due to space constraints, certain non-navigable tributaries and stretches of mainstream rivers and lakes serve as critical habitat for CMS-listed freshwater mammals. Maintaining the protected status of these key branches is vital for species conservation. For instance, in the Yangtze River, biosonar activity of the Yangtze Finless Porpoise (including click trains, buzzes, buzz ratio, and echolocation encounters) was consistently higher in non-shipping channels compared to shipping channels. This pattern correlates with significantly lower noise levels in these undisturbed areas. These quieter tributaries serve as critical acoustic refugia for this endangered species (Zhou et al., 2021).

4.9 Increasing the utilization of shore-to-ship power

Utilizing shoreside electrical power connections while berthed – with main and auxiliary engines switched off – reduces in-port emissions and underwater noise pollution. This is one of the measures also proposed for marine mammal protection in the CMS Technical Series No. 46 (Weilgart, 2023). Vessels at berth typically operate auxiliary engines while shutting down main engines to meet onboard power demands, a practice that contributes to environmental pollution. The adoption of shoreside power supply systems represents an effective solution to reduce ship-generated emissions. Since China's initial implementation of high-voltage shore power (HVSP) technology in 2010, this green port initiative has seen progressive nationwide adoption. The 2016 revision to China's Atmospheric Pollution Prevention and Control Law mandated that all new ports must incorporate shore power facilities in their planning and design, while existing ports are required to retrofit such infrastructure progressively, with docked vessels prioritized for shore power utilization. The ongoing enhancement of portside power infrastructure across China, coupled with the increasing adoption of shore power by berthed vessels, demonstrates significant potential for mitigating acoustic pollution in and near riparian and port environments through the reduction of auxiliary engine operation.

4.10 Advancing multimodal transport through ecologically meaningful organization of transportation

Significant efforts must be made to advance multimodal transport development, particularly rail-water and road-water combined transport. Technologies such as mobile/wireless solutions, big data, and cloud computing have been adopted to foster "Internet + Water Transport" integration, enabling seamless ship-port-shore connectivity. Additionally, initiatives to accelerate digital waterway navigation are expected to further enhance transportation efficiency (Wang et al., 2021a). Specifically, optimized speed control employs automated adjustments to maintain steady propulsion, eliminating unnecessary acceleration/deceleration and thereby reducing propeller cavitation noise. For vessel strike avoidance, AI-driven route coordination significantly minimizes emergency manoeuvres (e.g., abrupt course corrections), which are known to produce high-intensity transient noise. Shifting heavy cargo transport from rivers to land routes could benefit species whose habitat overlaps with busy waterways. However, any modal shift would need to be carefully evaluated for other environmental implications.

Road-water intermodal transport is also critical for certain freshwater mammals. For instance, in the narrow tributaries inhabited by the Irrawaddy dolphin, a shift from large coal barges to land-based transport alternatives is recommended (Jefferson et al., 2008). A possible positive development is that there are plans to improve a previously existing but hardly used road along the river, which leads to most of the coal- and gold-mining companies upstream. Thus, road traffic may become an alternative to river traffic and reduce underwater noise pollution for the local Irrawaddy dolphin (Kreb and Rahadi, 2004).

4.11 Increasing law enforcement patrols

Global compliance with vessel speed restrictions has been inconsistent across regulated areas. For instance, in the manatee speed zones along the Gulf Coast of Florida, compliance with posted speed zones has averaged 50-60%, though rates vary significantly depending on location, vessel type and size, and other factors (Gorzelany, 2004). Compliance levels range from as high as 85% in some waterways to as low as 14% in Palm Beach County (Gorzelany, 2013). Strengthening enforcement through increased patrols and implementing a mandatory boater licensing program could improve regulatory effectiveness, reduce underwater noise interference and reduce vessel strikes with aquatic animals.

4.12 Eliminating noise pollution from fishing vessels

Fishing net entanglement and vessel strikes constitute two of the most severe threats to CMS-listed freshwater mammals. Implementing fishing bans and/or restrictions in critical habitats can: (1) protect prey populations essential for these species' survival, (2) eliminate noise pollution from fishing vessels, and (3) reduce associated ecological impacts on aquatic ecosystems.

To conserve endangered Amazon River Dolphins, the Brazilian federal government implemented a five-year moratorium on the fishing and commercial trade of piracatinga (*Calophysus macropterus*) in 2015. The ban targeted the species' entire supply chain in Brazilian waters, addressing the unsustainable practice of using protected wildlife – notably river dolphins and other wild caiman species (*Caiman spp.*) – as bait in this fishery (da Silva et al., 2018; IWC, 2016). The no-fishing period system is also how the fishery resources of the Yangtze River basin are protected. A permanent ban on fishing over a provisional period of 10 years has been implemented in the main stream and important tributaries of the Yangtze River and large lakes such as Poyang and Dongting Lake, since 2021 (Wang et al., 2021a). Furthermore, at several important winter aggregation sites for the Florida Manatee, seasonal fishing closures have been implemented to reduce underwater noise pollution (Reep and Bonde, 2021).

4.13 Effects of noise on hearing and behaviour of freshwater species and determining species-specific safe noise exposure levels

Among freshwater mammal species, audiometric studies have only been conducted for three taxa: the Yangtze Finless Porpoise (Popov et al., 2005; Wang et al., 2025b; Wang et al., 2020c), the Baiji (Wang et al., 1992), the Indus River Dolphin (Zbinden et al., 1978) and the West Indian manatee (Gerstein et al., 1999). For other CMS-listed freshwater mammals, studies on the effects of underwater noise on hearing and on behavioural disruption are entirely lacking. This critical knowledge gap significantly impedes accurate assessment of anthropogenic underwater noise impacts on these vulnerable species.

Additionally, the linear threshold shift (LTS) phenomenon – characterized by a linear relationship between noise-induced temporary threshold shift and the sound pressure level difference between baseline hearing thresholds and noise exposure levels – has been documented in multiple fish species (Smith et al., 2004; Smith and Monroe, 2016). For marine mammals, current safe noise exposure guidelines are broadly categorized by hearing frequency ranges, including low-frequency cetaceans, high-frequency cetaceans, and very high-frequency cetaceans (National Marine Fisheries Service, 2024), while species-specific exposure thresholds remain unestablished.

For CMS-listed freshwater mammals, noise levels must be reduced below thresholds where behavioural reactions are caused or foraging efficiency is hindered. A targeted research effort is needed to identify these critical noise thresholds, through methods such as playback experiments and animal tagging, in order to develop effective mitigation measures.

4.14 Reducing overlap between cetaceans and noise by using real-time cetacean alert systems

Implementing real-time detection and alert systems to notify vessels of CMS-listed freshwater mammals in core habitats, coupled with mandatory speed restrictions and noise reduction protocols, may be critical for species conservation and animal welfare. The Whale Anti-Collision System, a passive monitoring system that detects the presence of cetaceans and other marine objects, was developed to provide real-time movement data to ships to prevent vessel strikes and minimize harmful operations in designated zones (André et al., 2011a). Additionally, the Right Whale Sighting Advisory System (WhaleMap) aims to reduce vessel strikes of endangered North Atlantic Right Whales by alerting mariners to their presence (Johnson et al., 2021). The WhaleReport Alert System (WRAS) is a critical tool designed to reduce ship strikes on whales by providing real-time alerts to mariners about cetacean (whale, dolphin, porpoise) presence in their vicinity (Scott et al., 2024). These alerting systems help vessels take proactive measures, such as slowing down or altering course, to mitigate underwater noise interference and avoid vessel strikes with animals. So far, such alerting systems have primarily been applied in marine environments, but development of similar systems adapted for freshwater environments could be beneficial in reducing underwater noise as well as risk of vessel strikes for freshwater mammals. However, such systems must account for the fact that manoeuvring—such as changing course or reducing speed—can be particularly challenging in freshwater environments due to constricted spaces and strong currents.

4.15 Enforcing responsible tourism guidelines

The global whale-watching industry has experienced rapid growth in recent years, providing significant economic benefits and promoting marine conservation (Paredes-Torres et al., 2025). Beyond their ecological significance, dolphins contribute to economic sustainability through ecotourism. While ecotourism offers valuable benefits, unregulated freshwater mammal watching activities can disrupt natural behaviours. Vessel noise, aggressive pursuit, and excessive human interaction may induce chronic stress in dolphins, impairing critical activities such as feeding, breeding, and social communication. Protective measures and dolphin eco-tourism initiatives should be implemented (Perveen et al., 2011), including establishing marine protected areas and enforcing regulations for dolphin-watching activities. Such measures would minimize noise impacts from tourist vessels on these animals. To ensure sustainable coexistence, strict enforcement of responsible tourism guidelines is essential for dolphin conservation. Many examples of both national and regional whale-watching guidelines exist that aim at minimizing ecological disturbance. A summary of recommended measures for ensuring the sustainability of marine wildlife watching activities, which among other things also aims at reducing disturbance from underwater noise, can be found in CMS Technical Series No. 49 International Guidelines for Sustainable Marine Wildlife Interactions: Boat-Based and In-Water Activities. While these guidelines apply specifically to marine species, many of the recommended measures will equally benefit freshwater species.

4.16 Reducing of the effects of particle motion on fish and invertebrate species

Regulators and other stakeholders have primarily focused on the effects of underwater noise on marine mammals and other protected species. However, assessing the broader ecological impacts on affected habitats is equally critical, as these may be driven largely by effects on fish and invertebrates – which exist in far greater biomass yet lack comparable legal protections.

Many assessments of underwater noise impacts on fish and invertebrates have neglected key issues, including the fact that a significant proportion of these species are sensitive to particle motion rather than sound pressure. While efforts have been made to establish sound exposure criteria – setting regulatory limits based on mortality, tissue injury, hearing impairment, behavioral disruption, and physiological effects – these standards have been developed almost exclusively for marine mammals. For fish and invertebrates, criteria have often been assumed or derived from studies with inadequate experimental design and controls (Hawkins and Popper, 2016b). Further research should be devoted to understanding how particle motion affects fish and invertebrate species in order to develop effective mitigation measures that address this specific acoustic impact.

4.17 Avoiding or minimizing underwater noise from construction, pile driving, seismic surveys and other anthropogenic activities

In addition to shipping, various anthropogenic activities – including construction work, military exercises, and seismic surveys – contribute significantly to underwater noise pollution. For instance, seismic airgun surveys have been proposed and already conducted in some riverine and estuarine systems (Boruah and Ganguli, 2017; Santos, 2025); these generate loud, repetitive pulses intended to penetrate subsurface geology and may severely disrupt or damage the hearing and behaviour of aquatic mammals. Though less studied in freshwater contexts, similar impacts are well documented in marine settings (CMS, 2017b). Given the confined nature of freshwater bodies, they may be even more severe. The planned and ongoing proliferation of airgun surveys in rivers, particularly in certain South Asian waterways, is a significant conservation concern. There are also indications that such operations may be proposed for other regions (Gill Braulik, personal communication). The use of this technology in confined freshwater systems poses a severe risk to acoustically sensitive species, including endangered freshwater dolphins and other aquatic fauna, due to the intense and repeated noise exposure in their limited habitat. Therefore, airguns are notably inappropriate technology for use in such restricted environments.

Noise generated by sand mining and construction activities—such as pile driving, blasting, and bankside construction—poses a significant threat to freshwater ecosystems. These operations, often associated with the development of new ports, jetties, flood control infrastructures, and riverside facilities, introduce high-intensity, impulsive sounds into aquatic environments. Pile-driving along riverbanks during the construction of ports, jetties, or flood-control infrastructure can generate intense impulsive sounds, affecting aquatic life. The confined nature of river systems amplifies these impacts, leaving species with limited avenues for escape. These noise-generating activities pose clear risks to freshwater mammals – disrupting communication, foraging, and navigation, and potentially inducing stress or physical harm (Santos, 2025).

To mitigate this, all activities generating intense noise, including pile-driving and seismic surveys, should be avoided or carefully managed in habitats where freshwater mammals occur (Boruah and Ganguli, 2017). The aforementioned CMS Family Guidelines on Environmental Impact Assessments for Marine Noise-Generating Activities specifically address a wide range of sources, including seismic surveys, construction works, and renewable-energy devices like wind, tidal, and wave turbines (CMS, 2017b). Moreover, CMS Technical Series No. 46, detailing Best Available Technology (BAT) and Best Environmental Practice (BEP) for mitigating noise from shipping, seismic airgun surveys, and pile driving, provides further valuable guidance for reducing impacts from both marine and freshwater noise-generating activities (Weilgart, 2023).

Conclusion

Through compilation and analysis of available data for all CMS-listed freshwater mammals (cetaceans, sirenians, and otters), this report summarises the state of knowledge on anthropogenic underwater noise impacts and noise mitigation measures for CMS-listed freshwater mammals, covering their prey species and freshwater habitats, such as estuaries, rivers and lakes. It is evident that anthropogenic underwater noise significantly impacts both these listed species and their prey populations.

Freshwater ecosystems are spatially restricted, which means that (i) the ability of freshwater mammals to escape threats (including high underwater sound levels) is limited and (ii) these animals experience more significant impacts due to the greater reverberation and persistence of noise in their environment. Therefore, the need to address the threat of acoustic pollution may be equally – if not more – urgent in freshwater ecosystems than it is in the marine environment.

Current noise mitigation measures focus on spatial and temporal management approaches, as well as Best Available Technology (BAT) and Best Environmental Practice (BEP) for mitigating shipping and pile driving noise. Existing guidelines on environmental impact assessments and mitigation measures for anthropogenic underwater noise-generating activities have been developed – e.g., by CMS, the EU and US – although the majority of these guidelines were developed for marine species and habitats. Key gaps remain for CMS-listed freshwater mammals, including: (1) no recognition as priority species in existing international and national regulation; (2) insufficient baseline data on habitat underwater noise levels; and (3) a lack of data on the effects of underwater noise on hearing and on disruption of behaviour for most freshwater mammals.

This report concludes that underwater noise mitigation guidelines must be developed for mammals, fish and other species in freshwater environments, as current regulatory frameworks and guidelines fail to adequately protect CMS-listed freshwater mammals and their prey. The report includes recommendations on which measures to include in specific guidance for freshwater habitats, such as restrictions on anthropogenic noise-generating activities, vessel-quieting technologies, slow-down or non-passable areas and maintaining ecological flow regimes. The development of underwater noise mitigation guidance tailored to CMS-listed freshwater mammals and their habitat would be expected to lead to improved conservation outcomes for these threatened species and pave the way for improved noise mitigation for all freshwater mammals.

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