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General Fisheries Commission for the Mediterranean
Commission générale des pêches pour la Méditerranée

Study on the potential effects of underwater noise on demersal fisheries in the fisheries restricted area of the Jabuka/Pomo Pit in the Adriatic Sea

In partnership with

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Contents

Preparation of this document

This document was prepared by the General Fisheries Commission for the Mediterranean (GFCM) of the Food and Agriculture Organization of the United Nations (FAO) in collaboration with OceanCare under the framework of an agreement between the Federal Food Safety and Veterinary Office of Switzerland (FSVO) of the Federal Council of Switzerland and the GFCM concerning the project ‘Socio-economic impacts of anthropogenic ocean noise’.

Abstract

Anthropogenic underwater noise (or noise pollution) in the ocean is a ubiquitous and ever-increasing source of pollution affecting the marine environment and its species. However, while the impact of ocean noise pollution on marine mammals has long been the focus of scientific studies and research, the impacts of underwater noise on fish and invertebrates have only recently been considered and more scrupulously investigated, marginal earlier efforts notwithstanding. Indeed, recent findings suggest that ocean noise may have detrimental impacts on fish and invertebrates' (e.g., including body malformations, higher egg or immature mortality, developmental delays, slower growth rates), anatomy, physiology, and behaviour of fish and invertebrates. This study presents an underwater noise modelling assessment of fishing activities in the Pomo/Jabuka Pit Fisheries Restricted Area (Adriatic Sea) established by the GFCM in 2017 offshore of Italy and Croatia. The demersal fisheries in this area target valuable species such as the European hake (*Merluccius merluccius*) and the Norway lobster (*Nephrops norvegicus*). Calculation of propagation distance and resulting acoustic levels are presented, including scenarios under various fishing efforts for an evaluation of cumulative noise levels. Potential impacts of calculated noise levels on fish and invertebrates are also described. This work represents a stepping-stone towards understanding the far-reaching and potential adverse effects of underwater noise on marine life and food webs better by providing insights into the potential impact of underwater noise produced by bottom trawling and demersal longliners. The estimated underwater sound fields were calculated for sound pressure levels (SPL) to compare with available impact criteria for fish and marine mammals. The SPL thresholds for recoverable barotrauma injury and temporary hearing threshold shift (TTS) in pressure sensitive fish from Popper *et al.* (2014) of 170 and 158 dB re 1 μPa respectively were not reached for any vessel at any location within the resolution of the modelling. Nonetheless, the modelled levels considered only the generated noise from demersal fishing activities and did not account for other significant sources of noise present. Noise from commercial vessels (e.g., cargo ships, tankers) and noise from seismic exploration, for example, should be considered in any further investigation into the effect of noise on sensitive receptors in the area. The social, economic, and cultural impact of anthropogenic underwater noise is beyond the scope of this investigation but should be considered in future inquiries so as to enhance understanding of the broader implications of human-generated noise activities.

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Background and methodology

Anthropogenic underwater noise pollution[1] in the ocean is a ubiquitous, ever-increasing source of pollution affecting the marine environment and the species living in it. The impact of ocean noise pollution on marine mammals has long been the focus of scientific studies and research. However, despite earlier efforts made in the 1990s, the impacts of underwater noise on fish and invertebrates has only recently started to be investigated in more detail. Indeed, findings suggest that ocean noise has detrimental impacts on development (e.g., body malformations, higher egg or immature mortality, development delays, slower growth rates), anatomy, physiology and behaviour of fish and invertebrates. These findings are alarming, showing that such impacts may endanger the overall health of the marine food web and in turn fisheries and human food security. In light of this, the need to carry out studies on the impact of underwater noise on fish stocks and fisheries has on several occasions also been recognized by both the United Nations General Assembly (UNGA) and the Food and Agriculture Organization of the United Nations (FAO) since the early 2000s. In 2018 and 2021, the FAO Committee on Fisheries (COFI) further expressed the concern over the potential adverse impacts of underwater noise on fish stocks and catch rates, echoing the requests of the UNGA to carry out new studies on the issue. In response to the committees' pleas, a GFCM/OceanCare workshop on Anthropogenic Underwater Noise and impacts on fish, invertebrates and fish resources (WKNOISE) was organized in 2019 (FAO headquarters, Rome, 21-22 February 2019). The workshop reviewed the effects of anthropogenic underwater noise effects on fish and invertebrates as reported from the literature and identified areas in the GFCM area of application, including where fishing activities are restricted (i.e. GFCM fisheries restricted areas), building upon the conclusions and recommendations of this workshop, the GFCM Scientific Advisory Committee on Fisheries (SAC) agreed to carry out a preliminary study on the potential impact of underwater noise pollution on fish resources and fisheries in order to start addressing this issue in the context of the Mediterranean Sea and toprovide decision-makers and other relevant stakeholders with better insights into the impacts of noise on fisheries, including potential socio-economic consequences. Indeed, the identification of noise sources and their impact is a critical component of effective mitigation and management efforts. Within this framework, too, this study seeks to contribute to the understanding on the effects of underwater noise on fish and invertebrates in the Adriatic Sea.

For this initial study, the GFCM Secretariat set up an independent Advisory Group (AG) comprised of experts with backgrounds in bioacoustics, noise pollution and marine biodiversity. These specialists headed the development of the study from a technical point of view as it related to expected outcomes and goals. This study aims to examine the impacts of noise generated by demersal fishing vessels in the study area (i.e. the Jabuka/Pomo Pit in the Adriatic Sea). The first part of the study presents a framework by providing relevant background information and data as available from a wide range of sources, including GFCM data. Section 1 briefly chronicles the efforts undertaken in both international and regional settings to address underwater noise (in particular by the UNGA and its specialized agencies and by multilateral environmental agreements (MEAs)). Section 2 presents the characteristics of the study area, including inter alia its geology, bathymetry, water circulation and hydrodynamics, as well as its ecological importance for fish resources (i.e. hosts important essential fish habitats). The section also describes the current management framework, and the provisions of the current GFCM Fisheries Restricted Area in force. The ecological and commercial importance serve as explanatory factors as to why the Jabuka/Pomo Pit is an appropriate case

[1] UNCLOS Definition: (4) "pollution of the marine environment" **means the introduction by man, directly or indirectly, of substances or energy into the marine environment**, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities;

study worthy of serving as the study's primary area of focus. Section 3 details the demersal fisheries operating in the area, and includes the landings value from the recent years past. Section 4 provides a biological and ecological description of the most important demersal fish and invertebrate species of the Adriatic Sea. Section 5 presents the current knowledge about the sensitivity of demersal fish and invertebrates to noise exposures as available from scientific literature and reports. The second part of the study, as alluded to above, describes the sources of underwater noise occurring in the study area and its potential effects on fish, invertebrates and other marine fauna. In Section 6, the sources of anthropogenic noise occurring in the area are briefly described together with the known effects of these on marine fauna. In Section 7, the noise levels produced by the demersal fishing vessels operating in the study area under various fishing effort scenarios. The section also compares obtained sound pressure levels (SPL) to the established impact criteria for fish and marine mammals. Such noise levels were obtained by modelling the characteristics of engines (e.g. length, type of gear, power, etc.), considering the physical and chemical characteristics of the water column, the sea bottom, the depth, etc. Finally, Section 8 provides conclusions and recommendations based on the study's findings.

1. Introduction

1.1. Aim of the study

Levels of underwater noise in the ocean are increasing. In some regions, noise has doubled every decade for the past several decades, mainly from shipping (Andrew, Howe and Mercer, 2002, Hildebrand, 2009; McDonald, Hildebrand and Wiggins, 2006). Other noise sources, including from seismic surveying, naval sonar uses and port construction activities, have also contributed to noise levels. Anthropogenic underwater noise is a highly transboundary form of pollution that poses a significant threat to marine life (e.g. Erbe *et al.*, 2019; Duarte *et al.*, 2021; Weilgart 2007, 2018), and may come both in the form of short impulsive noise sources or low frequency continuous noise. The impact of anthropogenic underwater noise is not limited to the immediate area around its source but can reach thousands of kilometres in distance. It is therefore important to look beyond the immediate origin of the noise source when assessing its impact on marine life, and, by extension, on human livelihoods.

While the impact of ocean noise has received particular attention in the context of marine mammals, the equally important impacts on fish and invertebrates have only garnered attention in the last few years. A review of 115 primary studies on the consequences of human-generated underwater noise on 66 species of fish and 36 species of invertebrates (Weilgart 2018) gives reason for concern. Indeed, findings suggest that ocean noise has detrimental impacts on the development of these creatures. These effects include body malformations, higher egg or immature mortality, developmental delays and slower growth rates (e.g. Aguilar de Soto *et al*., 2013, Banner and Hyatt, 1973, Nedelec *et al.* 2014, McCauley *et al.* 2017), as well as on the anatomy (e.g. Guerra *et al.* 2011, Solé *et al.* 2013, 2017) and physiology of fish and invertebrates (e.g. Day *et al.*, 2017, Nichols, Anderson and Širović,2015). These findings are alarming, as such impacts potentially endanger the health of the overall marine food web (Solan *et al.*, 2016). In addition, these repercussions impact fisheries and human food security. Fisheries provide nutritious food and generate an important income stream for communities around the world (Toppe *et al*., 2017). This is why a focus on food security is critical in achieving Sustainable Development Goal 1 'End poverty in all its forms everywhere' and 2 'End hunger, achieve food security and improved nutrition and promote sustainable agriculture' as outlined by FAO.

With these goals in mind, this study aims to provide decision-makers and other relevant stakeholders with better insights into the impacts of noise on fisheries. This study, too, hopes to give readers a better understanding of the potential socio-economic consequences of ocean noise. Indeed, identifying both the noise sources and their subsequent impacts on exposed fish is a critical element in effective mitigation and management efforts. The mandate to prepare such a study was granted by the Contracting Parties to the General Fisheries Commission for the Mediterranean (GFCM) and is intended to build upon the conclusions of the joint GFCM/OceanCare workshop on anthropogenic underwater noise and impacts on fish, invertebrates and fish resources, hosted by the GFCM in Rome in February 2019. For practical reasons and for geographic clarity, this study restricts its scope to the Fisheries Restricted Area (FRA) of the Jabuka/Pomo Pit, an area designated by the GFCM in 2017.

1.2. Putting the study in its appropriate context

There has been an increasing awareness of the importance of sound for marine species over the past few decades. The need to address the potential risks to marine life associated with anthropogenic underwater noise. This increase in awareness has given rise to several monitoring and regulatory efforts in international and regional fora that are intended to provide guidelines and standards for the management and mitigation of underwater noise emission to the marine environment. Such efforts have in particular been undertaken within the United Nations (UN) framework and several multilateral environmental agreements (MEAs). The opportunity to conduct a study that specifically explores the effects of underwater noise on selected fisheries in the Adriatic Sea, including a determination of its potential socioeconomic impacts, has been acknowledged in recent years in the context of the General Fisheries Commission for the Mediterranean of the FAO (GFCM). This study represents an important step towards better understanding the potential adverse effects of underwater noise on marine life and food webs. Its findings are expected to inform the work still left to be done in the context of relevant regional and international processes.

1.2.1. The United Nations and its entities

The United Nations General Assembly (UNGA) has been critical in recognizing the potential adverse effects of underwater noise and the need to address them. In its annual resolutions on Sustainable Fisheries (e.g., A/RES/75/89) and Oceans and the Law of the Sea (e.g., A/RES/75/239), the UNGA has consistently noted that anthropogenic noise could have a potential impact on marine species and recognized the importance of exploring the impacts of noise-generating activities on fish stocks and fisheries. The UNGA also acknowledges any associated socioeconomic impacts. This recognition has received continued appreciation and is reflected in the UNGA's encouragement on the need for '*further studies and consideration of the impacts of ocean noise on marine living resources*' (2005[2], 2006[3] and 2007[4]), and in '*requesting the Division [for Ocean Affairs and the Law of the Sea] to compile the peer-reviewed scientific studies it receives from member states [and intergovernmental organisations in 2009] and to make them available on its website*' (2006, 2007, 2008 and 2009). In 2010[5], 2011[6], and 2012[7], UNGA Oceans and the Law of the Sea resolutions deemed ocean noise a potential threat to living marine resources and reaffirmed the importance of scientific studies that consider the potential adverse impacts of underwater noise. One specific resolution worth deeper reflection is resolution 70/235 adopted by the UNGA in 2015. The resolution includes two important operative paragraphs on ocean noise, *inter alia*, highlighting the potential significant impacts of noise on marine resources. The resolution also calls "upon States and competent *international organizations* to cooperate and coordinate their research efforts in this regard so as to reduce these impacts and preserve the integrity of the whole marine ecosystem" (UNGA A/RES/70/235: 2015, operative para. 242 and 246). Resolution 75/89, most recently adopted by the General Assembly in 2020, specifically highlighted the role of the FAO by noting that further studies continue to remain a necessity, "including by the Food and Agriculture Organization of the United Nations" (UNGA RES/75/89, 2020, para. 222).

The UNGA has likewise noted the need for a better understanding of the socioeconomic impacts of ocean noise. For example, in resolution 65/39 brought forth in 2010, the UNGA supported studies (including those by FAO) that pay necessary tribute to associated socioeconomic effects on fish stocks and fishing catch rates (UNGA A/RES/65/38: 2010, para. 127). In 2018, the UNGA reminded countries of the importance of such studies by calling "upon States to consider potential environmental and socioeconomic impacts of anthropogenic underwater noise from different activities in the marine environment" (UNGA A/RES/73/125: 2018, para. 39).

The United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea dedicated its nineteenth meeting to anthropogenic underwater noise in 2018. The forum, which was established in 1999 with the intention of identifying areas of importance with respect to ocean affairs and the Law of the Sea, discussed the need to fill gaps in knowledge, potential management approaches, the transboundary

[2] See para. 84 of Resolution A/Res/60/30

[3] See para. 107 of Resolution A/Res/61/222

[4] See para. 120 of Resolution A/Res/62/215

[5] See para. 186 of Resolution A/Res/65/37

[6] See para. 185 of Resolution A/66/231

[7] See para. 205 of Resolution A/RES/67/78

pollutant nature of underwater noise and recognized the socioeconomic impacts associated with anthropogenic underwater noise, especially those on the fishing sector.

In 2019, the United Nations Environment Programme (UN Environment Programme) set out to assess the current state of the environment on the basis of which it could provide relevant information to decision-makers. This effort cumulated in the sixth edition of the Global Environment Outlook (GEO-6) under the theme "Healthy Planet, Healthy People". By analysing present and past environmental policy, the Assessment specifically seeks to provide the necessary information for achieving the "environmental dimension of the 2030 Agenda for Sustainable Development and internationally agreed environmental goals". It also endeavours "to implement the multilateral environmental agreements" (UN Environment (GEO-6) Report Summary, 2019, 04).

The Report in particular notes the many human activities that can have major impacts on the ocean. Of particular relevance is the Report's recognition of the increasing concern of the potential impacts of anthropogenic underwater noise generated by seismic surveys, shipping, offshore construction and military operations, should these activities be inadequately regulated (UN Environment (GEO-6) Report, 2019, 180 & 190). In 2021, the United Nations released the Second World Ocean Assessment (WOA II), a further assessment that took a holistic view of the state of the environment with a specific focus on the ocean. The WOA II in particular makes reference to the increasing amounts of anthropogenic underwater noise as a concern and refers to some of the economic and social consequences associated with noise-generating activities. In this respect, it is worth highlighting that WOA II is aware of the potential economic losses for concerned fisheries as a result of seismic surveys, noting "[t]he impacts of noise on species that are of particular social, economic and cultural relevance may have socioeconomic effects on coastal communities, in particular if they alter the availability of commercially…important marine species" (WOA II, 2021, 308).

Ocean noise and the Global 2030 Agenda for Sustainable Development

At the heart of the United Nations 2030 Agenda for Sustainable Development agreed by United Nations Member States in 2015 lie the 17 Sustainable Development Goals (SDGs). Building on the Millennium Development Goals, the SDGs are intended to shape national development plans until 2030 and to achieve a more sustainable future for the planet. Anthropogenic underwater noise is linked to the SDGs in a number of ways, particularly SDG14.1, which calls for a significant reduction of marine pollution of all kinds by 2025. Governments and other stakeholders must also consider the implications of ocean noise for global food security and the associated potential socioeconomic consequences, especially if noise levels are expected to continue to rise. Efforts to achieve SDG 14.4, which seeks to 'restore fish stocks in the shortest time feasible' may be directly compromised if the impacts of ocean noise are not properly understood and incorporated into fisheries management plans. Other SDGs however also remain pertinent, including: SDG 1: End poverty in all its forms everywhere, SDG 2: End hunger, achieve food security and improve nutrition and promote sustainable agriculture, SDG 8: Promote sustained inclusive and sustainable economic growth, and full, productive employment and decent work for all, SDG 13: Take urgent action to combat climate change and its impacts and, perhaps most notably SDG 14: Conserve and sustainable use the oceans, seas and marine resources for sustainable development.[8]

It is worth noting the nexus between anthropogenic underwater noise and food security (directly linked with ending poverty), enshrined in SDGs 1 and 2. It is estimated that approximately 56.6 million people across the globe are dependent on the fisheries sector (and thus aquaculture at large) for their livelihoods (OceanCare 'Ocean Noise and the Sustainable Development Goals: 2018, 2). In consideration of the

[8] For a more detailed treatment of the linkages between ocean noise and the SDGs see "Ocean Noise and the Sustainable Development Goals", available at: https://www.oceancare.org/wp-content/uploads/2017/12/Noise_neutral_2018_web.pdf

impacts of noise on fish (see Section 5 below) it will become increasingly difficult for people to support their nutritional needs and to secure food.

Food and Agriculture Organization of the United Nations – Committee on Fisheries

The concern over the adverse impacts of underwater noise on fish and fisheries has also been acknowledged by the FAO Committee on Fisheries (COFI) FAO in 2018. As a global technical committee of the FAO and serving as the only intergovernmental forum that examines the major challenges of an international character facing fisheries, COFI recognized the need of a review of its socioeconomic impact on marine resources (COFI Report 33, 2018, para. 108). During the 34th Session of COFI (held virtually from the 1 to 5 February 2021 due to the global outbreak of the COVID-19 pandemic), the Committee reiterated its concern over the impacts of anthropogenic underwater noise and also "encouraged FAO to assess its possible impacts, including socio-economic consequences, on marine resources" (Draft COFI Report 34: 2021, para. 102).

- *General Fisheries Commission for the Mediterranean*

Established by the FAO in 1949, the General Fisheries Commission for the Mediterranean (GFCM) is the first regional fisheries management organization (RFMO) and another United Nations entity that has acknowledged the potential impacts of anthropogenic underwater noise. GFCM plays a critical role in fisheries governance in the Mediterranean and the Black Sea and has the authority to adopt binding recommendations for fisheries conservation and management. Between 21 and 22 February 2019, the GFCM, in collaboration with OceanCare, organised and hosted a workshop on Anthropogenic Underwater Noise and impacts on fish, invertebrates and fish resources (WKNOISE) at FAO headquarters in Rome, Italy. The primary objectives of the workshop were to: i) review reported anthropogenic underwater noise effects on fish and invertebrates; ii) identify areas in the GFCM area of application where fishing is restricted but other human activities, in particular anthropogenic underwater noise, could impact fish stocks with attendant socio-economic consequences; iii) address the prevention of these impacts on fish and their prey, including through Environmental Impact Assessments; iv) discuss recent developments within the United Nations Convention on the Law of the Sea (UNCLOS) in connection with transboundary pollution in the high seas; and v) address the relevance of anthropogenic underwater noise in the context of a study on socio-economic impacts on Mediterranean fish stocks. During the meeting, several studies and regional experiences relevant to the topic of the workshop were presented. On the basis of the information provided, the discussions focused on diverse issues such as noise hot spots and species distribution, possible impacts of anthropogenic underwater noise in GFCM fisheries restricted areas (FRAs) and current conflicts between different human activities at sea, including fisheries. Recommendations for the GFCM to address anthropogenic underwater noise were adopted by the workshop (GFCM, 2019), which include:

- Coordination with CMS, CBD, IMO – and other relevant international organizations – should be fostered by the GFCM to ensure coherence in the implementation at the regional level of existing policies addressing, inter alia, the impacts of anthropogenic underwater noise on marine biodiversity;
- Multi-sectoral Strategic Environmental Assessments (SEAs) and Environmental Impact Assessments (EIAs) conducted should be examined by GFCM contracting parties and cooperating non-contracting parties (CPCs) so that the impacts of anthropogenic underwater noise, including cumulative and synergistic impacts on marine biodiversity, especially those affecting fisheries, be adequately addressed and monitored;
- CPCs should make all efforts to comply with recommendations adopted by the GFCM on the establishment of fisheries restricted areas, including recommendation GFCM/30/2006/3, and, to this end, ensure coordination among relevant national authorities

to protect these areas from the impacts of anthropogenic underwater noise (e.g. seismic surveys) to the extent possible;

- Potential impacts of anthropogenic underwater noise on marine biodiversity, especially those affecting fisheries, should be taken into consideration by the GFCM – through its Scientific Advisory Committee on Fisheries (SAC) – in coordination with relevant organizations – for example the Mediterranean Action Plan of the United Nations Environment Programme (UNEP/MAP) and the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS) – to the best extent possible; and
- A study on the impacts of anthropogenic underwater noise on fish stocks and fishing catch rates, as well as its associated socio-economic effects, in the GFCM area of application should be carried out, consistent with the calls by the UN General Assembly. This study would be prepared by GFCM and OceanCare, in coordination with other relevant regional organizations, and would be submitted to the SAC for consideration by CPCs.

International Maritime Organization

The International Maritime Organization (IMO) is also gradually becoming more aware of the threats posed by anthropogenic underwater noise, taking its first actions in 2004. In light of the growing evidence and awareness of the impact of continuous anthropogenic noise, primarily as a result of commercial shipping, the IMO’s Marine Environment Protection Committee (MEPC) introduced non-mandatory technical guidelines, which were formally approved by the sixty-sixth session of the IMO in 2014. The Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life, as they are formally called, provide ship designers, builders and operators with instruction of sorts on how to reduce underwater noise (IMO, 2014).

By improving the understanding of the co-benefits of reducing anthropogenic underwater noise and the reduction of greenhouse gas emissions, the Marine Environment Protection Committee improved its efforts of international coordination and collaboration on the reduction of underwater noise generated through shipping in 2020. At the 76th session held in 2021, the IMO agreed to “[r]eview the 2014 ‘Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life and [identify] next steps” until 2023 (IMO MEPC 76/WP.1/Rev/1, 2021. 83). In general terms, the MEPC, in the Work Programme of the Committee and Subsidiary bodies (MEPC 75/14) recognized both the impacts of noise generated by commercial shipping on marine life (see para. 9) as well as the necessity to review the 2014 Guidelines.

Regional and international multilateral environmental agreements

Noting the multilateral regional and sectoral efforts undertaken by countries over the past decades, ranging from addressing environmental challenges relating to biodiversity loss, the impacts of climate change and marine pollution, it is apparent that anthropogenic underwater noise has likewise received due attention, albeit to varying degrees and success. Countries have committed to a series of obligations and actions to further address the impacts of noise-generated by a range of anthropogenic activities (e.g., seismic surveying). Such efforts build an important pillar in international efforts to tackle the impacts of ocean noise on marine life. While this chapter cannot address such endeavours in their entirety, it is nevertheless worth noting efforts that have been undertaken and continue to be taken within the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS), the Convention on the Conservation of Migratory Species of Wild Animals (CMS), as well as the progress done within the framework of the Convention on Biological Diversity (CBD) and the International Whaling Commission (IWC).

Since 2004, ACCOBAMS has adopted a range of resolutions aimed at assessing and addressing the impact of anthropogenic underwater noise on marine mammals.[9] At the Seventh Meeting of the Parties (MoP) held between 5 and 8 November in 2019, parties adopted Guidelines to Address the Impact of Anthropogenic Noise on Cetaceans in the ACCOBAMS Area in Annex 2 of Resolution 7.13[10]. On a general note, the Guidelines lay out a series of considerations for mitigating the impacts of certain activities and to maximise environmental protection. For example, with respect to the mitigation of the effects seismic surveys the ACCOBAMS Guidelines foresee shut-down procedures whenever "a cetacean is seen to enter the EZ and whenever aggregations of vulnerable species (such as beaked whales) are detected anywhere within the monitoring area" (ACCOBAMS resolution 7.13, 2019, 13). The Convention on Migratory Species and the Convention on Biological Diversity have likewise considered the dangers posed by underwater noise, adopting a series of measures. For example, in 2017, at the Twelfth Conference of the Parties, Contracting Parties to CMS underscored their recognition of human-generated underwater noise as a pollutant and in particular noted that "[w]ildlife exposed to elevated or prolonged anthropogenic noise can suffer direct injury and/or temporary or permanent threshold shifts…These impacts are experienced by a wide range of species including fish, crustaceans…" (UNEP/CMS/Resolution 12.14/Annex, 2017, 8). Moreover, Parties to CMS, which currently includes 132 countries, adopted the CMS Family Guidelines on Environmental Impact Assessment for Marine Noise-generating Activities. The CMS Family Guidelines are intended to provide member states with a comprehensive and technical guidance on determining the impact of the respective activity on wildlife. More recently, the Thirteenth Meeting of the CoP endorsed a process with a view to developing guidance for the application of Best Available Technology (BAT) and Best Environmental Practice (BAP) for shipping, seismic airgun surveying and pile driving activities.

Furthering international efforts to curb the threat posed by underwater noise, The Fifteenth CoP to the CBD, set to take place in 2021, will further international efforts to curb the threat posed by underwater noise. This session will address anthropogenic underwater noise in its preparatory efforts. Indeed, the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA) of the CBD, in its Progress Report on Ecologically or Biologically Significant Marine Area, made specific note of underwater noise. It is also worth highlighting that the SBSTTA made specific mention of the "Synthesis on the Impacts of Underwater Noise on Marine and Coastal Biodiversity and Habitats"[11], which reiterated that noise has been recognized as an major stressor on marine life at a global proportion. Finally, the International Whaling Commission (IWC) further illustrates this point, contributing to the growing awareness of the rapid-growth of human-induced ocean noise. Indeed, the IWC raised the profile of this threat by including it in the Strategic Plan of its Conservation Committee. At the 2016 Conservation Committee meeting, the IWC listed anthropogenic sound as a priority threat.[12] Complementing its efforts, the IWC adopted resolution 2018-4, noting the far-reaching range of underwater noise and the rapid increase of noise-generating activities at sea. More so, resolution 2018-4 makes a reference to the precautionary approach, emphasising that "the lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to address the effects of anthropogenic underwater noise".[13]

One of the cornerstones of the European Union's (EU) effort to protect and manage the marine environment is the Marine Strategy Framework Directive (MSFD), adopted by the EU in 2008. A central objective of the MSFD is to consider the various threats posed to marine ecosystems and to achieve Good Environmental

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[9] For a detailed listing of resolutions adopted by ACCOBAMS and its Member States see https://accobams.org/documents-resolutions/resolutions/.
[10] See Annex 2 in ACCOBAMS-MOP7/2019/Doc38/Annex15/Res. 7.13.
[11] See UNEP/CBD/SBSTTA/16/INF/12, available at: https://www.cbd.int/doc/meetings/sbstta/sbstta-16/information/sbstta-16-inf-12-en.pdf A more recent version of the report was published in 2016 and is available at: https://www.cbd.int/doc/meetings/sbstta/sbstta-20/information/sbstta-20-inf-08-en.pdf
[12] See Conservation Committee: Strategic Plan 2016-2026, available at: https://iwc.int/private/downloads/R1-byaMSh5zEGie9HldFJA/IWC_MAY18_CCPG_INFO_02_AC.pdf
[13] See resolution 2018-4, operative para. 2, available at: https://iwc.int/private/downloads/0ymu0VhMN0_3YlwSi-QTcw/RESOLUTION_2018_NOISE.pdf

Status (GES) of EU marine waters, whereby GES is defined as a status “of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clear, healthy and productive” (MSFD, para. 3). In attempt to provide Member States with guidance on how to interpret GES, the MSFD moreover establishes 11 distinct descriptors of how the environment should look under GES. Descriptor 11 is most relevant to the mitigation of underwater noise, defining GES as achieved when “introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment”. Efforts by the EU to achieve GES on underwater noise are complemented by a number of projects that are aimed at improving coherence and comparability on this specific descriptor, including the projects QuietMed 1 and QuietMed 2, as well as QuietSeas.

This brief review, while not exhaustive, is indicative of the general recognition of anthropogenic underwater noise as a direct threat to marine life. It is evident that the international community believes that underwater noise mitigation warrants further consideration. This study is an important further reflection on the impacts of specific noise-generating activities on marine life and serves as a stepping-stone towards better grasping the broader implications (e.g., socioeconomic impacts) of such activities on both marine life and society at large.

2. Study area

The Adriatic Sea is one of the most productive seas of the Mediterranean. Promoting the recovery of essential fish habitats and ecosystems is a key priority for rebuilding fish stocks and supporting sustainable fisheries. With this aim, the Fisheries Restricted Area (FRA) located in the Jabuka/Pomo Pit in the central Adriatic Sea (GFCM Geographical Subarea, GSA, 17) was established by GFCM in 2017 (Figure 1). The area has been clearly identified as (1) a site of unique physical features influencing the dynamics of water circulation in the whole Mediterranean basin; (2) hosting important essential fish habitats (EFHs) for European hake (*Merluccius merluccius*) and other valuable species such as horned octopus (*Eledone cirrhosa*), monkfish (*Lophius budegassa*) and Norway lobster (*Nephrops norvegicus*); (3) a key area for cetaceans, sea turtles and seabirds; and (4) hosting vulnerable marine ecosystems (VMEs) that might be impacted by bottom trawling fishing.

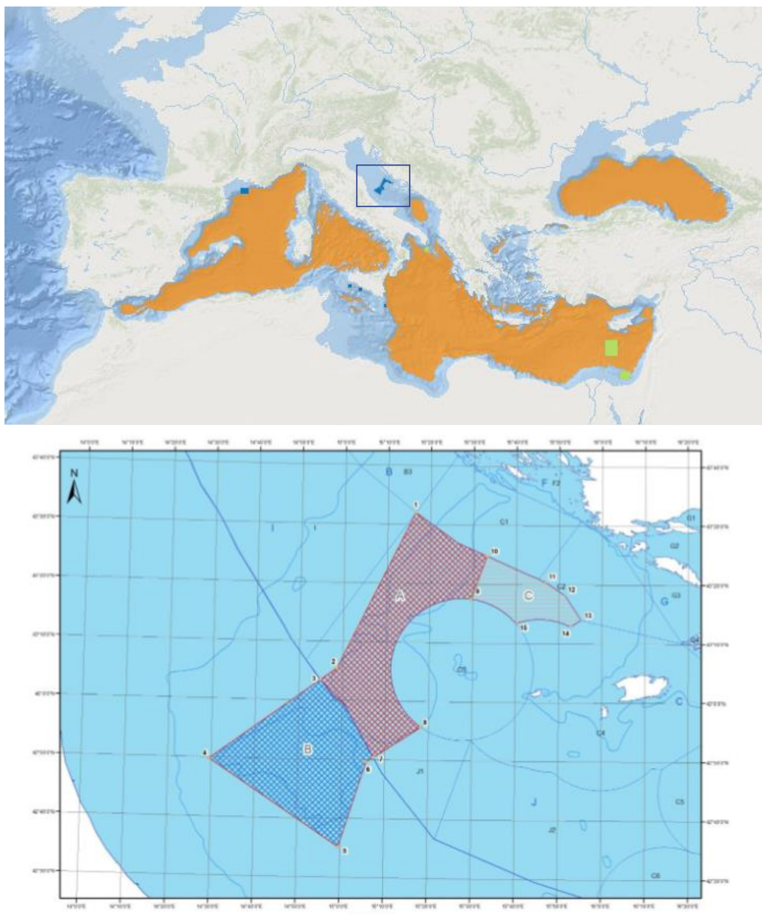


Figure 1. GFCM fisheries restricted areas (FRAs) (top) and location of the Jabuka/Pomo Pit FRA in the Adriatic Sea, GSA 17 (and its zoning) (bottom)

2.1. Geology and geomorphology

The Adriatic Sea is a semi-enclosed and elongated basin (about 800 km long by 200 km wide) with the major axis in the northwest–southeast direction, located between the Italian and the Balkan peninsulas. It is divided into three sub-basins showing clear morphological differences (Artegiani *et al.*, 1997). The north Adriatic basin is a wide and shallow continental shelf (with an average depth of about 35 m), extending from to the north from the 100 m bathymetric line off Giulianova, Italy. The middle Adriatic basin is a transition zone from the shallower northern basin to the open sea condition of the southern basin, and it spans from the 100 m contour to the 170 m deep Palagruža Sill, located on the bottom of the line between Vieste (Gargano) and Split. The south Adriatic basin reaches a depth of 1 200 m delimited by a rugged and steep continental shelf (Russo and Artegiani, 1996; Trincardi *et al.*, 1996; Maselli *et al.*, 2011; Spagnoli *et al.*, 2014). The Adriatic Sea level has undergone considerable changes over the course of geological time. In the Pliocene, the basin was wider than it is in the present-day. Its entire continental shelf has emerged and has been subjected to erosion by rivers, which in turn added a large amount of fluvial sediments into the basin. A large delta modelled the northern side of the middle Jabuka/Pomo Adriatic depression (van Straaten, 1970). The Jabuka/Pomo Pit is the most prominent feature of the central Adriatic basin. It is a complex transverse depression, forming the 'Meso-Adriatic Trench', reaching depths between 240 to 270 m (van Straaten, 1970). In particular, the slope of the Jabuka/Pomo Pit was shaped by the ancient delta, leading to a complex geomorphology. It is a depression separated by two sills, leading to the development of three small subareas. It is located in the central offshore areas of the Adriatic Sea extending from the area off Pescara on the western Italian coast to the small Croatian island Žirje on the eastern coast, covering a surface of about 11 500 km^2. South of this depression, the morphological elevation known as Palagruža Sill and formed during the Quaternary, represents the shelf break in the Adriatic Sea (Russo and Artegiani, 1996). The bottoms of the Jabuka/Pomo Pit are composed mainly of clay-loamy sediments (<0.01 mm), mostly of organic origin, derived from pelagic organisms (van Straatern, 1970). Gas-related morphologies such as pockmarks, mud volcanoes, and mud-carbonates mounds, have also been described in the Jabuka/Pomo Pit area (Geletti *et al.*, 2008; Panieri, 2003; Conti *et al.*, 2002).

2.2. Bathymetry

The Adriatic Sea's average depth is 259 m, and its maximum depth is 1 233 m; however, the North Adriatic basin rarely exceeds a depth of 100 m and it gradually deepens towards the southeast. The Middle Adriatic basin extends south of the imaginary Ancona–Zadar line down to the Gargano-Split line and features the 270 m deep Middle Adriatic Pit. The 170 metre deep Palagruža Sill south of the Middle Adriatic Pit, separates it from the 1 200 m deep South Adriatic Pit and the South Adriatic Basin in general (Figure 2). Further south, the sea floor rises to 780 m to form the Otranto Sill at the edge to the Ionian Sea (Randone, 2016).

2.3. Water circulation and hydrodynamics

The Adriatic basin is characterized by cold, dense sinking waters during the winter months, by the water's surface warming during the summer months, and by heavy rainfalls and run-off (in particular by the Po River) during spring and autumn months (Artegiani *et al.*, 1997; Cushman-Roisin *et al.*, 2001). Deep-water production in the Adriatic Sea is an important process (Cushman-Roisin *et al.*, 2001) that plays a crucial role in the thermohaline system of the eastern Mediterranean (Gačić *et al*., 2010). The Adriatic supplies up to one-third of the freshwater flow received by the entire Mediterranean. It is estimated that the Adriatic's entire water volume is exchanged into the Mediterranean Sea through the Strait of Otranto every three to four years, a very short period due to the combined contribution of rivers and submarine groundwater discharge (Franić, 2005). The Jabuka/Pomo Pit water circulation is influenced by the Mid Gyre and by the presence of the middle Adriatic deep water (MAdDW), which determines the circulation of the waters inside the basin and between the Adriatic and Ionian seas (Artegiani *et al.*, 1997) (Figure 2 and 3). The MAdDW with its low temperature (around 11.6°C on average) and high salinity (around 38.4 psu on average) represents the coldest bottom waters of the whole basin from spring to autumn (Artegiani *et al.*, 1997). Cold seawater temperatures with slight 'up-welling' effects positively affect the organic production and the presence of important commercially pelagic and demersal stocks. The Jabuka/Pomo Pit is fundamental in the route of Dense Water (DW) from the North to the South Adriatic basin (Marini *et al.*, 2016). The bottom morphology, formed by a set of depressions and sills located in the Mid-Adriatic

Depression, temporarily traps the DW formed on the continental shelf. After substantial chemical and biological activity, modified DW is released and flows towards the Southern Adriatic basin along the bathymetric morphology (Figure 3).

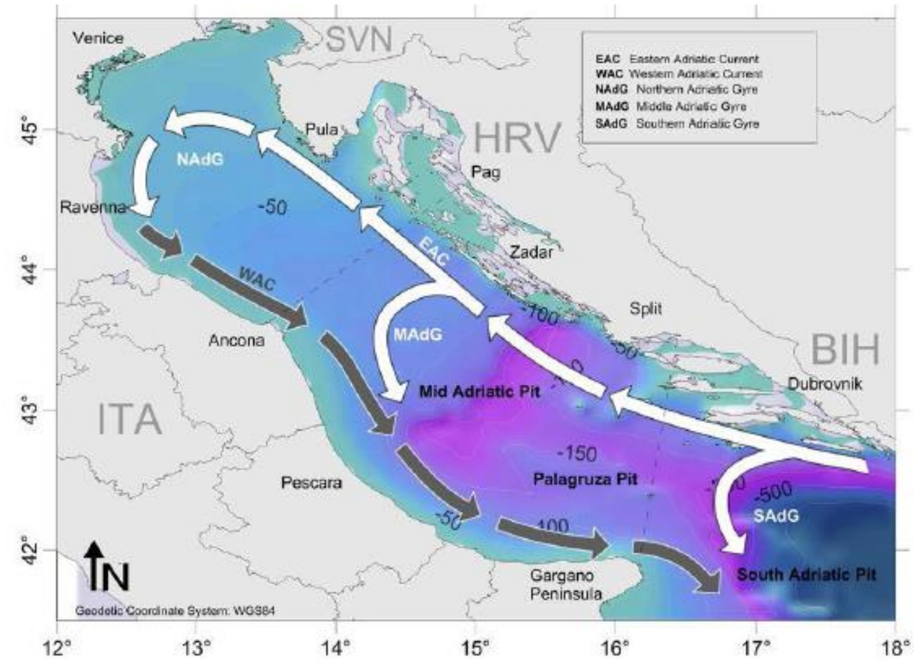


Figure 2. Adriatic Sea: main bathymetries, morphology and surface circulation (UNEP/MAP SPA/RAC, 2015)

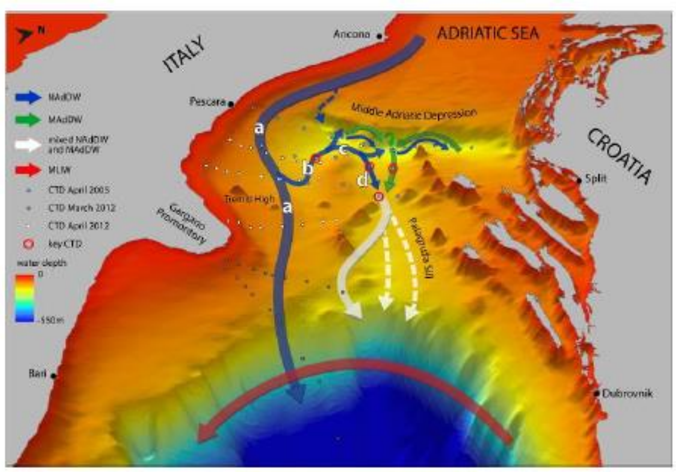


Figure 3. 3D view of the central Adriatic bathymetry showing the routes of NAdDW (North Adriatic Deep Water), MAdDW (Middle Adriatic Deep Water), and MLIW (Modified Levantine Intermediate Water) as blue, green and red arrows. The white line represents NAdDW and MAdDW mixing over Palagruža Sill. White dashed lines are presumed MAdDW branches (from Marini *et al*., 2016)

2.4. Biological features

Although the surface of the Jabuka/Pomo Pit covers less than 10 percent of the total surface of the Adriatic Sea, it represents one of the most productive areas of the Adriatic Sea and encompasses important spawning and nursery areas for key demersal fish stocks. With regards to its benthic community, the Jabuka/Pomo Pit has not been exhaustively studied; however, the composition of the bottom is likely too complex to provide adequate refuge to juvenile fish and invertebrates (Silva, Hamza and Martinos, 2014). The Jabuka/Pomo Pit hosts communities classified as sensitive and essential marine habitats (GFCM, 2008), though these have never been mapped by means of ROV/underwater camera surveys (Chimienti *pers. comm.*), such as Facies with *Pennatula phosphorea*; Facies with *Funiculina quadrangularis* and *Thena muricata* and Association with *Laminaria rodriguezii* (Žuljević *et al*., 2016). A considerable quantity of white corals, mainly large, thick morphotypes of *Lophelia pertusa* and *Madrepora oculata*, extremely well preserved but all dead and covered by a thin layer of mud, were recorded in the Jabuka/Pomo Pit (European Commission, 2009). Some specimens of *Dendrophyllia* corals, with subordinate *Desmophyllum dianthus* and *Caryophyllia smithii*, heavily bioeroded and encrusted by living epifauna, including polychaetes and *Neopycnodonte* oysters, were recovered in this area. This suggests that live yellow coral colonies still exist at this location (European Commission, 2009). Finally, the presence of pockmarks and mud volcanoes also increases the heterogeneity of sandy-muddy bottoms of the Jabuka/Pomo Pit supporting local biodiversity. It is likely that these habitats provide feeding, recruitment and nursery habitats for a range of species including commercially valuable fisheries species. For example, towed gear fisheries commonly have sea pens in their bycatch (Edinger, Wareham and Haedrich, 2007; Doyle *et al.*, 2015) suggesting habitat association between these harvested species and sea pen habitats. Furthermore, in the Jabuka/Pomo Pit, as also reported in other areas, *Nephrops norvegicus* shares the same habitat of *Funiculina quadrangularis* (Greathead *et al*., 2007; Martinelli *et al*., 2013).

Predominant habitats and biocenosis present in the Jabuka/Pomo Pit as listed and categorized in the priority habitats of the SPA/BIO Protocol of the Barcelona Convention are the following:

IV. 1. 1. Biocenosis of costal terrigenous muds

IV. 1. 1. 1. Facies of soft muds with *Turritella communis*

IV. 1. 1. 2. Facies of sticky muds with *Virgularia mirabilis* and *Pennatula phosphorea*

IV. 1. 1. 3. Facies of sticky muds with *Alcyonium palmatum* and *Stichopus regalis*

IV.2 .2 Biocenosis of the costal detritic bottom

IV. 2. 2. 7. Association with *Laminaria rodriguezii* on detritic and hard bottoms

V.1.1. Biocenosis of bathyal mud

V. 1. 1. 1. Facies of sandy muds with *Thenea muricata*

V. 1. 1. 2. Facies of fluid muds with *Brissopsis lyrifera*

V. 1. 1. 3. Facies of soft muds with *Funiculina quadrangularis*

The regionally most important species that occur in the area are: *Eledone cirrhosa*[14]*, *E. moschata*, Loligo vulgaris*, Lophius budegassa*, L. piscatorius*, Merluccius merluccius*, Micromesistius poutassou*, Mullus barbatus*, Nephrops norvegicus*, Parapenaeus longirostris*, Caretta caretta, Mobula mobular, Lamna nasus, Dalatias licha, Aetomylaeus bovinus, Bathytoshia centroura, Mustelus asterias*, Dipturus oxyrinchus, Dasyatis Pastinaca, Leucoraja melitensis, Rostroraja alba, Oxynotus centrina, Balaenoptera physalus, Dendrophyllia cornigera, Funiculina quadrangularis, Laminaria rodriguezii.*

[14]*species with commercial value

2.4.1. Essential fish habitats

The Jabuka/Pomo Pit is one of the most important nursery areas for European hake (*Merluccius merluccius*), supplying the entire Adriatic European hake stock (see Section 4). The species is the most productive demersal resource of the Adriatic in terms of commercial fish landings. Spawning of European hake in the central Adriatic occurs throughout the year peaking in winter with in waters down to 200 m in the Jabuka/Pomo Pit, and in summer with shallower waters (Jukic-Peladic and Vrgoc, 1998). The presence of early demersal juveniles (16–30 mm, c. 40 days old) has been reported in the Jabuka/Pomo Pit by several studies (Županović and Jardas, 1986; Arneri and Morales-Nin, 2000; Druon *et al.*, 2015). The largest Adriatic population and nursery of the high-value Norway lobster (*Nephrops norvegicus*) is located in the area of Jabuka/Pomo Pit (AdriaMed, 2010). Moreover, recent studies highlighted that *Nephrops norvegicus* inhabiting the Jabuka/Pomo Pit appears to be a "subpopulation" of the GSA 17 stock, different from that found elsewhere in GSA 17. Therefore, it may be treated as a separate stock (GFCM, 2016). The Jabuka/Pomo Pit represents also a nursery ground for the horned octopus (*Eledone cirrhosa*), monkfish (*Lophius budegassa*) and broadtail shortfin squid (*Illex coindetii*). It is also an important area for the deep-sea fisheries targeting the deepwater rose shrimp (*Parapenaeus longirostris*) (Bensch *et al*., 2008). The Jabuka/Pomo Pit also represents a key area for cetaceans, sea turtles and birds feeding during migration due to its high productivity (UNEP-MAP-RAC/SPA. 2014). The importance of the Jabuka/Pomo Pit area for such a number of benthic and demersal species is linked to its physical and oceanographic characteristics, which support the existence of EFH in this location. The water circulation in the Jabuka/Pomo Pit (Figure 3) is involved in fundamental processes of nutrient fluxes between northern and southern Adriatic sub-basins. The Jabuka/Pomo Pit area is an up-welling region of cooler and nutrient rich bottom waters resulting from mineralisation processes that occur during the water residence (at least one year) within the pits. The Dense Water (DW) then flows through the Gargano-Split transect (Grilli *et al*., 2013) and around 19 percent of DW volumes flow southward, while the remaining volumes mix with less dense and warmer waters or return in the mid-Adriatic basin (Benetazzo *et al.*, 2014).

2.5. Management framework

2.5.1. The GFCM fisheries restricted area

The area of Jabuka/Pomo Pit has been long recognized as a crucial area from both an ecological and commercial point of view. Yet in 1992, this area was also identified as an Ecological or Biological Significant Area (EBSA) under the Convention on Biological Diversity. Indeed, the occurrence of important exploited species and their essential fish habitats in the area have encouraged Italy and Croatia to implement a series of regulations in their respective national waters aiming at managing and restricting fishing activities to ensure sustainable exploitation of these resources beginning in the late 1990s.

In 2017, following the advice of the GFCM Scientific Advisory Committee on Fisheries (SAC) – including of NGO advice, the GFCM established a fisheries restricted area (FRA) in the Jabuka/Pomo Pit by means of Recommendation GFCM/41/2017/3.

The scope of this recommendation was to establish a FRA in this area of the Adriatic Sea, to contribute to the protection of important essential fish habitats for demersal stocks. With the aim of achieving the objectives set by the recommendation, the FRA was divided into three contiguous zones: zone A, zone B and zone C (Figure 1). The recommendation focused on two main directions: (1) management and monitoring of fishing capacity and fishing effort and (2) control measures.

The recommendation sets different standards of fishing activities in the zones of the FRA. As zone A is the core of the region, any professional fishing activity with bottom-set nets, bottom trawls, set longlines and traps is prohibited, including recreational fishing activities. Fishing activities have been prohibited annually from 1 September to 31 October in zone B since 2017. The restrictions are the same for zone C, but with an added stipulation that recreational fishing activities are also prohibited during the same sixty day period.

The measures also foresee further control mechanisms and responsibilities for relevant contracting parties and cooperating non-contracting parties (CPCs) of GFCM. Based on the recommendation, CPCs have the responsibility of (i) communicating the list of authorized vessels to the GFCM Secretariat annually (Authorized Vessel List, Appendix 2), (ii) designating landing points in which landings of demersal stocks from the Jabuka/Pomo Pit FRA are authorized, and (iii) communicating the list of these designated landing points to GFCM Secretariat annually. Finally, fishing vessels authorized to fish in zone B/zone C must be equipped with vessel monitoring systems (VMS) and/or automated identification systems (AIS) in proper working order and the fishing gear on board should be identified and marked. Fishing vessels are allowed to transit across the FRA without authorization, providing they follow a direct route at constant speed not less than seven knots and have active VMS and/or AIS on board.

Recommendation GFCM/41/2017/3 on the establishment of the Fisheries Restricted Area of Jabuka/Pomo Pit was expected to apply until 31 December 2020 pending GFCM advice on the extension of such deadline. However, due to the COVID-19 pandemic beginning in 2020, it was not possible for the GFCM to either review the management measures nor to discuss the renewal of the current closure to fisheries in the area; as of today, the fisheries restricted area is still in force, pending the new advice expected to be issued in the course of 2021.

In 2019, GFCM adopted Recommendation GFCM/43/2019/5 to establish a multiannual management plan for sustainable demersal fishing activities in the Adriatic Sea. The primary goal of this management plan is to ensure that demersal fishing capacity is not increased while fishing effort is managed in a sustainable way (including the introduction of minimum landing sizes for several species). Part three of the Recommendation further recalls the technical measures related to the FRA, as introduced by Recommendation GFCM/41/2017/3.

It must also be noted that in 2018, GFCM adopted Recommendation GFCM/42/2018/8 on further emergency measures in 2019–2021 for small pelagic stocks in the Adriatic Sea (geographical subareas 17 and 18). This recommendation addresses the sustainable exploitation of anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*) by introducing some new emergency measures. These also include specific temporal and permanent closures at the fleet level (even if not simultaneous for purse seiners and pelagic trawlers) in view of protecting small-pelagic fish stocks during spawning periods. Such closures shall cover the entire distribution of small pelagic stocks in the Adriatic Sea. Regarding permanent closures, in 2019, 2020 and 2021 any fishing activity with purse seiners and pelagic trawlers targeting anchovy or sardine is prohibited in the entire Jabuka/Pomo Pit Fisheries restricted area.

2.5.2. Other frameworks

As fishing in one country has impacts on the fish distribution in another, environmental protection often might take on a transnational dimension and will thus be governed by international frameworks.

In 1975, 16 Mediterranean countries and European Community adopted the Mediterranean Action Plan (MAP). In 1976, MAP was followed by an adoption of the Convention for the Protection of the Mediterranean Sea against Pollution (Barcelona Convention). The Barcelona Convention scope covers all maritime spaces of the Mediterranean Sea, which are under sovereignty or jurisdiction of the coastal States or in the high seas. An additional objective of the Barcelona Convention Protocol concerning Specially Protected Areas and Biological Diversity in the Mediterranean is the conservation and the sustainable use of biological diversity in the Mediterranean. All three states surrounding Jabuka/Pomo Pit area are also contracting parties of the convention.

The European Union has since adopted several other measures for the protection of vulnerable marine ecosystems, namely: Council Regulation (EC) No 1967/2006 of 21 December 2006 concerning management measures for the sustainable exploitation of fishery resources in the Mediterranean Sea, amending Regulation (EEC) No 2847/93 and repealing Regulation (EC) No 1626/94; Council Regulation (EC) No 1005/2008 of 29 September 2008 establishing a Community system to prevent, deter and eliminate illegal, unreported and unregulated fishing, amending Regulations (EEC) No 2847/93, (EC) No 1936/2001 and (EC) No 601/2004 and repealing Regulations (EC) No 1093/94 and (EC) No 1447/1999; Council Regulation (EC) No 734/2008 of 15 July 2008 on the protection of vulnerable marine ecosystems in the high seas from the adverse impacts of bottom fishing gear. The Regulation of the European Parliament and of the Council of amending Regulation (EU) No. 1343/2011 on certain provisions for fishing in the GFCM Agreement area is linked with GFCM Recommendation and includes specific information on the provisions that should be implemented in the Jabuka/Pomo Pit FRA based on the Recommendation GFCM/41/2017/3 on the establishment of a fisheries restricted area in the Jabuka/Pomo Pit in the Adriatic Sea.

Under the European Council's Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, the conservation of a wide range of rare, threatened or endemic animal and plant species is ensured. Adopted in 1993, the Habitats Directive helps to maintain biodiversity and protects over 1 000 animals and plant species and over 200 types of habitats. This directive recognises the several different natural habitat types within the European territory including in the Mediterranean, which therefore covers the Jabuka/Pomo Pit area.

3. Description of the demersal fisheries operating in the area

The Adriatic Sea is one of the most important fishing grounds in the Mediterranean Sea, due to the predominance of shallow and soft bottom habitats amenable to trawling. It forms the largest and the best-defined area of shared fish stocks in the Mediterranean (Vrgoč *et al*., 2004). Most of the Adriatic fleet (93 percent) is composed by vessels under 15 m of overall length (LOA) (GFCM data).

With 1,099 trawlers Italy has the largest trawl fleet in the Adriatic, of which 569 vessels between 12 m and 40 m are registered in GSA 17. Croatia has the second largest demersal trawl fleet of the Adriatic with 352 bottom trawlers registered for GSA 17 in 2019, of which 82 vessels with LOA between 12 m and 40 m (GFCM data). Croatia gives priority to fishing capacity reduction measures for trawlers and purse seiners, including scrapping and effort reduction measures. The fishing fleet of Slovenia consists of 135 vessels, 90 percent of which are vessels under 12 metres LOA (GFCM data).

3.1. Authorized vessels operating in the FRA of Jabuka/Pomo Pit

In the Jabuka/Pomo Pit area, multispecies fisheries operate to catch both pelagic and demersal resources. With demersal fisheries, Recommendation GFCM/41/2017/3 on the establishment of a fisheries restricted area in the Jabuka/Pomo Pit introduced a list of vessels authorized to operate in zone B and C of the FRA. According to this provision, Italy and Croatia have reported the list of authorized vessels each year since 2018. This list includes the information as detailed in Appendix 1. Table 1 shows a summary of the fishing fleet that has been authorized to operate in the FRA since 2018.

Table 1. Summary of the fleet that has been authorized to operate in zones B and C of the Jabuka/Pomo Pit FRA since 2018 (GFCM data)

	Total (year)	Bottom trawlers	Longlines
Croatia	63 (2020)	51	12
	51 (2018)	40	11
Italy	75 (2019)	56	19
	74 (2018)	55	19

3.2. Landings from GSA 17 (northern Adriatic Sea)

Demersal and pelagic catches from the Jabuka/Pomo Pit area are composed of more than one hundred species (fish, crustaceans and cephalopods), the majority of which are commercially important (e.g. *Merluccius merluccius*, *Nephrops norvegicus*, *Parapenaeus longirostris*, *Eledone cirrhosa*, *Illex coindetti*, *Trachurus trachurus*, *Lophius budegassa*, *Micromesistius poutassou*). Catches display considerable seasonal and annual variation, but young individuals (ages 0+, 1 and 2), especially of European hake, are concentrated in the Jabuka/PomoPit area (AdriaMed, 2006).

Overall, bottom trawls landing for GSA 17 accounts for approximately 4 100 tonnes in 2019 (GFCM data); the catch composition in Croatia demersal trawl fleet mainly included European hake (23 percent), red mullet (18 percent) deep-water rose shrimp (17 percent), Norway lobster (5 percent), squid (5 percent) and horned and musky octopuses (5 percent) (GFCM data) (Figure 4), while the main species caught by Italian demersal trawl fleet in GSA 17 during 2019 were: spottail mantis squilid (10 percent), red mullet (8 percent), European hake (8 percent), purple dye murex (8 percent), common sole (7 percent), horned and musky octopuses (7 percent) and common cuttlefish (7 percent) (GFCM data 2019) (Figure 5).

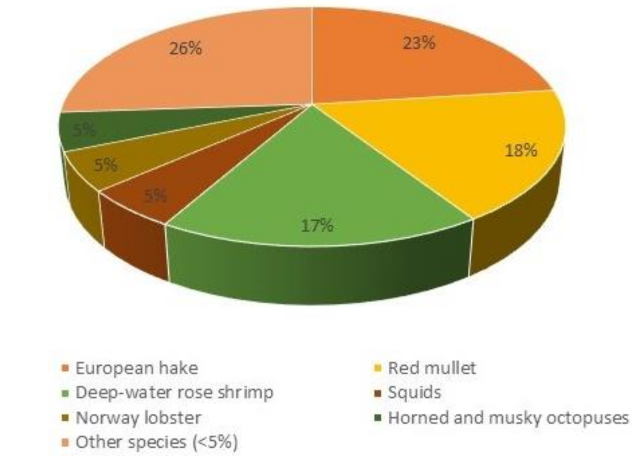


Figure 4. Catch composition of the Croatian demersal trawl fleet in GSA 17 (GFCM data, 2019)

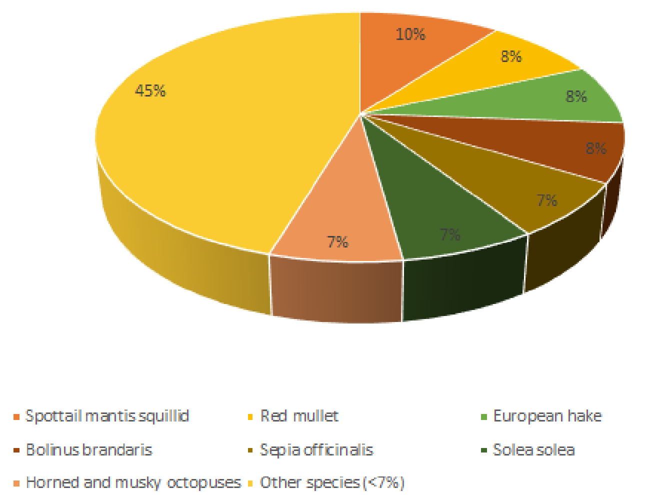


Figure 5. Catch composition of the Italian demersal trawl fleet in GSA 17 (GFCM data, 2019)

As of 2019 in Croatia, European hake landings from GSA 17 by Croatian bottom trawlers and by other types of fishing vessels amounted to 945 and 188 tonness respectively, representing the 41 percent of the total landings of this species from GSA 17. European hake landings by Italian bottom and beam trawlers from GSA 17 amounted to 1 633 tonnes, comprising 59 percent of the total landings of this species from GSA 17 (GFCM data, 2019). The catch rate between the two countries has progressively levelled over the last 4 years, as shown in Figure 6.

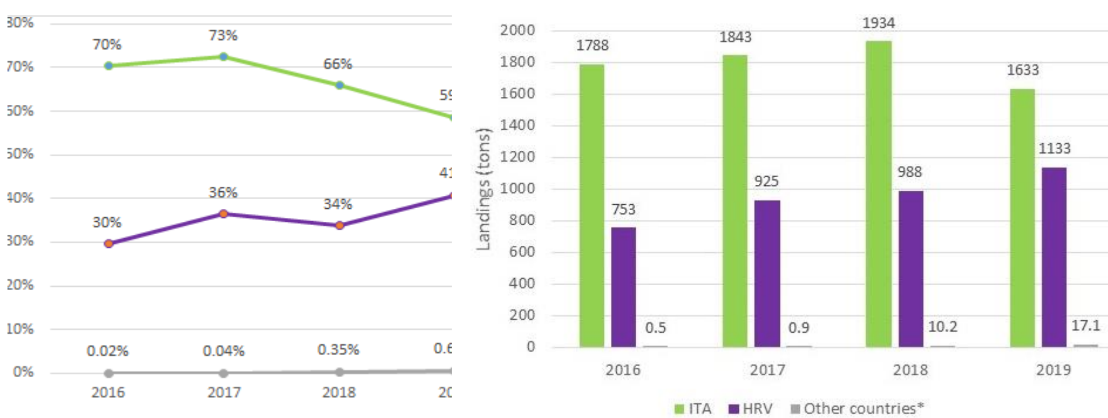


Figure 6. Landings of *Merluccius merluccius* from GSA 17 over the period 2016–2019 (ITA: Italy, HRV: Croatia) (GFCM data, 2019).

In 2019, landings of Norway lobster from GSA 17 amounted to 393 tonnes in Italy and to 266 tonnes in Croatia (60 and 40 percent respectively). The catch rate between the two countries has remained overall stable over the last four years, as shown in Figure 7. (GFCM data, 2019).

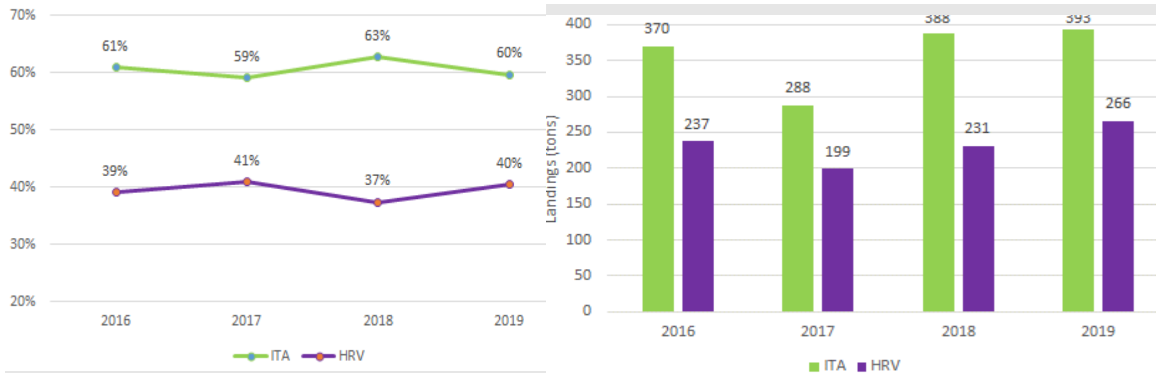


Figure 7. Landings of *Nephrops norvegicus* from GSA 17 over the period 2016–2019 (ITA: Italy, HRV: Croatia) (GFCM data, 2019).

3.3. Percentage of total catches in the Jabuka/Pomo Pit FRA

This information is not available. It should be noted that despite the Authorized Vessel List (AVL) for the Jabuka/Pomo Pit FRA including both bottom trawlers and demersal longlines from the Italian and Croatian fleet (see Table 1), no European hake catches have been reported by Italy and Croatia to GFCM from demersal longlines operating in GSA 17 since 2018. Therefore, it is assumed that only bottom trawlers have fished in the Jabuka/Pomo pit area since the establishment of the FRA in 2017.

3.4. Economic value of the landings

According to the latest official revenue figures from the GFCM, the total value of landings at first sale from Adriatic fisheries (in GSA 17 and GSA 18) is USD 598 187 512, respectively composed of revenue from Italy (USD 497 650 329), Croatia (USD 71 616 583), Albania (USD 27 848 000), Montenegro (USD 1 361 687) and Slovenia (USD 1 072 600) (FAO, 2020). Trawlers and beam trawlers account for an overwhelming 58 percent of all catch by value, followed by purse seiners and pelagic trawlers (19 percent) and small-scale vessels (12 percent). Notably, the Adriatic Sea provides around 49 percent of Italy's fish landings (GFCM data, 2019); however, declines in catch in both biomass and price value over the past ten years have contributed to the overall deterioration in the economic performance of the Italian fleet. For example, between 2008 and 2014, the landed weight of Norway lobster decreased by 56 percent. Landings of the European hake – the species with the highest landing value (USD 40 million) – and European anchovy (USD 59 million) have dropped by about 35 to 40 percent over the past decade. In Croatia, European hake landing value accounted for EUR 3.1 million (or 4.38 percent of total landing value) and Norway lobster landings value accounted for EUR 5.1 million or 7 percent of total landing value in 2014 (STEFC AER, 2016). Regarding GSA 17 only, the total value of landings of demersal species at first sale is USD 425 339 553, respectively composed of revenue from Italy (USD 352 650 370), Croatia (USD 71 616 583), and Slovenia (USD 1 072 600) (FAO, 2020). Trawlers and beam trawlers account for an overwhelming 50 percent of all catch by value, followed by purse seiners and pelagic trawlers (22 percent) and small-scale vessels (14 percent) (FAO, 2020). A further breakdown of the most important fish and cephalopod species in GSA 17 by economic value and fleet segment group can be found in Figure 8.

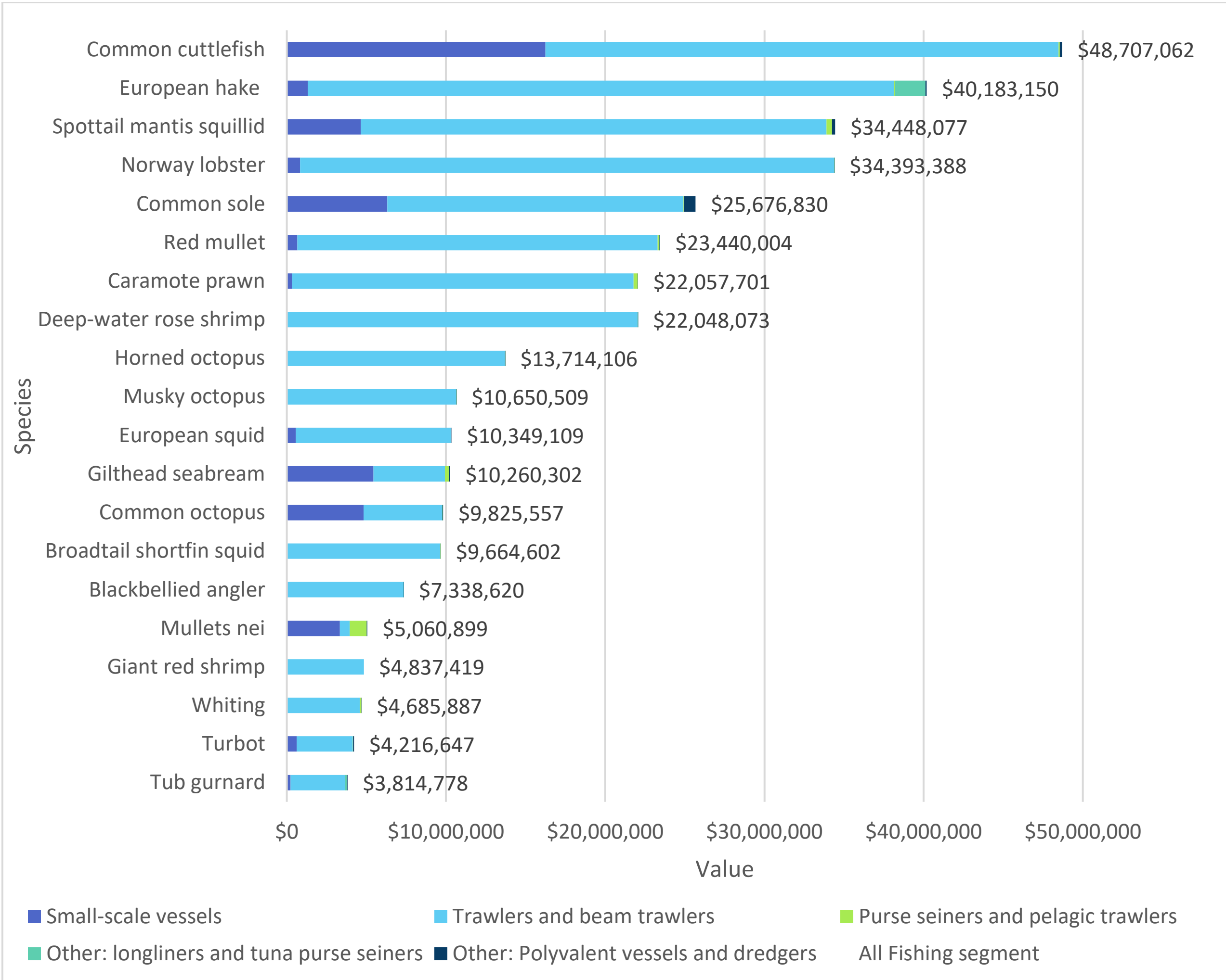
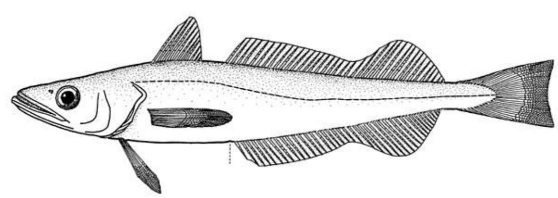


Figure 8. Main commercial species in terms of economic value (not including small pelagic, clam, and gastropod species) in GSA 17 by fleet segment group (FAO, 2020)

4. Description of the most important demersal resources

4.1. European hake



Since ancient times, European hake (*Merluccius merluccius*) has been an important food for the population of Europe. It is primarily caught by bottom and pelagic trawlers; however, the fish can be caught with the use of longlines or bottom-set gillnets.

European hake is distributed in the eastern Atlantic from Norway and Iceland, in the southern Atlantic along the European coast to the Straits of Gibraltar and even further south along the west coast of Africa down to Mauritania. European hake is also present in the Mediterranean Sea and can also be found in the Black Sea, mostly in the southern part (Jardas, 1996; Relini, Bertrand and Zamboni, eds, 1999). The main fishing grounds of this species are the areas north and west of Scotland, west and south of Ireland, the Bay of Biscay, the coasts of Portugal, and the coast of western North Africa. The Mediterranean countries with the largest catches are typically Spain and Italy (Lloris, Matallanas and Oliver, 2005). The fish is primarily sold fresh, but can also be found frozen (especially European hake hailing from distant fishing grounds), dried, salted, or canned (Lloris, Matallanas and Oliver, 2005).

European hake is a slim-bodied fish with a steel grey colouring on its back, light grey on its sides and silvery white on its belly, with a large head and large jaws (Lloris, Matallanas and Oliver, 2005). The body is long and cylindrical and rather slender compared with other hake species. The widest part of the body is behind the head. There are two dorsal fins: the first being short and triangular and the second long. The anal fin is similar in shape and size to the second dorsal fin. The ventral fins are located before the pectorals and the caudal fin is cut in a straight line (FAO AdriaMed, online).

Its depth distribution ranges between 70 and 370 m (Muus and Nielsen, 1999), but may also occur within a wider range, from inshore waters (30 m) down to 1000 m (Lloris, Matallanas and Oliver, 2005). The European hake's distribution may change due to two main aspects: its ontogenetic stage and habitat geomorphology (Hidalgo, 2007) and its vertical migrations, wherein the fish remains on the sea bottom during daytime and moves from the bottom at night. Recruits are mainly found in the depth range of 100 to 250 m, whereas intermediate ages (1–2 year old individuals) are mainly distributed at depths shallower than 100 m. Adults live in deeper waters on the slope of the continental shelf (Abella, Serena and Ria, 2005, Bartolino *et al.*, 2008).

Hakes are batch spawners with asyncronic reproduction (Murua and Saborido-Rey, 2003). The fecundity is reported as two to seven million eggs per female. The spawning period is very long and varies with populations, with the latest period being in the northernmost area in which the species can be found: December through June in the Mediterranean, February through May in the Bay of Biscay, April through July off of western Iceland, and May through August off of western Scotland. This biological process is conditioned by water temperature, which ranges between ten to 10–13°C (Coombs and Mitchell, 1982). In the Mediterranean Sea, spawning occurs between 100 and 300 m, in the Celtic Sea, above 150 m.

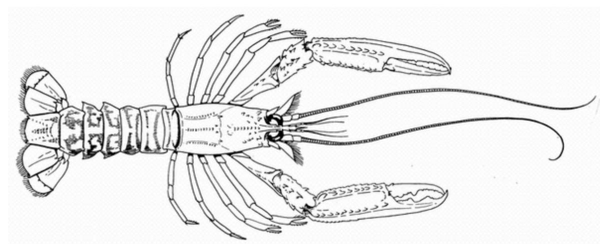
Eggs and larvae are distributed over the continental shelf (Olivar *et al*., 2010). Juveniles live on muddy bottoms until age of three, moving toward the coast afterwards, while adults live in deeper waters on the slope of the continental shelf (Abella, Serena and Ria, 2005, Bartolino *et al.*, 2008). First maturity for the Atlantic population is reached during the seventh year for most females (57 cm) and during the fifth year for males (40 cm); in the Mediterranean, males mature at 26–27 cm, females at 36–40 cm. Females grow faster than males. After three years, body length reaches 25 cm. it; it measures about 79 cm (males) and 100 cm (females). The Mediterranean stock grows more slowly than that found in the Atlantic (Mellon-Duval *et al.,* 2010). European hake is a carnivorous fish with a key predator role at inshore of Mediterranean communities (Carpentieri *et al.*, 2005). Its feed pattern has been considered opportunistic, with varying prey consumption, according to availability and ontogeny (Bozzano, Recasens and Sartor, 1997; Modica *et al.* 2011). Young European hake feed on small crustaceans – especially euphausiids and amphipods (Lloris, Matallanas and Oliver, 2005). However, as the fish grows in size, its feeding pattern varies, evolving into a more piscivorous diet (Bozzano, Recasens and Sartor, 1997, Cartes *et al.*, 2004, 2009, Ferraton *et al.*, 2007). Adults feed mainly on finfish (small hakes, anchovies, sardines and gadoid species) and squids. In addition, adults can also feed on crustacea, molluscs, algae, and plant detritus (Cartes *et al.*, 2009).

4.1.1. Insights on the ecology of the species with focus on the Adriatic Sea

According to available data, European hakes are distributed throughout the Adriatic Sea; however, it is most abundant in the open central Adriatic Sea, in the Jabuka/Pomo Pit area and further south (Županović, 1961, Županović and Jardas, 1986). European hake prefer muddy bottoms but are also found on other types of bottom as well (muddy-sandy and sandy bottoms). Bathymetric distribution of the species in the Adriatic is from shallow bottoms in the coastal area down to 800 m in the south Adriatic Pit (Ungaro, Rizzi and Marano, 1993; Jukić *et al*., 1999). There are only limited areas to the north of the Po river delta in which European hake are not caught (Jukić-Peladić and Arneri, 1984; Frattini and Casali, 1998). At depths between 100 and 200 m, European hake catches are primarily composed of juveniles (Ungaro, Rizzi and Marano, 1993; Vrgoč, 2000). In addition to circadian migrations (European hakes stay on the bottom during the day and move to shallower waters at night), the species can also feature horizontal migrations due to the search of food (Jardas, 1996).

During the spring months, there are localised movements of sexually immature young hakeswhich move into the shallower channel waters of central Adriatic Sea among the Croatian islands. These juveniles display foraging migration patterns. Adult European hakes migrate to shallower coastal waters for spawning during springtime and are mainly caught at depths of 100 to 150 m. During the winter months, adult fish migrate towards deeper waters after spawning, wintering with the juveniles (Županović and Jardas, 1989). In the southern Adriatic sea, the largest specimens are caught in waters deeper than 200 m, whereas medium-sized fish are usually in areas not exceeding 100 m (Ungaro, Rizzi and Marano, 1993).

4.2. Norway lobster



Norway lobster (*Nephrops norvegicus*) is a medium to large sized crustacean decapod with well-calcified teguments, very pronounced rostrum, carapace with orange-red bands on chelae and on the anterior part of the cephalothorax. It is a slim, orange-pink lobster with orange-red bands on chelae and on the anterior part of the cephalothorax. It grows up to 25 cm long and is considered one of the most important commercial crustaceans in Europe (Bell, Redant and Tuck, 2006). Its body is long and more or less flat laterally. There are three to four bones on the dorsal side and one to two on the ventral side of cephalothorax. The abdomen is long and ends with a fan-shaped telson that enables the lobster to swim. However, when moving, *Nephrops norvegicus* walks more than it swims (Fischer, Schneider and Bauchot, 1987; Relini, Bertrand and Zamboni, eds, 1999). The first pair of cephalic appendices has composite eyes, each with a mobile peduncule. The first pair of antennae is short and forked. Each of the second pair is long and simple. The telson is long, with two pronounced bones at its apex. The first pair of legs is well developed with strong chelae. The second and third are thinner and have chelae as well (Relini, Bertrand and Zamboni, eds, 1999).

The Norway lobster lives in the north-eastern Atlantic Ocean, in the Mediterranean Sea (primarily in the western and central basins) and in the Adriatic Sea. It is absent in the eastern Mediterranean, the Black Sea, and Baltic Sea. It lives in a depth range from 20 to 800 mon muddy, soft bottoms in which it digs its burrows. It is nocturnal and feeds on detritus, crustaceans and worms. Ovigerous females are found practically throughout the year; eggs are carried for about nine months, with births peaking in July. Currently, the Norway lobster the only extant species in the genus *Nephrops*, after several other species were moved to the closely related genus *Metanephrops*. The species is of considerable commercial value and is fished for practically throughout its range. It is caught mostly by trawling but can also be caught more rarely with lobster pots (Holthuis, 1991).

4.2.1. Insights on the ecology of the species with focus on the Adriatic Sea

In the Adriatic Sea, the species was recorded at depths from about 30 m in the north, off of the coast of Ancona, Italy, to 400 m in the southern part of the Sea (Vrgoč, 1995; Marano *et al*., 1998). The densest population of Norway lobster can be found in the Jabuka/Pomo Pit region. Additonally, there are rich fishing grounds in the Velebit Channel, Kvarner and Kvarnerić region along the Croatian coast (Crnković, 1965). The population is less dense the southern Adriatic Sea, along the western (Italian) and eastern (Albanian) coasts (Karlovac, 1953; Marano *et al*., 1998).

Norway lobster can be considered a mud-loving species, not restricted to a particular biocenosis or to a biocenotical zone (Froglia and Gramitto, 1981). This can be linked with the lobster's habit of digging burrows for shelter (Froglia, 1972; IMBC, UMBSM and IRPEM, 1994).

Because the range of this species in the Adriatic Sea is continuous, particular Norway lobster settlements cannot be regarded as isolated (Karlovac, 1953). Nevertheless, some differences do exist, primarily in length frequencies among the settlements around Ancona and the Jabuka/Pomo Pit (Froglia and Gramitto, 1981, 1988; IMBC, UMBSM and IRPEM., 1994), as well as within the populations found in the northern Adriatic channels and the Jabuka/Pomo Pit (Karlovac, 1953; Crnković, 1959; Jukić-Peladić, 1974; Županović and Jardas, 1989. Using genetic analysis, Mantovani and Scali (1992) found that differences between Norway lobster off Ancona and the Jabuka/Pomo Pit did not surpass those at the population level. The differences were merely a consequence of different environments.

Norway lobster (*Nephrops norvegicus*) is a species with separate sexes. Males are, on an average, larger than females. The growth of Norway lobster, as is the case with other crustaceans, is a discontinuous process with a succession of moults separated by intermoult periods. During each moult, the old exoskeleton is shed, and the animal grows very quickly before the new exoskeleton hardens. A well-defined moulting periodicity was not found among juveniles, they appear to moult year-round. However, there is a moult synchronism in the adult population. Indeed, it could be generally said that in the Mediterranean, females have just one moulting period each year (December through March), right after hatching the eggs (Gramitto, 1998). The moulting period of grown males is in late summer and autumn (August through October) (Gramitto, 1998). In the Adriatic Sea, adult males have a moult peak between June and September. Little is known about adult females' moult cycles , except that adult females do not moult between August and January, when they carry eggs externally (Gramitto, 1998). In the Adriatic Sea, *N. norvegicus* spawn once a year (Froglia and Gramitto, 1981). The proportion of females with mature ovaries peaks in spring or at the beginning of summer (Froglia and Gramitto, 1981; Orsi Relini *et al.*, 1998). 'Berried' females were found in October and November (Orsi Relini *et al*., 1998), but some specimens can be present up to late spring (Froglia and Gramitto, 1981). According to Karlovac (1953), Norway lobster larvae are present in Adriatic plankton in late winter, from January to April (Relini, Bertrand and Zamboni, eds, 1999).

The sex ratio changes through the year. When carrying external eggs, the proportion of females in the catch is lower as they are less active and frequently hide away in burrows. However, during the mating period, this proportion increases (Jukić-Peladić, 1971; Froglia and Gramitto, 1981; Ungaro *et al*., 1999).

Norway lobster feed mainly on other decapod crustaceans and, to a lesser extent, on different crustaceans (euphausiids and peracarids) and fish. Parts of carapace, shells and gastropoda scales, vertebra and fish otoliths and similar fragments were found in *N. norvegicus* stomachs. These surveys confirmed that the dominant prey-species in the alimentation were those usually found in demersal communities where Norway lobster lives. It was also determined that its stomach was least full in summer, when the Norway lobster's gonads grow most intensively and occupy a significant portion of the body cavity (Cristo and Cartes, 1998).

In the Adriatic Sea, the catch of Norway lobster fluctuates significantly in different times of day and night (circadian fluctuation), and during the year (seasonal fluctuation) (Jukić-Peladić, 1971, Froglia, 1972; Froglia and Gramitto, 1981; Marano *et al*., 1998; Županović and Jardas, 1989; Relini, Bertrand and Zamboni, eds, 1999). Generally, the catch is highest at sunrise and sunset. This is most likely due to the behaviour of this species as it spends most of its day burrowed in the sea sediment, leaving its burrow only in search for food before dawn and dusk (Froglia, 1972; Froglia and Gramitto, 1981). This kind of behaviour is more obvious in younger specimens and ovigerous females. As a result, different parts of the population are accessible to fishing gear at different times of day. Seasonal fluctuations exist for the same reason. For example, the catch is biggest in spring, when the sex ratio is in favour of females (Froglia, 1972; IMBC, UMBSM and IRPEM, 1994), in winter the catch is at a minimum (IMBC, UMBSM and IRPEM, 1994; Marrs *et al.,* 2000.)

In the Adriatic Sea, *N. norvegicus* is caught primarily with two types of gear, with bottom trawls catching the majority and traps catching the rest (mainly in channel areas of the northern Adriatic).

4.3. Other commercially important demersal species

Other important commercial species exploited by demersal fisheries in the Jabuka/Pomo Pit area are the deep-water rose shrimp (*Parapenaeus longirostris*) and the black-bellied angler (*Lophius budegassa*),

The deep-water rose shrimp is a large decapod crustacean. It occurs in the deeper central Adriatic Sea, in the Pomo/Jabuka Pit and in the southern Adriatic Sea. It inhabits only muddy sediments, at depths over 130 m (Karlovac, 1949). In the Jabuka/Pomo Pit region, this species lives on sea bottoms from 150 to 190 m (Jukić-Peladić, 1975; Županović and Jardas, 1989). In the southern Adriatic along the Italian coast the population is the densest at depths from 200 to 400 m. In addition, the lobster is also abundant along the Albanian coast (Pastorelli *et al*., 1996). In the Adriatic Sea, *P. longirostris* is fished only with bottom trawl nets. Although the biggest specimens have greater commercial value, the entire catch of *P. longirostris* is marketable.

The black-bellied angler can be found througout the Adriatic Sea, in the Croatian channel regions, and in the open sea. It is more abundant than its relative *L. piscatorius* (Jardas, 1987). It lives on soft bottoms, but does not prefer any specific type of sediment (Tortonese, 1975, Fisher, Schneider and Bauchot, 1987; Jardas, 1996). According to Jardas (1987), the depth range of *L. budegassa is* between 13 and 400 m. Most individuals, however, were fished between 90 and 170 m. Therefore, it is quite likely that this species prefers depths between 90 and 200 m (Jardas, 1987). In the southern Adriatic, Merker and Ninčić (1973) recorded *L. budegassa* at depth between 20 and 500 m. In the central Adriatic, *L. budegassa* was fished more intensively in the north-eastern edge of the Jabuka/Pomo Pit and in the transitive areas towards the channels, whereas in the deepest central areas it was either not fished or only few specimens were noted (Jukić-Peladić, 1975; Županović and Jardas, 1989). Although some authors find that the catches are larger on muddy bottoms (Jukić-Peladić and Crnković, 1974; Grubišić, 1982), what seems to be decisive for the distribution of the species is not the type of sediment, but the depth (Jardas, 1987, Županović and Jardas, 1989). In the Adriatic, the black-bellied angler is fished primarily with bottom trawl nets. However other gears is also used as well (trammel-nets, for example).

5. Insights into the sensitivity of demersal fish and invertebrates to noise exposures and related effects

As with other groups of marine species most fish and invertebrates use sound for vital life functions. Sound is the propagation of a mechanical disturbance through a medium, such as air or water, taking the form of acoustic waves (Wartzok and Ketten, 1999). To obtain a wider insight into the nature of the sound field and its impact on marine biodiversity, several concepts need to be clarified. For instance, "intensity or pressure", measured in decibels (dB), determines whether sound is weak or loud. The term of "frequency", measured in Hertz (Hz), refers to whether a sound is high-pitched (high frequency) or low-pitched (low frequency). Low frequency sounds are characterised by wavelengths longer than those of higher frequency (Figure 9).

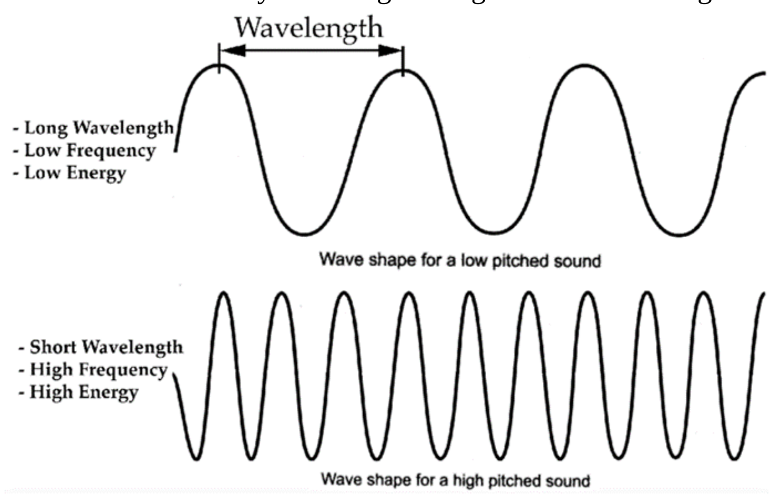


Figure 9. Sound wave scheme, representing high and low frequencies

Underwater sound is made up of both particle motion (oscillation of the water molecules) and acoustic pressure (Edmonds *et al*., 2016), but particle motion is more dominant in the low frequencies of a few hundred Hertz (Kunc *et al.*, 2016). Particle motion is also considered to be more relevant over short distances, where it is not proportional to pressure, but may also be important over longer distances (Normandeau Associates, 2012). While marine mammals mainly detect acoustic pressure (Nedelec *et al*. 2015), all fish and invertebrates can detect particle motion, with many also able to detect acoustic pressure. Particle motion is especially important to marine animals for locating sound sources through directional hearing (Hawkins and Popper, 2017).

Fish and invertebrates have sensory systems to interact with the ecosystem and use information that can boost their survival. Sound transmits information very quickly and over long distances. Fish use sound for a wide range of purposes, which are essential for survival, such as feeding (prey detection), avoiding predators, territorial defence, reproduction (mate attraction and courtship) and navigation (Popper *et al*., 2004; Duarte *et al.*, 2021). In the case of invertebrates, less is understood about the use of these stimuli, although some studies on crustaceans indicate that their ability to detect specific underwater sounds/vibrations plays a particularly important role in the orientation and settlement of pelagic crab larvae, besides attracting individuals for spawning during agonistic behaviours. (Kunc *et al*., 2016; Stanley, Radford and Jeffs, 2012; Edmonds *et al*., 2016; Solan *et al*., 2016).

The sounds that fishes and invertebrates use to gain information about the acoustic "scene" are produced not only by other organisms, but also by natural phenomena and human activity. Acoustic interference produced by anthropogenic sources can impact the natural behaviour of marine biota. Artificial noise or acoustic pollution has the potential to mask or interfere with the detection of biologically important signals, displace animals away from their migratory paths or home territories and, in the case of very loud sounds, actually injure or kill individuals (Kunc *et al*., 2016). In a review on the impact of ocean noise pollution on fish and invertebrates, Weilgart (2018) reported the results of several studies that have demonstrated how noise can affect fish and invertebrates in many ways. During invertebrate development stages, noise can cause body malformations, higher egg or immature mortality, developmental delays (in metamorphosing and settling), and slower growth rates. Zooplankton can suffer high mortality in the presence of certain levels of noise.

Anatomical impacts from noise involve massive internal injuries, cellular damage to statocysts and neurons, causing disorientation and even death, and hearing loss. In fish species, some studies also reported the production of higher levels of stress hormones, greater metabolic rate, oxygen uptake, cardiac output, parasites, irritation, distress, and mortality rate, sometimes due to disease and cannibalism, and worse body condition, lower growth, weight, food consumption, immune response, and reproductive rates. Behaviourally, animals showed alarm responses, increased aggression, hiding, and flight reactions; and decreased anti-predator defense, nest digging, nest care, courtship calls, spawning, egg clutches, and feeding. Noise causes more distraction, producing more food-handling errors, decreased foraging efficiency, greater vulnerability to predation, and less feeding. Fish schooling became uncoordinated, unaggregated, and unstructured due to noise. Masking reduced communication distance and could cause misleading information to be relayed (Weilgart, 2018).

To establish and be able to quantify the consequences that artificial sound sources can cause in fishes and invertebrates, it is essential to ascertain the extent to which sound can be heard or sensed.

5.1. Hearing capabilities of fish and invertebrates

To determine the vulnerability of these organisms, we must examine their sound detection and hearing capabilities (HELCOM, 2018). Sound reception organs and their development may help establish auditory detection capabilities of some marine organisms. Fish and invertebrates possess organs and a diverse range of mechanisms that assist in perceiving marine noise. For example, fish sound sensory organs include the inner ear, lateral line and swim bladder (the latter, in some cases, may be not present) whereas invertebrate sound sensory organs are mainly statocysts.

5.1.1. Inner ear, lateral line and swim bladder in fish

For a fish perceiving acoustic stimuli, both the pressure and displacement components may be detected. Sensitivity depends on the specific sensory structures involved (Popper and Fay, 1999; Montgomery *et al.*, 2006; Higgs, Lui and Mann, 2006; Higgs and Radford, 2013). Fish encompass a multitude of morphologies adapted to different environments and survival strategies. There are diverse adaptations in sound detection in fish, besides variation on the level of development. These hearing mechanisms provide information about their environment gained by listening to background noises, especially when they come from beyond the visual range of the animal (Popper *et al*., 2004). The acoustic sensory system of fish is composed of three sensorial organs: the inner ear, lateral line and swim bladder. However, not all of them are found in each taxonomic group. Swim bladders, for instance, can be missing in some species (Popper, Salmo and Horch, 2001).

The inner ear of a teleost fish is composed of a semi-circular canal where the otoliths are found (Figure 10), responsible for balance and the perception of acoustic signals. The functional units of the inner ear are sensory hair cells. Additionally, the swim bladder plays an accessory role in hearing (Chapman and Hawkins, 1973) (Figure 10), acting as a pressure gradient sensor. It can provide information on components of sound waves detected by vibration of this internal gas-filled structure (Popper and Fay, 1999; Higgs and Radford, 2013).

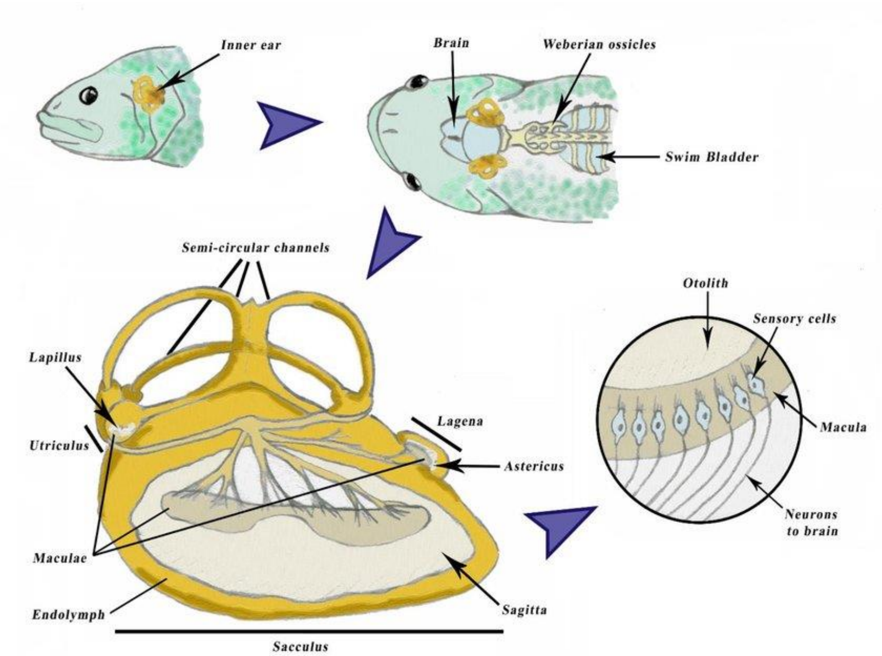


Figure 10. Scheme of the location of the inner ear, its components, and the innervation of the otolith to the brain in teleost fish (Ashworth, 2016)

The lateral line system acts as a mechanoreceptor. It provides information about water currents, the presence of obstacles, and underpins prey detection, predator avoidance, hydrodynamic scanning, and courtship communication (Coombs and Montgomery, 1999). The lateral line system is usually externally visible at the body surface and consists of sensory cells called neuromasts (Figure 11), which are found on the skin or underneath the skin surface (Coombs, 2001; Bleckmann, 2006). Neuromasts on the skin are sensitive to low-frequency vibrations, such as water motion and flow velocity, while those found inside the canals are sensitive to higher frequencies, such as pressure and tactile information (Montgomery, Coombs and Halstead, 1995; Coombs and Montgomery, 1999). The number of neuromasts can vary from 100 to over 1 000 and are distributed on the head and along the body (Figure 11) (Coombs, 2001). Other variations in neuromasts between species include their distribution, size and morphology (Higgs and Radford, 2013).

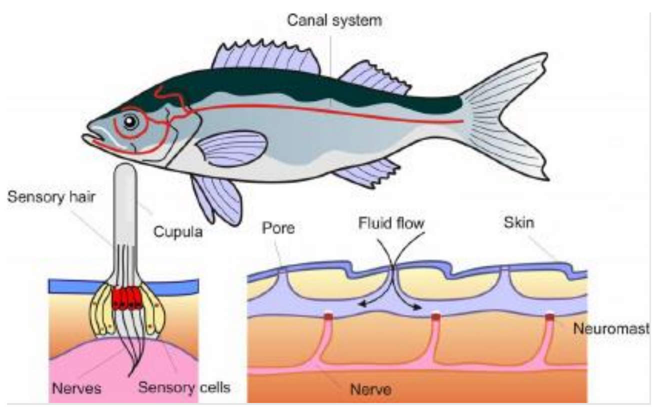


Figure 11. Schematic drawing of fish lateral line. Bottom right shows configuration of canal. Bottom left, close up of a neuromast (Izadi *et al.*, 2009)

5.1.2. Statocysts in invertebrates

Invertebrates lack gas-filled organs (i.e. swim bladders in fish) required for sound pressure detection but appear sensitive to low frequency acoustic stimuli arising from particle motion (Goodall, Chapman and

Neil, 1990; Roberts *et al.*, 2016). Invertebrates' awareness of sound seems to be associated with mechanical disturbances of surrounding water and sediment as detected by a pair of statocysts organs (Edmonds *et al.*, 2016). These sensorial organs are associated with geo-orientation and serve primarily as an equilibrium organ (Solan *et al.*, 2016).

In crustaceans, a statocyst lies in the basal segment of each of the two antennules placed on the cephalothorax (Figure 12) and has been described as 'an ectodermal sac, fluid-filled and lined by hairs which are in contact with a relatively dense mass, the statolith' (Cohen, 1960; Cohen and Dijkgraaf, 1961). They are associated with joints of antennae, legs and an array of internal and external hair-like mechano-receptors called sensilla (Breithaupt, 2001; Popper, Salmon and Horch, 2001).

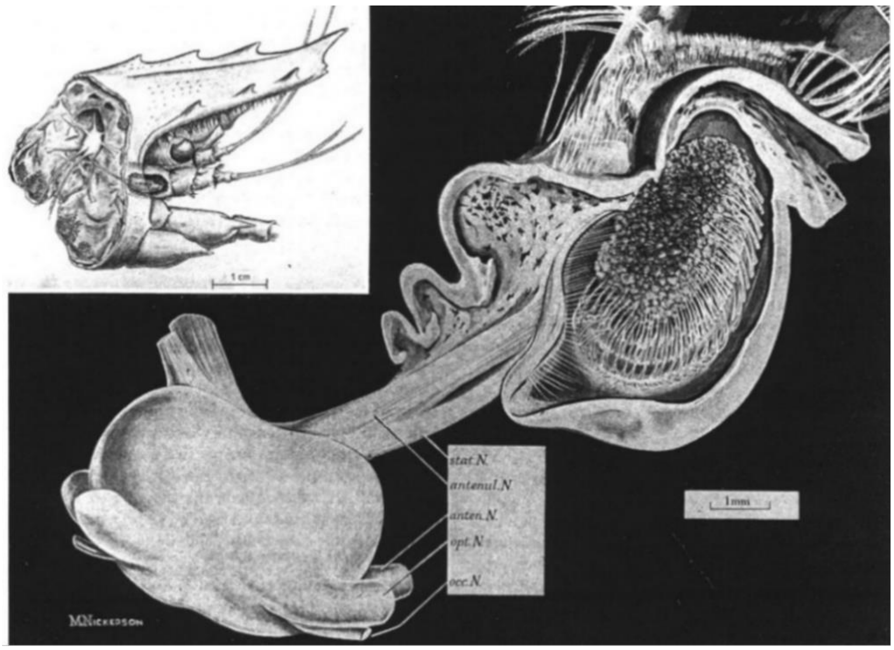


Figure 12. The anterior cephalothoracic region of the American lobster, *Homarus americanus*, with the exposed statocyst (in the basal segment of the right antennule). The statocyst nerve (stat.N.) on the dorsolateral aspect of the antennular nerve (antennul.N.) is seen as a distinct bundle. The sensory hairs are arranged in a crescent shape, with the inner three rows contacting the statolith. The fine thread hairs are projecting horizontally into the cyst fluid from the medial cyst wall. anten.N., Antennal nerve; opt.N., optic nerve; occ.N., oculomotor nerve (Cohen, 1960)

The statolith could serve as a receptor of kinetic sound components (Kaifu, Akamatsu and Segawa, 2011). When there is an external stimulus, tiny deflations occur in the hair bundles, resulting in cell body depolarization and subsequent transmission of the information to the sensory nervous system (Figure 12). The outputs of several hair cells converge onto an afferent neuron whereas the efferent fibers of the statocyst terminate on both hair cells and the axons of afferent neurons (Budelmann, Sachse and Staudigl, 1987). The statolith sensilla provide information about the amplitude and direction of body movement, although not on body position (Janse, 1980). In the central nervous system, the information received by the statocysts is also used to regulate a wide range of behaviours, including locomotion, posture, control of eye movement, and, in the case of cephalopods, body colouration patterns (André *et al*., 2016).

5.2. Frequency sensitivities and ranges of marine life

Marine organisms are sensitive to a diverse spectrum of acoustic frequencies. This range is used to establish communication among individuals as well as sense the surrounding ecosystem. The study of animals' hearing thresholds, and of the frequencies emitted by artificial sources is important in understanding the impact of anthropogenic noise on the environment, and especially how increased noise levels associated with a wide range of human activities can interfere with communication, foraging, prey evasion and other important biological traits of animals (Wright *et al.*, 2018).

The communication signals detected and produced by marine organisms have particular frequency bands. Invertebrates and fishes, together with reptiles, generally use lower sound frequencies than marine mammals (Figure 13) (Wright *et al.*, 2018; Duarte *et al.*, 2021). There is a huge imbalance between the number of articles addressing the impact of noise on fishes compared with marine mammals which reflects the relative dominance of cetaceans in bioacoustics. However, this gap is currently shrinking (see Weilgart, 2018). Fish present a wide frequency range of hearing that is almost comparable with small cetaceans, which predominantly hear mid- to high-frequency sounds (Wright, 2008; HELCOM, 2018). In addition, low-frequency-hearing cetaceans (e.g. baleen whales) can also perceive and thus be affected by mid-frequency sounds (Frankel, 2009). Bony fish perceive sounds of relatively low frequency, generally less than 5 kHz, is widespread for bony fish (HELCOM, 2018). However, some discrepancies in the frequency sensitivity of bony fish have been found depending on various authors: 100 Hz–7 kHz (Kunc *et al*., 2016), 10 Hz–4 kHz (Slabbekoorn et al., 2010) and 80 Hz–1 kHz (NOAA, 2014). One of the most recent studies published proposed increasing the hearing capacity of bony fish up to 10 kHz (Duarte *et al.*, 2021).

More research has been carried out on fish hearing ranges than on those for invertebrates. There have been recent studies involving crustaceans, with results of various frequency sensitivities (Figure 13): 10 Hz–3 kHz (Kunc *et al*., 2016), 100 Hz–5 kHz (Duarte *et al.*, 2021) and less than 5 kHz (HELCOM, 2018).

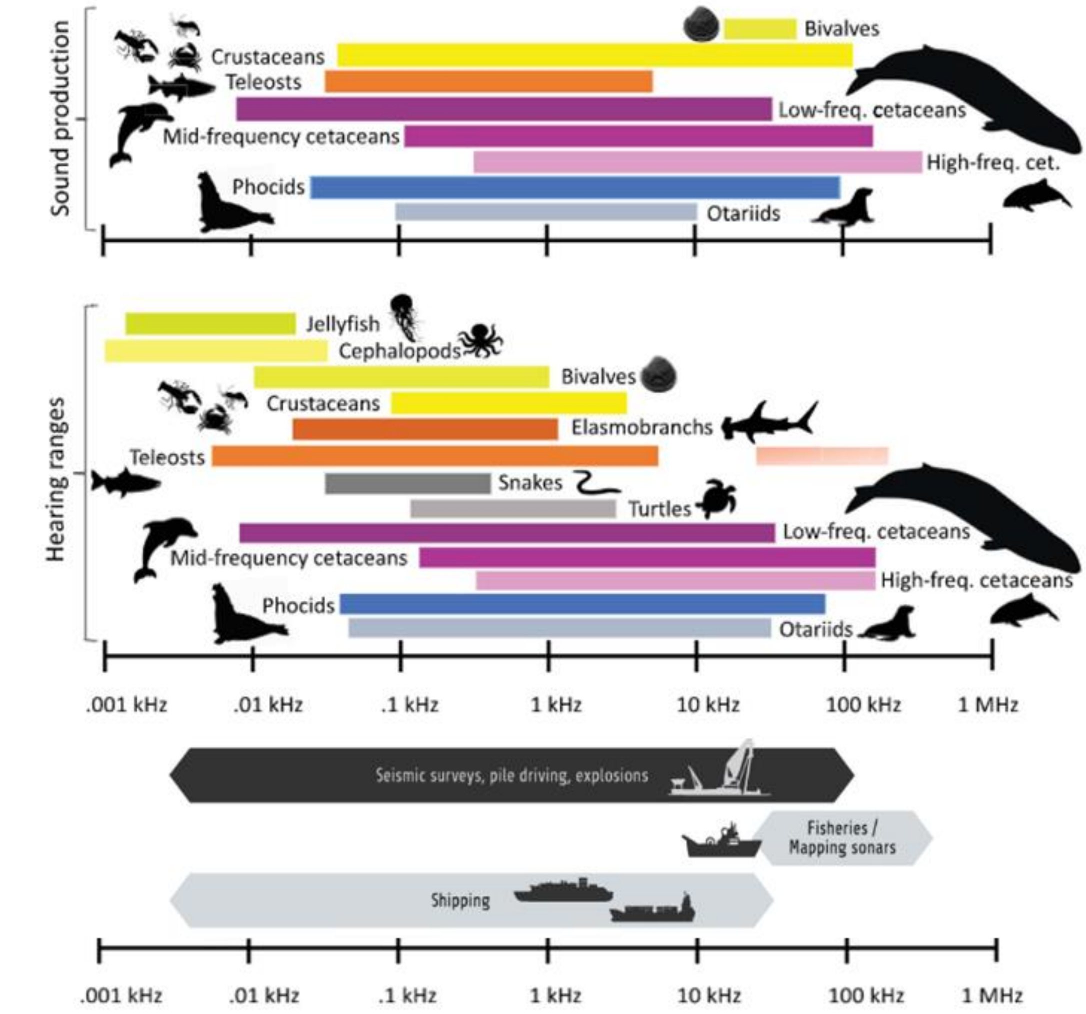


Figure 13. Frequency range of marine biodiversity sounds (hearing and sound production) and anthropogenic activities (mod. from HELCOM, 2018 and Duarte *et al.*, 2021)

5.3. Effects of anthropogenic underwater noise on fish and crustaceans

Weather conditions contribute to the marine soundscape. Natural phenomena such as wind blowing over the ocean, bubbles, waves breaking and rain falling onto the sea surface generate a particular sound spectrum (Kasumyan, 2009). The range of sound dispersion varies. Sound can be propagated by thousands of kilometres, especially those created by geological processes such as earthquakes or seismic and hydro-thermal activity (Winn, 1964).

In addition to natural sound sources, marine biota must cope with noise from increasing human activity at sea. Marine (or underwater) noise pollution has been defined as **any source of anthropogenic sound occurring in the marine environment capable of producing deleterious effects on marine life** (André *et al.*, 2016; MSDF; European Union, 2008). Noise generated by anthropogenic activities is often a loud, low frequency sound, which is particularly problematic due to its ability to propagate over large distances (Wright, 2008; Edmonds *et al.*, 2016). Underwater noise pollution is generally produced by seismic surveys, piling, explosions, military sonar, operating and maintaining windfarms, and the most common source, maritime shipping (including fishing vessels) (Wright, 2008). The exponential development of technology from the industrial revolution is a cause of concern in terms of underwater noise. Studies indicate that the acoustic pollution due to shipping activity has resulted in an increase of at least a 15–20 dB increase in ambient noise conditions compared to pre-industrial levels (Wright, 2008). The predominant noise levels associated with large vessels are in the frequency range of 5 Hz–1 kHz (low frequency), which overlaps with the frequency spectrum of invertebrates (such as crustaceans and molluscs), elasmobranchs and bony fish species (Figure 13). Hence, both invertebrates and fish are likely affected by the degradation of the soundscape.

Sounds from marine fauna have been recently used as a proxy for the health status of marine ecosystems. For instance, the number of snaps produced by snapping shrimps has been shown to be an indicator of ecological state in oxygen-depleted water (Watanabe *et al*. 2002) or in CO_2-rich water (Rossi, Connell and Nagelkerken, 2017). However, baseline data used to assess the impact of underwater noise pollution on marine life in management and monitoring programs are largely lacking (Duarte *et al.*, 2021).

As already described, most fish and invertebrates use sound for vital life functions so human-generated sound can, among other impacts, lead to the masking of important natural sounds (Popper and Hawkins, 2019; Duarte *et al.*, 2021). Hence, a better understanding of the influence of increasing noise pollution on these organisms is essential to examine how human activities dependent on healthy fish and invertebrate populations (such as fishing) are affected. Many studies indicate that degrading the ocean soundscape will jeopardize marine life (McCauley, Fewtrell and Popper, 2003; Wright *et al.* 2007; Wright, 2008; Smith, Kane and Popper, 2004; Gill, Bartlett and Thomsen, 2012; Weilgart, 2018).

The possible adverse effects on biota by anthropogenic underwater noise include physiological stress, changes in behaviour, physical injury, impairment of hearing and, death (Kunc *et al.,* 2016; Edmonds *et al.*, 2016; Solan *et al.*, 2016; Weilgart, 2018; Roberts and Laidre, 2019; Pierett *et al.,* 2020; Di Franco *et al.*, 2020; Duarte *et al.*, 2021). Stress impacts caused by noise on fish and invertebrates are not uncommon, including higher levels of stress hormones (cortisol), greater metabolic rate, oxygen uptake, cardiac output, parasites, irritation, distress, and mortality rate. Stress can cause a weakened immune response as well as compromised reproduction (Wright *et al*. 2007). Organisms can also show an alteration of their regular behaviour, increasing aggression, hiding, flight reactions; decreasing anti-predator defense (Weilgart, 2018), changes in their navigation and migration abilities (Popper, Hawkins and Thomsen, 2020) and delays in metamorphosing and settling (Pine, Jeffs and Radford, 2012) have also been noted. Additionally, food consumption can be compromised due to displacement from feeding grounds (Gill, Bartlett and Thomsen, 2012; Nagelkerken, Doney and Munday, 2019), which affects weight, and thus, generating slower growth rates. Indeed, reproduction is influenced by body condition as it requires extra energy reserves. Therefore, if the environment is not favourable, fish and invertebrates may reduce their egg production or indirectly influence reproduction by altering courtship calls and nest care (Popper, Hawkins and Thomsen, 2020). Anatomical impacts from noise involve massive internal injuries, cellular damage to statocysts and neurons (André *et al*. 2011), damage either to the ears or swim bladders in fish, causing loss of buoyancy control, disorientation, and sometimes fatal strandings (McCauley, Fewtrell and Popper, 2003; Weilgart, 2018).

The impact of noise pollution should be assessed not just at an individual level, as it directly affects regional ecosystems which impact human activities. For instance, noise pollution has the potential affect the marine food web, which thusly triggers effects on the whole ecosystem (Roberts and Laidre, 2019). McCauley *et al.* (2017) found that even zooplankton (small or microscopic organisms), especially immatures, can be killed by the shots emitted from a single seismic airgun, halving the species. These shots could also alter the feeding patterns of predators by shifting them from usual feeding grounds, which, in turn, has the potential to reduce fishing catches (Popper, Hawkins and Thomsen, 2020).

5.3.1. European hake

Despite the genus *Merluccius*'s high value as commercial species throughout its geographic distribution and its seemingly calm coexistence with certain sources of underwater noise pollution, there is a gap in knowledge on its hearing capability as well as its vulnerability to noise pollution. Some scientific papers have referred to European hake (Popper and Fay, 2011; Pierett *et al.*, 2020) but there is no specific research focusing on the range of audition in the genus or species or on its response to degrading the natural soundscape. However, studies on other species of the same order (Gadiformes), mainly Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), are available. Hence, an overall insight into its response to noise can be inferred considering the taxonomic close relation between these species and *M. merluccius* (Popper and Fay, 2011).

The Atlantic cod uses sounds mainly to gather in large aggregations and coordinate spawning activities (Locascio, Burghart and Mann, 2012). These fish show a reaction to low frequencies, especially between 50 Hz–1 kHz, and greatest sensitivity in the range between 60 and 310 Hz (Chapman and Hawkins, 1973). However, a changeover to particle displacement sensitivity was noted at frequencies below 50 Hz when the sound source was relatively close (1 m). In addition to the inner ear and lateral line, the swim bladder also plays a role in hearing for cod (Chapman and Hawkins, 1973). Some scientists examined the consequences of anthropogenic noise on Gadiformes generated by shipping (Nedelec *et al.* 2015), fishing vessels (Engås *et al.*, 1998), pile driving and wind turbines (Thomsen *et al.*, 2006), linear sweeps (Sierra-Flores *et al.*, 2015) and seismic surveys (Engås *et al.*, 1996; Løkkeborg, 1991; Løkkeborg *et al.* 2012)

Over the course of two days, Atlantic cod larvae were exposed to both regular and random ship noise. Individuals exposed to regular noise showed lower body width–length ratios, which is a sign of poorer body condition as well as a higher vulnerability to be caught in a predator-avoidance experiment (Nedelec *et al*., 2015). Regular noise was more disturbing to the larvae than random noise, possibly because regular noise events (every 45 minutes) did not allow for sufficient energetic recovery from the disruption of foraging (Weilgart, 2018).

Thomsen *et al.* (2006) reported that tagged individuals of Atlantic cod showed a high hearing sensitivity by reacting to 1) wind turbines up to about 4 km, 2) very low noise levels (82–92 dB) produced by an approaching fishing trawler and 3) pile driving (189 dB@400 m dB@400 m) possibly up to 80 km away from the source. At these distances, masking of communication between individuals was possible; noise was also affecting the gregarious patterns, as at relatively low received sound pressure levels (140–161 dB), less aggregation and more movement was observed among cod (Thomsen *et al.* 2006).

Another commercially important demersal specie such as common sole (*Solea solea*) was included in behavioural impact studies of exposure to pile-driving noise. Mueller-Blenkle *et al*. (2010) observed less aggregation and more movement, swimming significantly faster during noise at relatively moderate received sound pressure levels (144 to 156 dBpeak re 1µPa; particle motion between 6.51x10-3 m/s^2 peak). In essence, the study found that sole swam significantly faster in the presence of pile-driving noise, while cod "froze", or moved more slowly, at the beginning and end of playbacks.

Sierra-Flores *et al*. (2015) exposed cod to a linear sweep with a frequency range of 100 to 1000 Hz. They found an increase in cortisol levels with higher intensity noise but returning to baseline levels within an hour. However, when broodstock were exposed to noise in a nine-week-long experiment, the higher cortisol content in females may have been transferred to the resulting eggs significantly suppressing the fertilization rate. In males, the noise may have generated lower sperm quality, either or both effects possibly causing the reduction in fertilization success. Overall, the addition of noise reduced fertilization rates by around 40 percent, which decreased viable egg productivity by over 50 percent. Hence, acoustic pollution negatively impacted cod spawning and reproductive performance (Sierra-Flores et al., 2015). Løkkeborg et al. (2012) suggested that haddock can respond to airguns' noise by descending to the sea bottom. Engås *et al.* (1996) found seismic shooting (with maximum peak value of 248.7 dB recorded) to affect cod and haddock distribution, abundance, and catch rates over the entire 5 500 km^2 study area. The acoustic abundance estimates of cod and haddock in this area were carried out through Geostatistic (Petitgas and Poulard 1989; Simmonds et al.1991; Petitgas 1993). Results for cod showed abundance was reduced from 33 000 tonnes before shooting, to 16 500 tonnes during shooting, and further to 9 700 tonnes after shooting. In the case of haddock, catches over the same area were reduced from 6 000 to around 3 200 tonnes after shooting. Catches of cod and haddock dropped on average by about 50 percent (45.5 and 68 percent, respectively). Reductions in catch rates occurred over a radius of 33 km from the seismic shooting. Abundance and catch rates did not return to pre-survey levels during the five-day period after shooting ended (Engås *et al.* 1996).

Løkkeborg (1991) examined the effects of a seismic survey on longline catch rates of Atlantic cod and he found catch rates dropped by 55–80 percent, over a distance of 9.5 km of radius from the noise source and for at least 24 hours. However, the cods in this study were migrating, so the catches likely did not drop as much as they could have, since new fish were always replacing seismic noise-exposed fish (Løkkeborg, 1991). As highlighted in these studies, fishing yields may be negatively affected by acoustic pollution as consequence of vertical and horizontal migrations of fish to escape of the source of noise pollution (Ona and Godø, 1990). As effect to noise exposure, zooplankton death was observed (McCauley *et al.*, 2017) and fish observed to displace and/or alter their natural feeding patterns (Popper, Hawkins and Thomsen, 2020).

5.3.2. Norway lobster

Relatively little is known about the use of sound for crustacean communication and the potential for anthropogenic noise interfering with it (Solan *et al.*, 2016), though sound-based communication exists among crustaceans and is found to be highly species-specific (Hawkins and Popper, 2012). Knowledge gaps exist for many species such as *Nephrops norvegicus* (Stanley, Radford and Jeffs, 2010; Edmond *et al.*, 2016). Despite the frequency-specific hearing/particle motion detection capability not being assessed, preliminary experiments showed that this species, including juvenile stages, responds to water vibrations and particle motion in the low frequency range 20–180 Hz (Goodall, Chapman and Neil, 1990; Radford, Jeffs and Montgomery, 2007; Stanley, Radford and Jeffs, 2010; Hughes, Mann and Kimbro, 2014; Edmonds *et al.*, 2016; Solan *et al.*, 2016). Accordingly, several studies concluded that both adults and juveniles of *N. norvegicus* are sensitive to low frequency sound such as from percussive piling and seismic surveys (Radford, Jeffs and Montgomery, 2007; Stanley, Radford and Jeffs, 2010; Hughes, Mann and Kimbro, 2014; Solan *et al.,* 2016). Especially for larval and post-larval stages, this frequency range is used for orientation; therefore, overlapping or masking noise could make them more vulnerable to predation and compromise their survival (Jeffs *et al.*, 2003). Solan *et al.* (2016) and Di Franco (2020) showed that anthropogenic noise affected the depth and water circulation within *N. norvegicus* burrows and reduced the movement of this species.

Studies on related species such as brown shrimp (*Crangon crangon*), Dungeness crab (*Cancer magister*), and yes, shore crabs (*Carcinus maenas*), showed that due to noise exposure the metabolic rates increased (Regnault and Lagardère, 1983; Pearson *et al.,* 1994; Wale, Simpson and Radford, 2013). In general, it is widely acknowledged that crustaceans can be influenced by underwater noise. Exposure to some anthropogenic sound sources could directly affect the functionality and sensitivity of their hearing organs, the statocysts (André *et al*., 2016). Noise can also delay metamorphosis (Pine, Jeffs and Radford, 2012). Tidau and Briffa (2016) found various biological and ecological effects in giant hermit crab (*Petrochirus diogenes)*, spiny lobster (*Palinurus elephas)*, and Danube crayfish (*Astacus leptodactylus*), ranging from increased stress, slower antipredator behaviour, and changes in feeding patterns, to changes to social and aggressive behaviour among individuals of the same species. Roberts *et al*. (2016) showed that blasting and pile driving may induce the retraction of antennas and reduce locomotion in adult hermit crabs. Other invertebrates such as the following cephalopods: Mediterranean cuttlefish (*Sepia officinalis*), common octopus (*Octopus vulgaris*) (André *et al*., 2016) and European squid (*Loligo vulgaris*) (Solé *et al.*, 2013) also showed signs of physical damage in hearing structures as a consequence of artificial noise.

5.4. Knowledge gaps and research needs

Further research on the influence of anthropogenic noise on commercially important target stocks of the Mediterranean fisheries is needed to assess any possible derived impact on fisheries yields (Hawkins, Pembroke and Popper, 2015; Kunc *et al*., 2016; Solan *et al*., 2016; Franco *et al*. 2020; Pierett *et al*., 2020). In particular, more studies on fish species *Merluccius merluccius,* and crustaceans *Parapenaeus longirostris* and *Lophius budegassa* are needed since no studies were found. Although some information has been written on *Nephrops norvegicus*, little is known about biological responses to artificial noise exposure.

The main research needs to progress our knowledge are i) their hearing/sound sensitivity spectrum (frequency range); ii) the noise characteristics (intensity and frequency thresholds) triggering behavioural and biological responses/alterations; iii) intra-specific differences in behavioural response (e.g. species' mobility); iv) potential for recovery, habituation and adaptation to noise, which is fundamental to understanding whether some responses are permanent or temporary. However, any possible recovery, habituation, or adaptation may come at a cost to other aspects of the species’ biology, so this needs to be studied carefully. Research should include field measurements of particle motion, intensity, frequency and duration of noise exposure along with species-dependent after-exposure recovery time, should this occur. For crustaceans, the anthropogenic noise characteristics that overlap and mask intra-specific communication should be defined (Hawkins, Pembroke and Popper, 2015; Solan *et al*., 2016) , recognizing that noise, even if it does not overlap intra-specific communication, may still be injurious or detrimental to the animal.

6. Potential sources of underwater noise in the study area

There are multiple sources of anthropogenic underwater noise that can be found in the marine environment and their impact on fish species varies, as the previous section (Section 5) has highlighted. Although there are certainly also natural forms of noise in the ocean, human activities are responsible for the biggest portion of noise generated. In this respect, it is worth noting that anthropogenic sounds can be made of short pulses (e.g. impulsive sounds such as explosions or nearby airguns from seismic surveys) or long lasting (e.g. continuous noise such as shipping and dredging), and depending on the noise source and a number of propagation characteristics, which may include frequency levels, depth of activity, distance to surface, noise levels and impact vary. Noise pollution is transboundary in nature and travels across borders, potentially impacting species and ecosystems far from the source of origin. Therefore, it is critical to not only consider the human activities that take place in a given area but also those around the area when trying to understand the effects of underwater noise on the marine fauna in general.

This section briefly describes the type of noise (impulsive or continuous) generated by the most common human activities potentially occurring in the study area. While focus will mainly rest on the noise generated by fishing vessels (see Section 7), other forms of anthropogenic underwater noise are here described, including from maritime transport (e.g. commercial shipping), dredging in the course of offshore construction, oil and gas exploration activities using seismic airguns, low- and mid-frequency sonar and other construction activities (e.g. pile-driving and explosions/demolitions) (Figure 14). A common widespread source of noise is also sonar sound emitted for fishing, military and scientific purposes (WOA II, 2021, Figure 14). It is important to note that in some cases noise is an incidental byproduct of the activity (e.g., shipping), whereas in other cases it is a critical and intentional aspect of the underlining operation (e.g. seismic surveys).

In the Jabuka/Pomo Pit area (and in the Adriatic Sea in general), the main sources of anthropogenic noise stem from maritime traffic (e.g. commercial ships, fishing vessels and cruise ships), offshore industrial activity (e.g. oil and gas exploration and exploitation, pile-driving, and building and operating offshore wind parks) and coastal activities and development (e.g. harbour constructions).

While there have increasingly been efforts to establish noise registries in some areas, this effort is largely fragmented, is only progressing slowly, is regionally limited (e.g. OSPAR and HELCOM) and noise type specific (i.e., impulsive noise). With this is mind, it is inherently difficult to establish a comprehensive and all-encompassing list of noise activities in the Adriatic Sea and to identify which specific activities contribute to noise pollution in the Jabuka/Pomo Pit area. Nevertheless, several observations should be made. First, there have been numerous seismic surveying activities that may have potentially impacted the Jabuka/Pomo Pit can be identified. Secondly, with the help of MarineTraffic and other related software, it is possible to gain both a real time and historical overview of maritime activity in a specific area of the ocean. This is made possible with the assistance of the Automatic Identification System (AIS), self-reporting and position reports as satellite locators, although only vessels of tonnage equal or greater than 300 tonnes are required to have built-in AIS stations. More so, other portals, such as EMODnet[15], enhance our understanding of human activities at sea, yet much of the data inserted relies on voluntary contributions and does not always provide the necessary context (e.g., noise frequency, exact duration) that would be need for precise analysis of the noise levels produced over long periods of time. Additionally, due to the confidential nature of military exercises, particularly as relates to the exact scope of the activity and in extension the identification of the noise-generating activity, it is difficult to assert if and to what extent military exercises in the Adriatic have potentially contributed to noise levels in the Jabuka/Pomo Pit.

[15] Access to a list of human activities via EMODnet is available here https://www.emodnet-humanactivities.eu/

Industry/sector	Sound source	Sound type	Source level (dB re 1 µPa at 1 m)	Frequency of main energy (kHz)
Commercial shipping				
Medium-sized ships (50–100 m)	Propeller/cavitation	Continuous	165–180[a]	< 1
Large vessels (e.g., supertankers and container ships)	Propeller/cavitation	Continuous	180–219[a]	< 0.2
Resource exploration and exploitation				
Oil and gas	Seismic airgun	Impulsive	220–262[c]	0.05–0.1
	Drilling	Continuous	124–190[a]	0.1–1
Renewable energy	Impact pile-driving	Impulsive	220–257[c]	0.1–2
	Operational wind farm	Continuous	144[a]	< 0.5
Navy	Low-frequency sonar	Impulsive	240[b]	0.1–0.5
	Mid-frequency sonar	Impulsive	223–235[b]	2.8–8.2
	Explosions (e.g., ship shock trials and exercises)	Impulsive	272–287[a]	0.006–0.02
Fishing	Propeller/cavitation	Continuous	160–198[a]	< 1–10
	Deterrent/harassment device	Impulsive	132–200[b]	5–30
	Sonar (echo sounder)	Impulsive	185–210[b]	20–260
Dredging	Propeller/cavitation, cutting, pumping, grabbing and digging	Mainly continuous	163–188[a]	0.1–0.5
Marine scientific research (e.g., research vessel)	Propeller/cavitation	Continuous	165–180[a]	< 1
Recreational activities (e.g., recreational craft and speedboat)	Propeller/cavitation	Continuous	160–175[a]	1–10
Tourism (e.g., whale and dolphin watching and cruise ships)				
Vessels (<50m– >100m)	Propeller/cavitation	Continuous	160–190[a]	< 0.2–10
Harbour construction	Impact pile-driving (e.g., sheet piling)	Impulsive	200[b]	0.1–0.5

Source: United Nations document A/73/68, annex.

[a] Root-mean-square sound pressure level.

[b] Peak sound pressure level.

[c] Peak-to-peak sound pressure level.

Figure 14. Summary of the main sources of the most common anthropogenic underwater noise and source levels at sea (Source: WOA II, 2021)

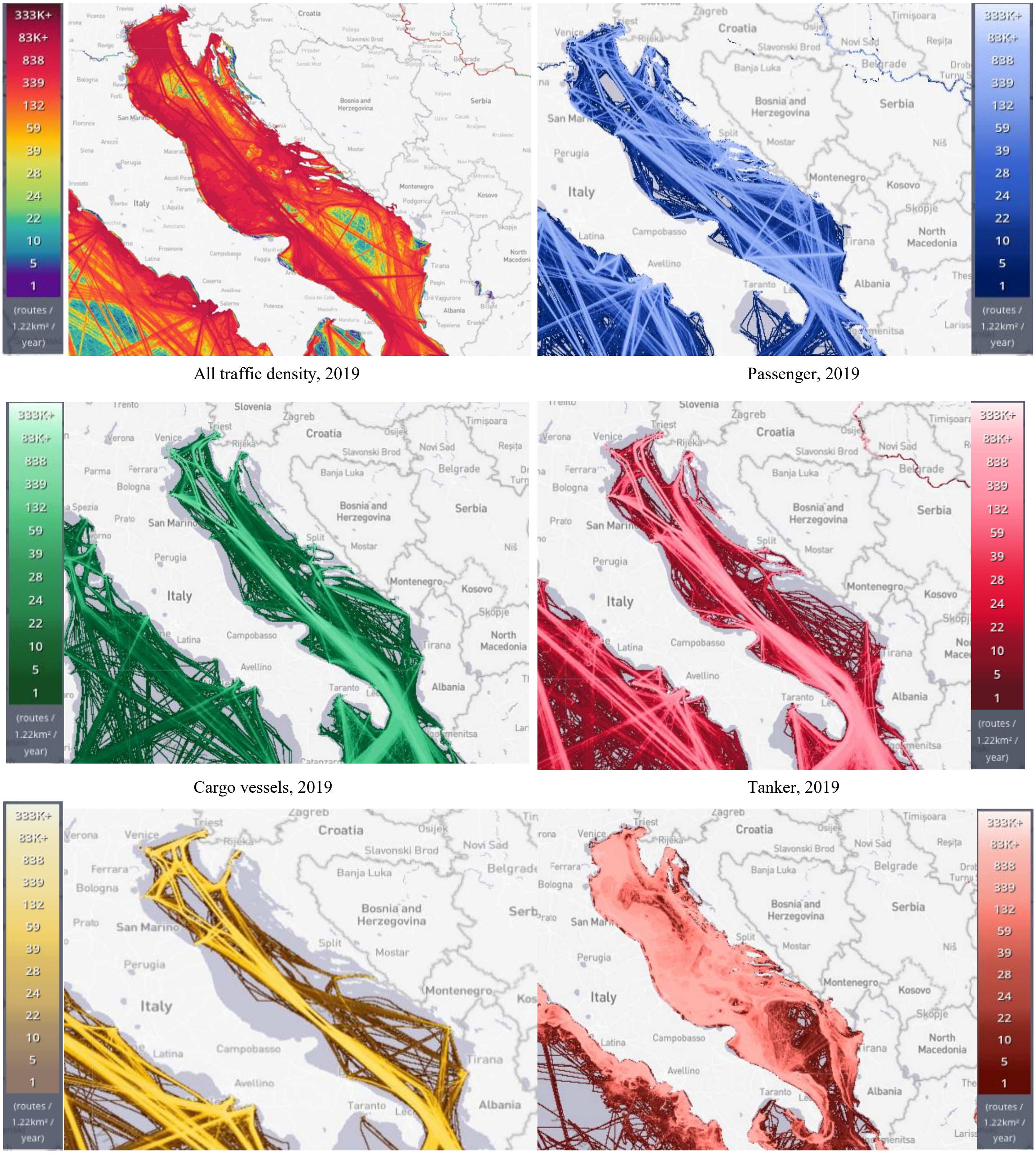
6.1. Maritime transport

One of the most dominant contributors to underwater noise in the ocean is maritime traffic (see figures below). The sharp increase in shipping and trade around the globe due to globalisation and the resulting sharp increase in shipping and trade across the globe undoubtedly contribute to noise generated by commercial shipping. While the COVID-19 pandemic perhaps briefly mired global trade, the projections indicate a mean annual growth of 3.8 per cent of seaborn trade for the period between 2018 and 2023

(WOA II 2021, 302). In general, the levels of noise contributed by vessels vary depending on several reasons, including the overall dimension of the ship, tonnage, the load and speed as well as wind and sea conditions as the vessel advances through the water. Concerns over the effects of underwater noise pollution from shipping are widely acknowledged (Leaper *et al*., 2014; Simmonds *et al.*, 2014). In fact, one prominent example led to the adoption of the International Maritime Organization's Guidelines For The Reduction of Underwater Noise From Commercial Shipping To Address Adverse Impacts on Marine Life in 2014 (IMO MEP.1/Circ.833; 2014).

The Adriatic Sea, with its strategic position, is an important hub for trade and tourism related transport, providing an important transit destination for ships (Randone, 2016). There is a wide range of marine traffic found across the Adriatic Sea, including large vessels such as passenger vessels, cargo ships (e.g. bulk carrier, container ship, heavy load carrier), tankers (e.g. oil products tanker, crude oil tanker or chemical tanker) as well as fishing vessels (e.g. fish carrier, trawler) (Figure 15 and Figure 16). Data collected by MarineTraffic[16], mostly data related to ship positions, allows for a better understanding of the most travelled sea routes in the Adriatic for a given period. This in turn clarifies traffic patterns and movements in the study area. Figure 15 and Figure 16 display the marine vessel density per vessel type for both 2019 and 2020, respectively, and is a useful indicator of the density of shipping routes per km^2 per year. A cursory reading of the density maps generated by the MarineTraffic for 2019 and 2020 demonstrate that the Jabuka/Pomo Pit area is frequently travelled by the vessels considered (Figure 15 and Figure 16) and that while maritime traffic may have briefly stagnated due to the outbreak of the COVID-19 pandemic, vessel traffic from large vessels remained a constant appearance in the Adriatic Sea.

[16] Refer to vessel filters for further detail on the sub-categories of the types of vessels, available at: https://www.marinetraffic.com/en/ais/home/centerx:73.5/centery:-27.1/zoom:2



All traffic density, 2019

Passenger, 2019

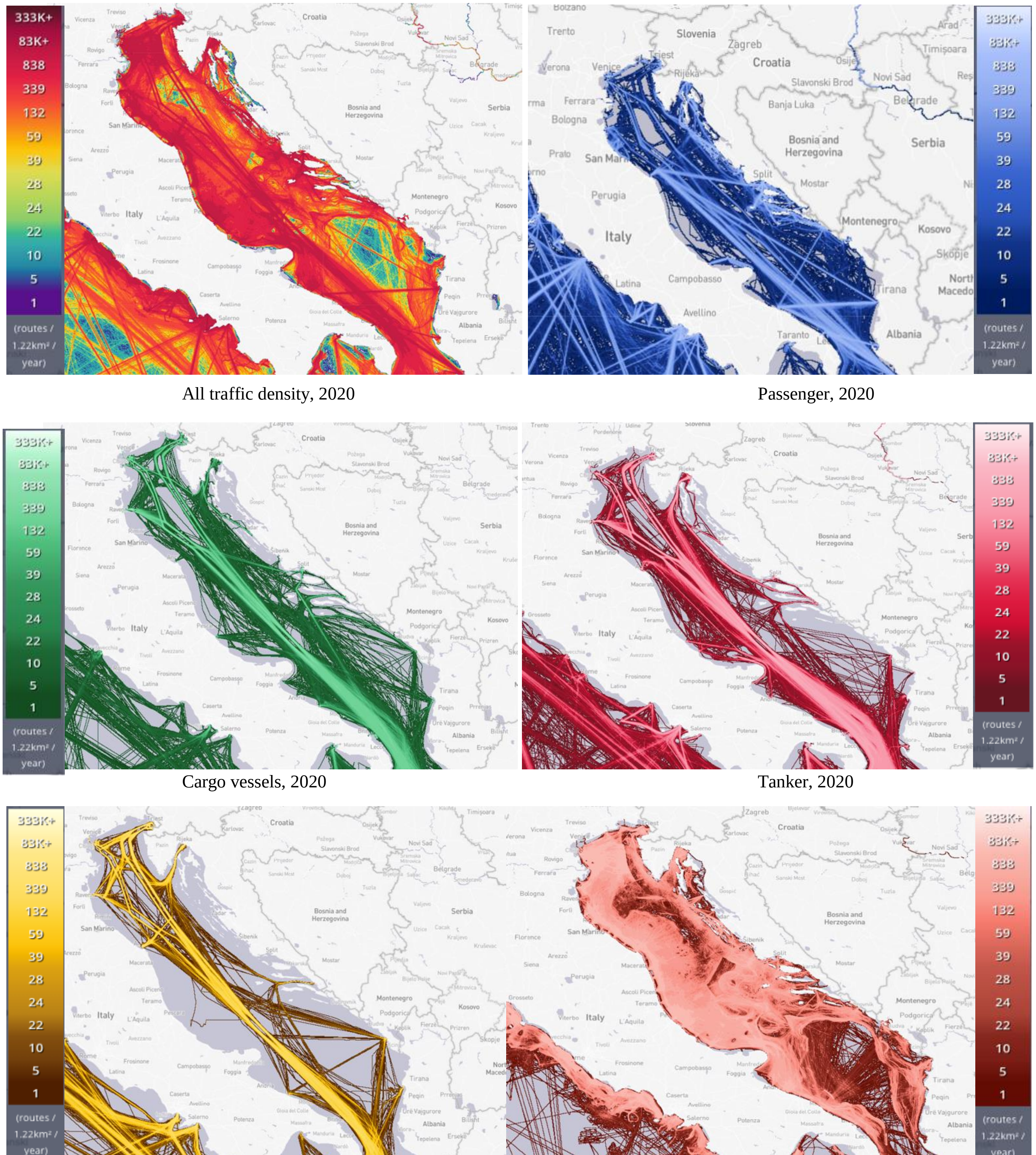
Cargo vessels, 2019

Tanker, 2019

Container ships, 2019

Fishing, 2019

Figure 15. Traffic density according to ship type for the year 2019 (Source: Marinetraffic) (Scale in routes/km^2/year)



All traffic density, 2020

Passenger, 2020

Cargo vessels, 2020

Tanker, 2020

Container ships, 2020

Fishing, 2020

Figure 16. Traffic density according to ship type for the year 2020 (Source: Marinetraffic) (Scale in routes/km^2/year)

Other more medium sized vessels may also be present in the area of study and range from 50–100 m in size, including such vessels such as tugboats, crew-boats, larger fishing/trawler, and research vessels (Prideaux, 2017) as well as small leisure and commercial vessels (e.g., yachts or other forms of domestic traffic) (Ibid, 2016) that are no larger than 50 m (see Table 2 for noise characteristics). Depending on the ship class (i.e. length) and speed, the vessel has a distinct noise signature, and in turn the impact on the environment varies. For example, a commercial container ship operating at a speed of 12 meters per second emits sound levels of 195 dB re 1μPa at 1 m (Gassmann, Wiggins and Hildebrand, 2017), while smaller sized vessels (e.g. fishing boats, jet skis) generate sound levels that range between 128–142 dB re 1μPa at 1 m (Erbe, 2013).

Table 2. Noise characteristics according to vessel type (Source: Richardson *et al.* 1995 and OSPAR, 2009 in Prideaux, 2017, in Technical Support Information to the CMS Family Guidelines on Environmental Impact Assessments for Marine Noise-generating Activities).

Type of vessel	Sound Intensity Level (dB re1μPa)	Bandwidth (frequency)	Duration
Small vessels (up to 50 m)	160–180rms @1 m	20Hz–10kHz	Continuous
Medium vessels (50–100 m)	165–180rms @1 m	Below 1kHz	Continuous
Large vessels (>100 m)	Low Frequency 180–190rms @1 m High	Low Frequency A few hundred Hz High	Continuous

6.2. Geophysical surveying

The use of seismic surveys to image the sub-sea floor and its geological structure using seismic surveys is the predominant method deployed by the offshore oil and gas industry to generate better understanding of the properties of the seabed. The method of seismic surveying "is simply sound energy emitted from a sound source (airgun array) several meters below the sea surface that penetrates subsurface layers of the seabed and is reflected and refracted to the surface..." (Prideaux, 2017) [17]. Such air guns fire at regular and reoccurring intervals of every 10–15 seconds, twenty-four hours a day for weeks – and in some cases months – at a time. The signals are then registered by hydrophones that are towed behind the ship (Gillespie, 2011).

In the last few years, the Adriatic Sea has increasingly become of interest for hydrocarbon exploration (and exploitation), with several countries in the region establishing licensing rounds for exploration permits. There are numerous types of technology deployed, which depend on the type of data that is sought, including 2D, 3D and 4D surveys (Figure 17). In the case of 2D surveys, a single seismic cable and a single or several air guns (the sound source) are towed behind the surveying vessel to get a better understanding of the general geophysical nature of a broader area. A 3D survey is the acquisition of many 2D lines closely spaced over the area. 3D surveys can take many months to complete. 4D surveys, or so called 'Time Lapse' surveys, are 3D surveys that are repeated over the same geographical area, but at different times. 4D surveys

[17] For a more detailed reading on seismic surveys see Caldwell and Dragoset's (2000) "A brief overview of seismic air-gun arrays" and Dragoset's (2000) "Introduction to airguns and air-gun arrays", as well as Clay and Medwin's (1997) "Acoustical Oceanopgraphy".

are being used regularly on established fields to monitor fluid (oil and gas) movement during the field's production phase (Gillespie, 2001).

It is difficult to calculate and predict peak source levels for airgun arrays using a standard 1 m measure of reference (see section above on noise generated by shipping). However, Turner *et al.* (2006) used a simplified estimation method by considering it as a single source, determining that it can reach 260 dB re 1μPa at 1 m. This is remarkably loud as the ocean natural ambient noise levels roughly ranges between 60 and 100 dBs. In comparison, commercial supertankers (e.g., container ship) generate noise levels that range from 195 dB re 1 μPa at 1 m (Gassmann, Wiggins and Hildebrand, 2017).

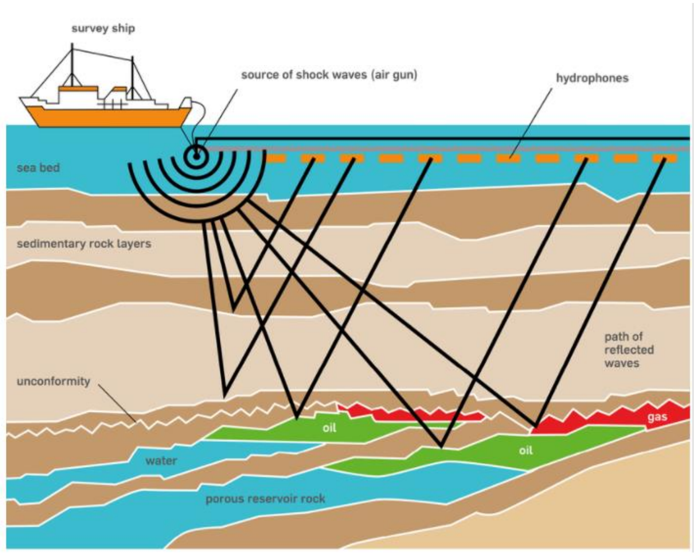


Figure 17. Example of an offshore seismic survey (Source: krisenergy.com)

The Adriatic Sea has seen numerous seismic surveys over the past years. It is also worth emphasising that countries have held several licensing rounds and while these do not necessary provide confirmation for the acquisition of 2D, 3D or 4D seismic surveying data, they nevertheless serve as an indication of potential future noise activities. For example, in Croatia around 15 000 km of new 2D seismic data of underexplored Adriatic basin were acquired from 2013 to 2014.[18]

6.3. Fisheries

While general anthropogenic noise has been shown to cause serious negative impacts on marine fauna, trawling noise has not been studied specifically. There is little information on trawling noise when compared to that on the wider effects of bottom trawling on the marine environment. However, it has been recognised that trawling noise had a behavioural effect on its target species (see Section 5). More detailed measurements of trawler noise outputs in line with published standards for vessel noise were taken while the vessel was in transit (Daly and White, 2021). However, these measurements do not include active trawling. Further studies have included trawl activity, while still focusing on catch reduction due to scaring away the target species. Daly and White (2021) quantified the impact of bottom trawling noise on two surrounding marine acoustic habitats in Ireland using fixed mooring acoustic recorders. Noise during trawling activity was shown to be considerably louder than ambient noise, as well as that emitted from a nearby research vessel underway. Estimated source levels were above cetacean thresholds for hearing

[18] See 'Exploration and production history' for more details, available at: https://www.azu.hr/en/exploration-and-production/exploration-and-production-history/

damage. Measurements at a submarine canyon indicated potential noise focusing, as such features could enhance down slope noise propagation at continental margin sites.

As previously presented, multispecies fishers in the GFCM fisheries restricted area of Jabuka/Pomo Pit operate to catch both pelagic and demersal resources. The recommendation GFCM 41/2017/3 on demersal fisheries established the FRA of Jabuka/Pomo Pit as well as introduced the list of vessels authorized (AVL) to operate in zone B and C of the FRA 1. According to this provision, Italy and Croatia have reported the list of authorized vessels every year since 2018 (see Appendix 1 and Table 1).

According to the AVL submitted to the GFCM Secretariat, 138 vessels are authorised to fish in certain areas of the Jabuka/Pomo Pit FRA. Of this number, 107 (77.5 percent) vessels are bottom otter trawlers (OTB), with the rest being demersal longliners (LLS). The overall length (LOA) of these vessels spans from 6.8 to 30 m. The acoustic modelling for assessing the noise generated by the demersal fishing vessels in the study area done considering the technical main characteristics of the vessels (Appendix 2 and Table 2) to forecast the noise produced by such types of vessels in terms of intensity (dB) and frequency (Hz) is presented in Section 7.

6.4. Other sources

Oil and gas exploration and maritime shipping (commercial shipping) are two of the most substantial contributors of ocean noise pollution to the marine environment. However, other offshore activities and axillary operations likewise contribute to ocean noise. For example, in addition to the seismic survey operations that produce loud impulsive noise for weeks or months at a time, the oil and gas industry also contributes to anthropogenic ocean noise through the construction of platforms, installation of pipelines and the running of support vessels (WOA II, 2021).

Pile-driving

One of the most significant sources of noise generated by offshore (or near shore) construction activities is pile-driving. Pile-driving involves dropping weights, vibrating, jacking, jetting, or detonating explosives in order to drive stabilising structures into the seabed to construct the foundation require above-surface structures, such as wind turbines/windfarms. As an impulsive form of underwater noise, it is one of the most substantial and impactful sources of noise that can be heard at great distances from the point of origin (Thomsen *et al*., 2006). Peak source levels for this activity may range from 226 to 248 dB peak re 1 μPa at 1 m (Bailey, Brookes and Thompson., 2014; Miller *et al*., 2017).

Operation of windfarms

Offshore wind farms that generate electricity out at sea, and which can be installed through pile-driving methods, are a further prominent source of anthropogenic underwater noise. While the dominant source of noise generated by wind farms is in respect to pile-driving activities (see above), and hence limited in time, the operation and maintenance of wind farms remains a persistent source of noise throughout the duration of the activity, that is, the operation of the turbines to produce energy, whereas the continuous noise produced through the operation of the wind farm is at levels of 150 dB re 1 μPa at 1 m (Nedwell and Howell, 2004; Hildebrand, 2009). Construction and maintenance (e.g., carrying parts and maintenance of construction platforms) associated with offshore wind farms also involves a high volume of ship traffic (Thomsen et al, 2006), which leads to continuous noise through shipping. Such sound exposure has in the past impacted marine species. Most relevantly, noise from wind turbines has discouraged larval settlement and delayed metamorphosis in crab species, masking critical natural acoustic settlement cues (Pine *et al.*, 2012).

Sonars

In addition, the use of sonars[19] can contribute to the propagation of underwater noise in the ocean. Sonar use can vary in application and can, for example, be deployed for commercial or recreational purposes as well as by navy/military entities. In the military context, sonars are primarily deployed as an anti-submarine warfare tactic for both operational activities and naval exercises.

It is important to differentiate between low-frequency active sonar (LFA) and mid-frequency active sonar (MFA). While the former operates in the 500Hz band at an overall source level of 230–240 dB re 1 μPa at 1 m (the exact source level is classified and could be much higher) the latter operates at frequencies between 2–8 kHz and has a minimum source level of 235 dB re 1 μPa at 1 m and is intended for detecting submarines at a range typically less than 10km (Hildebrand, 2009; Prideaux 2017). Responses to mid-frequency active sonar varies by both population and species. Overall, however, MFA has been associated with physiological damage in cetaceans (Fernández *et al.*, 2005) and fatal strandings and deaths at sea, while low-frequency active sonar has led to temporary hearing impairment in rainbow trout, although differences among the same species of trout were observed (Popper *et al.* 2007). Research showed that migrating gray whales avoided LFA sonar when located in their migrating path and there were indications that humpback whale song was altered, and that humpback and sperm whales avoided playbacks of LFA sonar.

[19] Other uses for sonar include side-scans and as fish finders. Multibeam echosounders are also used and have been associated with impacts on beaked whales and a fatal mass stranding of melon-headed whales.

7. Acoustic modelling for assessing the noise generated by the demersal fishing vessels in the study area

The Pomo/Jabuka Pit FRA is divided into three zones: A, B and C. While no fishing is permitted in Zone A at any time, it is permitted in Zones B and C albeit subject to restrictions imposed by regulators in Italy and Croatia, respectively. Three modelling locations were selected in each of Zones B and C corresponding to the geometric centre of each zone and two others based on geography and bathymetry; a list of the modelling locations is presented in Noise produced by vessels that has no impulsive quality is typically described in terms of sound pressure levels (SPL) (0). The results in this report are therefore presented as SPL and are presented in comparison with the latest published guidelines from Popper *et al.* (2014) for impacts of noise on fish (see Section 7.1). Section 7.2 provides an overview to the modelling methods and details the acoustic source and environmental parameters used in the propagation models. The results of the modelling are presented and discussed in Sections 7.3 and 7.4 respectively.

Table 3 and these locations are shown in Figure 18. No sources were modelled in Zone A since fishing is prohibited in this area. The GFCM provided a spreadsheet containing details of Italian and Croatian fishing vessels, specifically set longlines (LLS) and otter-board bottom trawlers (OTB). These vessel types were separated by size into small (S), medium (M), and large (L) categories. Each vessel type and size combination was modelled at each modelling location to produce 36 single vessel sound fields.

Consideration was given to the likely fishing schedule in each zone in order to assess the multiple vessel sound fields. It is understood that in Zone B, authorised Italian fishing vessels are allowed to operate on any day of the week, with any single vessel entitled to no more than two fishing days per week. In Zone C authorised Croatian vessels are only allowed to operate on specific days based on fishing gear; LLS vessels are entitled to fish Monday to Thursday only, while OTB vessels are entitled to fish Saturday and Sunday only. Two scenarios were therefore modelled considering sound fields from multiple vessels:

- Croatian OTB vessels operating in Zone C and a mixture of Italian vessels in Zone B, representing Saturday–Sunday, and;
- Croatian LLS vessels operating in Zone C and a mixture of Italian vessels in Zone B, representing Monday–Thursday.

These two scenarios were chosen to represent the worst-case scenario for the maximum number of vessels operating in the region simultaneously. Since neither of the vessel types considered is entitled to fish in Zone C on Fridays, this day is not represented in either scenario.

Noise produced by vessels that has no impulsive quality is typically described in terms of sound pressure levels (SPL) (0). The results in this report are therefore presented as SPL and are presented in comparison with the latest published guidelines from Popper *et al.* (2014) for impacts of noise on fish (see Section 7.1). Section 7.2 provides an overview to the modelling methods and details the acoustic source and environmental parameters used in the propagation models. The results of the modelling are presented and discussed in Sections 7.3 and 7.4 respectively.

Table 3. List of modelling locations in zones B and C of the Pomo/Jabuka Pit fisheries restricted area. Six vessel types were modelled at each location: LLS S, M, and L; and OTB S, M, and L

Zone	Site name	Description	Latitude	Longitude	UTM (WGS84), Zone 33 N		Water depth (m)
					Easting (m)	Northing (m)	
	B1	Zone centre	42° 49' 45.8" N	14° 51' 25.4" E	488317	4741878	227.0
B	B2	Zone shallow point	43° 02' 34.7" N	14° 53' 18.1" E	490906	4765593	127.4
	B3	Zone mid-depth point	42° 38' 41.0" N	14° 58' 27.8" E	497900	4721364	200.0
	C1	Zone centre	43° 18' 10.4" N	15° 41' 24.2" E	555969	4794683	137.3
C	C2	Zone shallow point	43° 14' 58.2" N	15° 52' 59.7" E	571700	4788900	124.2
	C3	Zone deep point	43° 23' 50.1" N	15° 34' 22.0" E	546385	4805089	181.6

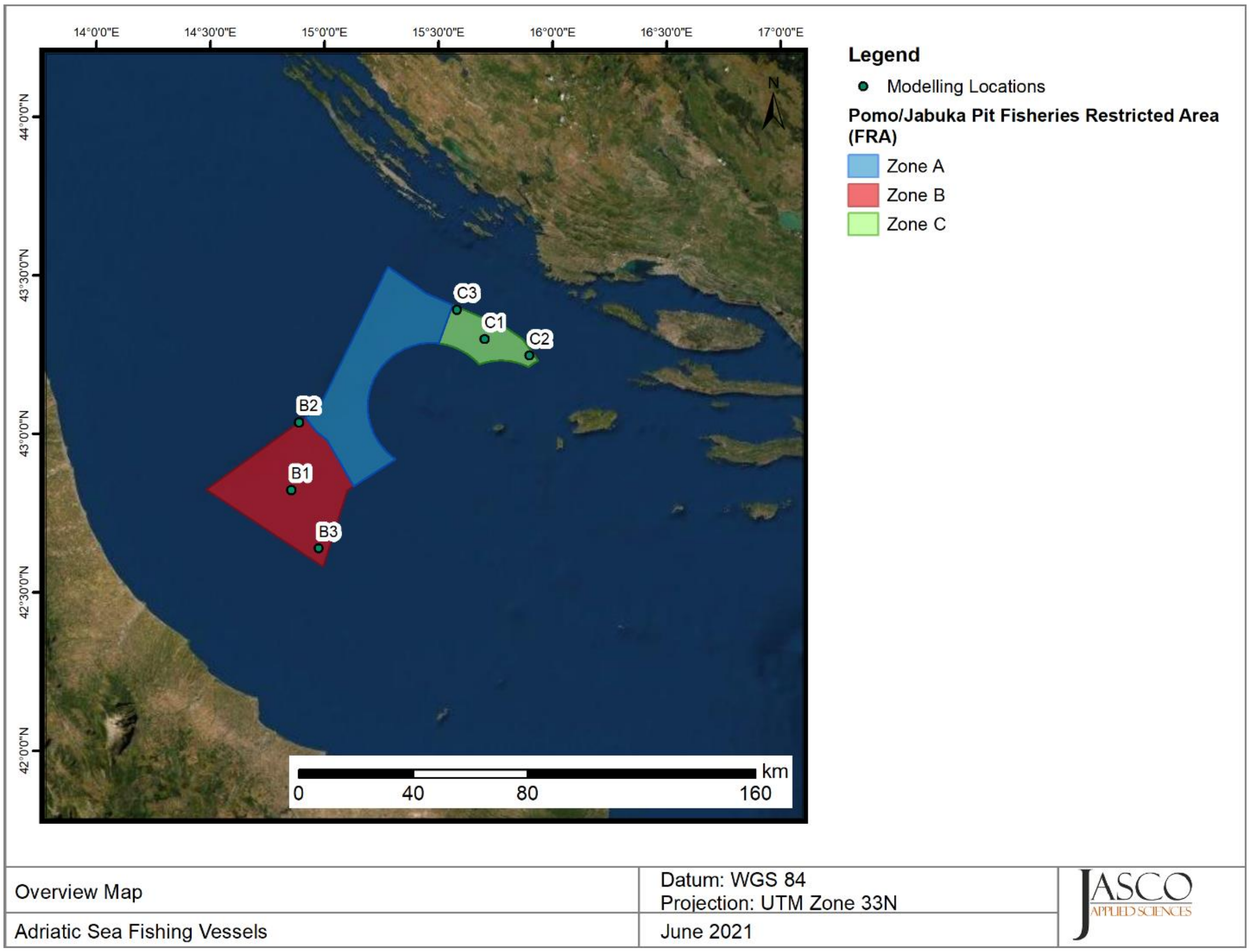


Figure 18. A map of the modelled area showing the Zones of the FRA and the modelling locations

7.1. Modelled acoustic impact criteria and thresholds

Underwater noise can affect marine fauna in several ways, and the criteria on which impact assessments are based can be complex.

Underwater noise emissions from vessels falls under the category of continuous noise. GFCM provided a list of the fauna of particular interest for this study (presented in Table 4) and the relevant noise criteria used to assess impacts on fish and other marine fauna are discussed in Sections 7.1.1 to 7.1.3.

Table 4. A list of fauna in the modelling area and their broad taxonomic groups

Broad taxonomy	Scientific name	Common name
Fish	*Merluccius merluccius*	European hake
	Mugil cephalus	Flathead mullet
	Trachurus trachurus	Atlantic horse mackerel
	Micromesistius poutassou	Blue whiting
	Engraulis encrasicolus	European anchovy
	Sardina pilchardus	European pilchard
	Lophius budegassa	Blackbellied angler
Crustaceans	*Nephrops norvegicus*	Norway lobster
	Parapenaeus longirostris	Deep-water rose shrimp
Cephalopods	*Illex coindetii*	Southern shortfin squid
	Eledone cirrhosa	Curled octopus
Gastropods	*Bolinus brandaris*	Purple dye murex

7.1.1. Fish (adults, eggs, and larvae)

Fish have all of the basic acoustic processing capabilities of other vertebrates (Popper *et al*., 2004, Ladich and Popper, 2004). Fish can differentiate sounds of different magnitudes or frequencies, detect specific sounds when other signals are present and determine the direction of a sound source. However, their auditory systems differ from those of marine mammals.

The pressure component of sound is represented by sound waves, which are characterised by the medium compressing and expanding as sound energy moves through it. At the same time, the particles that form the medium move back and forth (particle motion). All fishes directly sense the particle motion component of sound (Fay 1984), although relatively few fishes sense both the particle and pressure components (Popper *et al.*, 2004). The ears of all fish species consist of otolith- (or otoconia-) containing end organs that function as inertial accelerometers. Fishes that sense pressure have additional morphological adaptations that allow them to detect acoustic pressure (Popper *et al.*, 2004). In these fishes, gas-filled bladders such as the swim bladder, which is near the ear, or mechanical connections such as Weberian ossicles, which are between the gas-filled bladder and the ear, convey sound pressure from the water to the ear when pressure deforms the bladder.

Most fish detect only particle motion, not pressure, and their hearing frequency range is typically limited to frequencies below 1 kHz. Pressure-sensing fish tend to have extended hearing bandwidth and lower hearing thresholds. They are often capable of detecting signals up to 3–4 kHz, with thresholds that may be 20 dB or more lower than for fish that are not sensitive to pressure (Hastings and Popper, 2005). Several fish taxonomic groups contain fish that can sense pressure, but this feature is not used to allocate fish into groups. Hearing abilities have been determined for relatively few (about 100) of the more than 27 000 extant fish species (see Fay 1988, Popper *et al.*, 2004). Hearing capabilities between different species, especially those that are taxonomically or geographically distant, must be extrapolated with caution.

In 2006, the Working Group on the Effects of Sound on Fish and Turtles was formed to continue developing noise exposure criteria for said animals, work begun by a NOAA panel two years earlier. The Working Group developed guidelines with specific thresholds for different levels of effects for several species groups (Popper *et al.* 2014). The guidelines define injury thresholds for three types of direct effects:

- mortality, including injury leading to death,
- recoverable injury, including injuries unlikely to result in mortality, such as hair cell damage and minor haematoma, and;
- temporary hearing threshold shift (TTS).

Masking and behavioural effects can be assessed qualitatively, by assessing relative risk rather than doing so by specific sound level thresholds. Because the presence or absence of a swim bladder has a role in hearing, a fish's susceptibility to injury from noise exposure depends on the species and the presence and possible role of a swim bladder in hearing. Thus, different thresholds were proposed for fishes without a swim bladder (also appropriate for sharks and applied to whale sharks in the absence of other information), fishes with a swim bladder not used for hearing, and fishes that use their swim bladders for hearing. Turtles, fish eggs, and fish larvae are considered separately; however, due to a lack of data regarding the effects of noise on turtles, the thresholds for this group are largely based on those for fish.

Fish disturbance thresholds are not well documented. NOAA advises using a 150 dB re 1 μPa (SPL) criterion to predict fish behavioural responses to impulsive sources (Mueller-Blenkle *et al.* 2010, NMFS 2013, Illingworth & Rodkin 2013); however the rationale for using this criterion is not clear (Popper *et al.* 2014)

Table 5 lists the relevant guidance from Popper *et al.* (2014) for the effects of shipping and continuous noise. Due to a lack of data regarding the effects of particle motion from these sources, the guidelines are presented as sound pressure. There is some evidence to suggest that acoustic pressure sensitive fish show a recoverable loss in hearing sensitivity, or injury when exposed to high levels of noise (Scholik and Yan 2002, Amoser and Ladich 2003, Smith, Miller and Popper, 2006); this is reflected in the SPL thresholds for fish with a swim bladder involved in hearing. As the likelihood of impact from exposure to continuous noise is related to both the amplitude of the noise and the duration of time of exposure, these SPL metrics also have an associated exposure duration. Where insufficient data exist to make recommendation for guidelines, effects are assessed qualitatively by assessing relative risk rather than by specific sound level thresholds. These effects are considered at three distances from the source: near, intermediate, and far, defined as approximately in the order of tens of metres, hundreds of metres, and thousands of metres, respectively. These relative risk ratings are highly subjective and represent general consensus of the Working Group (Popper *et al.* 2014); they are not based on the specific findings of this study. We consider these thresholds and guidelines the appropriate benchmark for assessing the impacts of vessel noise on fishes as the most recent internationally recognised criteria.

Table 5. Thresholds and subjective ratings of relative risk for impacts of vessel noise exposure on fish, adapted from Popper et al. (2014). Relative risk (high, moderate, or low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F)

Type of animal	***Mortality and potential mortal injury***	***Impairment***			***Behaviour***
		Recoverable injury	**TTS**	**Masking**	
Fish: No swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	170 dB SPL for 48 h	158 dB SPL for 12 h	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Fish eggs and fish larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Sound pressure level dB re 1 µPa.

7.1.2. Marine invertebrates (crustaceans, cephalopods, and gastropods)

Research is ongoing into the relationship between sound and its effects on marine invertebrates, including the relevant metrics for both effect and impact. Available literature suggests particle motion detection via the statocyst (a sensory organ providing orientation cues), rather than sound pressure detection, is a more important factor for marine invertebrate hearing (Solé *et al.* 2013, Tidau and Briffa 2016).

There remains limited real-world data on absolute levels of sound pressure or particle motion from non-impulsive sources inducing adverse effects in benthic invertebrates (Hawkins, Pembroke and Popper, 2015; Popper and Hawkins 2018) and hence there are no current widely accepted criteria for assessing the impact of this type of noise on these animals. However, there are studies to suggest short-term behavioural and physiological effects of exposure to vessel noise. Solan *et al.* (2016) found that Norway lobster (*Nephrops norvegicus*) exposed to broadband continuous noise in a tank at levels between 135–140 dBdB re 1 µPa demonstrated repressed burying behaviour and bioirrigation, and reduced locomotion. Other behavioural effects have been observed in crustaceans exposed to vessel noise, including disrupted feeding in the common shore crab (*Carcinus maenas*), increase in distance and velocity moved by groups of European spiny lobster (*Palinurus elephas*), and increased resting behaviour in individual common prawn (*Palaemon* *serratus*) (Tidau and Briffa 2016, Weilgart 2018). Murchy *et al.* (2019) conducted a meta-analysis on the effect of anthropogenic noise on various taxonomic groups of marine invertebrates, concluding a significant negative effect size for cephalopods and gastropods. Effects were further broken down by response type, indicating a significant reduction in foraging and predator response in cephalopods.

7.1.3. Marine mammals

The latest National Oceanic and Atmospheric Administration (NOAA) criteria for auditory injury (NMFS, 2018) and its earlier iterations (NOAA 2013 and 2015, NMFS 2016) have been scrutinized by the public, industrial proponents and academics. In addition, these publications present frequency-weighted sound exposure level (SEL) thresholds for marine mammal auditory injury, which have not been considered in this assessment.

NMFS currently uses step function (all-or-none) SPL thresholds of 120 dB re 1 µPa for non-impulsive sounds to assess and regulate noise-induced behavioural impacts for marine mammals (NOAA 2019). This threshold has also been incorporated in the ACCOBAMS guidelines (ACCOBAMS, 2013). This 120 dB re 1 µPa threshold is associated with continuous sources and was derived based on studies examining behavioural responses of gray whales (*Eschrichtius robustus*) to drilling and dredging (NOAA, 2018), referring to Malme *et al.* (1983, 1984, 1986), which were considered in Southall *et al*. (2007). Malme *et al.* (1986) found that playback of drillship noise did not produce clear evidence of disturbance or avoidance for SPL below 110 dB re 1 µPa, possible avoidance occurred for SPL approaching 119 dB re 1 µPa. Malme *et al.* (1984) determined that measurable reactions usually consisted of rather subtle short-term changes in speed and/or heading of the whale(s) under observation. It has been shown that both SPL and proximity of the sound source is a contributing factor in eliciting behavioural reactions in humpback whales (Dunlop *et al.*, 2017, 2018).

7.2. Methods

7.2.1. Modelling sound propagation

A combined range-dependent parabolic equation and gaussian beam acoustic ray-trace model (MONM-BELLHOP; Appendix 4) was used to predict the acoustic field around the vessels for frequencies from 10 Hz to 25 kHz. The acoustic source spectrum of each vessel (Section 7.2.2) was used in the propagation modelling to calculate the SPL field in the modelled area. The modelled SPLs only consider the generated noise field from fishing activities and do not account for the existing ambient noise levels in the area.

The sound field of each vessel was modelled up to distances of at least 85 km from the source location (Noise produced by vessels that has no impulsive quality is typically described in terms of sound pressure levels (SPL) (0). The results in this report are therefore presented as SPL and are presented in comparison with the latest published guidelines from Popper *et al.* (2014) for impacts of noise on fish (see Section 7.1). Section 7.2 provides an overview to the modelling methods and details the acoustic source and environmental parameters used in the propagation models. The results of the modelling are presented and discussed in Sections 7.3 and 7.4 respectively.

Table 3) with a horizontal separation of 10 m between receiver points along the modelled radials. Sound fields were modelled with a horizontal angular resolution of 2.5° for a total of 144 radial planes. Receiver depths were chosen to span the entire water column in the modelled areas, from 1 m to a maximum of 270 m, with step sizes increasing with depth.

7.2.2. Acoustic source parameters

Underwater sound that radiates from vessels is produced mainly by propeller and thruster cavitation (Ross 1976, §8.6), with a smaller fraction of noise produced by sound transmitted through the hull, such as by engines, gearing, and other mechanical systems. Sound levels thus tend to be highest when propulsion systems are used at high power, for example during dynamic positioning or transiting at high speeds. A vessel's sound signature depends on the vessel's size, power output and propulsion system characteristics (e.g., blade shape and size). It produces broadband acoustic energy with most of the energy emitted below a few kilohertz. Sound from onboard machinery, particularly sound below 200 Hz, dominates the sound spectrum before cavitation begins (Spence *et al*. 2007).

Based on the list of vessels provided by GFCM, the vessels in each category (OTB or LLS) were split evenly into three sub-categories by length overall (LOA): small, medium, and large. The median vessel in each size category was used as a proxy for that category. Draft information was obtained, where available, from an online vessel database service (VesselFinder 2021). For the small and large LLS proxy vessels where no information on vessel draft was available, the draft was estimated by multiplying each LOA by the draft to LOA ratio of the medium LLS proxy vessel. A summary of the proxy vessel properties for each category is presented in Table 6.

Table 6. A summary of proxy vessel properties for the modelled vessel categories

Vessel category		Vessel	LOA (m)	Draft (m)	Total power (kW)	Source depth (m)	Broadband Source Level (dB re 1 µPa·m)
LLS	S	*215-KŽ*	9.9	Unknown	55	1.5	149.2
	M	*Ariete I*	12.8	3.0	81	2.0	151.4
	L	*Vitoantonia*	14.8	Unknown	169	2.3	152.6
OTB	S	*Indomita*	15.9	2.3	220	1.5	171.3
	M	*Princeza Grejn*	20.2	3.2	276	2.1	173.4
	L	*Marc*	24.8	4.0	445	2.7	175.2

7.2.2.1. Source levels

Estimated source level spectra were calculated using the JOMOPANS-ECHO model developed by MacGillivray and de Jong (2021). The model calculates a ship source level spectrum based on vessel size and speed, while also incorporating specific reference speeds and spectrum coefficients based on AIS ship type.

Source spectra for each vessel category were calculated using the vessel lengths as specified in Table 6 and the appropriate parameters for the fishing vessel category. The vessel speed for LLS vessels was set as 6 knots based on a realistic worst-case speed for this type of vessel as determined by AIS data for a single vessel provided by GFCM. Trawlers typically travel at lower speed than this when actively trawling, around 3–4 knots. There is evidence to suggest, however, that noise levels are higher when trawling than transiting at similar speeds. De Robertis and Wilson (2006) determined that a vessel pulling a pelagic trawl at 3.3 knots produced similar spectrum levels to the same vessel free running at 11.2 knots. Similarly, Hovem et al. (2015) presented measurements showing that a vessel bottom-trawling at 4 knots produced slightly higher noise levels than the same vessel transiting at 12.4 knots. The speed for OTB vessels was therefore approximated as 12 knots to represent the trawling condition. The resulting source levels and spectra are presented in Table 7 and Figure 19 respectively for all vessel types. Full decidecade source levels can be found in Appendix 5.

Table 7. Broadband monopole source levels (MSL; dB re 1 μPa·m) for the modelled vessel categories

Vessel category		Broadband MSL (dB re 1 μPa·m)
LLS	S	149.2
	M	151.4
	L	152.6
OTB	S	171.3
	M	173.4
	L	175.2

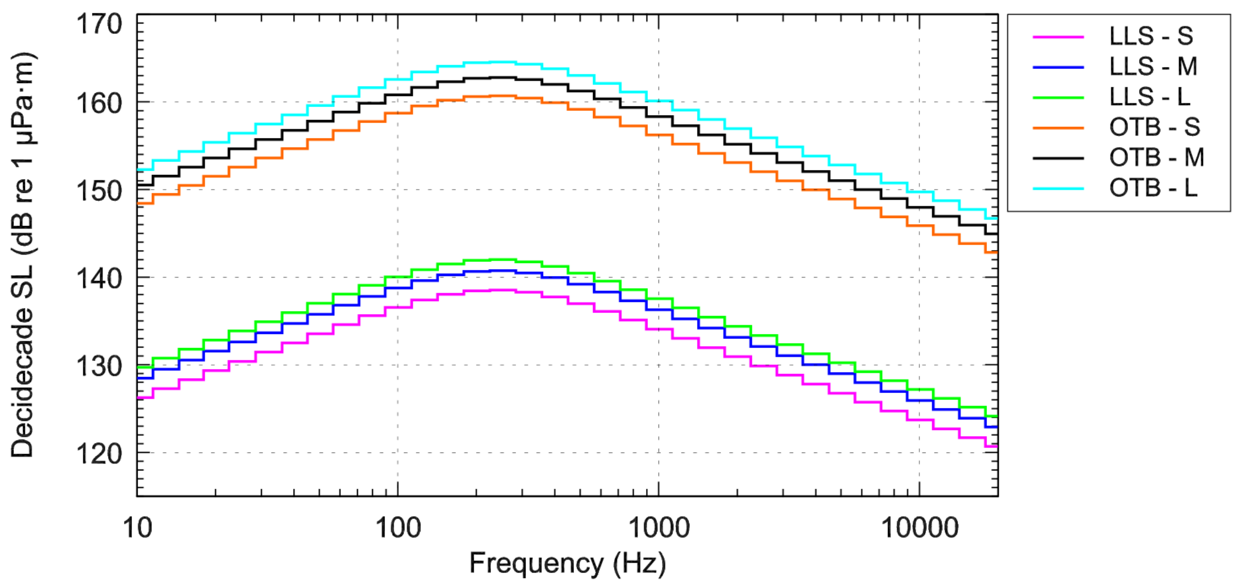


Figure 19. Modelled source spectra for the three different modelled sizes of OTB and LLS fishing vessels

7.2.2.2. Source depth

Typically, the acoustic source depth of a vessel can be estimated from the vessel draft and the diameter of the propeller (Gray and Greeley, 1980). However, in the absence of propeller diameter information the source depth has been approximated as two-thirds of the vessel draft.

Since set longlines are static in the water, the fishing gear for the LLS vessels is unlikely to generate noise at any substantial level compared to the vessel generated noise. Conversely, the trawl gear utilised by the OTB vessels is mobile and hence is more likely to generate additional noise on a more consistent basis through humming in trawl cables under tension, rattling chains and shackles, and noise related to the otter boards contacting the seabed (Daly and White 2021). Several studies have measured the noise from demersal trawl gear, and in all cases the vessel generated noise was considered to dominate, particularly in the case of soft sediment (Chapman and Hawkins 1969, Buerkle, 1977). For these reasons, the vessel has been considered the primary noise source, and the source depth has been chosen accordingly (Table 6).

7.2.3. Environmental parameters

7.2.3.1. Bathymetry

Water depths throughout the modelled area were extracted from the EMODnet European bathymetry grid, a one-sixteenth arc minute resolution (approximately 115 metres by 115 metres) grid rendered for European sea basins. A map showing the modelled bathymetry in the area is shown in Figure 20.

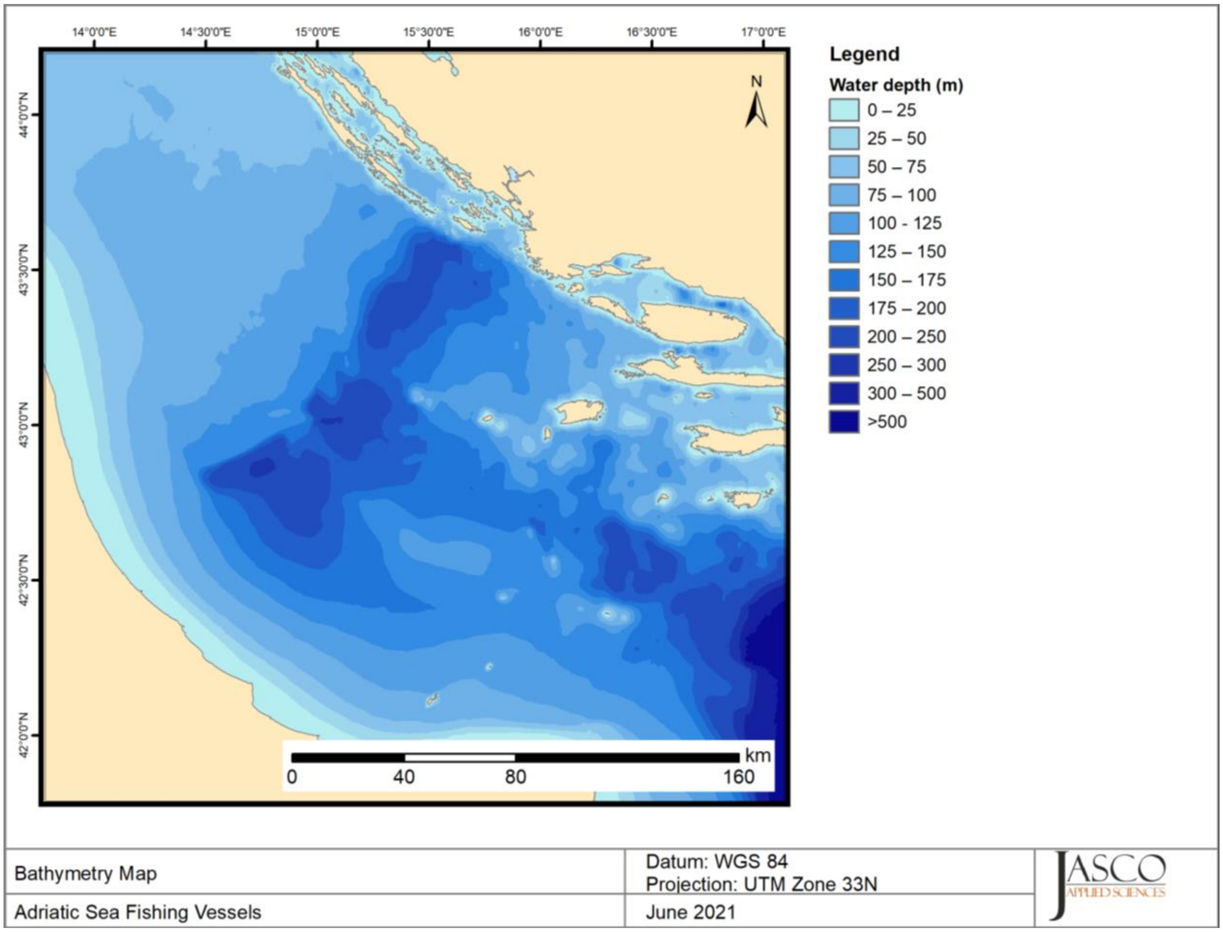


Figure 20. A map showing the bathymetry in the modelled area

7.2.3.2. Sound speed profile

The sound speed profile (SSP) for the modelled sites was derived from temperature and salinity profiles from the US Naval Oceanographic Office's *Generalized Digital Environmental Model V 3.0* (GDEM; Teague, Carron and Hogan, 1990, Carnes, 2009). GDEM provides an ocean climatology of temperature and salinity for the world's oceans on a latitude-longitude grid with 0.25° resolution, with a temporal resolution of one month, based on global historical observations from the US Navy's Master Oceanographic Observational Data Set (MOODS). The climatology profiles include 78 fixed depth points to a maximum depth of 6800 m (where the ocean is that deep; the Mediterranean sea does not reach this depth in any part). The GDEM temperature-salinity profiles were converted to sound speed profiles according to Coppens (1981). GFCM requested the SSP for June to be used in the modelling; the modelled SSP is shown in Figure 21.

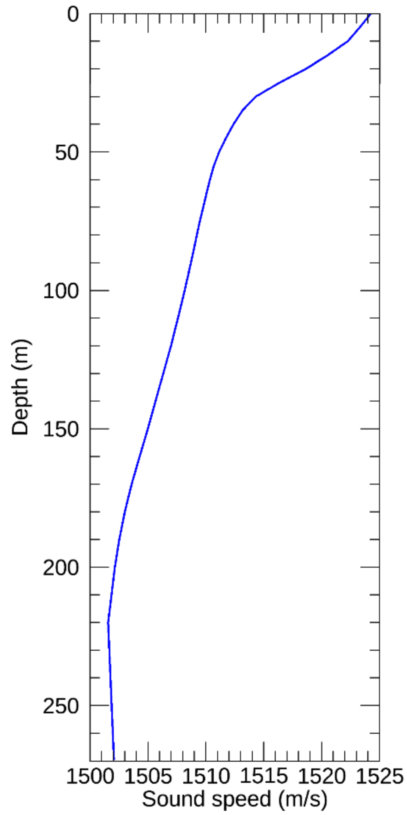


Figure 21. Mean monthly sound speed profile for Junederived from data obtained from GDEM V 3.0 (Teague *et al.* 1990, Carnes, 2009).

7.2.3.3. Geoacoustics

In a shallow environment, interactions between the acoustic field and the seabed are important and accurate geoacoustic profiles are needed for proper acoustic modelling. Since the modelled area is large and geoacoustic information is limited, two simplified geoacoustic profiles were constructed to represent the major features of the sediment at the modelled sites.

The modelled sites were divided into two geoacoustic areas based on the water depth at the source. Sites with a water depth greater than 150 m were categorised as an organic clay-loam substrate (here modelled as calcareous silt-clay), while sites with a water depth shallower than 150 m were categorised as a terrigenous sand-silt-clay, based on information provided by GFCM and the EMODnet Seabed Substrate map (Correggiari *et al.* in press). The EMODnet Seabed Substrate map is made available by the EMODnet Geology project, (http://www.emodnet-geology.eu) funded by the European Commission Directorate General for Maritime Affairs and Fisheries. Well logs available through the *Visibilità dei Dati afferenti all'attività di Esplorazione Petrolifera in Italia* (ViDEPI; Società Geologica Italiana, 2021) project indicated that sediment is likely quite thick in the region of interest, and in the absence of any more detailed information no other sub-surface layers were modelled.

Depth-dependent geoacoustic profiles were calculated from the values of Hamilton (1980), and are presented in Table 8 and 9 for water depths greater than 150 m, and shallower than 150 m respectively. MONM-BELLHOP only considers shear wave properties of the surficial layer; hence, these values are constant throughout the seabed.

Table 8. Estimated geoacoustic profile for sites B1, B3, and C3, which have a water depth at source of greater than 150 m. Within each depth range, each parameter varies linearly within the stated range. The compressional (P) wave is the primary wave. The shear (S) wave is the secondary wave

Depth below seafloor (m)	Material	Density (g/cm^3)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0.0–62.5	Silt-clay	1.40–1.51	1510–1610	0.17–0.21	116	2.00
62.5–125.0		1.51–1.60	1610–1710	0.21–0.35		
125.0–187.5		1.60–1.67	1710–1810	0.35–0.73		
187.5–250.0		1.67–1.72	1810–1910	0.73–1.07		
250.0–312.5		1.72–1.76	1910–2010	1.07–1.38		
312.5–375.5		1.76–1.80	2010–2100	1.38–1.64		
375.0–437.5		1.80–1.83	2100–2200	1.64–1.50		
437.5–500.0		1.83–1.86	2200–2270	1.50–1.35		

Table 9. Estimated geoacoustic profile for sites B2, C1, and C2, which have a water depth at source shallower than 150 m. Within each depth range, each parameter varies linearly within the stated range. The compressional (P) wave is the primary wave. The shear (S) wave is the secondary wave

Depth below seafloor (m)	Material	Density (g/cm^3)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0.0–62.5	Sand-silt-clay	1.60–1.68	1550–1630	0.23–0.63	250	3.65
62.5–125.0		1.68–1.76	1630–1700	0.63–1.04		
125.0–187.5		1.76–1.83	1700–1770	1.04–1.32		
187.5–250.0		1.83–1.90	1770–1830	1.32–0.98		
250.0–312.5		1.90–1.97	1830–1890	0.98–0.92		
312.5–375.5		1.97–2.03	1890–1950	0.92–0.91		
375.0–437.5		2.03–2.09	1950–2000	0.91–0.89		
437.5–500.0		2.09–2.14	2000–2050	0.89–0.87		

7.2.4. Multiple vessel sound fields

The noise footprint for multiple vessels operating within the FRA zones simultaneously was analysed by modelling the SPL for each vessel type at the individual transmission loss modelling sites (Table 3, Figure 18), and by transposing and summing these footprints at various other locations within the FRA zones. This method acceptably reflects large-scale sound propagation features, primarily dependent on water depth, which dominate the multiple source field, and is thus considered to provide a meaningful estimate of the sound field.

Two multiple vessel scenarios were determined based on the local fishing regulations in Zones B and C, set by Italy and Croatia respectively (see beginning of Section 7). Scenario 1 represents a day where only OTB vessels are allowed to fish in Zone C, and Scenario 2 represents a day where only LLS are allowed to fish in Zone C. In both Scenarios, as a conservative estimate of the number of vessels it was assumed that all authorised Croatian vessels using the relevant fishing gear type were present in Zone C. In Zone B, since vessels are only allowed to fish for two days in any given week it was assumed that approximately one quarter of the authorised Italian vessels using each fishing gear type were present. A breakdown of the number of the vessels modelled in each FRA zone is presented in Table 10.

Source locations for each scenario were generated by using Geographic Information System (GIS) software to randomly distribute the correct number of source locations in each FRA zone. The minimum point separation parameter of the GIS tool was adjusted to ensure the points were approximately evenly distributed throughout the area. The source locations within each zone were then arbitrarily ordered, and a list randomiser was used to assign vessel categories to each location as appropriate for the zone and scenario. The modelled single vessel sound field within the relevant zone (either B or C) with the closest water depth at source was selected to represent the sound field at each source location. The source locations and the type of vessel modelled at each location for each scenario are presented in Appendix 5.

Table 10. A summary of the vessel types modelled in each FRA zone for each multiple vessel scenario

FRA Zone	Vessel category		Number of modelled vessels	
			Scenario 1	Scenario 2
B	LLS	S	0	0
		M	2	2
		L	3	3
	OTB	S	2	2
		M	6	6
		L	6	6
C*	LLS	S	–	11
		M	–	1
		L	–	0
	OTB	S	26	–
		M	13	–
		L	12	–

*The number of modelled vessels in Zone C represents an assumption from the total number of vessels of each type authorised to fish in the region. This is a conservative estimate in the absence of any further information since not all these vessels will necessarily operate within Zone C simultaneously.

7.2.5. Estimating ranges to threshold levels

Sound level contours were calculated based on the underwater sound fields predicted by the propagation models, sampled both at the seafloor as well as by taking the maximum value over all modelled depths above the seafloor for each location in the modelled region. The predicted distances to specific levels were computed from these contours. Two distances relative to the source are reported for each sound level: (1) R_{max}, the maximum range to the given sound level over all azimuths, and (2) $R_{95\%}$, the range to the given sound level after the 5 percent farthest points were excluded (see examples in Figure 22.).

The $R_{95\%}$ is used because sound field footprints are often irregular in shape. In some cases, a sound level contour might have small protrusions or anomalous isolated fringes. This is demonstrated in the image in Figure 22.a. In cases such as this, where relatively few points are excluded in any given direction, R_{max} can misrepresent the area of the region exposed to such effects, and $R_{95\%}$ is considered more representative. In contrast, in strongly radially asymmetric cases such as shown in Figure 22b, $R_{95\%}$ neglects to account for substantial protrusions in the footprint. In such cases, R_{max} might better represent the region of effect in specific directions. Cases such as this are usually associated with bathymetric features that affect propagation. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the non-uniformity of the acoustic environment.

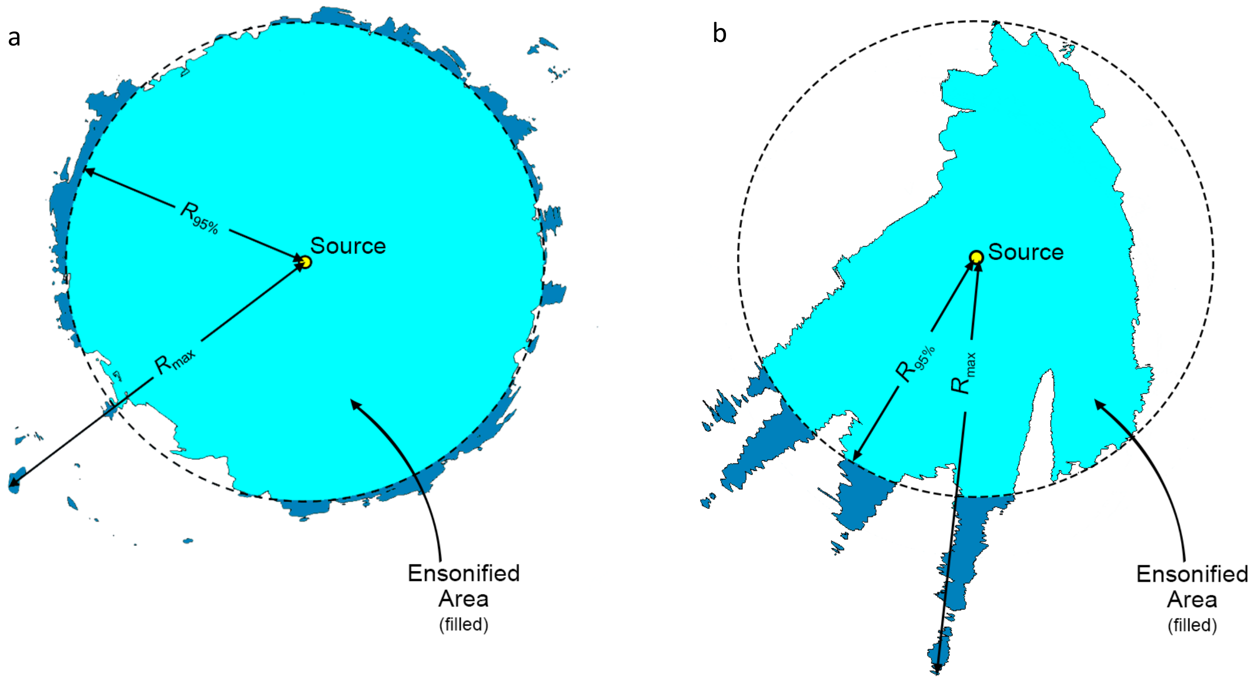


Figure 22. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two contrasting scenarios: (a) a largely radially symmetric sound level contour with small protrusions, for which $R_{95\%}$ best represents the ensonified area; and (b) a strongly asymmetric sound level contour with long protrusions, for which R_{max} best represents the ensonified areas in some directions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the ensonified areas beyond $R_{95\%}$ that determine R_{max}.

7.3. Results

This section presents results for the modelled scenarios involving single vessels and multiple vessels in Sections 7.3.1 and 7.3.2 respectively. The tabulated results present the maximum and 95 percent distances (see Section 7.2.5) to specified isopleths and impact criteria. Results are presented both at the seafloor and as maximum-over-depth, meaning that the specified threshold is reached at some point in the water column at the range presented; see Appendix 4 for further explanation of this approach.

7.3.1. Single vessel

Received SPLs near the seabed at 750, 1500, and 3000 m from the source are presented in Table 11 for the six vessel types at the six modelled locations. Results are the maximum level modelled along any radial around the source at the specified distance, and hence may not be along the same radial for different distances. Ranges to various SPL isopleths from each of the six vessel types are listed in Tables 12 to 17, and ranges to the SPL thresholds for fish from Popper *et al.* (2014) are presented in Table 18. Supplementary plots showing examples of the variation in the sound field with distance and depth from the source are presented in Appendix 5.

Table 11. Modelled SPL at three distances (750, 1500, and 3000 m) from each modelled source at all modelled locations. Levels are given near the seabed and are the maximum along any radial around the source

Vessel type	Distance from source (m)	SPL (dB re 1 µPa) near the seabed					
		Site					
		B1	B2	B3	C1	C2	C3
LLS – S	750	92.9	94.0	92.5	94.4	93.7	92.1
	1500	82.6	83.9	80.6	82.5	83.9	78.6
	3000	68.3	80.9	67.4	80.7	81.2	67.1
LLS – M	750	96.0	97.7	95.7	98.1	97.5	95.5
	1500	86.4	87.3	84.3	85.8	87.4	82.5
	3000	72.1	84.8	71.4	84.6	85.1	71.3
LLS – L	750	97.6	99.7	97.3	100.0	99.4	97.2
	1500	88.4	89.1	86.3	87.5	89.2	84.6
	3000	74.1	86.8	73.6	86.6	87.0	73.5
OTB – S	750	115.0	116.1	114.6	116.6	115.9	114.3
	1500	104.8	106.0	102.7	104.6	106.1	100.8
	3000	90.5	103.1	89.5	102.9	103.4	89.3
OTB – M	750	118.1	120.0	117.9	120.4	119.8	117.7
	1500	108.7	109.6	106.6	108.0	109.6	104.8
	3000	94.4	107.1	93.8	106.9	107.4	93.6
OTB – L	750	120.5	122.9	120.3	123.2	122.7	120.2
	1500	111.8	112.2	109.8	110.6	112.3	108.1
	3000	97.5	110.1	97.2	110.0	110.3	97.1

Table 12. Maximum (R_{max}) and 95 percent ($R_{95\%}$) horizontal distances (in km) from the small LLS vessel to modelled maximum-over-depth SPL isopleths.

SPL (dB re 1 µPa)	B1		B2		B3		C1		C2		C3	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
80	1.66	1.58	4.44	3.72	1.52	1.46	4.15	3.09	3.83	3.49	1.45	1.38
90	0.95	0.92	0.91	0.88	0.91	0.88	0.95	0.92	0.91	0.88	0.88	0.85
100	0.32	0.31	0.39	0.38	0.33	0.32	0.38	0.37	0.39	0.38	0.34	0.33
110	0.09	0.09	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
120†	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
130	–	–	–	–	–	–	–	–	–	–	–	–

† Behavioural response threshold for marine mammals (NOAA 2019)

A dash indicates the stated level was not reached within the minimum horizontal range step of the modelling

Table 13. Maximum (R_{max}) and 95 percent ($R_{95\%}$) horizontal distances (in km) from the medium LLS vessel to modelled maximum-over-depth SPL isopleths.

SPL (dB re 1 µPa)	B1		B2		B3		C1		C2		C3	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
80	1.83	1.74	7.39	5.66	1.83	1.64	6.65	4.98	5.99	4.99	1.79	1.73
90	1.24	1.19	1.79	1.66	1.16	1.12	1.77	1.65	1.81	1.65	1.12	1.07
100	0.48	0.47	0.62	0.60	0.48	0.47	0.61	0.59	0.62	0.60	0.48	0.46
110	0.13	0.13	0.14	0.14	0.13	0.13	0.14	0.13	0.14	0.13	0.13	0.13
120†	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**
130	–	–	–	–	–	–	–	–	–	–	–	–

† Behavioural response threshold for marine mammals (NOAA 2019)

A dash indicates the stated level was not reached within the minimum horizontal range step of the modelling

Table 14. Maximum (R_{max}) and 95 percent ($R_{95\%}$) horizontal distances (in kilometres, km) from the large LLS vessel to modelled maximum-over-depth SPL isopleths.

SPL (dB re 1 µPa)	B1		B2		B3		C1		C2		C3	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
80	2.39	2.07	8.64	7.21	2.10	2.01	7.97	7.08	7.13	6.54	2.09	1.96
90	1.40	1.35	2.16	1.99	1.31	1.26	2.23	2.01	2.17	2.00	1.26	1.20
100	0.58	0.56	0.73	0.71	0.57	0.55	0.75	0.73	0.72	0.70	0.57	0.55
110	0.16	0.16	0.17	0.16	0.16	0.16	0.16	0.16	0.17	0.16	0.16	0.16
120†	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
130	–	–	–	–	–	–	–	–	–	–	–	–

† Behavioural response threshold for marine mammals (NOAA 2019)

A dash indicates the stated level was not reached within the minimum horizontal range step of the modelling

Table 15. Maximum (R_{max}) and 95 percent ($R_{95\%}$) horizontal distances (in km) from the small OTB vessel to modelled maximum-over-depth SPL isopleths.

SPL (dB re 1 µPa)	B1		B2		B3		C1		C2		C3	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
80	5.94	5.49	43.4	32.8	5.47	5.07	34.9	26.9	26.4	21.4	5.39	4.98
90	3.71	3.32	19.9	13.5	3.16	2.96	14.3	12.4	13.10	10.92	2.99	2.79
100	1.76	1.68	6.00	4.66	1.61	1.55	5.19	4.61	4.78	4.41	1.53	1.46
110	1.12	1.07	1.57	1.43	1.05	1.02	1.51	1.43	1.56	1.40	1.01	0.98
120†	**0.44**	**0.42**	**0.52**	**0.50**	**0.44**	**0.43**	**0.51**	**0.49**	**0.52**	**0.50**	**0.44**	**0.42**
130	0.12	0.12	0.13	0.13	0.13	0.12	0.13	0.13	0.13	0.13	0.12	0.12
140	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
150	–	–	–	–	–	–	–	–	–	–	–	–

† Behavioural response threshold for marine mammals (NOAA 2019)

A dash indicates the stated level was not reached within the minimum horizontal range step of the modelling

Table 16. Maximum (R_{max}) and 95 percent ($R_{95\%}$) horizontal distances (in km) from the medium OTB vessel to modelled maximum-over-depth SPL isopleths.

SPL (dB re 1 µPa)	B1		B2		B3		C1		C2		C3	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
80	8.90	7.74	50.8	42.5	8.03	7.07	45.1	36.0	35.7	27.9	7.78	6.86
90	4.65	4.10	26.6	19.6	4.15	3.91	21.1	17.1	18.8	14.6	4.00	3.75
100	2.43	2.12	8.80	7.36	2.16	2.05	8.01	7.21	7.43	6.67	2.13	2.00
110	1.42	1.37	2.20	2.04	1.32	1.28	2.27	2.07	2.20	2.07	1.27	1.22
120†	**0.61**	**0.60**	**0.74**	**0.72**	**0.60**	**0.59**	**0.77**	**0.74**	**0.74**	**0.72**	**0.60**	**0.58**
130	0.17	0.17	0.19	0.18	0.18	0.17	0.18	0.18	0.18	0.17	0.18	0.17
140	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
150	–	–	–	–	–	–	–	–	–	–	–	–

† Behavioural response threshold for marine mammals (NOAA 2019)

A dash indicates the stated level was not reached within the minimum horizontal range step of the modelling

Table 17. Maximum (R_{max}) and 95 percent ($R_{95\%}$) horizontal distances (in km) from the large OTB vessel to modelled maximum-over-depth SPL isopleths

SPL (dB re 1 µPa)	B1		B2		B3		C1		C2		C3	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
80	11.5	10.1	60.8	50.1	10.1	9.21	48.0	41.6	45.7	34.5	10.5	9.51
90	5.65	5.26	38.9	26.8	4.98	4.68	30.7	22.5	23.7	18.6	4.85	4.52
100	3.25	2.86	12.7	9.87	2.86	2.67	11.0	9.76	10.9	8.86	2.71	2.54
110	1.62	1.55	3.98	2.84	1.49	1.44	3.16	2.73	3.48	2.82	1.42	1.36
120†	**0.79**	**0.77**	**0.89**	**0.85**	**0.77**	**0.75**	**0.91**	**0.88**	**0.87**	**0.84**	**0.76**	**0.74**
130	0.23	0.23	0.26	0.26	0.23	0.23	0.25	0.24	0.26	0.26	0.23	0.23
140	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
150	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

† Behavioural response threshold for marine mammals (NOAA 2019)

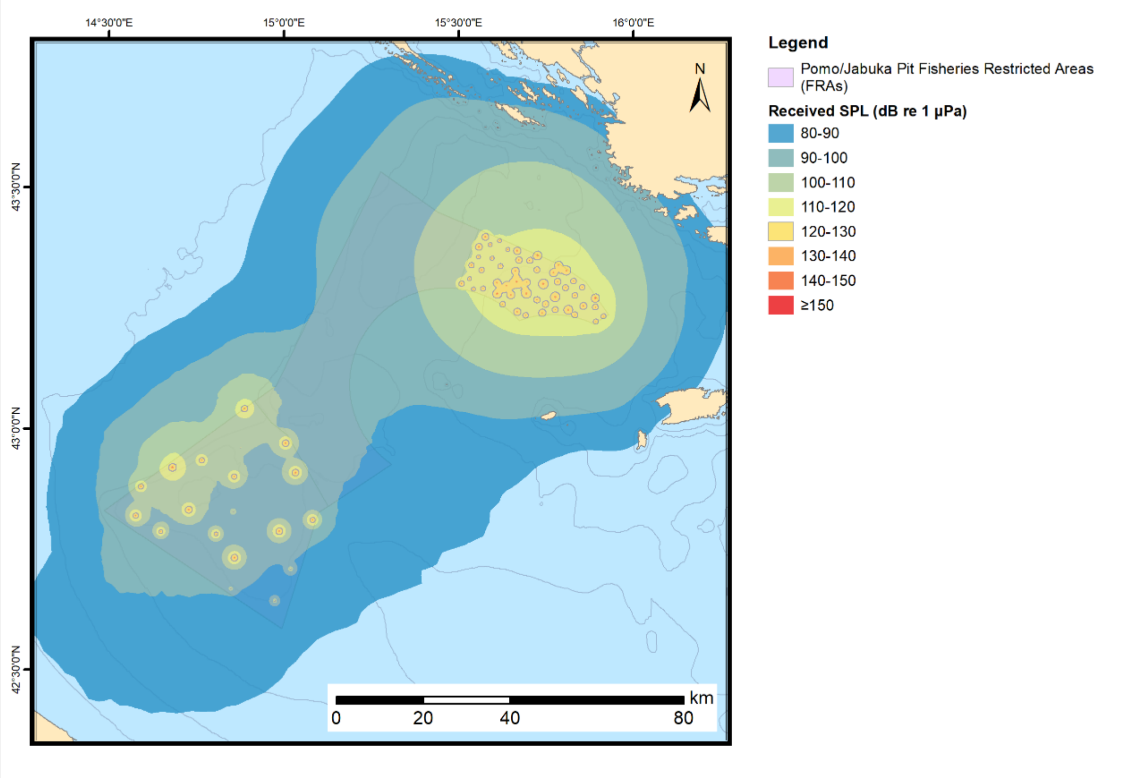
Table 18. Modelled distances to impact thresholds for fish specified in Popper *et al.* (2014) from each modelled source at all modelled locations

Vessel Type	Criteria for Fish: Swim Bladder Involved in Hearing		R_{max} (km)					
			Site					
	Impairment	SPL threshold (dB re 1 µPa)	B1	B2	B3	C1	C2	C3
LLS – S	TTS	158	–	–	–	–	–	–
	Recoverable injury	170	–	–	–	–	–	–
LLS – M	TTS	158	–	–	–	–	–	–
	Recoverable injury	170	–	–	–	–	–	–
LLS – L	TTS	158	–	–	–	–	–	–
	Recoverable injury	170	–	–	–	–	–	–
OTB – S	TTS	158	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
	Recoverable injury	170	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
OTB – M	TTS	158	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
	Recoverable injury	170	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
OTB – L	TTS	158	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
	Recoverable injury	170	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

A dash indicates the level was not reached at any distance from the source

7.3.2. Multiple vessel

Results are presented in this section for multiple vessel Scenario 1 (a day where only OTB vessels are allowed to fish in Zone C) and Scenario 2 (a day where only LLS vessels are allowed to fish in Zone C); results are shown in Figure 23 and Figure 24. In Figure 23, it appears as if the modelled sound field passes through some island land masses where this would not happen. This a result of the methodology where sound fields modelled elsewhere were transposed to the new modelling locations (see Section 7.2.4) and effectively overlapping the land.



Multiple Vessel Scenario 1 SPL: Modelled maximum-over-depth sound field	Datum: WGS 84 Projection: UTM Zone 33N	JASCO APPLIED SCIENCES
Adriatic Sea Fishing Vessels	June 2021	

Figure 23. Scenario 1, SPL: Sound level contour map showing unweighted maximum-over-depth results. Modelled vessels are Croatian OTB vessels operating in Zone C and a mixture of Italian LLS and OTB vessels in Zone B representing Saturday–Sunday. The 120 dB re 1 µPa behavioural response threshold for marine mammals is outlined in grey

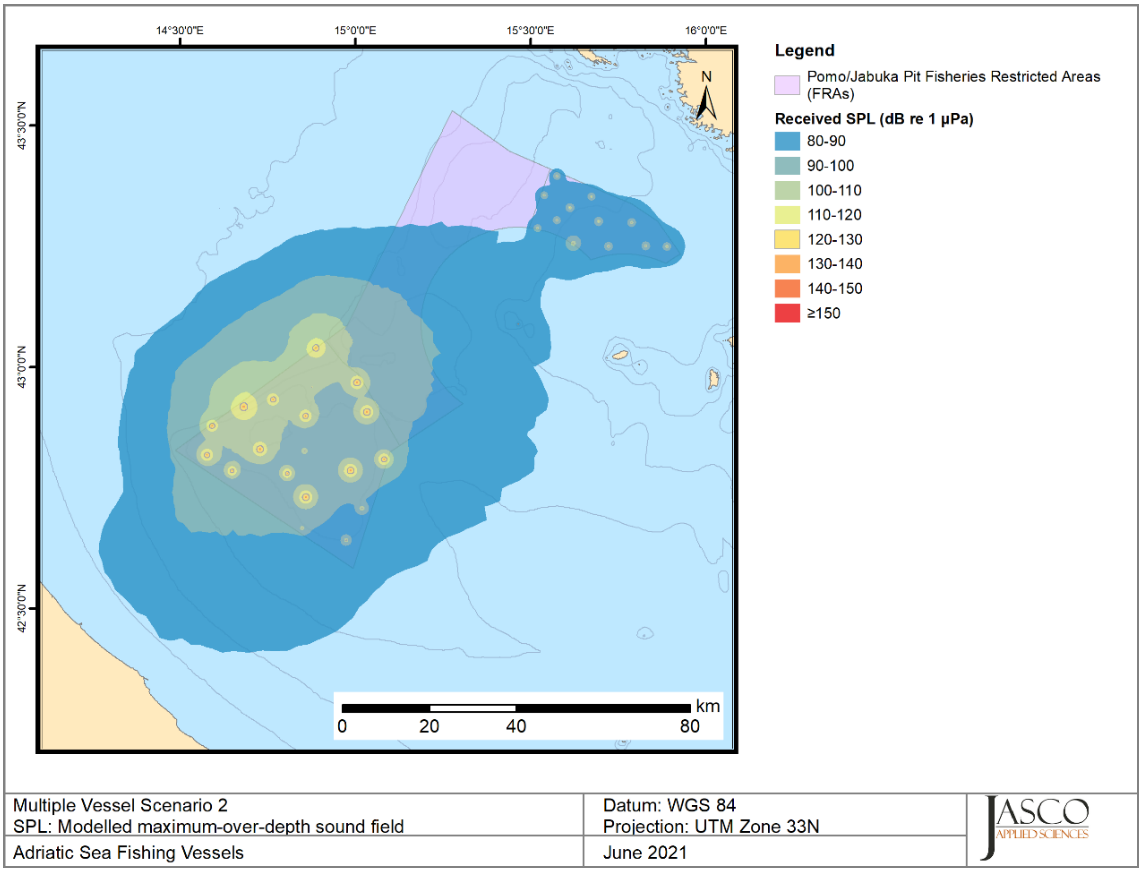


Figure 24. Scenario 2, SPL: Sound level contour map showing unweighted maximum-over-depth results.Modelled vessels are Croatian LLS vessels operating in Zone C and a mixture of Italian LLS and OTB vessels in Zone B representing Monday–Thursday. The 120 dB re 1 µPa behavioural response threshold for marine mammals (NOAA 2019) is outlined in grey

7.4. Discussion

This modelling study predicted noise levels associated with fishing activities in the Pomo/Jabuka Pit FRAs. The underwater sound field was modelled at six different locations (see beginning of Section 7) for two vessel types employing different fishing gear each split into three size categories (Section 7.2.2), and for two scenarios involving multiple vessels operating simultaneously based on realistic fishing schedules (Section7.2.4). For the month of June, a sound speed profile was selected by the GFCM (Section 7.2.3.2). In addition, the model also accounted for site-specific bathymetric variations (Section 7.2.3.1) and local geoacoustic properties (Section 7.2.3.3).

Modelled broadband MSLs ranged from 149 to 153 dB re 1 µPa·m for LLS vessels, and from 171 to 175 dB re 1 µPa·m for OTB vessels. Source levels were significantly higher for the OTB vessels than the LLS vessels since they were larger and more powerful in all modelled size categories (see Table 6). Additionally, the effective speed used in the source model for the OTB vessels was double that used for the LLS vessels to account for the increase in source levels during the trawl condition (see Section 7.2.2.1).

Predicted SPL near the seabed was extracted at three distances (750, 1500, and 3000 m) from the modelled single vessel source locations to assess the impact on the demersal fauna of interest (see Table 4); the lowest and highest predicted levels at all distances were observed for the small LLS and large OTB vessels, respectively. The predicted levels at 750 m ranged from 92 to 123 dB re 1 μPa (at C3 and C1 respectively), levels at 1500 m ranged from 79 to 112 dB re 1 μPa (at C3 and C2 respectively), and levels at 3000 m ranged from 67 to 110 dB re 1 μPa (at C3 and C2 respectively). The SPL thresholds for recoverable injury and TTS in pressure sensitive fish from Popper et al. (2014) of 170 and 158 dB re 1 μPa respectively were not reached for any vessel at any location within the resolution of the modelling (20 m), though source levels for all sizes of OTB vessels exceeded these values. The ranges to these thresholds for OTB vessels can therefore be considered to lie at some distance within 20 m of the source (Table 18). Ranges to the behavioural response threshold for marine mammals from NOAA (2019) of 120 dB re 1 μPa varied between 0.03 and 0.05 km for LLS vessels and between 0.44 and 0.91 km for OTB vessels. Ranges to levels below approximately 110 dB re 1 μPa are significantly larger at the shallower sites (B2, C1, and C2) compared to the deeper sites (B1, B3, and C3). This is likely due to the complex interactions of the sound emanating from the source with the sea surface and seabed which is further exaggerated by the difference in geoacoustics between the different groups of sites; the coarser grained sediment at the shallower sites is more reflective than the softer sediment in the deeper waters and hence sound propagates further.

Results of the multiple vessel scenarios indicated that with vessels operating in close proximity there is some coalescing of the individual sound fields into a single larger sound field, which is largely dominated by the noise from OTB vessels (see difference between Figures 23 and 24) In Scenario 1 with OTB vessels only operating in Zone C (representing Saturday–Sunday), the entirety of Zone C is ensonified above 110 dB re 1 μPa, and there are some coalesced areas ensonified above 120 dB re 1 μPa where several large and medium OTB vessels are near each other. In Scenario 2 with LLS vessels only operating in Zone C (representing Monday–Thursday), the overall ensonified area is much smaller since the overall number of vessels is lower and there are no OTB vessels operating in Zone C.

Comparing the modelled levels to the subjective assessment of relative risk for fishes from Popper *et al.* (2014) (see Table 5) there is unlikely to be any risk of mortality for any fish species, eggs, or larvae due to noise from fishing vessels in the Pomo/Jabuka Pit area. The guidelines also consider there to be a low risk for non-pressure sensitive fish of recoverable barotrauma injury at any distance, and a moderate risk of TTS at close range to the source only. These relative risk scores may be reasonable considering the limited coalescing of sound fields at high levels even when multiple vessels are closely located (see Section 7.2.4) There may be a greater risk of masking and behavioural effects than stated by Popper *et al.* (2014) considering the large predicted ensonified region caused by multiple vessels, though this does not consider the relative levels caused by the fishing vessels compared to the broader soundscape of the Adriatic. Caution should be emphasised when comparing to the stated values of relative risk as these are highly subjective and make no reference to source or received levels.

8. Conclusions and recommendations

Underwater noise derived from human activities is a chronic stressor that has a wide range of impacts on marine species, including fish and invertebrates.

Fishing by means of vessels is one among the human activities that generate noise at sea. As sound generated by a trawler or a longliner falls within the hearing range of fish and crustaceans, fish may hear sounds from an approaching vessel and fishing gear and respond with a diversified range of behaviors including at a long distance from the vessels (Buerkle, 1977). A 'natural' reaction would be a change in the swimming direction away from the approaching vessel as it was observed on Atlantic cods at sea by Engås *et al.* (1996) and Buerkle (1977). Catch records of three trawlers built to the same specifications showed that the noisiest boat (5–10 dB higher at frequencies >60 Hz than the other two boats) caught significant less of another gadiform, *Pollachius virens*, but about the same amount of cod (Engås & Løkkeborg 2002). Ona & Godø (1990) suggested that this horizontal and vertical vessel avoidance will influence bottom-trawl selectivity to a substantial degree, especially in situations where a mix of species and size classes with different swimming capacity and behavior are being sampled. Pre-vessel avoidance during trawling was observed at depths shallower than 200 m. No such avoidance was observed at depths from 200 to 500 m.

In this study, underwater sound fields were modelled at six different locations for vessels employing set longlines (LLS) and otter-board trawls (OTB), with each vessel type split into small, medium, and large categories. Broadband monopole source levels for the small, medium, and large LLS vessels were 149, 151, and 153 dB re 1 μPa·m respectively, and for the small, medium, and large OTB vessels were 171, 173, and 175 dB re 1 μPa·m respectively. Estimated underwater sound fields were calculated for sound pressure levels (SPL) to compare with established impact criteria for both fish and marine mammals.

The SPL thresholds for recoverable injury and temporary hearing threshold shift (TTS) in pressure sensitive fish from Popper *et al.* (2014) of 170 and 158 dB re 1 μPa respectively were not reached for any vessel at any location within the resolution of the modelling. The maximum modelled range to the behavioural response threshold for marine mammals from NOAA (2019) of 120 dB re 1 μPa was 0.91 km. Two multiple vessel scenarios were modelled based on realistic fishing schedules: Scenario 1 involved Croatian OTB vessels operating in Zone C and a mixture of Italian vessels in Zone B and Scenario 2 involved Croatian LLS vessels operating in Zone C and a mixture of Italian vessels in Zone B. Since modelled source levels for OTB vessels were significantly higher than those for LLS vessels, the overall ensonified area was larger in Scenario 1 than Scenario 2. However, it must be noted that the modelled levels consider only the generated noise from demersal fishing activities, and do not account for other transient sources of noise. Anthropogenic (human-generated) sound can be a by-product of vessel operations, or it can be a product of active acoustic data collection with seismic surveys, military sonar, and depth sounding as the main contributors. Oil and gas exploration with seismic airguns, marine pile driving and oil and gas production platforms elevate sound levels over radii of 10 to 1000 km when present (Bailey *et al.,* 2010, Miksis-Olds and Nichols 2016, Delarue *et al.* 2018). Still, as noted by Daly and White (2021), who investigated the energy emitted by bottom trawling activity, the noise from this type of vessels is a source of pollution that requires further consideration, in line with other pervasive trawling pressures on marine species and seabed habitats, especially in areas of heightened ecological susceptibility.

In terms of the reliability of the results produced by the noise modelling presented in this study, some comparisons with the recent study by Daly and White (2021) can be made. Daly and White (2021) recorded two different trawlers in two different locations and calculated decidecade source levels using propagation loss modelling. There is no size information for one of the vessels measured, but the other is listed as 17–20 m long with a calculated broadband source level between 170–173 dB re 1 μPa·m. The small OTB vessel modelled in this study was 15.9 m LOA with a broadband source level of 171.3 dB re 1 μPa·m and the medium OTB vessel modelled in this study was 17.1 m LOA with a broadband source level of 173.4 dB re 1 μPa·m. While the modelled broadband levels are similar to those measured by Daly and White (2021) the spectrum was different, which is expected when comparing measured data to a generalized source model. It should also be noted that the source levels determined by Daly and White (2021) appear to have been calculated opportunistically rather than according to ISO 17208 (Part 1: 2016, Part 2: 2019).

Regarding the reliability of the results produced by the noise modelling presented in this study, some comparisons with the recent study by Daly and White (2021) can be made. In their study, Daly and White (2021) recorded two different trawlers in two different locations; in the PANiC area (the deeper location on the slope) there is no information on the size of the trawler but in the GIST area (shallower region) the trawler they recorded is listed as 17–20 m long. The Small and Medium OTB vessels from the Adriatic Sea modelled in this study were 15.9 m and 20.2 m LOA respectively. The broadband source level they calculated at the GIST area was between 170–173 dB re 1 μPa·m, and the source levels we modelled for OTB – S and OTB – m were 171.3 and 173.4 dB re 1 μPa·m respectively, so the modelled broadband source levels presented for the OTB operating in the Pomo Pit area are at least very similar to the measured and calculated ones for a similar size vessel, though from a different region. The spectrum Daly and White measured was different to the one modelled in this study, although this is expected since in this study a generalised source model was used while in reality every vessel has its own unique source signature. It should also be pointed out that there is an ISO standard for determining the source level from vessels involving multiple hydrophones at different depths and a specific, repeatable vessel track, which Daly and White seem not to have followed. Otherwise, it is quite hard to compare their results with the modelling of this study directly because the environments are different and there are many variables that can affect both measured and modelled noise.

In conclusion, the Adriatic Sea is a busy area for commercial shipping, and small vessels such as fishing vessels do not typically generate a large noise footprint compared to large ships with high source levels. A modelling study investigating the change in the soundscape of the Northern Adriatic due to the COVID-19 pandemic by Sertlek (2021) concluded that while the largest proportion of vessels in the area comprised fishing vessels, the contribution to the overall sound energy density was considerably smaller than that from cargo vessels and tankers. The Adriatic is also an established area for oil and gas exploration and exploitation (AZU 2021), and the effect of impulsive noise from seismic sources on fish, marine mammals, and (to a lesser extent) marine invertebrates is well studied and documented with established thresholds for injury (Payne *et al.,* 2008, Popper *et al.,* 2014, Day *et al.,* 2016, NMFS 2018, Day *et al.,* 2019, Southall *et al.,* 2019a).

This study should be regarded as a first step at scientifically assessing the impacts of underwater noise pollution on fisheries. To this end, it has addressed in particular noise levels associated with fishing activities in the Jabuka/Pomo Pit area. The findings of this study and the research that was carried out to build the foundation towards its compilation point to the need for further inquiries that should be the subject of further scientific research. In this regard, it is recommended as a next step to:

- improve the state of knowledge on the noise-footprint of other noise generating activities in the Adriatic Sea, including marine transit of larger ships, oil and gas exploration prospection and offshore construction and maintenance,

- collect and analyse date and information on the level of catch rates and any potential fluctuations over the years in conjunction to exposure to underwater noise sources. This effort should be supported by a proactive stakeholder engagement and could include, for example, requests to fishers in given coastal communities to report variations they observed in catch rates following anthropogenic underwater noise activities,

- consider the associated socio-economic impacts of underwater noise pollution on coastal communities concerned by decreased fishing catch rates and map all stakeholders which would be potentially affected. This effort should support the identification of types and forms of socio-economic impacts associated with underwater noise based on existing socio-economic knowledge of fisheries management,

- evaluate costs and benefits of different mitigation measures countering the impacts of anthropogenic underwater noise pollution,

- encourage other RFMOs to engage in the study and assessment of the impacts of anthropogenic underwater noise pollution on fisheries, and;

- apply the precautionary principle whenever gaps in knowledge and understanding would prevent the prompt taking of measures aimed at addressing the impacts of anthropogenic underwater noise pollution on fisheries.

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Glossary

absorption

The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

acoustic noise

Sound that interferes with an acoustic process.

ambient sound

Sound that would be present in the absence of a specified activity, usually a composite of sound from many sources near and far, e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

attenuation

The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium.

auditory frequency weighting

The process of applying an auditory frequency weighting function. In human audiometry, C-weighting is the most commonly used function, an example for marine mammals are the auditory frequency weighting functions published by Southall et al. (2007).

auditory frequency weighting function

Frequency weighting function describing a compensatory approach accounting for a species' (or functional hearing group's) frequency-specific hearing sensitivity. Example hearing groups are low-, mid-, and high-frequency cetaceans, phocid and otariid pinnipeds.

azimuth

A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation it is also called bearing.

bandwidth

The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI R2010).

boxcar averaging

A signal smoothing technique that returns the averages of consecutive segments of a specified width.

broadband level

The total level measured over a specified frequency range.

cavitation

A rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates a lot of noise.

cetacean

Any animal in the order Cetacea. These are aquatic species and include whales, dolphins, and porpoises.

compressional wave

A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called primary wave or P-wave.

continuous sound

A sound whose sound pressure level remains above ambient sound during the observation period; non-intermittent sound. The sound may gradually vary in intensity with time, for example, sound from a marine vessel.

decade

Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 80000-3:2006).

decidecade

One tenth of a decade. *Note*: An alternative name for decidecade (symbol ddec) is "one-tenth decade". A decidecade is approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct) and for this reason is sometimes referred to as a "one-third octave".

decidecade band

Frequency band whose bandwidth is one decidecade. *Note*: The bandwidth of a decidecade band increases with increasing centre frequency.

decibel (dB)

Unit of level used to express the ratio of one value of a power quantity to another on a logarithmic scale. Unit: dB.

ensonified

Exposed to sound.

frequency

The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

frequency weighting

The process of applying a frequency weighting function.

frequency-weighting function

The squared magnitude of the sound pressure transfer function. For sound of a given frequency, the frequency weighting function is the ratio of output power to input power of a specified filter, sometimes expressed in decibels. Examples include the following:

- *Auditory frequency weighting function*: compensatory frequency weighting function accounting for a species' (or functional hearing group's) frequency-specific hearing sensitivity.

- *System frequency weighting function*: frequency weighting function describing the sensitivity of an acoustic acquisition system, typically consisting of a hydrophone, one or more amplifiers, and an analogue to digital converter.

geoacoustic

Relating to the acoustic properties of the seabed.

hearing group

Category of animal species when classified according to their hearing sensitivity and to the susceptibility to sound. Examples for marine mammals include very low-frequency (VLF) cetaceans, low-frequency (LF) cetaceans, mid-frequency (MF) cetaceans, high-frequency (HF) cetaceans, very high-frequency (VHF) cetaceans, otariid pinnipeds in water (OPW), phocid pinnipeds in water (PPW), sirenians (SI), other marine carnivores in air (OCA), and other marine carnivores in water (OCW) (NMFS 2018, Southall et al. 2019). See **auditory frequency weighting functions**, which are often applied to these groups. Examples for fish include species for which the swim bladder is involved in hearing, species for which the swim bladder is not involved in hearing, and species without a swim bladder (Popper et al. 2014).

hearing threshold

The sound pressure level for any frequency of the hearing group that is barely audible for a given individual for specified background noise during a specific percentage of experimental trials.

hertz (Hz)

A unit of frequency defined as one cycle per second.

impulsive sound

Qualitative term meaning sounds that are typically transient, brief (less than 1 second), broadband, with rapid rise time and rapid decay. They can occur in repetition or as a single event. Examples of impulsive sound sources include explosives, seismic airguns, and impact pile drivers.

isopleth

A line drawn on a map through all points having the same value of some quantity.

knot

One nautical mile per hour. Symbol: kn.

level

A measure of a quantity expressed as the logarithm of the ratio of the quantity to a specified reference value of that quantity. Examples include sound pressure level, sound exposure level, and peak sound pressure level. For example, a value of sound exposure level with reference to 1 μPa^2 s can be written in the form *x* dB re 1 μPa^2 s.

masking

Obscuring of sounds of interest by sounds at similar frequencies.

median

The 50th percentile of a statistical distribution.

monopole source level (MSL)

A source level that has been calculated using an acoustic model that accounts for the effect of the sea-surface and seabed on sound propagation, assuming a point-like (monopole) sound source.

non-impulsive sound

Sound that is not an impulsive sound. A non-impulsive sound is not necessarily a continuous sound.

parabolic equation method

A computationally efficient solution to the acoustic wave equation that is used to model propagation loss. The parabolic equation approximation omits effects of back-scattered sound, simplifying the computation of propagation loss. The effect of back-scattered sound is negligible for most ocean-acoustic propagation problems.

permanent threshold shift (PTS)

An irreversible loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.

power spectral density

Generic term, formally defined as power in a unit frequency band. Unit: watt per hertz (W/Hz). The term is sometimes loosely used to refer to the spectral density of other parameters such as squared sound pressure. ratio, E_f, to time duration, Δt, in a specified temporal observation window. In equation form, the power spectral density P_f is given by:

$$P_f = \frac{E_f}{\Delta t}.$$

Power spectral density can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement).

power spectral density level

The level ($L_{P,f}$) of the **power spectral density** (P_f). Unit: decibel (dB).

$$L_{P,f} := 10 \log_{10}\left(P_f / P_{f,0}\right) \text{ dB}.$$

The frequency band and integration time should be specified.

As with **power spectral density**, power spectral density level can be expressed in terms of various field variables (e.g., sound pressure, sound particle displacement). The reference value ($P_{f,0}$) for power spectral density level depends on the nature of field variable.

pressure, acoustic

The deviation from the ambient pressure caused by a sound wave. Also called sound pressure. Unit: pascal (Pa).

propagation loss (PL)

Difference between a source level (SL) and the level at a specified location, PL(x) = SL − L(x). Also see **transmission loss**.

received level

The level measured (or that would be measured) at a defined location, e.g., at the ear or sound sensing organ of a marine animal. The type of level should be specified.

reference values

standard references values used for calculating sound levels underwater, e.g., the reference value for expressing sound pressure level underwater in decibels is 1 µPa.

Quantity	Reference value
Sound pressure	1 µPa
Sound exposure	1 µPa^2 s
Sound particle displacement	1 pm
Sound particle velocity	1 nm/s
Sound particle acceleration	1 µm/s^2

rms

abbreviation for root-mean-square.

shear wave

A mechanical vibration wave in which the direction of particle motion is perpendicular to the direction of propagation. Also called a secondary wave or S-wave. Shear waves propagate only in solid media, such as sediments or rock. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

sound

A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium.

sound exposure

Time integral of squared sound pressure over a stated time interval. The time interval can be a specified time duration (e.g., 24 hours) or from start to end of a specified event (e.g., a pile strike, an airgun pulse, a construction operation). Unit: Pa^2 s.

sound exposure level

The level (L_E) of the sound exposure (E). Unit: decibel (dB). Reference value (E_0) for sound in water: 1 µPa^2 s.

$$L_E := 10 \log_{10}(E/E_0) \text{ dB } = 20 \log_{10}\left(E^{1/2}/E_0^{1/2}\right) \text{ dB}$$

The frequency band and integration time should be specified. Abbreviation: SEL.

sound field

Region containing sound waves.

sound particle motion

smallest volume of a medium that represents its mean physical properties.

sound pressure

The contribution to total pressure caused by the action of sound.

sound pressure level (rms sound pressure level)

The level ($L_{p,\mathrm{rms}}$) of the time-mean-square sound pressure (p_{rms}^2). Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 μPa^2.

$$L_{p,\mathrm{rms}} := 10 \log_{10}(p_{\mathrm{rms}}^2/p_0^2)\ \mathrm{dB}\ = 20 \log_{10}(p_{\mathrm{rms}}/p_0)\ \mathrm{dB}$$

The frequency band and averaging time should be specified. Abbreviation: SPL or Lrms.

sound speed profile

The speed of sound in the water column as a function of depth below the water surface.

soundscape

The characterization of the ambient sound in terms of its spatial, temporal, and frequency attributes, and the types of sources contributing to the sound field.

source level (SL)

A property of a sound source obtained by adding to the sound pressure level measured in the far field the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 μPa^{2}m^2.

spectrum

An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound exposure distribution with frequency.

temporary threshold shift (TTS)

Reversible loss of hearing sensitivity. TTS can be caused by noise exposure.

transmission loss (TL)

The difference between a specified level at one location and that at a different location, TL(x1,x2) = L(x1) − L(x2). Also see **propagation loss**.

unweighted

Term indicating that no frequency weighting function is applied. Synonymous with flat weighting.

wavelength

Distance over which a wave completes one cycle of oscillation. Unit: metre (m). Symbol: λ.

Appendix 1

Information included in the list of vessels authorized to operate in certain areas of the FRA of Jabuka / Pomo Pit

- Vessel name
- Vessel register number
- GFCM registration number (country ISO 3-alpha code + 9 digits, e.g. xxx000000001)
- Previous name (if any)
- Previous flag (if any)
- Previous details of deletion from other registers (if any)
- International radio call sign (if any)
- Type of vessel, length overall (LOA) and gross tonnage (GT)
- Name and address of owner(s) and operator(s)
- Main gear used to fish in the FRA
- Seasonal period authorized for fishing in the FRA
- Number of fishing days that can be exerted by each vessel
- Designated port

Appendix 2

Technical information about the vessels authorized to operate in certain areas of the FRA of Jabuka/Pomo Pit used to assess the level of noise generated at sea

- Number of vessels
- Number of fishing days that can be exerted by each vessel
- Type of vessel (fishing gear)
- Length overall (LOA)
- Gross tonnage (GT)
- Number of engines
- Type of engine(s)
- Total horsepower (HP)
- Total kilowatts (kW)
- Number of axes
- Number of blades

Appendix 3

Underwater acoustics metrics and modelling

This section describes in detail the acoustic metrics, impact criteria, and frequency weighting relevant to the modelling study. The technical details of the modelling methodology are described thereafter.

This section describes in detail the acoustic metrics, impact criteria, and frequency weighting relevant to the modelling study. The technical details of the modelling methodology are described thereafter.

1. Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the perceived loudness of sound, especially pulsed sound such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate sound and its effects on marine life. Here we provide specific definitions of relevant metrics used in the accompanying report. Where possible, we follow International Organization for Standardization definitions and symbols for sound metrics .

The zero-to-peak sound pressure, or peak sound pressure (PK or $L_{p,pk}$; dB re 1 μPa), is the decibel level of the maximum instantaneous acoustic pressure in a stated frequency band attained by an acoustic pressure signal, $p(t)$:

$$L_{p,\mathrm{pk}} = 10\log_{10}\frac{\max|p^2(t)|}{p_0^2} = 20\log_{10}\frac{\max|p(t)|}{p_0} \tag{A-1}$$

PK is often included as a criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of an acoustic event, it is generally a poor indicator of perceived loudness.

The peak-to-peak sound pressure (PK-PK or $L_{p,pk\text{-}pk}$; dB re 1 μPa) is the difference between the maximum and minimum instantaneous sound pressure, possibly filtered in a stated frequency band, attained by an impulsive sound, $p(t)$:

$$L_{p,pk\text{-}pk} = 10\log_{10}\frac{[\max(p(t)) - \min(p(t))]^2}{p_0^2} \tag{A-2}$$

The sound pressure level (SPL or L_p; dB re 1 μPa) is the root-mean-square (rms) pressure level in a stated frequency band over a specified time window (T; s). It is important to note that SPL always refers to an rms pressure level and therefore not instantaneous pressure:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T g(t)\,p^2(t)\,dt \Big/ p_0^2\right)\ \mathrm{dB} \tag{A-3}$$

where $g(t)$ is an optional time weighting function. In many cases, the start time of the integration is marched forward in small time steps to produce a time-varying SPL function. For short acoustic events, such as sonar pulses and marine mammal vocalizations, it is important to choose an appropriate time window that matches the duration of the signal. For in-air studies, when evaluating the perceived loudness of sounds with rapid amplitude variations in time, the time weighting function $g(t)$ is often set to a decaying exponential function that emphasizes more recent pressure signals. This function mimics the leaky integration nature of mammalian hearing. For example, human-based fast time-weighted SPL ($L_{p,fast}$) applies an exponential function with time constant 125 ms. A related simpler approach used in underwater acoustics sets $g(t)$ to a boxcar (unity amplitude) function of width 125 ms; the results can be referred to as

$L_{p,boxcar\ 125ms}$. Another approach, historically used to evaluate SPL of impulsive signals underwater, defines $g(t)$ as a boxcar function with edges set to the times corresponding to 5% and 95% of the cumulative square pressure function encompassing the duration of an impulsive acoustic event. This calculation is applied individually to each impulse signal, and the results have been referred to as 90% SPL ($L_{p,90\%}$).

The sound exposure level (SEL or L_E; dB re 1 µPa^2·s) is the time-integral of the squared acoustic pressure over a duration (T):

$$L_E = 10\log_{10}\left(\int_T p^2(t)\,dt \Big/ T_0 p_0^2\right)\ \text{dB} \tag{A-4}$$

where T_0 is a reference time interval of 1 s. SEL continues to increase with time when non-zero pressure signals are present. It is a dose-type measurement, so the integration time applied must be carefully considered for its relevance to impact to the exposed recipients.

SEL can be calculated over a fixed duration, such as the time of a single event or a period with multiple acoustic events. When applied to pulsed sounds, SEL can be calculated by summing the SEL of the N individual pulses. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, the SEL can be computed by summing (in linear units) the SEL of the N individual events:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right)\ \text{dB} \tag{A-5}$$

2. Decidecade band Analysis

The distribution of a sound's power with frequency is described by the sound's spectrum. The sound spectrum can be split into a series of adjacent frequency bands. Splitting a spectrum into 1 Hz wide bands, called passbands, yields the power spectral density of the sound. This splitting of the spectrum into passbands of a constant width of 1 Hz, however, does not represent how animals perceive sound.

Because animals perceive exponential increases in frequency rather than linear increases, analysing a sound spectrum with passbands that increase exponentially in size better approximates real-world scenarios. In underwater acoustics, a spectrum is commonly split into decidecade bands, which are one tenth of a decade (approximately one-third of an octave) wide. Each decade represents a factor 10 in sound frequency. Each octave represents a factor 2 in sound frequency. The centre frequency of the ith decidecade band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{\frac{i}{10}}\ \text{kHz} \tag{A-6}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the ith decidecade band are defined as:

$$f_{\text{lo},i} = 10^{\frac{-1}{20}} f_c(i) \quad \text{and} \quad f_{\text{hi},i} = 10^{\frac{1}{20}} f_c(i) \tag{A-7}$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure A-1).

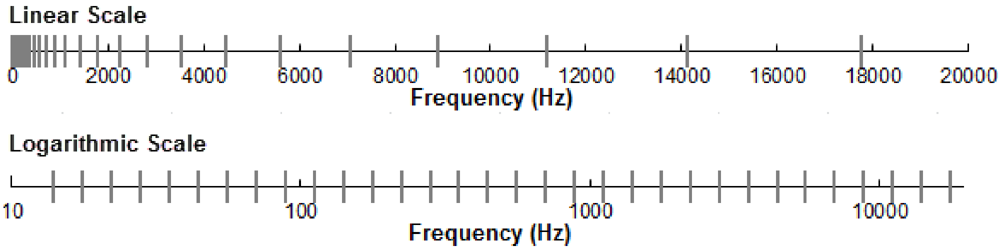

Figure A-1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale.

The sound pressure level in the ith band ($L_{p,i}$) is computed from the spectrum $S(f)$ between $f_{lo,i}$ and $f_{hi,i}$:

$$L_{p,i} = 10 \log_{10} \int_{f_{\mathrm{lo},i}}^{f_{\mathrm{hi},i}} S(f)\, \mathrm{d}f \text{ dB} \tag{A-8}$$

Summing the sound pressure level of all the bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10 \log_{10} \sum_i 10^{\frac{L_{p,i}}{10}} \text{ dB} \tag{A-9}$$

Figure A-2 shows an example of how the decidecade band sound pressure levels compare to the sound pressure spectral density levels of an ambient noise signal. Because the decidecade bands are wider than 1 Hz, the decidecade band SPL is higher than the spectral levels, especially at higher frequencies.

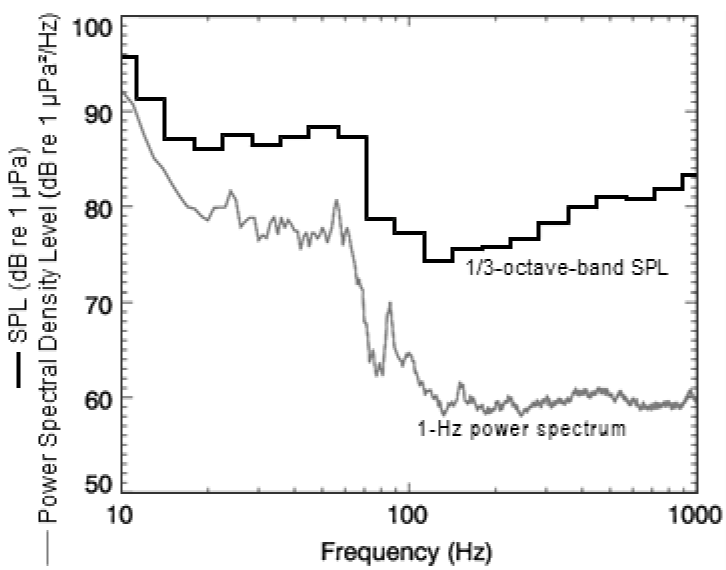

Figure A-2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.Because the decidecade bands are wider with increasing frequency, the 1decidecade band SPL is higher than the power spectrum.

Appendix 4

Sound propagation modelling

MONM-BELLHOP

Underwater sound propagation was predicted for frequencies from 10 Hz to 1.25 kHz with JASCO's Marine Operations Noise Model (MONM). MONM computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the US Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM accounts for the additional reflection loss at the seabed, which results from partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modelled area, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

Results from MONM were supplemented with results from the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994) for frequencies above 1.25 kHz. BELLHOP accounts for sound attenuation due to energy absorption through ion relaxation and viscosity of water in addition to acoustic attenuation due to reflection at the medium boundaries and internal layers (Fisher and Simmons 1977). The former type of sound attenuation is important for frequencies higher than 5 kHz and cannot be neglected without noticeably affecting the model results.

MONM-BELLHOP computes acoustic fields in three dimensions by modelling transmission loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding $N = 360°/\Delta\theta$ number of planes (Figure B-1). MONM-BELLHOP treats frequency dependence by computing acoustic transmission loss at the centre frequencies of decidecade bands. Sufficiently many decidecade frequency-bands, starting at 10 Hz, are modelled to include most of the acoustic energy emitted by the source. At each centre frequency, the transmission loss is modelled within each of the N vertical planes as a function of depth and range from the source. The decidecade received SPLs are computed by subtracting the band transmission loss values from the source level in that frequency band. Composite broadband levels are then computed by summing the received decidecade levels.

The received sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size (Δr in Figure B-1). At each sampling range along the surface, the sound field is sampled at various depths (Δd in Figure B-1), with the step size between samples increasing with depth below the surface. The received SPL can then be taken at a specific receiver depth (e.g. closest to the seabed) or as the maximum value that occurs over all samples within the water column, i.e., the maximum-over-depth received SPL (right panel, Figure B-1).

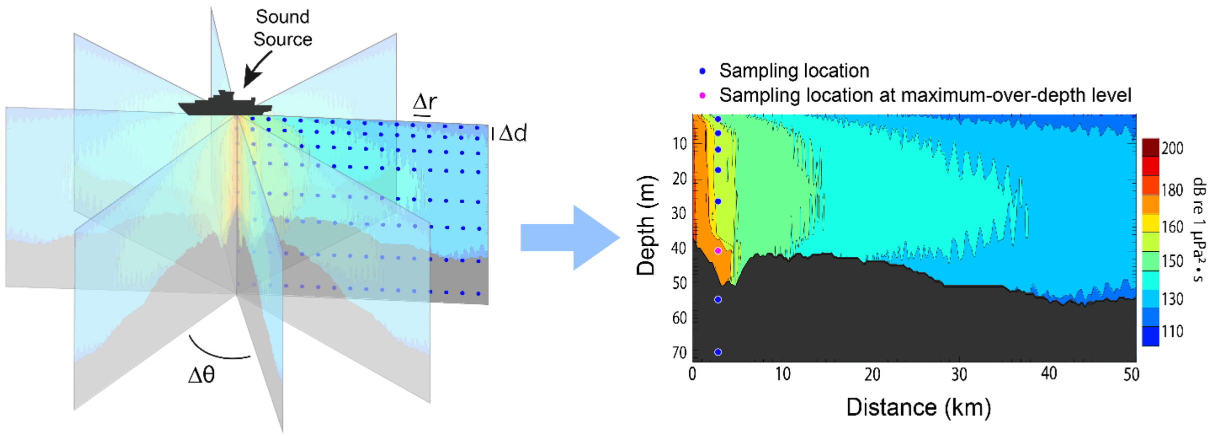

Figure 1. Representation of N×2-D and maximum-over-depth approaches

Supplementary modelling materials

1. Decidecade source levels

Table 1. Decidecade band source levels for all modelled vessel types

Band Centre Frequency (Hz)	Decidecade band source level (dB re 1 µPa·m)					
	LLS – S	LLS – M	LLS – L	OTB – S	OTB – M	OTB – L
10	126.3	128.5	129.7	148.4	150.5	152.3
13	127.3	129.5	130.8	149.4	151.5	153.3
16	128.3	130.5	131.8	150.5	152.6	154.3
20	129.3	131.6	132.8	151.5	153.6	155.4
25	130.4	132.6	133.9	152.6	154.6	156.4
32	131.4	133.7	134.9	153.6	155.7	157.5
40	132.5	134.7	136.0	154.7	156.8	158.5
50	133.5	135.8	137.0	155.7	157.8	159.6
63	134.6	136.8	138.1	156.7	158.8	160.6
79	135.6	137.8	139.1	157.8	159.9	161.6
100	136.5	138.8	140.0	158.7	160.8	162.6
126	137.4	139.6	140.9	159.5	161.6	163.4
158	138.0	140.3	141.5	160.2	162.3	164.1
200	138.4	140.7	141.9	160.6	162.7	164.5
251	138.5	140.7	142.0	160.7	162.8	164.6
316	138.3	140.5	141.8	160.4	162.5	164.3
398	137.7	140.0	141.2	159.9	162.0	163.8
501	137.0	139.2	140.5	159.1	161.2	163.0
631	136.1	138.3	139.6	158.2	160.3	162.1
794	135.1	137.3	138.6	157.3	159.4	161.1
1000	134.1	136.3	137.5	156.2	158.3	160.1
1259	133.0	135.2	136.5	155.2	157.3	159.1
1585	132.0	134.2	135.4	154.1	156.2	158.0
1995	130.9	133.1	134.4	153.1	155.2	156.9
2512	129.9	132.1	133.3	152.0	154.1	155.9
3162	128.8	131.0	132.3	151.0	153.1	154.9
3981	127.8	130.0	131.3	150.0	152.1	153.8
5012	126.8	129.0	130.2	148.9	151.0	152.8
6310	125.7	128.0	129.2	147.9	150.0	151.8
7943	124.7	126.9	128.2	146.9	149.0	150.8
10000	123.7	125.9	127.2	145.9	148.0	149.7
12589	122.7	124.9	126.2	144.9	147.0	148.7
15849	121.7	123.9	125.2	143.8	145.9	147.7
19953	120.7	122.9	124.2	142.8	144.9	146.7
25119	119.7	121.9	123.1	141.8	143.9	145.7

2. Slice plots

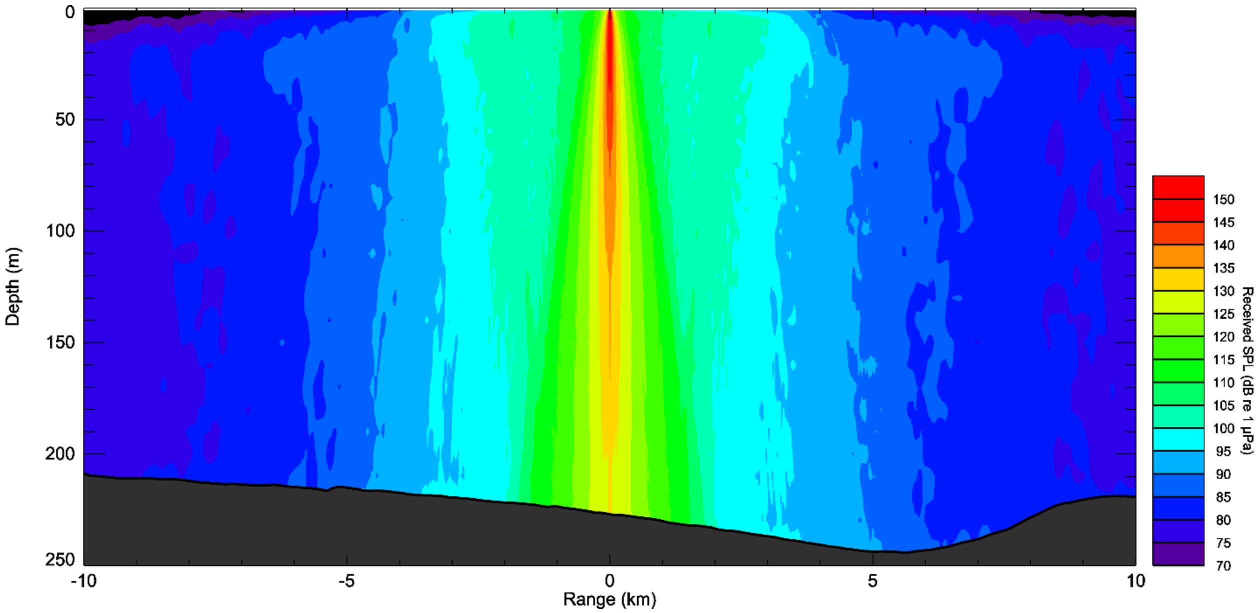

Figure 1. Vertical slice plot showing received SPL with distance from the source and depth in the water column for the large OTB vessel at location B1. The positive x direction is North

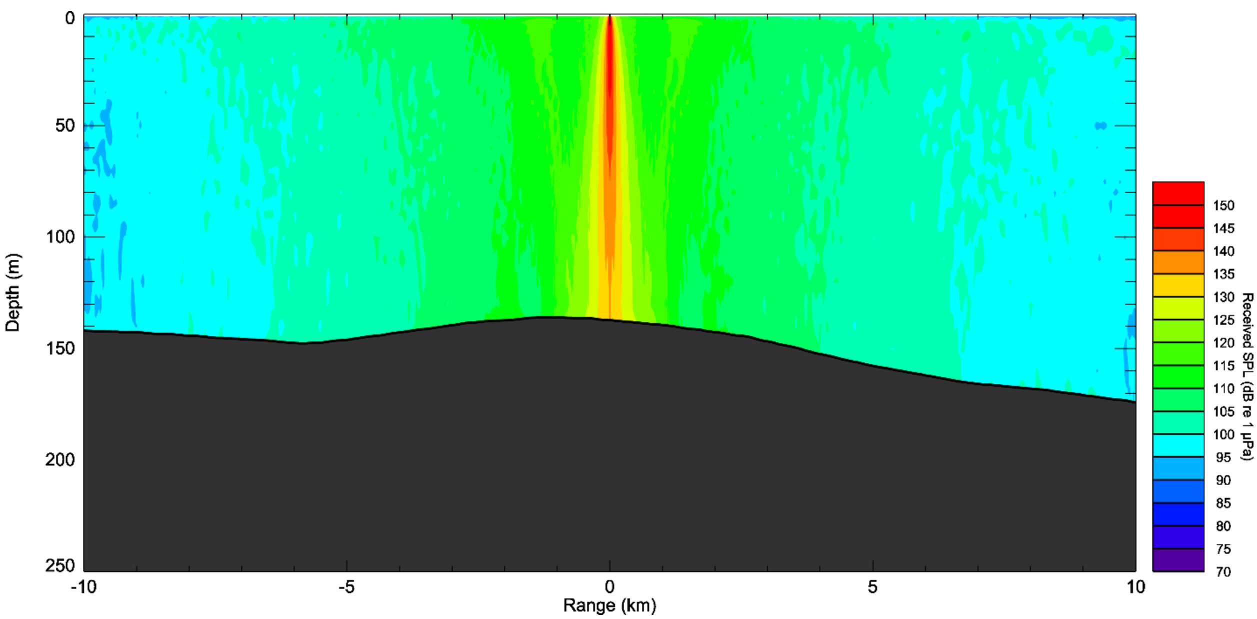

Figure 2. Vertical slice plot showing received SPL with distance from the source and depth in the water column for the large OTB vessel at location C1. The positive x direction is North

3. Multiple vessel scenario source locations

The types of vessel modelled at each location for the multiple vessel scenarios are presented graphically in Figures 3 to 5. The types of vessel and source locations are the same in Zone B for Scenarios 1 and 2.

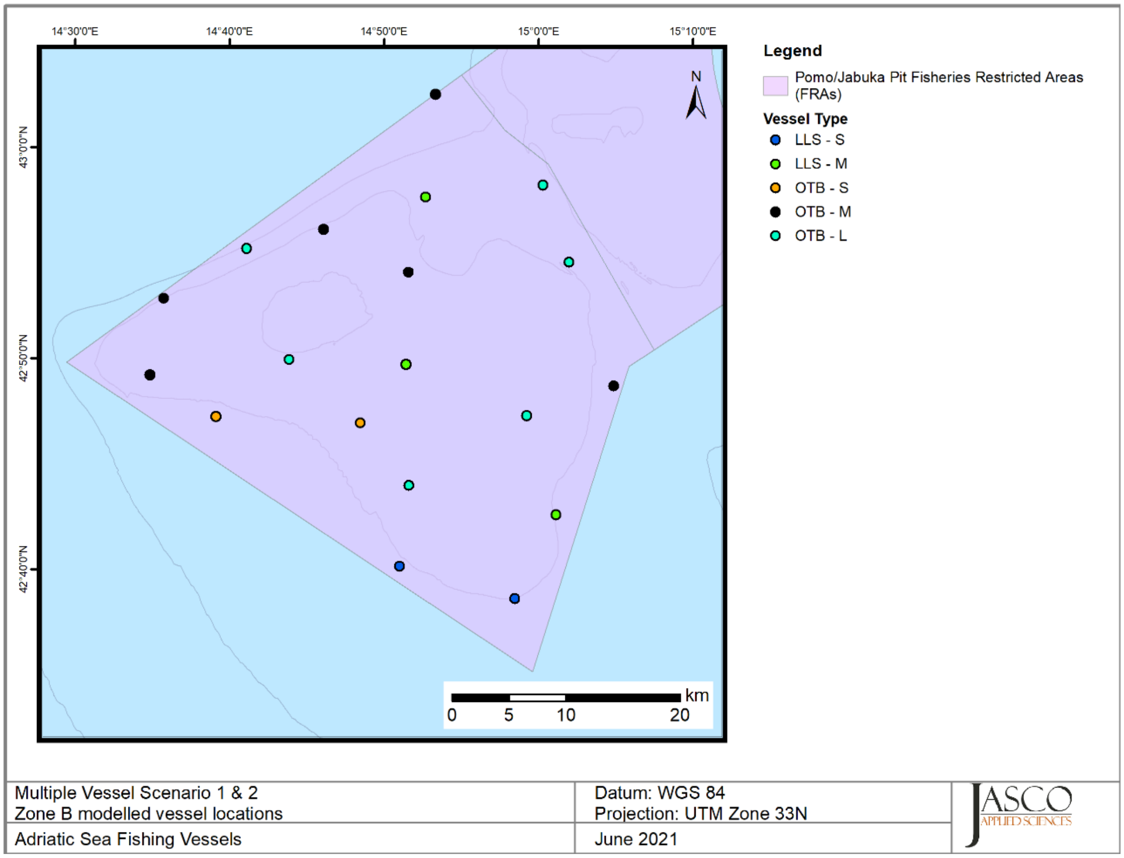

Figure 3. Modelled source locations in Zone B for multiple vessel Scenarios 1 and 2

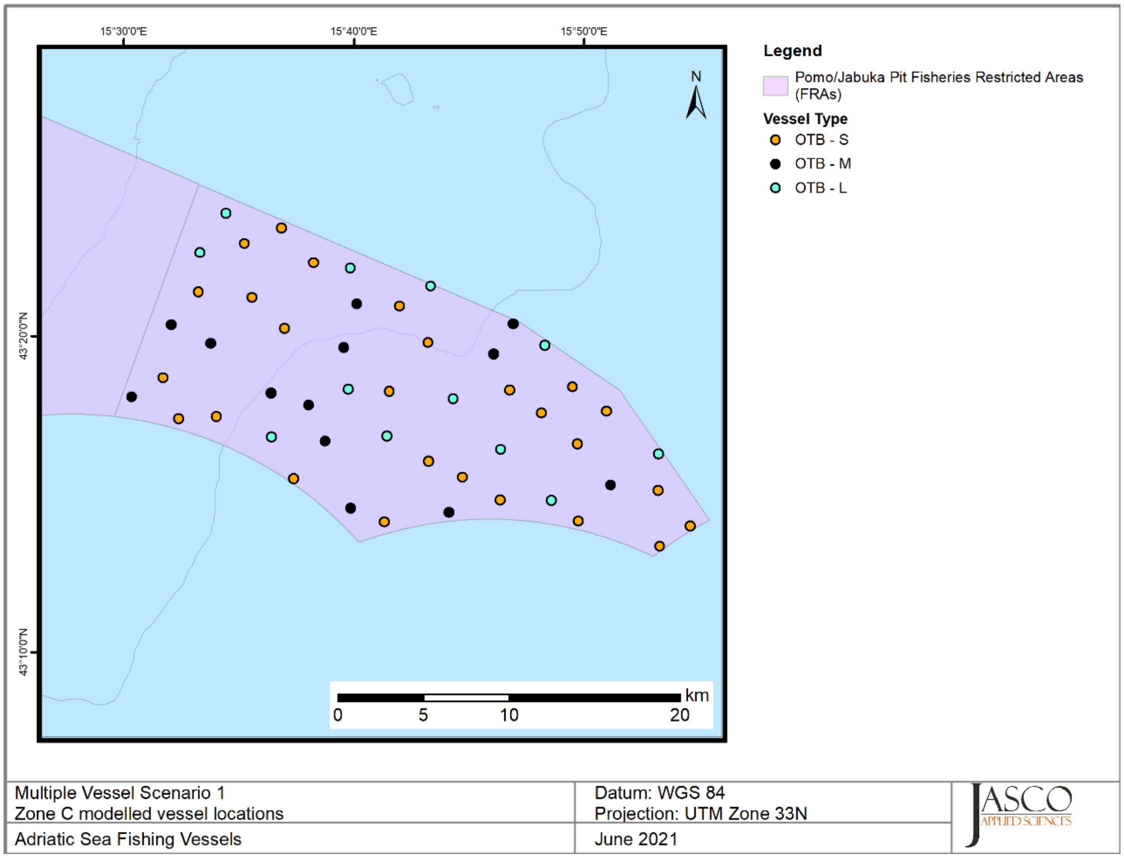

Figure C-4. Modelled source locations in Zone C for multiple vessel Scenario 1

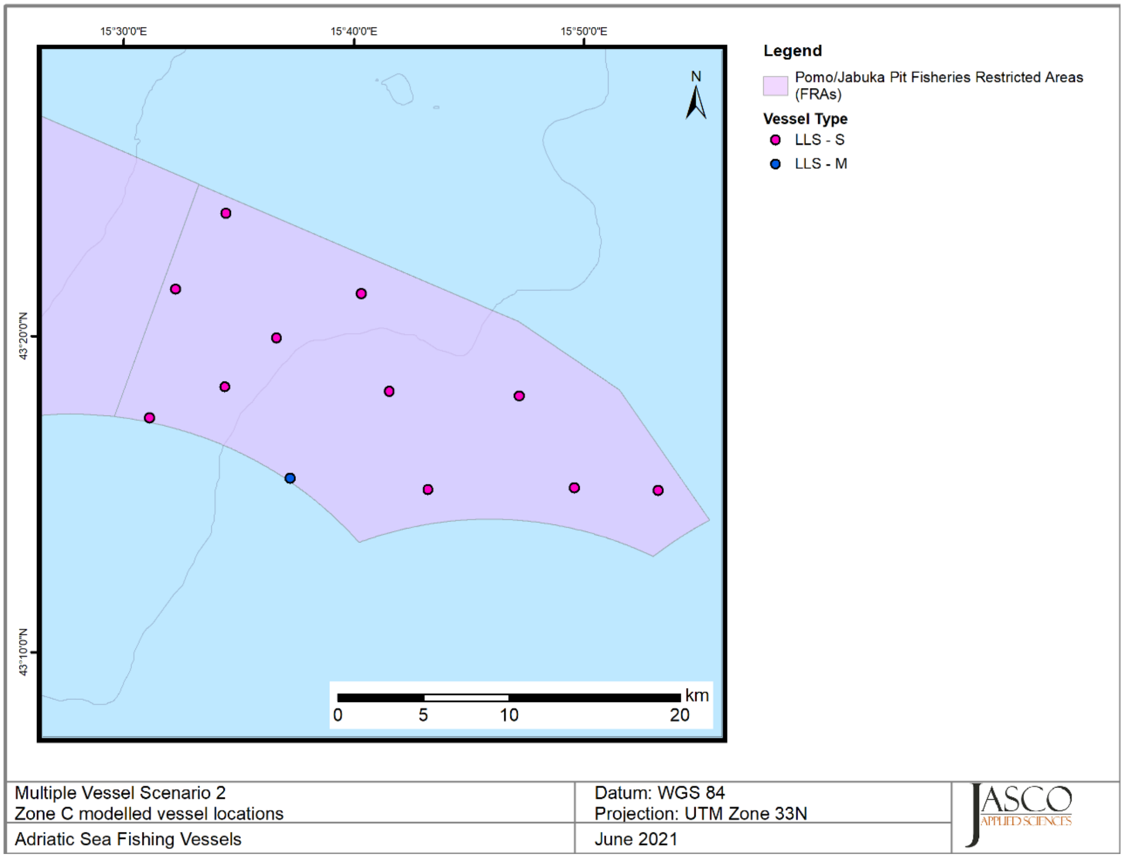

Figure C-5. Modelled source locations in Zone C for multiple vessel Scenario 2