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DELIVERABLE 6.2

D 6.2 "Joint proposal of a methodology to establish thresholds values for impulsive noise in the Mediterranean Sea Region"

Deliverable: D6.2. Joint proposal of a methodology to establish thresholds values in the Mediterranean Sea Region

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Abstract

This document is the Deliverable "***D6.2. Joint proposal of a methodology to establish thresholds***" of the QUIETMED2 project funded by the DG Environment of the European Commission within the call "DG ENV/MSFD 2018 call". This call funds projects to support the implementation of the second cycle of the Marine Strategy Framework Directive (2008/56/EC) (hereinafter referred to as MSFD), in particular to implement the new GES Decision (Commission Decision (EU) 2017/848 of 17 May 2017 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU) and Programmes of Measures according to Article 13 of the MSFD.

The QUIETMED2 project aims to support Member States Competent Authorities in the Assessment of the extent to which GES on Descriptor 11 (D11C1: underwater impulsive noise) has been achieved in the Mediterranean Region by providing practical outcomes to implement the new GES Decision through:

- a joint proposal for an indicator of the risk of impact caused by impulsive noise in the Mediterranean Region;
- a common methodology for Competent Authorities to establish thresholds values, together with associated lists of elements and integration rules;
- a data and information tool to support the implementation of the monitoring programmes on impulsive noise based on the current ACCOBAMS joint register which will be demonstrated on;
- an operational pilot of the tool;
- several activities to boost current regional cooperation efforts of Barcelona Convention developing new Mediterranean Region cooperation measures.

The main goal of this document is to develop a joint proposal of a methodology for the establishment of thresholds to implement the GES decision regarding the D11 in the Mediterranean Region.

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List of Abbreviations

CTN	Centro Tecnológico Naval y del Mar
ACCOBAMS	Permanent Secretariat of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area
DFMR	Department of Fisheries and Marine Research
IZVRS	Inštitut za vode Republike Slovenije/Institute for water of the Republic of Slovenia
HCMR	Hellenic Centre for Marine Research
IOF	Institute of Oceanography and Fisheries
UM	University of Malta -The Conservation Biology Research Group
POLIMI-DICA	Politecnico di Milano-Department of Civil and Environmental Engineering
GSNEW	General Secretariat for Natural Environment and Water
SPA/RAC	Specially Protected Areas Regional Activity Centre
ICES	International Council for the Exploration of the Sea
MSFD	Marine Strategy Framework Directive
MSCG	Marine Strategy Coordination Group
GES	Good Environmental Status
MS	Member States
MED	Mediterranean Sea Region
CA	Competent Authority
NR	National Representative
SO	Specific Objective
CIS WG	Common Implementation Strategy Working Group
WG GES	GES Working Group
Comm. Dec. 2017	Commission Decision 2017/848/EU
TVs	Threshold Values
D11	Descriptor 11
RL	Received Levels
PUHA	Potentially Usable Habitat Area
HS	Habitat Suitability
EHAI	Exposed Habitat Area Index
DUNE	Duration of Noise Event
SPL	Sound Pressure Level
SEL	Sound Exposed Level
INR-MED	Impulsive Noise Register for the Mediterranean Sea

1. Introduction

The QUIETMED2 Project is funded by DG Environment of the European Commission within the call "DG ENV/MSFD Second Cycle/2018". This call funds the next phase of MSFD implementation, in particular, to implement the new GES Decision (Commission Decision (EU) 2017/848 of 17 May 2017 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU) and Programmes of Measures according Article 13 of the MSFD.

The QUIETMED2 project aims to enhance cooperation among Member States (MS) in the Mediterranean Sea Region (MED) to implement the Second Cycle of the Marine Directive and in particular to assist them in the preparation of their MSFD reports through the following specific objectives:

- Develop and implement a candidate impact indicator in the Mediterranean Region for Criterion D11C1.
- Make a joint proposal of a methodology to establish threshold values, list of elements and integration rules to implement the GES decision in reference to D11 in the Mediterranean Region.
- Build an efficient data and information tool to support the implementation of the Criterion D11C1 and the update of the monitoring programmes of Impulsive Noise according to the new GES Decision.
- Perform an operational pilot of an impulsive noise impact monitoring programme implemented with the updated Joint register to demonstrate its feasibility.
- Promote Mediterranean Region Coordination by i) boosting current regional cooperation efforts of Barcelona Convention and others and ii) developing new cooperation measures.
- Enhance collaboration among a wide network of stakeholders through the dissemination of the project results, knowledge share and networking.

To achieve its objectives, the project is divided in 3 work packages around 3 priorities and 10 activities whose relationships are shown in Figure 1.

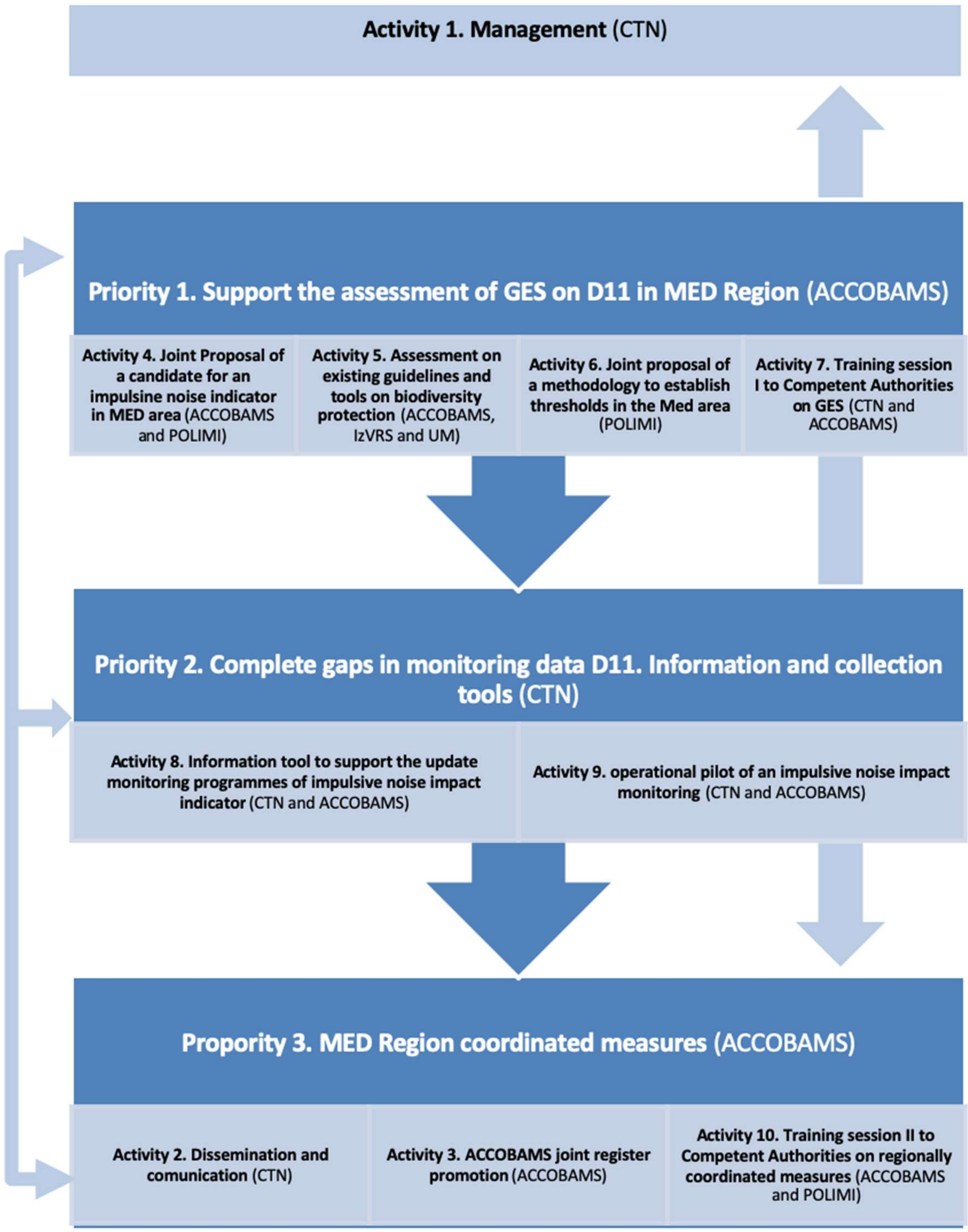

Figure 1. Work Plan Structure

The project is developed by a consortium made up of 11 entities coordinated by CTN and it has a duration of 24 months starting in February 2019.

Activity 6 of QUIETMED2 Project has the following specific objectives:

- Establishment of effective links with MSFD Common Implementation Strategy Working Group (CIS WG) (mainly TG Noise) to guarantee coordination across the regions or subregions and to MS national administrations.
- Identify key representative/s in GES Working Group (WG GES).
- Identify national and regional barriers and difficulties for the establishment of thresholds, request information during the training session and planned workshop with Competent Authorities (CA) (see Deliverable 6.1 "*National barriers and difficulties for the establishment of thresholds – summary report*").
- Review and assessment of the existing documents from other projects and initiatives and CIS WG.
- Identification of requirements to include additional functionalities into the Impulsive Noise Register for the Mediterranean Sea (INR-MED).
- Developing a joint proposal methodology to establish Thresholds Values (TVs), lists of elements and integration rules to implement the GES decision concerning the D11C1 in the MED.
- Development of recommendations about how to implement the methodology to establish thresholds in the MED.
- Results' implementation of the tool for impulsive noise (D11C1-MSFD) monitoring and assessment in the Mediterranean Sea Region.

This document addresses the issue related to developing a joint proposal methodology to establish TVs for D11C1 (anthropogenic impulsive noise in water).

2. Threshold Value definition in Commission Decision 2017/848/EU

In 2008, the European Commission approved the Marine Strategy Framework Directive (MSFD, 2008/56/EC; Commission Decision 2008) which was the new legislation aimed to achieve and maintain Good Environmental Status (GES) in EU waters by 2020. After consulting all interested parties, the Commission issued the decision on criteria and methodological standards for the GES of marine waters for implementation of the MSFD (Commission Decision 2010/477/EU). This defined the qualitative description of GES in relation to 11 descriptors, along with a set of related criteria and indicators to be applied for quantitative assessment. The new Commission Decision 2017/848/EU (Comm. Dec. 2017) lays down criteria and methodological standards on GES of marine waters and specifications and standardised methods for monitoring and assessment, and repeals Decision 2010/477/EU. This new Decision requires the setting of "*threshold values*" (TVs), thereby contributing to an improved and clearer way to achieve the environmental objectives.

Article 2 of the Comm. Dec. 2017 introduced the definition of TVs as follows:

*'**threshold value**' means a value or range of values that allows for an assessment of the quality level achieved for a particular criterion, thereby contributing to the assessment of the extent to which good environmental status is being achieved.*

For Descriptor 11, the Commission Decision requires EU MS to establish TVs to ensure that levels of anthropogenic noise do not exceed levels that adversely affect populations of marine animals.
According to *Article 4*, EU MS should establish TVs through cooperation at Union level, taking into account regional or sub-regional specificities (i.e. different biotic and abiotic characteristics of the regions, subregions and subdivisions), allowing the comparison between marine areas, but they also should be consistent with Union legislation.
TVs should also be set on the basis of the precautionary principle, reflecting the potential risks to the marine environment (Comm. Dec. 2017, Point 13).
TVs should be specified and, consequently, contribute to MS' determination of a set of characteristics for GES and inform their assessment of the extent to which GES is being achieved (Comm. Dec. 2017, Points 6 and 8).

The Comm. Dec. 2017 also requires that criteria, including TVs, methodological standards, specifications and standardised methods for monitoring and assessment should be based on the best available science. To date, most of the MS are still far from declaring thresholds as per definition (see Deliverable 6.1 "*National barriers and difficulties for the establishment of thresholds – summary report*" for further details).

3. Review of the methodology proposed by TG Noise

As a result of several workshops focused on setting TVs and of WG GES advice, TG Noise is proposing a unified stepwise methodological framework for the risk assessment of impulsive underwater noise (Descriptor 11 of the MSFD; Criterion D11C1), taking into account earlier approaches in EU MS, work developed in the frame of Regional Sea Conventions (OSPAR and HELCOM) (Boyd et al., 2008; Heinis et al., 2015; HELCOM 2019; Merchant et al., 2017; OSPAR 2017), and more recently in the frame of the Barcelona Convention in close cooperation with ACCOBAMS, or under development within the EU-funded project QUIETMED2. The above framework offers the possibility to select between two different approaches:

- **Habitat approach:** the determination whether GES is reached will be based on quantifying the amount (in space and time) that a predefined area (habitat), using a generic or representative species, is negatively affected by anthropogenic impulsive sound (as for example: % loss of habitat, habitat degradation);
- **Species approach:** The determination whether GES is reached will be based on quantifying the impact of anthropogenic noise on a predefined population/species or a generic indicator species (Numbers of a given species or % population that is estimated to be affected by anthropogenic impulsive noise).

3.1 The stepwise methodological framework

Methodological framework proposed by TG Noise is based on 9 steps as follows:

Step 1. Implementation of joint monitoring of impulsive sound sources, in accordance with the JRC-published monitoring guidance

The Monitoring Guidance for Underwater Noise in EU Seas (Dekeling et al., 2014), developed by TG Noise, suggested that for impulsive sound a common register should be set up at least at the Regional Sea level, based on the rationale that to obtain insight into the effects of noise, a MS may need to have information on activities taking place within adjacent waters of other MS. There are two international noise registers, a joint one for the OSPAR and HELCOM regions, managed by ICES (https://underwaternoise.ices.dk/impulsive/map.aspx); and one for the ACCOBAMS region, which covers Mediterranean and Black Seas, managed by ACCOBAMS (http://80.73.144.60/CTN_Geoportal/map/), following the OSPAR/HELCOM structure of register to be compatible. MS should continue to monitor compatible impulsive sound sources and collect it in the noise registers, which should be used as the best available knowledge when they gradually become ready for use.

Step 2. Define scope of assessment: specific purpose, area covered, period or duration

As previously stated, the Article 4 of the Comm. Dec. 2017 requires that EU MS set TVs through cooperation at Union level, taking into account regional or sub-regional specificities (i.e., scales, species or other specific ecosystems). Given that underwater sound can travel over long ranges, across boundaries, and the populations potentially affected can be of larger scale (regional or subregional level) than a single MS's territory, to have ecological relevance a larger scale assessment is a better option than assessment by a single MS. However, this approach will be more complicated in the Mediterranean or Black Seas than in the Baltic and North Seas, because a greater proportion of non–EU countries are involved. The aim of these assessments is to ensure that GES is achieved.

For D11C1, this means that cumulative impacts associated with noise-generating activities should be assessed, rather than that of individual activities, projects or programmes (Van der Graaf et al., 2012). Regarding the assessment time period or duration, there is not enough experience on these data to provide concrete advice over the best period; however, since the criterion addresses cumulative effects, TG Noise advises that MSFD assessments should cover multiple years (a relatively long period of time in order to include periods that could be dependent on specific situations in the assessment area), without providing any kind of concrete guidance on temporal scale.

Step 3. Decide on use of indicator/representative species or other method (e.g. habitat) to define sound characteristics likely to affect populations of marine animals

As mentioned above, TG Noise proposed two different approaches of quantifying the impact of underwater sound: a "*species-oriented approach*", aiming to quantify the sound exposure of a predefined species or hearing group/population or a generic indicator species; a "*habitat approach*", aiming to quantify the amount of a predefined habitat that is negatively affected (i.e., where there is potential for disturbance leading to displacement). For both cases, in order to choose one or more indicator species or habitat, different aspects should be considered such as hearing sensitivity, vulnerability to sound, data availability, etc. Furthermore, the "*compatibility with assessments under other MSFD descriptors*" (e.g., Descriptor 1 - Biodiversity) and the "*threat status*" of the species should be taken into account. As mentioned in Comm. Dec. 2017, the precautionary principle must be followed. This is feasible only with a habitat-based approach since there are regions or subregions where knowledge about species distribution and abundance, that would enable to implement a species-based approach, is still very poor or not available.

Step 4. Define sound characteristics to be used in the assessment

Quantifying the level of anthropogenic pressure on a species/habitat is a key element for the TVs implementation. In order to quantify the affected area by a noise source, it is necessary to define the source characteristics (e.g., sound pressure levels, duration, relevant frequencies, etc.) and identify areas where the impulsive noise is emitted, to allow estimation of the potential range of effects.

Step 5. Produce pressure (activity) maps based on impulsive noise register data and the sound characteristics chosen

To produce pressure maps, the area that is ensonified by impulsive sound needs to be quantified. The methods for deriving effect distances are:

- Assume the effect covers the area (or multipliers of it) of the Noise Register-block that the activity takes place;
- Use of sound propagation modelling to determine distances to relevant response sound level TVs (or dose-response relationships);
- Use of observed effects ranges from the scientific literature that are species- and source-specific or extrapolated from a suitable proxy.

Where the first approach is less detailed, it will directly give an indication what proportion of the total assessed area may be affected by anthropogenic sound. For the second approach, assumptions may be needed for factors such as source properties, propagation conditions, species and habitats, while additional aspects that should be considered include: the "*context*" (e.g., the activities of the animals such as feeding, breeding; the past experiences of the animals), which might affect responses; the "*distance to source*", which can be an important factor in some situations (Bain and Williams, 2006; DeRuiter et al., 2013; Wensveen et al., 2019). The third approach (standardised effect ranges) is a complex task, involving a series of parameters regarding source, environmental and representative receiver, and the construction of related tables or tools would require a separate project. At this step MS have a first opportunity to define TV at the pressure level. "*Such threshold values could be the (maximum) amount of pressure (with the metric still to be defined) that is considered to be the point where good environmental status still occurs. Such a pressure threshold value would still require some insight to the relationship between pressure (exposure to underwater sound) and impact*". At activity level, a TV could be defined as "*the maximum allowed sound pressure level at a certain distance to the source".*

Step 6. Specify estimated species densities or habitat area (of one or more indicator species, if such have been chosen)

Both species/habitat approaches need data (e.g., absolute or relative density, distribution, species potential habitat) to quantify the impact from the footprint of accumulated sound sources over a given time period. Furthermore, it should be ensured that variability in animal distribution (e.g., due to seasonality) and activities of the animals (e.g., foraging or breeding) or habitat importance for these activities, are taken into account.

Step 7. Produce 'sound exposure' risk maps combining sound pressure and species distribution or habitat area

The impulsive noise pressure maps and the animal density or distribution or habitat coverage are combined to produce exposure maps, which show the spatial and temporal overlap of these components.

Step 8. Compute proportion of species population (if such data are available) or proportion of habitat area that may be exposed to sound, potentially using an exposure curve or index or other metrics which could be used as basis to define GES thresholds both in terms of spatial and temporal extent

To explain these data, identified options include either the '*exposure curve*' or the '*exposure index*' (Merchant et al., 2017) or other metrics which could be used as a basis to define GES thresholds both in terms of spatial and temporal extent. The exposure curve by Merchant et al. (2017) quantifies the proportion of time that a given proportion of a habitat or population is exposed to anthropogenic underwater noise. The exposure index, derived from the exposure curve, combines the proportion of a habitat or population that has been exposed to impulsive noise sources during the assessment period with the duration of that exposure. When exposure maps have been produced by MS, there is a second opportunity to define TVs. Such a TV could be the (maximum) amount of animal exposure or habitat affected, in time and space (with the metric still to be defined), that is considered to be the point where GES still occurs. Although such a TV is more clearly aligned to the Comm. Dec. 2017 than a pressure-based TV, other information is needed to correlate exposure to impacts at the population level in order to make an assessment of environmental status. Finally, a critical issue is to effectively translate the scientifically derived threshold into a policy target while taking into consideration the specificities at the regional or subregional scale.

Step 9. Determine potential for negative effects at population level (habitat displacement/avoidance/loss)

To date, it's still not clear which effects of impulsive noise affect species at the population level, due to the fundamental knowledge gaps, and so this remains a priority for research topic (Borsani et al., 2014; OSPAR, 2017). However, a scientifically justified case can be made that many or most of these impacts could validly and logically result in negative consequences to the population, especially using the precautionary approach, even without requiring conclusive evidence.

3.2 Main recommendations and gaps highlighted by TG Noise for the MED

The Comm. Dec. 2017 requires EU MS to develop TVs for the Descriptor 11 "*underwater noise*", which includes both impulsive (D11C1) and continuous (D11C2) anthropogenic underwater sounds, contributing to ensure that levels of anthropogenic noise do not exceed levels that adversely affect populations of marine animals. TG Noise, in consultation with the EC and the WG GES, was tasked to provide further advice to EU MS on the development of TVs for D11.

In order to enable EU MS to further develop TVs for the assessment of GES, TG Noise advises MS to:

- continue with the monitoring programmes for underwater sound in order to complement and improve the quality of the data at pressure level;
- continue to cooperate in order to provide options to define TVs at appropriate geographical levels (e.g., regional or subregional or other sub-unit level);
- continue to address the existing knowledge gaps, including the impacts of anthropogenic noise on the welfare of cetacean populations as well as those of other species (i.e., fish, invertebrates) and the marine ecosystem in general.

4. Applicability of the habitat approach in the Mediterranean context

The bathymetry of the Mediterranean Sea is extremely variable, ranging from shallow waters with an extended continental shelf to deep water zones with steep continental slopes and seamounts. This heterogeneity leads to a wide variety of habitats and therefore to the presence of different communities of species, species richness and biodiversity. The Mediterranean Sea presents a high number of cetacean species (see Deliverable 5.1 "*Set of cetacean species representative at national, subregional and regional level in the Mediterranean Region*"), so a multi-species habitat approach would be the recommended for the Mediterranean Region.

4.1 Scale of assessment in the Mediterranean Region

Spatial assessment areas are needed to determine the environmental status in the Mediterranean Region. According to the *Article 4* of the MSFD, in order to take into account the specificities of a particular area, MS may implement this Directive by reference to subdivisions at the appropriate level of the Mediterranean Region (Figure 2; https://www.eea.europa.eu/data-and-maps/data/msfd-regions-and-subregions-1), provided that such subdivisions are delimited in a manner compatible with the following marine subregions (Figure 3):

- the Western Mediterranean Sea;
- the Adriatic Sea;
- the Ionian Sea and the Central Mediterranean Sea;
- the Aegean-Levantine Sea.

Figure 2. The MSFD marine region of interest: the Mediterranean Sea.

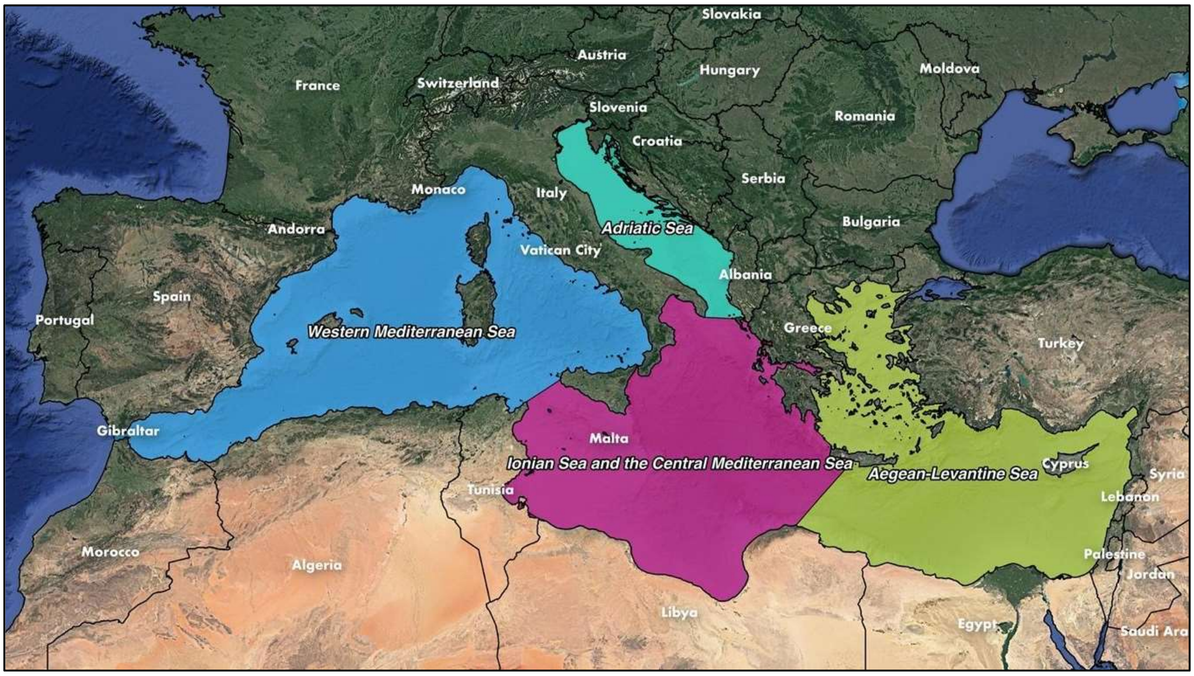

Figure 3. The MSFD Mediterranean marine subregions.

The Impulsive Noise Register in the Mediterranean Sea Region (INR-MED) is a tool for the calculation of the spatial distribution and the temporal extent of D11C1. However, as the MSFD activities progress towards achieving GES, the assessment units may change, and the TVs may be adapted to these changes accordingly.

4.2 Applicability of the habitat approach in the Mediterranean Region

The heterogeneity of the knowledge level about species' presence among different countries makes the identification of representative target species at national or subregional level (i.e., Levantine Sea, Aegean Sea, Adriatic Sea, Tyrrhenian Sea, Central Mediterranean Sea, etc.) a difficult task. In addition, the Mediterranean subregions present a different level of biodiversity in terms of the numbers of cetacean species. In the Northern Adriatic Sea, for example, the dominant species is the Common bottlenose dolphin, *Tursiops truncatus* (Montagu, 1821) (Bearzi et al., 1997, 1999, 2008; Fortuna, 2007; Fortuna et al., 2018a, 2018b; Genov et al., 2008, 2016, 2019), while in many other parts of the Mediterranean Sea the dominant species is striped dolphin (Aguilar and Gaspari, 2012; Notarbartolo di Sciara, 2016). In addition, in specific Mediterranean Sea areas some autochthonous subspecies are present, e.g., the Black Sea harbour porpoise subspecies, *Phocoena p. relicta* (Abel, 1905), which is regularly present in the Northern Aegean Sea (Birkun and Frantzis, 2008; Fontaine, 2016).

Such heterogeneity causes further difficulties in the implementation of harmonized methodologies enabling GES comparisons among subregions (as requested by Comm. Dec. 2017).

The use of habitat suitability models, developed based on data collected in the field, is expected to facilitate the process allowing estimation of the potential habitat of each species of interest in the MED.

For this reason, the **habitat approach** is proposed to be used in the methodological framework for a risk-based assessment of D11C1:

"*determination of GES thresholds based on the amount (in space and time) that a pre-defined area (habitat) is negatively affected by anthropogenic noise*".

Throughout the last decades, ecologists have focused on the applicability of habitat thresholds for conservation purposes (Andrén, 1994; Johnson, 2013; Lindenmayer and Luck, 2005; Mönkkönen and Reunanen, 1999; Pe'er et al., 2014; Swift and Hannon, 2010; Van der Hoek et al., 2015). As highlighted by Pe'er et al. (2014) a potentially important concept, also for the conservation planning and policy, is the Minimum Area Requirements of species (MAR), defining the amount of space (suitable habitat) that is required for the long-term persistence of a population. Conservation actions to safeguard both species and their habitats should be ideally based on careful analyses of species- and area-specific long-term data.

Several works, focused on the sensitivities of threshold models and estimates, lead to a general consensus that thresholds largely depend on factors such as the statistical approach used, the scale of the study, the focal species, and the geographic location of the threshold study (Betts et al., 2010; Ewers and Didham, 2006; Ficetola and Denoël, 2009;

Johnson, 2013; Lindenmayer and Luck, 2005; Villard and Jonsson, 2009). Interpreting habitat thresholds, the use of amounts or percentages of habitat at which dramatic changes take place in the state of a population or species as conservation targets may be especially problematic, because thresholds vary largely across species and regions (Rhodes et al., 2008; Van der Hoek et al., 2013, 2015). One of the main messages that emerges from the above studies is that it is not always possible to define habitat in ways that are ecologically relevant to our study species (e.g., because we do not know the habitat needs of a species a priori, or because we do not have the data to assess habitat availability at the scales required for threshold modelling). Nevertheless, it is important striving not to overgeneralize and simplify the habitat variables too much (Johnson, 2013; Lindenmayer and Luck, 2005; Van der Hoek et al., 2015) and consider instead specific descriptors of a species' habitat.

A primary step in use of threshold analyses is to identify species vulnerable to sound or habitats where these species live. Further, when habitats are protected at the most vulnerable species level ("umbrella species"), many other species are indirectly protected (Suarez-Rubio et al., 2013). To do that, we need to know the vulnerability of each representative species to the underwater impulsive noise. To better understand the level of vulnerability to sound and the potential range of the impact of impulsive noise on Mediterranean cetaceans, it is necessary to increase the knowledge about their hearing sensitivity and the characteristics of their bioacoustics. Most of the knowledge on the hearing thresholds of Mediterranean cetacean species are inferred from studies done in different areas or in captivity (see Table 1).
It is well known that underwater noise can potentially cause an impact on cetaceans (Erbe et al., 2019; Perry, 1998; Prideaux, 2017; Richardson et al., 1995; Slabbekoorn et al., 2018; Southall et al., 2007, 2019b; Weilgart, 2007; Würsig & Richardson, 2002). Several studies reported behavioural responses of cetacean species to impulsive noise. Some of the findings pertain to species present in the Mediterranean Sea, so results can be used to predict Mediterranean species' responses. However, these results clearly indicate that cetacean species are not equally sensitive to human-made noise disturbance.

In the Table 15 of the Deliverable 5.1 ("*Set of cetacean species representative at national, subregional and regional level in the Mediterranean Region*"), an overview of observed effects of noise on marine mammals has been reported, including masking, behavioural disturbance, hearing loss (i.e., Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS)), direct physical damage (i.e., the enhanced gas bubble growth and traumatic brain injury) as well as death of the receiver.

Table 1. Proposed marine mammal hearing groups for the Mediterranean cetacean species, applicable auditory weighting functions (LF, HF, VHF), auditory anatomy, and sound production are reviewed (Southall et al., 2019).

Taxon	Marine Mammal Hearing Group	Auditory Weighting Function	Audiometry	Ear Type	Auditory Modeling	Sound Production	Click Type	References
Fin Whale (*Balaenoptera physalus*)	Low-frequency cetaceans	LF	--	Mysticete middle ear, Type M cochlea	0.02 to 20 kHz	0.01 (rumble, thud, 20-Hz signal) to 1 kHz (slam)	--	Audiometry: No data Anatomical modeling: Cranford & Krysl, 2015 Acoustic: Watkins et al., 1987; Edds, 1988; Thompson et al., 1992; McDonald et al., 1995a; Charif et al., 2002; Širović et al., 2007, 2013; Weirathmueller et al., 2013
Sperm Whale (*Physeter macrocephalus*)	High-frequency cetaceans	HF	--	Physeteroid middle ear, Type I cochlea	--	SOC: 0.4 (squeal) to 9 kHz (coda) ECH: 3 to 26 kHz+	MP	Audiometry: No data Anatomical models: No data Acoustic: Backus & Schevill, 1966; Levenson, 1974; Watkins & Schevill, 1977, 1980; Watkins, 1980; Weilgart & Whitehead, 1988; Goold & Jones, 1995; Madsen et al., 2002a, 2002b; Møhl et al., 2003; Weir et al., 2007
Cuvier's Beaked Whale (*Ziphius cavirostris*)	High-frequency cetaceans	HF	--	Physeteroid middle ear	--	ECH: 28 to 47 kHz+	FM	Audiometry: No data Anatomical models: No data Acoustic: Frantzis et al., 2002; Zimmer et al., 2005; Baumann-Pickering et al., 2013b
Short Beaked Common Dolphin (*Delphinus delphis*)	High-frequency cetaceans	HF	--	Odontocete middle ear	--	SOC: 0.3 (whistle) to 44 kHz (whistles) ECH: 25 to 35 kHz+	BBHF	Audiometry: No data Anatomical models: No data Acoustic: Busnel & Dziedzic, 1966; Fish & Turl, 1976; Moore & Ridgway, 1995; Oswald et al., 2003; Ansmann et al., 2007; Petrella et al., 2012; Azzolin et al., 2014
Long Finned Pilot whale (*Globicephala melas*)	High-frequency cetaceans	HF	AEP: < 4 to 89 kHz	Odontocete middle ear	--	SOC: 0.1 (chirp, squeal) to 24 kHz (whistle)	BBHF	Audiometry: AEP: Pacini et al., 2010— n = 1 Anatomical models: No data Acoustic: Steiner, 1981; Rendell et al., 1999; Nemiroff, 2009; Azzolin et al., 2014
Risso's Dolphin (*Grampus griseus*)	High-frequency cetaceans	HF	BEH: < 1.6 to 100 kHz AEP: < 4 to 142 kHz	Odontocete middle ear, Type II cochlea	--	SOC: 0.1 (grunt) to 29 kHz (whistle) ECH: 24 to 131 kHz+	BBHF	Audiometry: BEH: Nachtigall et al., 1995—n = 1; AEP: Nachtigall et al., 2005— n = 1 Anatomical models: Wartzok & Ketten, 1999; Nummela, 2008 Acoustic: Au, 1993; Rendell et al., 1999; Corkeron et al., 2001; Philips et al., 2003; Madsen, 2004; Soldevilla et al., 2008; Smith et al., 2016
Striped Dolphin (*Stenella coeruleoalba*)	High-frequency cetaceans	HF	BEH: 2 to 154 kHz	Odontocete middle ear	--	SOC: 1 (whistle) to 34 kHz (whistles)	--	Audiometry: BEH: Kastelein et al., 2003—n = 1 Anatomical models: No data Acoustic: Oswald et al., 2003; Azzolin et al., 2013; Papale et al., 2013
Common Bottlenose Dolphin (*Tursiops truncatus*)	High-frequency cetaceans	HF	BEH: < 0.4 to 146 kHz AEP: < 5 to 169 kHz	Odontocete middle ear, Type II cochlea	0.15 to 163 kHz	SOC: 0.1 (thunk) to 165 kHz (creak) ECH: 23 to 102 kHz+	BBHF	Audiometry: BEH: Johnson, 1967; Ljungblad et al., 1982; Lemonds, 1999; Brill et al., 2001; Schlundt et al., 2008; Finneran et al., 2010—n = 6; exclude Finneran et al., 2005a, 2007; AEP: Popov & Supin, 1990; Houser & Finneran, 2006; Popov et al., 2007; Finneran et al., 2008, 2011; Houser et al., 2008; Mann et al., 2010— n > 39 Anatomical models: Ketten, 1994b; Tubelli et al., 2012f; Ketten et al., 2014a, b; Racicot et al., 2016a Acoustic: Lilly & Miller, 1961; Evans & Prescott, 1962; Lilly, 1963; Caldwell & Caldwell, 1968, 1979; Diercks et al., 1971; Evans, 1973; Au et al., 1974; Fish & Turl, 1976; Kamminga, 1979; Au & Penner, 1981; Steiner, 1981; Au et al., 1982; Wiersma, 1982; dos Santos et al., 1990; Au, 1993, 2004; Jacobs et al., 1993; Ding et al., 1995; McCowan & Reiss, 1995; Schultz et al., 1995; Connor & Smolker, 1996; Blomqvist & Amundin, 2004; Boisseau, 2005; Azevedo et al., 2007; van der Woude, 2009; Hawkins, 2010; Simard et al., 2011; Wahlberg et al., 2011b; Branstetter et al., 2012; Azzolin et al., 2014; Frankel et al., 2014; Buscaino et al., 2015; Gridley et al., 2015
Killer Whale (*Orcinus orca*)	High-frequency cetaceans	HF	BEH: < 0.2 to 140 kHz AEP: < 1 to 90 kHz	Odontocete middle ear	--	SOC: 0.1 (click burst) to 75 kHz (ultrasonic whistles) ECH: 22 to 80 kHz+	BBHF	Audiometry: BEH: Szymanski et al., 1999—n = 2; exclude Hall, 1972; AEP: Szymanski et al., 1999—n = 2; see also recent paper from Branstetter et al., 2017—n = 6, with individuals "A" and "B" excluded 90 kHz whistles) Anatomical models: No data Acoustic: Schevill & Watkins, 1966; Diercks et al., 1971; Steiner et al., 1979; Dahlheim & Awbrey, 1982; Ford & Fisher, 1983; Hoelzel & Osborne, 1986; Morton et al., 1986; Moore et al., 1988; Ford, 1989; Barrett-Lennard et al., 1996; Thomsen et al., 2001; Au et al., 2004; Van Opzeeland et al., 2005; Miller, 2006; Riesch et al., 2006, 2008; Simon & Ugarte, 2006; Simon et al., 2007; Samarra et al., 2010; Riesch & Deecke, 2011; Simonis et al., 2012
Rough-Toothed Dolphin (*Steno bredanensis*)	High-frequency cetaceans	HF	AEP: < 10 to 120 kHz	Odontocete middle ear	--	SOC: 3 (whistle) to 29 kHz (whistle) ECH: 16 to 29 kHz+	BBHF	Audiometry: AEP: Mann et al., 2010—n = 1 Anatomical models: No data Acoustic: Norris & Evans, 1967; Oswald et al., 2003; Seabra de Lima et al., 2012; Rankin et al., 2015
Harbour Porpoise (*Phocoena phocoena*)	Very high-frequency cetaceans	VHF	BEH: < 0.3 to 160 kHz AEP: < 10 to 160 kHz	Odontocete middle ear, Type I cochlea	0.25 to 220 kHz	SOC: endnote [1]ECH: 125 to 200 kHz+	NBHF	Audiometry: BEH: Kastelein et al., 2002, as updated by Kastelein, 2010; Kastelein et al., 2010, 2015—n = 3; exclude Andersen, 1970; AEP: Popov et al., 1986; Popov & Supin, 1990; Ruser et al., 2016—n = 28 Anatomical models: Ketten, 1994a; Ketten et al., 2014b; Racicot et al., 2016a Acoustic: Busnel & Dziedzic, 1966; Schevill et al., 1969; Dubrovskii et al., 1971; Møhl & Andersen, 1973; Kamminga & Wiersma, 1981; Wiersma, 1982; Verboom & Kastelein, 1995; Au et al., 1999; Kastelein et al., 1999; Teilmann et al., 2002; Villadsgaard et al., 2007; Hansen et al., 2008; Madsen et al., 2010; Clausen et al., 2011; Kyhn et al., 2013

[1] Note that Verboom & Kastelein (1995) describe whistles for *Phocoena Phocoena* with a frequency range of 0.04 to 0.6 kHz and clicks of 1,800 Hz; further, Busnel & Dziedzic (1996) also describe signals with a frequency range up to 8 kHz. However, the production of low-frequency clicks has been explained as insignificant components of high-frequency clicks or acoustic artifacts by Hansen et al. (2008), and there is no substantive updated evidence that harbor porpoises produce whistles.

According to the literature, the most vulnerable cetacean species to impulsive noise are the deep diving ones, such as Sperm whales (Fahlman et al., 2014; Farmer et al., 2018; Isojunno et al., 2016; Kvadsheim et al., 2012; Madsen P.T., 2006; Miller et al., 2009, 2012; Sivle et al., 2012; Weir C.R., 2008), Cuvier's beaked whales (de Quirós et al., 2012, 2019; DeRuiter et al., 2013; Fahlman et al., 2014; Kvadsheim et al., 2012; Miller et al., 2015; Stimpert et al., 2014; Tyack et al., 2011), and Fin whales (Borsani et al., 2008; Castellote et al., 2012; Clark and Gagnon, 2006; Southall et al., 2019a).

Southall et al. (2019b) have calculated, for each marine mammal hearing group, the associated impulsive Sound Exposure Level (SEL) and peak Sound Pressure Level (SPL) TTS- and PTS-onset criteria, and the resulting exposure thresholds which are presented in Table 2 (for further details see Southall et al., 2019b).

Table 2. TTS- and PTS-onset thresholds for cetaceans exposed to impulsive noise: SEL thresholds in dB re 1 μPa2 s under water; and peak SPL thresholds in dB re 1 μPa underwater. (Southall et al., 2019b).

Marine mammal hearing group	TTS onset: SEL (weighted)	TTS onset: Peak SPL (unweighted)	PTS onset: SEL (weighted)	PTS onset: Peak SPL (unweighted)
LF	168	213	183	219
HF	170	224	185	230
VHF	140	196	155	202

Cetacean habitat preferences are generally well documented in the literature (Arcangeli et al., 2016, 2017; Azzellino et al., 2008, 2011, 2012, 2014; Cañadas et al., 2002, 2005, 2008, 2018; Carlucci et al., 2016; Claro et al., 2020; Cotté et al., 2010; Druon et al., 2012; Giannoulaki et al., 2017; Lambert et al., 2017; Marini et al., 2015; Moulins et al., 2008; Panigada et al., 2008; Pace et al., 2018; Pennino et al., 2017; Pirotta et al., 2011, 2020; Praca et al., 2009; Tepsich et al., 2014) and the information about their occurrence, distribution and relative abundance is available and accessible.

Habitat use of seven different species of cetaceans inhabiting the Pelagos Sanctuary was studied by Azzellino et. al (2008, 2011, 2012, 2014) using long-term data series resulting from summer shipboard surveys, in an area of approximately 25,000 km^2. Presence/absence habitat models, using robust physiographic predictors (e.g., depth and slope descriptive statistics obtained through the elaboration of GEBCO one-minute Digital Atlas and gridded by means of a GIS software) as covariates, have been used to estimate the potential habitat of each species of interest (Figure 4 and Table 3).

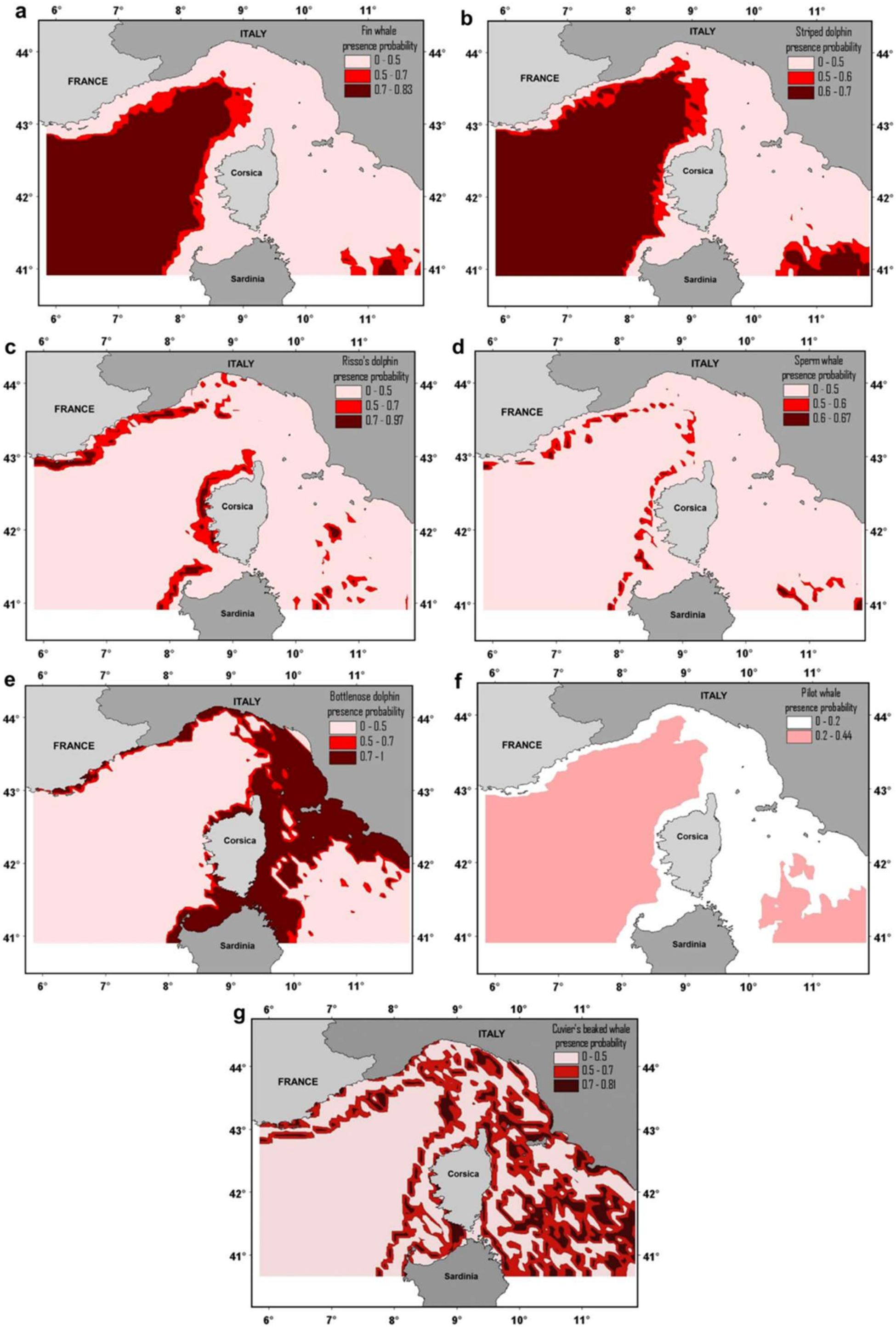

Figure 4. (a) Spatial prediction of fin whale relative presence probability. Higher probabilities of presence are indicated in red (more than 50%) and brown (more than 70%). (b) Spatial prediction of striped dolphin relative presence probability. Higher probabilities of presence are indicated in red (more than 50%) and brown (more than 60%). (c) Spatial prediction of Risso's dolphin relative presence probability. Higher probabilities of presence are indicated in red (more than 50%) and brown (more than 70%). (d) Spatial prediction of sperm whale relative presence probability. Higher probabilities of presence are indicated in red (more than 50%) and brown (more than 60%). (e) Spatial prediction of bottlenose dolphin relative presence probability. Higher probabilities of presence are indicated in red (more than 50%) and brown (more than 70%). (f) Spatial prediction of long-finned pilot whale relative presence probability. Higher probabilities of presence are indicated in light red (from 20% up to 44%). (g) Spatial prediction of Cuvier's beaked whale

relative presence probability. Higher probabilities of presence are indicated in red (more than 50%) and brown (more than 70%). (Azzellino et al., 2012).

Table 3. Confusion matrix showing the logistic models classification performances of presence and absence for every species considered. The overall percentages of presence/absence classification are shown in bold. (Azzellino et al., 2012).

	Observed	Absence	Presence	Overall percentage
Fin whale	Absence	347	217	63.3
	Presence	75	516	87.3
	Overall percentage			**75.3**
Striped dolphin	Absence	1384	501	73.3
	Presence	718	1167	61.9
	Overall percentage			**66.9**
Risso's dolphin	Absence	89	29	75.4
	Presence	30	88	74.6.
	Overall percentage			**75**
Sperm whale	Absence	68	31	68.7
	Presence	29	70	70.7
	Overall percentage			**69.7**
Common bottlenose dolphins	Absence	19	6	76
	Presence	4	21	84
	Overall percentage			**80**
Long finned pilot whales	Absence	8	15	34.8
	Presence	3	20	87
	Overall percentage			**60.9**
Cuvier's beaked whale	Absence	14	4	77.8
	Presence	7	11	61.1
	Overall percentage			**69.4**

Note: The cut value is 0.5.

The accuracy of these predictions was found adequate, and elements are given to account for the uncertainties associated with the use of models developed in areas different from their calibration site (Azzellino et al., 2011). The understanding offered by this long-term study is essential for managing the conservation status of these wide-ranging species.

This approach is potentially open to other marine species for which suitable habitat can be predicted. Regardless the existence of appropriated models, QUIETMED2 is focused on cetaceans.

5. Proposed methodology to establish thresholds in the Mediterranean Region

The development of the methodology to establish TVs for impulsive noise in the MED used a risk-based approach (i.e., the risk of impact is estimated for selected species), based on the pressure distribution) and followed the stepwise methodological framework proposed by TG Noise, as described below:

Step 1. Implementation of joint monitoring and reporting of impulsive sound sources

This step requires, first, the establishment and implementation of coordinated monitoring programmes. It is already in progress, since it is a requirement for the MSFD (*Article 11*) and Ecosystem Approach (EcAp) process (Decision IG.22/7) implementation (United Nations Environment Programme (UNEP)/ Mediterranean Action Plan (MAP) – Barcelona Convention). The Impulsive Noise Register for the Mediterranean Sea Region (INR-MED; http://80.73.144.60/CTN_Geoportal/home/) has been developed under the QUIETMED project (http://www.quietmed-project.eu; QUIETMED Deliverable 4.1 "*Joint register for impulsive noise in the Mediterranean Sea Region*", http://www.quietmed-project.eu/deliverables/), taking advantage of the work done by ICES for the OSPAR and HELCOM regions on the same topic (Drira et al., 2018; Merchant et al., 2017; Von Benda-Beckmann et al., 2017), and it is in line with Commission Decision 2017/848 and the TG-Noise's guidance documents (Dekeling et al., 2014). The INR-MED will be upgraded from a noise register to a complete tool for impulsive noise (D11C1) monitoring and assessment (e.g., to calculate the spatial distribution and the temporal extent of D11C1) in the Mediterranean Sea Region, within the QUIETMED2 project, under ACCOBAMS management (Maglio et al., 2016, 2019). Furthermore, it will be used to test new functionalities such as the implementation of this proposed methodology (QUIETMED2 Deliverable 4.1. "*Proposal for MED impulsive noise impact candidate indicator. Definition of key elements and technical specification on indicator development and application for decision-making purpose*", https://quietmed2.eu/outputs/). Reporting of noise events to the INR-MED is yet at the early stage. Within the framework of QUIETMED2, there is an effort to collect compatible impulsive noise events from the EU Mediterranean MS as well as to raise awareness of the INR-MED in the non-EU countries.

Step 2. Definition of scope of assessment: specific purpose, area covered, period or duration

The purpose of the proposed assessment is to support the implementation of the MSFD and the assessment of environmental status with respect to the cumulative effects of impulsive noise on marine animals within the MED, as well as the management/planning of activities involving impulsive noise sources. The methodology is applicable to the whole MED, and effort will be made so that the area covered include most of the MED waters;

however, the availability of data may restrict in the short-term the implementation to specific subregions and/or subdivisions (if established). The starting (testing) period of the assessment will be one year, divided into an autumn-winter (i.e., from October to March) and a spring-summer scenario (i.e., from April to September). Upon collecting data for impulsive noise events year by year, the period of assessment could be extended to multiple years.

Step 3. Definition of indicator/representative species or habitat to define sound characteristics likely to affect populations of marine animals

After assessing the knowledge and its application in legal instruments, policymaking, conservation status ranking and risks due to noise pollution for each cetacean species found to be found in the Mediterranean (Deliverable 5.1 " *Set of cetacean species representative at national, subregional and regional level in the Mediterranean Region*", https://quietmed2.eu/outputs/), it became possible to suggest representative species as indicators to support monitoring of D11-underwater noise and of D1-biodiversity according to the new GES Decision. Such candidates include regular species in the MED: Sperm whale (*Physeter macrocephalus*), Fin whale (*Balaenoptera physalus*), Cuvier's beaked whale (*Ziphius cavirostris*), Common bottlenose dolphin (*Tursiops truncatus*), Striped dolphin (*Stenella coeruleoalba*).
Additionally, if the assessment area is smaller (subregion, subdivision or other), additional representative species of that area could be identified, such as the Endangered Short-beaked common dolphin (*Delphinus delphis*) in Greek waters (Aegean-Levantine Sea subregion), the Endangered Black Sea harbour porpoise (*Phocoena phocoena relicta*) regularly present in the northern coast areas and islands of the Thracian Sea (in Nothern Aegean subdivision), and the Killer whale (*Orcinus orca*) population in the Straits of Gibraltar.
Furthermore, species rated by IUCN as Data Deficient such as Risso's dolphin (*Grampus griseus*) and Long-finned pilot whale (*Globicephala melas*), also deserve consideration and should be included as additional candidates wherever these species are found at national to subregional scales as well.

In light of the considerations previously described, rather than selecting a single representative or a generic species, it was chosen to follow the habitat approach and to assess the *GES based on the amount (in time and space) that selected habitats are negatively affected by impulsive noise*.

For six species, models for predicting the potential habitat based on bathymetric characteristics are available in Table 4 (see Azzellino et al., 2012 for further details):

Table 4. Results of the binary logistic regression analysis model by species: presence/absence of cetaceans were correlated with the statistics (i.e. mean, minimum, maximum and standard deviation) of the physiographic features depth and slope.

		B	*S.E.*	*Wald*	*df*	*P*
Fin whale	***Depth Min***	0.002	0	147.659	1	0.000
	Slope Min	0.009	0.003	9.677	1	0.002
	Constant	-3.711	0.394	116.355	1	0.000
Striped dolphin	***Depth Max***	0.001	0	188.988	1	0.000
	Slope Min	0.004	0.001	23.823	1	0.000
	Constant	-1.918	0.169	282.33	1	0.000
Risso's dolphin	***Depth SD***	0.008	0.001	50.709	1	0.000
	Constant	-1.555	0.265	34.45	1	0.000
Sperm whale	***Depth Max***	0.001	0	15.671	1	0.000
	Slope Min	0.009	0.005	3.885	1	0.049
	Slope Mean	0.018	0.006	8.8	1	0.003
	Constant	-4.144	0.888	21.788	1	0.000
Common bottlenose dolphins	***Depth Max***	-0.005	0.002	9.33	1	0.002
	Slope SD	-0.107	0.046	5.367	1	0.021
	Constant	6.921	2.315	8.941	1	0.003
Long finned pilot whales	***Depth Mean***	0.001	0.001	3.635	1	0.057
	Constant	-2.628	1.454	3.269	1	0.071
Cuvier's beaked whale	***Slope Range***	0.019	0.008	5.233	1	0.022
	Constant	-0.694	0.463	2.245	1	0.134

NOTE: The following statistics are shown: **B**: unstandardized regression coefficient; **S.E.**: Standard Error of B; **Wald** statistic for the included parameter; **df**: degrees of freedom; **P**: level of significance.

Step 4. Define sound characteristics to be used in the assessment

There is strong scientific evidence that noise can cause marine mammals to interrupt their feeding, alter their vocalizations, or leave important habitat, among other behavioural responses (Erbe et al., 2019; Perry, 1998; Prideaux, 2017; Richardson et al., 1995; Slabbekoorn et al., 2018; Southall et al., 2007, 2019a, 2019b; Weilgart, 2007; Würsig and Richardson, 2002). Gomez et al. (2016) conducted a systematic literature review (370 papers) and analysis (79 studies, 195 data cases) and summarized information on species, sound sources, context of exposure, and marine mammal behavioural responses with the goal of evaluating which variable(s) best explained marine mammal behavioural responses to noise. The analysis emphasized that behavioural responses in cetaceans (measured via a linear severity scale) were best explained by the interaction between sound source type (continuous, sonar, or seismic/explosion) and functional hearing group (a proxy for hearing capabilities). Importantly, more severe behavioural responses were not consistently associated with higher Received Levels (RL) and vice versa, suggesting that monitoring and regulation of noise effects on cetaceans' behaviour should not exclusively rely upon generic multispecies RL thresholds. The authors recommend replacing the behavioural response severity score with a response/no response dichotomous score as a measure of impact in terms of habitat loss and degradation.

It is also worthwhile to remind readers here that the effects of noise exposure on marine mammals have been typically quantified using some thresholds for the level of sound intensity (received level, RL) to which an individual (receiver) is predicted to display significant behavioural responses (often termed harassment) (NOAA, 2018; Scholik-Schlomer, 2015). In general terms, and ignoring location-specific patterns of sound signal constructive and destructive interference, RL thresholds are applied using models of sound propagation where RL decreases with increasing distance from the sound source and where the severity of the effect is expected to parallel this change in RL (Richardson et al., 1995). While RL thresholds for injury (e.g., PTS, TTS) are considered to be specific to marine mammal's functional hearing group (a proxy for individual's hearing capabilities) and are generally expressed in terms of sound pressure level (SPL) and sound exposure level (SEL) (NOAA, 2018; Southall et al., 2007), no specific RL thresholds have been proposed so far for explicitly assessing masking or stress responses, even though there are tools available to quantify the potential loss of acoustic communication space, and thus, to potentially include this effect as part of noise impact assessments (Clark et al., 2009; Erbe, 2015; Erbe et al., 2015; Hatch et al., 2012; Moore et al., 2012). Current scientific knowledge recognizes that acoustic characteristics of the sound source, the marine mammal's hearing sensitivity, and context of exposure must be considered in addition to RL and species sensitivity to predict the probability and severity of behavioural response of a marine mammal exposed to a sound source (Wartzok et al., 2003; Southall et al., 2007; Ellison et al., 2012).

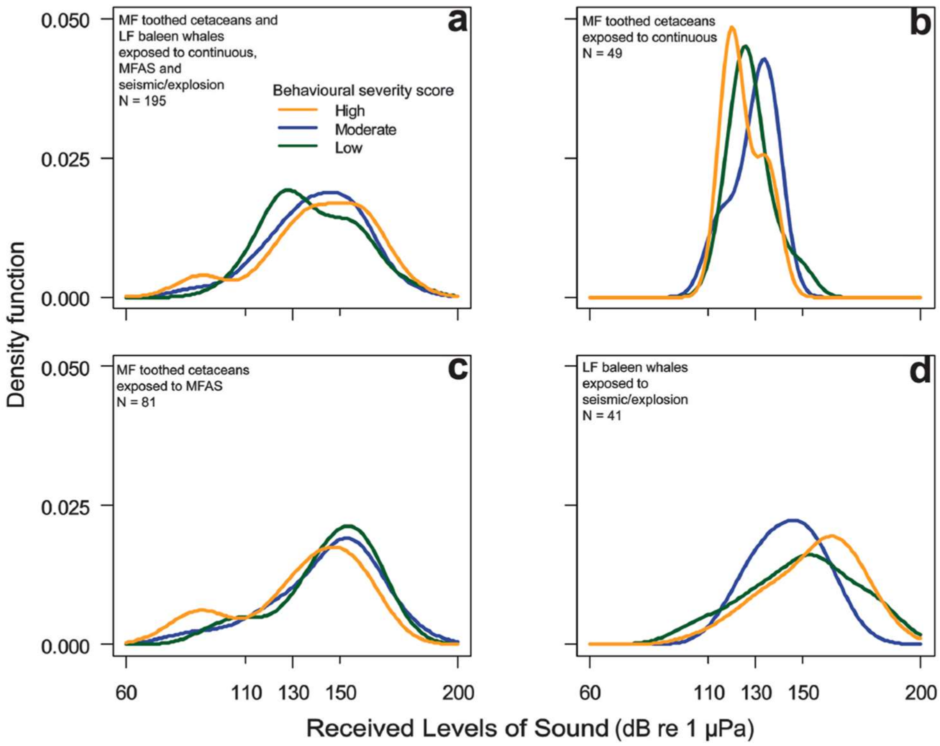

Figure 5. Probability density function of the behavioural response severity score (low, moderate, high) of low-frequency (LF) baleen whales (a, d) and mid-frequency (MF) toothed cetaceans (a, b, c) in relation to received levels (RL) of continuous mid-frequency active sonar (MFAS) and seismic/explosions sound sources. (Gomez at al., 2016).

Gomez et al. (2016) considered the three functional hearing groups proposed by Southall et al. (2007) and used by NOAA and other groups conducting environmental impact assessments with the aim of representing similarities among cetacean species in known or expected hearing capabilities: (i) low-frequency hearing (LF baleen whales), (ii) mid-frequency hearing (MF toothed cetaceans; toothed cetaceans other than those in the HF hearing category), (iii) high frequency hearing (HF toothed cetaceans; e.g., harbour porpoises (Phocoena phocoena) and river dolphins).
Based on Gomez et al. (2016) review, a **Received Sound Pressure Level of 110 dB re 1 µPa** could be set for both MF toothed cetaceans (hearing range 150 Hz to 160 kHz) and LF baleen whales (hearing range: 7 Hz to 30 kHz) hearing groups as a threshold mostly associated with a mild behavioural response. So, this RL was assumed as a reference value representing non-impacted areas in the pressure maps produced (see next step).

Step 5. Production of pressure maps based on impulsive noise register data and the sound characteristics chosen

The Impulsive Noise Registry for MED (INR-MED) will be the basic tool for producing the pressure maps. The activity maps will be constructed based on the position of sources and the number of days per semester in which impulsive sound activity occurred within a unit INR-MED cell. In the INR-MED, the grid used is the grid provided by the General

Fisheries Commission for the Mediterranean (GFCM). GFCM grid has a size of 30´x30´ (http://www.fao.org/gfcm/data/maps/grid). The size of the ensonified area (in cells units of INR-MED), within the assessment area (region, subregion or subdivision), affected by potential SPL ≥ 110 dB re 1 µPa (Figure 6), can be determined either with the use of underwater sound propagation models or of a predefined buffer (Figure 7).

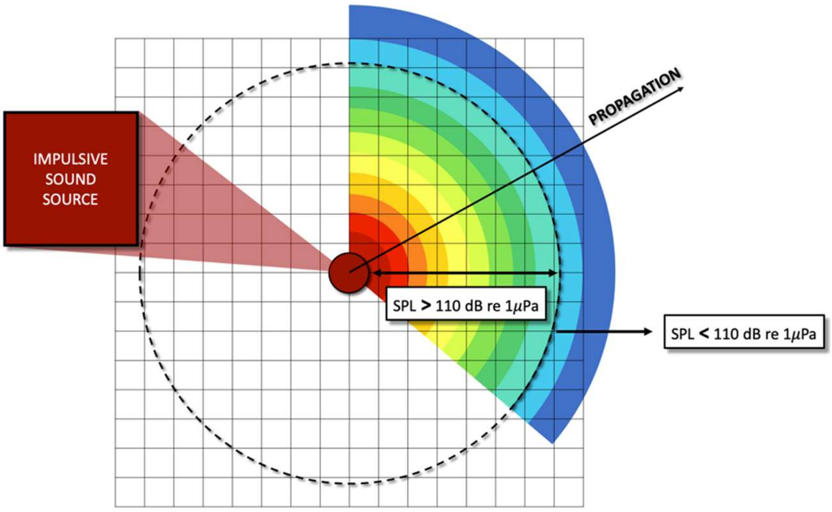

Figure 6. Example of pressure map: dark red square cell shows the impulsive noise source position; cells coloured from red to green, within the dashed circle, are cell units where SPL exceed the 110 dB re 1 µPa; cells outside the dashed circle, are the cells where the SPL is lower than 110 dB re 1 µPa.

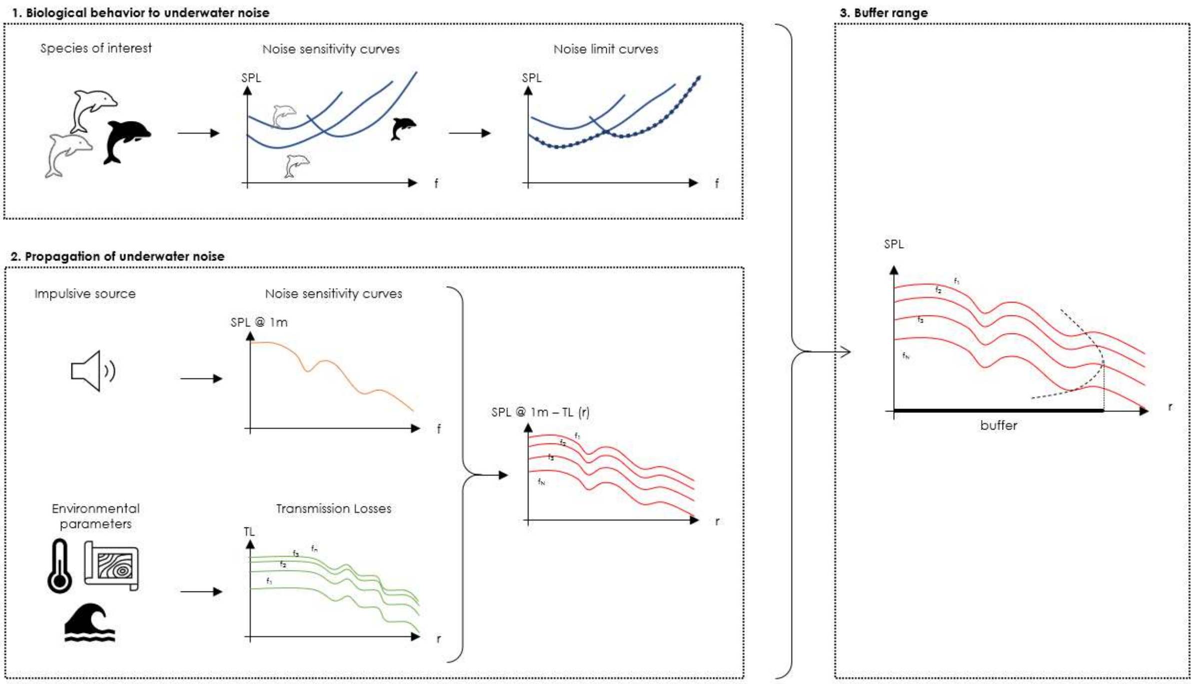

Figure 7. Block diagram showing how to obtain the buffer.

To determine the buffer, the first steps aim to establish a threshold for underwater sound pressure based on the available knowledge present in literature of cetaceans' response to underwater noise and their hearing sensitivity (Aguilar de Soto, 2006; Alves et al., 2014;

Antunes et al., 2014; DeRuiter et al., 2013; Goldbogen et al., 2013; Harris et al., 2018; Isojunno et al., 2016, 2017, 2020; Miller et al. 2009, 2012, 2014; Pirotta et al., 2012; Sivle et al., 2012; Southall et al., 2016; Tyack et al., 2011; Wensveen et al., 2015, 2019). In the case that all the needed frequency-based information for the species of interest is not available, these steps can be simplified by establishing at least a threshold value for, a priori, Sound Pressure Level (SPL), and for all frequency bands in the 1/3 octave (e.g., the 110 dB re 1uPa for 10 Hz – 10 kHz). Once the species of interest, depending on the area (MED region, subregion or subdivision) and time, have been selected, noise sensitivity curves are gathered; then, the envelope curve, based on the combination of sensitivity curves from species of interest, has been extracted to identify the lowest threshold per frequency for the selected species (Figure 7.1).

As a second step, for each impulsive source a SPL at 1 m from the source is determined as well as its directionality and duration, considering the environmental setting and the bathymetry. The best propagation model (Figure 8) is selected and simulations are carried out for different directions, for all depths, and for all 1/3 octave frequency bands between 10 Hz and 10 kHz (or higher if there are indications that vulnerable species may present some type of response) up to a distance typically greater than any expected buffer (e.g. 100 km); with the sound emission spectrum of the source and the transmission losses provided by the underwater propagation models, the sound pressure levels are obtained (Figure 9) as a function of the distance, depth and frequency (Figure 7.2).

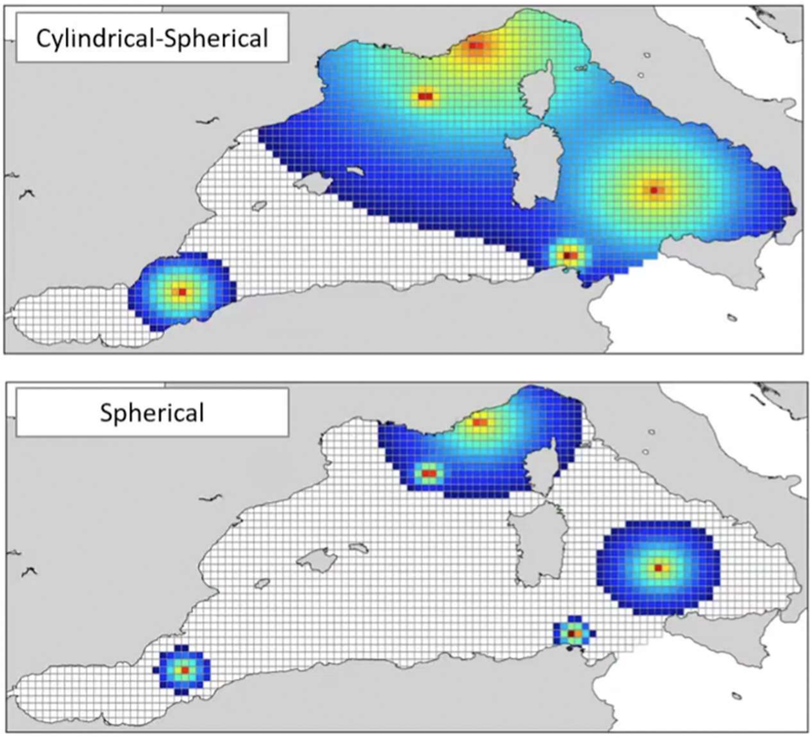

Figure 8. Example of two possible underwater propagation models: cylindrical-spherical (20·log[r]) and spherical (15·log[r]).

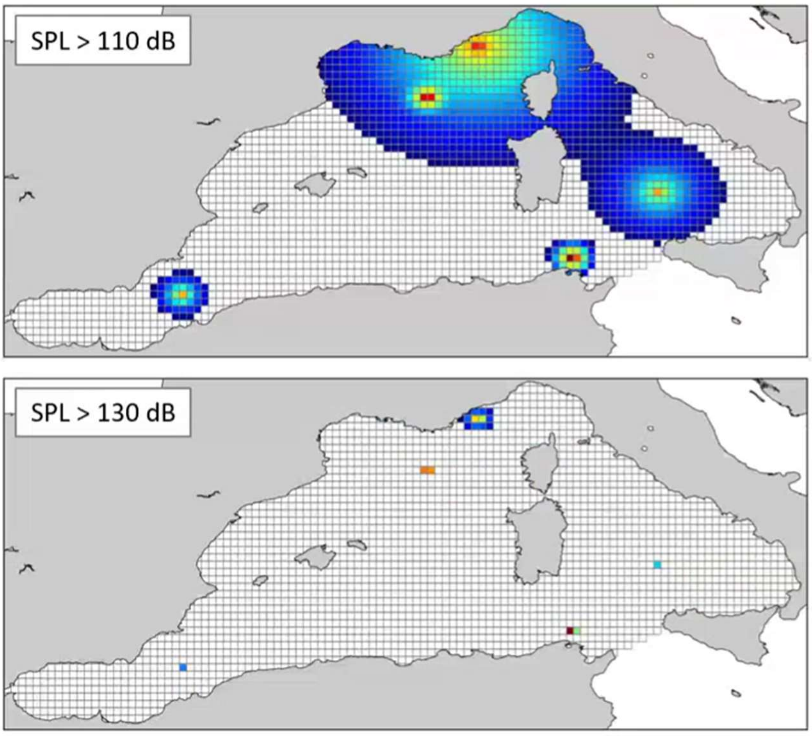

Figure 9. Example of the same spherical underwater propagation model with reference threshold values from 110 dB re 1µPa to 150 dB re 1µPa such as in Gomez et al., 2016.

Comparing the species RL with the propagated SPL obtained, for each 1/3 octave band, the distance at which the propagated SPL no longer exceeds the RL limit for each 1/3 octave band is obtained (Figure 7.3).

In these steps the physical quantity to be limited has been considered to be the SPL, but the same methodology could be implemented for SEL or other metrics, and the most conservative buffer should be chosen (Figure 10).

Further details on this analysis are reported in the ANNEX I of this deliverable.

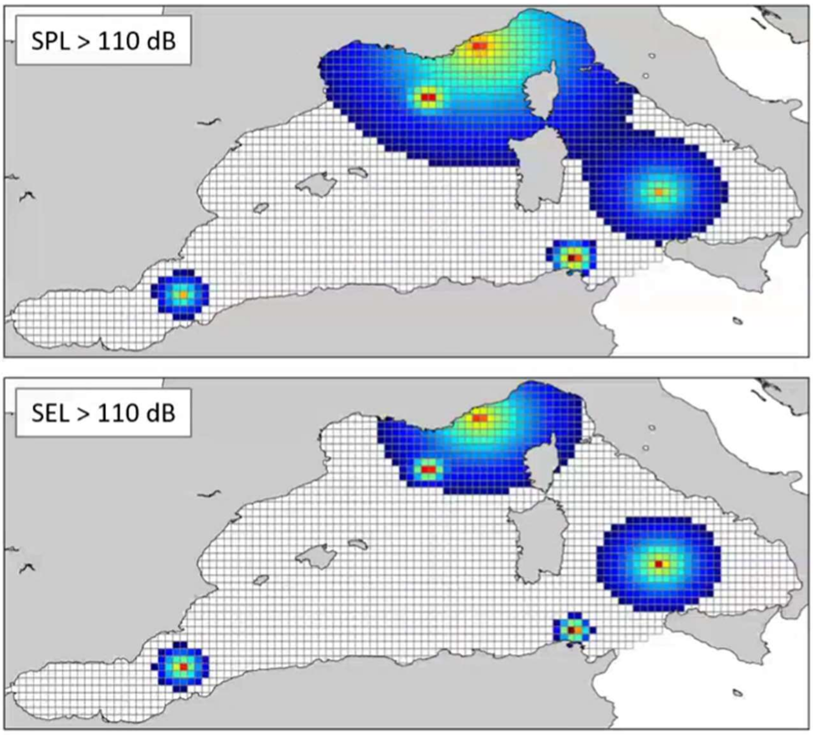

Figure 10. Examples of underwater propagation models with the same reference threshold value (110 dB re 1µPa for 10 Hz – 10 kHz) but different metrics: SPL (dB re 1µPa) and SEL (dB re 1µPa^2·s).

Step 6. Definition of estimated habitat area potentially used by indicator/representative species

Presence/absence habitat models, using robust physiographic predictors (e.g., depth and slope) as covariates, developed on long-term data series and validated on areas where calibration was not performed (see Azzellino et al., 2012 and 2011 for reference methodology), can be used to estimate the presence probability for six species of cetaceans regularly occurring in the MED (see Step 2). The physiographic predictors for the study can be obtained through the elaboration of General Bathymetric Chart of the Oceans (GEBCO; https://www.gebco.net). The physiographic predictors for the study can be obtained through the elaboration of General Bathymetric Chart of the Oceans (GEBCO; https://www.gebco.net) One-minute Digital Atlas, or the new European Marine Observation and Data Network (EMODnet) Bathymetry World Base Layer Service (EBWBL) which combines gridded data from different sources and provides the highest resolution currently available (https://tiles.emodnet-bathymetry.eu), and then these predictors can be gridded by means of a GIS software (ESRI ArcView version 3.2, Spatial Analyst and 3D Analyst extensions and QGIS version 2.18).

Based on the presence probability for the species, called ***Habitat Suitability (HS),*** a ***Potentially Usable Habitat Area (PUHA)*** can be evaluated in every unit cell unit of the grid as follows:

$$PUHA = \sum_{i=1}^{n} HS \times a_i \qquad \text{(Eq. 1)}$$

where HS is the Habitat Suitability and a_i is the area of the i-th unit cell.

Example: Considering a grid of 20 km of grid size, the area of each unit cell will be 400 km^2 with various bathymetric characteristics. Assuming that:

- HS_{sp1} = 65%
- HS_{sp2} = 25%
- HS_{sp3} = 75%
- HS_{sp4} = 0%
- HS_{sp5} = 0%
- HS_{sp6} = 0%

then, the *PUHA*s for *HS* higher than zero will be the following:

- ***PUHA*$_{sp1}$ =** (0.65x400) = 240 km^2
- ***PUHA*$_{sp2}$ =** (0.25x400) = 100 km^2
- ***PUHA*$_{sp3}$ =** (0.75x400) = 300 km^2

A schematic representation of the above example is shown in Figure 11.

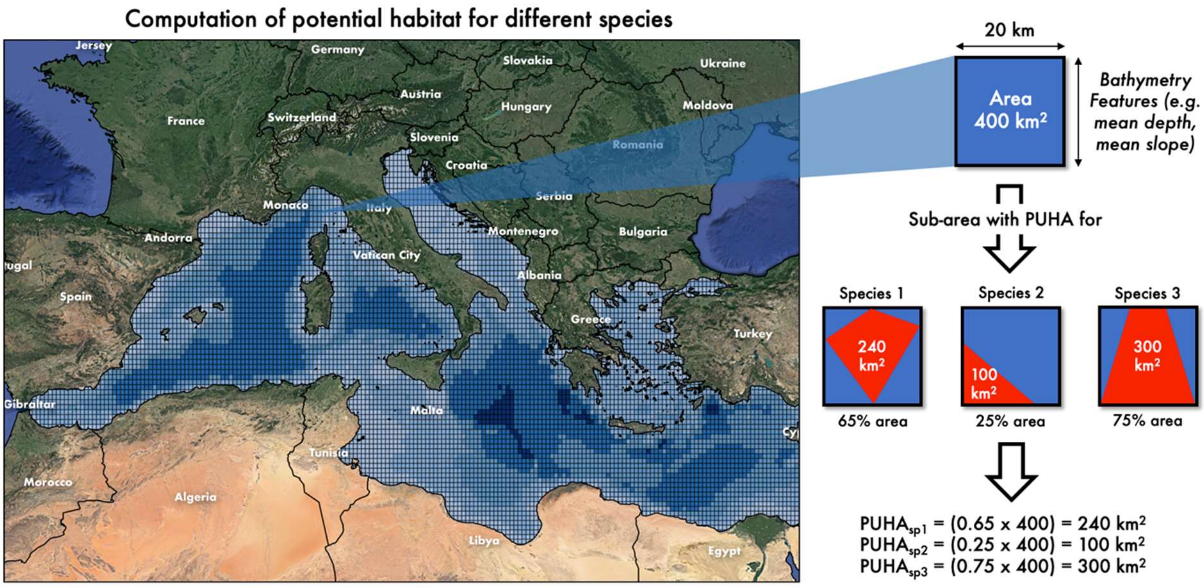

Figure 11. Example of PUHA calculation.

Step 7. Produce 'sound exposure' risk maps combining sound pressure and species habitat area

The cumulative $PUHA_{sp}$ (i.e., the sum of all the unit-cell PUHAs within the assessment area) for the different species obtained from the habitat models, as described in the previous Step 5, will be overlaid to the pressure map produced at Step 4. This will allow the evaluation of the proportion of potential habitats impacted, in time and space, for the six MED cetacean species present in Table 4 (Step 2).

Step 8. Compute proportion of habitat area exposed using an exposure index

To quantify the total exposure of the habitat area to impulsive sound, the Exposed Habitat Area Index (EHAI) is introduced.
This species-dependant index is defined for each one of the six representative species as the % percentage of PUHA that is exposed to noise levels (SPL) higher than 110 dB re 1 µPa ($PUHA_{Exposed}$) with respect to the cumulative PUHA ($PUHA_{Total}$), as estimated in Step 5, considering a one-year or a six-month period (It should be noted here that the spring-summer period is the most critical).

$$EHAI_{sp} = \frac{PUHA_{Exposed}}{PUHA_{Total}} \cdot 100$$

Despite some caveats and criticism by scientists (see, for instance, van der Hoek et al., 2015; Lindenmayer and Luck, 2005), TVs are widely used as clear-cut conservation targets. A potentially important concept in this context is the Minimum Area Requirements of species (MAR), which defines the amount of space (suitable habitat) that is required for the long-term persistence of a population (e.g. Pe'er et al., 2014). Obviously, the presence of a species within a site does not guarantee its survival: populations occurring within remnants of suitable habitats may be declining, threatened or under an ''extinction debt'' from past environmental changes (Tilman et al., 1994) or may require a larger area than other species in order to buffer against environmental, demographic or genetic stochasticity. Therefore, a major challenge for conservation planning is to ensure that sufficiently protected areas contribute to the viability of as many species as possible, in consideration of both their habitat association and area requirements.
So, in defining some tentative TVs, the reasoning of Germany is followed (Müller et al., 2020), where a 10 % spatial threshold has been adopted for the North Sea area of the German EEZ, implying that 90 % of the area must be unaffected by noise. In the particularly sensitive reproduction period for harbour porpoises, however, only 1% of the German EEZ in the North Sea can be disturbed by noise.

Concerning the temporal duration of the noise events, the tentative threshold was based on the findings of the study on killer whales reported by Williams et al. (2006), and on the review of case studies reported by Tyne et al. (2018; see the following Table 5 extracted from this paper), which reported variable proportions of the time exposed to human activities for some free-ranging cetacean populations, ranging from 10% to up to 83% of their activity time budget. Some coastal populations showing a high site-fidelity were found to be the ones with the highest proportion of time exposure to human activities.

Based on the aforementioned rationale, GES Thresholds Values (TVs) *might be determined as a fixed percentage of the Cumulative* $EHAI_{Ssp}$ *over the considered assessment area (*$TV_{1,spatial}$*) and in terms of a fixed percentage of the Duration of Noise Events (DUNE) in days (*$TV_{1,temporal}$*) over the assessment time period.* Furthermore, for the six-month period from May to October.

A more conservative $TV_{2,spatial}$ should be foreseen when the assessment area includes Marine Protected Areas and/or Natura 2000 sites.

Table 5. Extracted from Tyne et al., 2018. Studies that have quantified exposure rates of dolphins to human activities and whether authors noted or inferred an impact. MV, motorized vessels; K, Kayaks; SUP, stand-up paddleboard; S, swimmers.

species	proportion of time exposed to human activities %	impact distance (m)	source of disturbance	behavioural response	study
Bottlenose dolphin (*Tursiops truncatus*)	9	400	MV, K	yes	[7]
Bottlenose dolphin (*T. truncatus*)	10.8	400	MV, K	yes	[16]
Bottlenose dolphin (*T. truncatus*)	12.8	400	MV, K	yes	[16]
Bottlenose dolphin (*T. truncatus*)	15.5	400	MV, K	yes	[50]
Common dolphin (*Delphinus* sp.)	21	300	MV, SUP, K	yes	[51]
Hector's dolphin (*Hectori hectori*)	23.6	200	MV	no	[52]
Bottlenose dolphin *T. truncatus*	24	50	MV, S	yes	[53]
Common dolphin (*Delphinus* sp.)	29	300	MV	yes	[54]
Killer whale (*Orcinus orca*)	28.5	100	MV	yes	[55]
Dusky dolphin (*Lagenorhynchus obscurus*)	31	200	MV	yes	[56]
Killer whale (*O. orca*)	37.6	100	MV	yes	[55]
Bottlenose dolphin (*T. truncatus*)	45	50	MV, S	yes	[57]
Dusky dolphin (*L. obscurus)*	51.6	300	MV	yes	[58]
Bottlenose dolphin (*T. truncatus*)	58	300	MV	yes	[26]
Spinner dolphin (*S. longirostris*)	77	300	MV, K, S	not reported	[59]
Spinner dolphin (*S. longirostris*)	26, 42 and 53[a]	300	MV, S	yes	[60]
Spinner dolphin (*S. longirostris*)	82.7	100	MV, K, S	n.d.	this study

[a]The proportion of time the spinner dolphins were exposed to human activities in three different areas in the Red Sea, Egypt.

Step 9. Determine potential for negative effects at population level (habitat displacement/avoidance/loss)

To date, no experimental study is available on Mediterranean cetacean species to assess potential disturbance associated with threshold values as proposed in Step 7. Literature data and baseline monitoring studies should be the basis to preliminarily define TVs, which could be refined based on experimental studies when available.

5.1 Summary overview of the proposed methodology

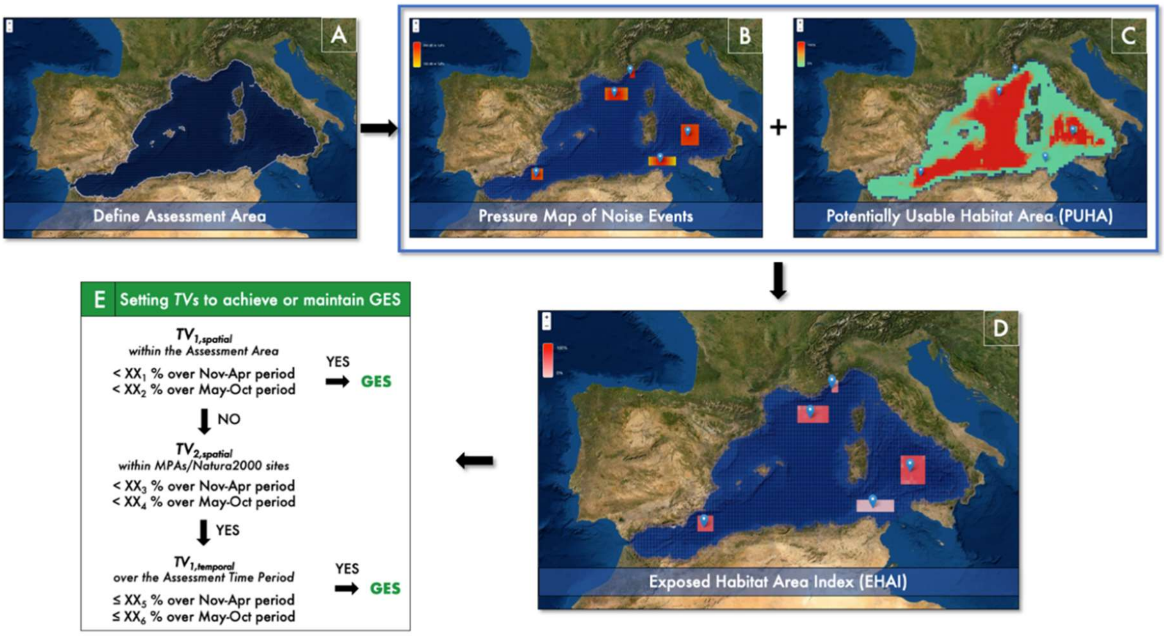

Figure 12. Example of the risk-based assessment workflow describing the QUIETMED2 methodology: A) definition of assessment area, B) noise pressure map, C) quantification of Potentially Usable Habitat Area (PUHA) for specific target species, D) calculation of the Exposed Habitat Area Index (EHAI), E) proposed framework for the definition of TVs for GES.

Main points concerning the methodology and its implementation can be summarised as follows:

- Select assessment area (habitat, see Fig. 12A), assessment period and representative species of the habitat;
- Use Impulsive Noise Registry (INR-MED) data to assess noise events, produce a noise pressure map by using appropriate propagation algorithms or predefined buffers (see Fig. 12B) and setting a pressure threshold based on the best available science (scientific literature). This threshold represents the sound level above which cetaceans may respond to noise.
- Use of habitat models enabling quantification of the Potentially Usable Habitat Area (PUHA) for each one of the representative species as a function of physiographic predictors (see Fig. 12C) within the assessment area;

- Produce risk maps using Exposed Habitat Area Index (EHAI), constructed by superimposing PUHA for each one of the representative species with the noise pressure map (Fig. 12D);
- Setting GES thresholds in terms of cumulative EHAI of the species exposed to fixed sound levels (TV1,spatial) and in terms of a percentage of the Duration of Noise Events (DUNE) in days (TV1,temporal) over the assessment time period (Fig. 12E). Furthermore, a ceiling value for TV1,spatial should be set, and a more restrictive TV2,spatial should be foreseen when the assessment area includes Marine Protected Areas and/or Natura 2000 sites.

5.2 Implementation of the proposed methodology: Virtual example

The INR-MED can represent the joint management tool for cumulative noise exposure from impulsive sources based on actionable targets planned at regional, subregional or subdivision level. During the QUIETMED2 project, the INR-MED has been updated (QUIETMED2 Deliverable 8.2 "*Data and information tool to support the update monitoring programmes of impulsive noise impact indicator*", https://quietmed2.eu/outputs/) and the "*Risk of impact on Biodiversity*" section has been added. This functionality enables the users to view on a map a graphic representation of the different steps included in the mentioned methodology to establish thresholds in the Mediterranean Sea Region (Figure 13).

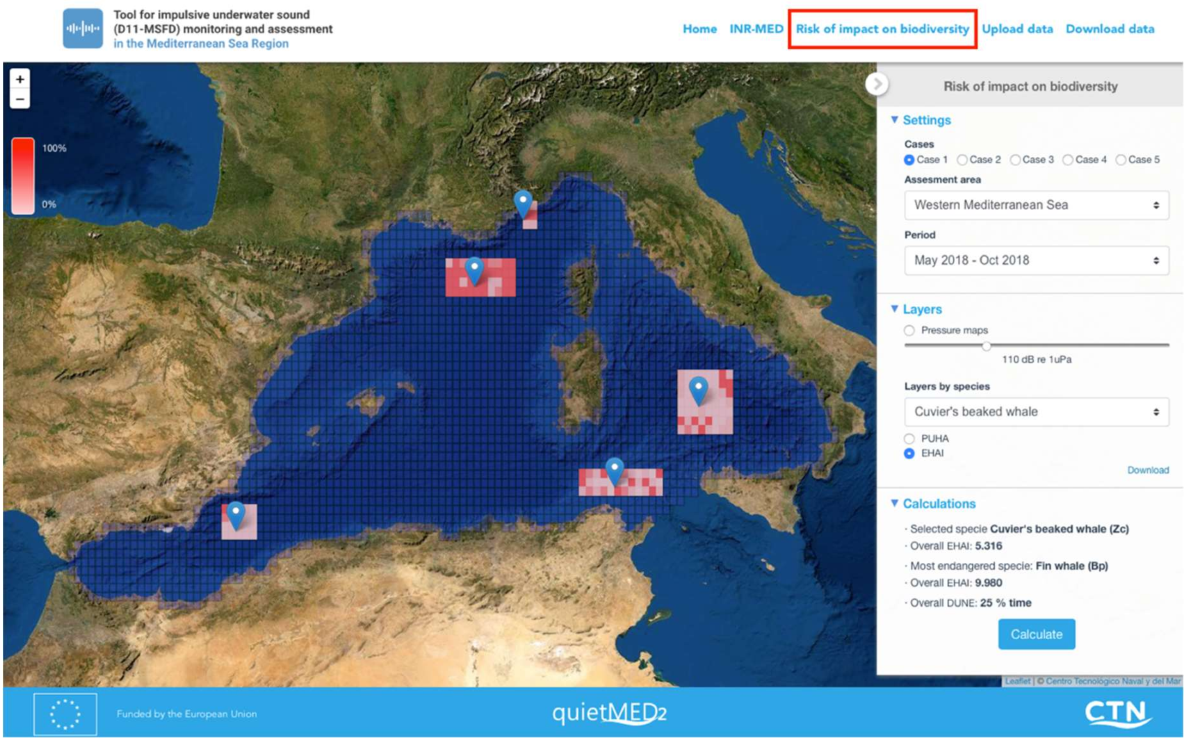

Figure 13. Prototype of the tool for impulsive underwater sound (D11-MSFD) monitoring and assessment in the Mediterranean Sea Region developed during QUIETMED2 project for the Competent Authorities of MS, where five hypothetical case studies have been implemented. The tool is available at the link http://quietmed2.ctninnova.com.

Below, an example of the calculations presented in Steps 5-6-7 follows for five hypothetical impulsive noise events (Figure 14 and Table 6) with different sound characteristics and duration.

- Noise Event 1 – Military sonar exercise (DUNE: 70 days);
- Noise Event 2 – Military sonar exercise (DUNE: 46 days);
- Noise Event 3 – Geophysical exploration - airguns (DUNE: 30 days);
- Noise Event 4 – Geophysical exploration - airguns (DUNE: 74 days);
- Noise Event 5 – Construction works - impact pile driving (DUNE: 300 days).

The considered assessment area is the Western Mediterranean subregion. The spatial and temporal extent of the noise events are considered separately. As regards the spatial assessment, in the right marginal column of Table 6, the overall EHAI has been calculated as the sum of the EHAIs for each of the six representative species in the subregion, and it is used as a metric of the overall amount of the species habitat exposed to the noise generated by the five sources. It can be seen that the fin whale EHAI is the highest among the six species' EHAIs. As regards the temporal assessment, the durations of the different noise events (DUNE – Duration of Noise Event) are considered with respect to the assessment period of one year or the critical six-month time period from May to October. The worst condition for DUNE in this example concerns noise event 5, ranging from 82.2 % over the whole year to 100% over the 6 months.

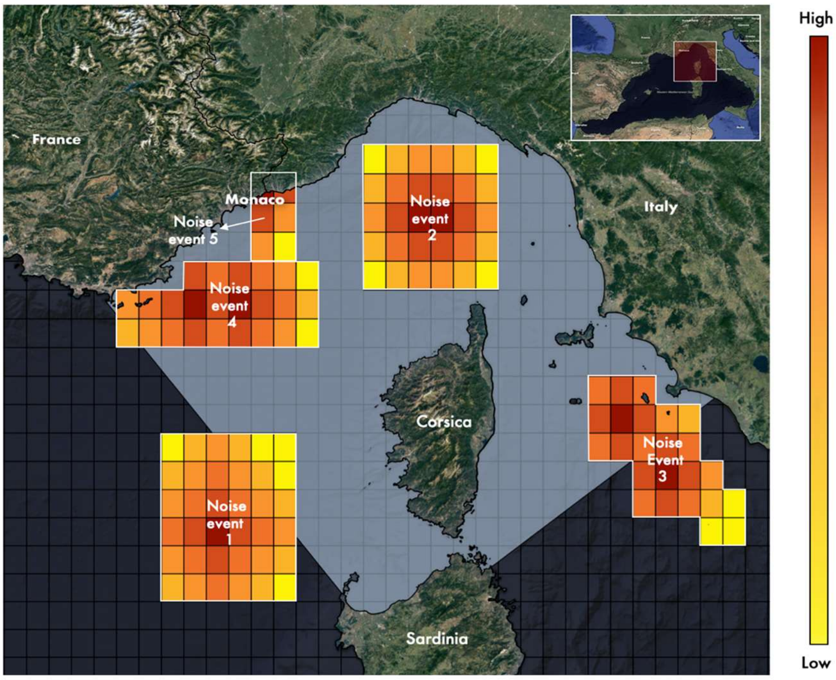

Figure 14. Example of five hypothetical noise events (represented with colour-graded cells: yellow represents low level of impact; red represents high level of impact) in a part of the Western Mediterranean subregion (represented with black cells).

Table 6. Virtual example of single-species' and overall EHAI calculation considering an assessment time period of a) one year and b) six months.

Species	Exposed Habitat Area Indices (EHAIs)					Overall EHAI
	Noise event 1	Noise event 2	Noise event 3	Noise event 4	Noise event 5	
Fin whale	1.18	0.28	0.08	0.60	0.05	**2.19**
Striped dolphin	0.79	0.32	0.17	0.59	0.05	1.92
Risso's dolphin	0.24	0.26	0.18	0.43	0.04	1.16
Sperm whale	0.21	0.22	0.11	0.32	0.04	0.9
Common bottlenose dolphin	0.00	0.13	0.09	0.11	0.00	0.34
Cuvier's beaked whale	0.28	0.21	0.15	0.31	0.03	0.99
	Duration of Noise Event - DUNE (days)					**Overall DUNE**
	70	**46**	**30**	**74**	**300**	**300**
a) % time over 6 months	38.4	25.5	16.4	40.5	100[2]	**100**
b) % time over year	19.2	12.6	8.2	20.3	82.2	**82.2**

Based on the aforementioned rationale, setting GES thresholds in terms of cumulative EHAI of the species exposed to fixed sound levels ($TV_{1,spatial}$) and in terms of a percentage of the Duration of Noise Events (DUNE) in days ($TV_{1,temporal}$) over the assessment time period could be applied as shown in Figure 15:

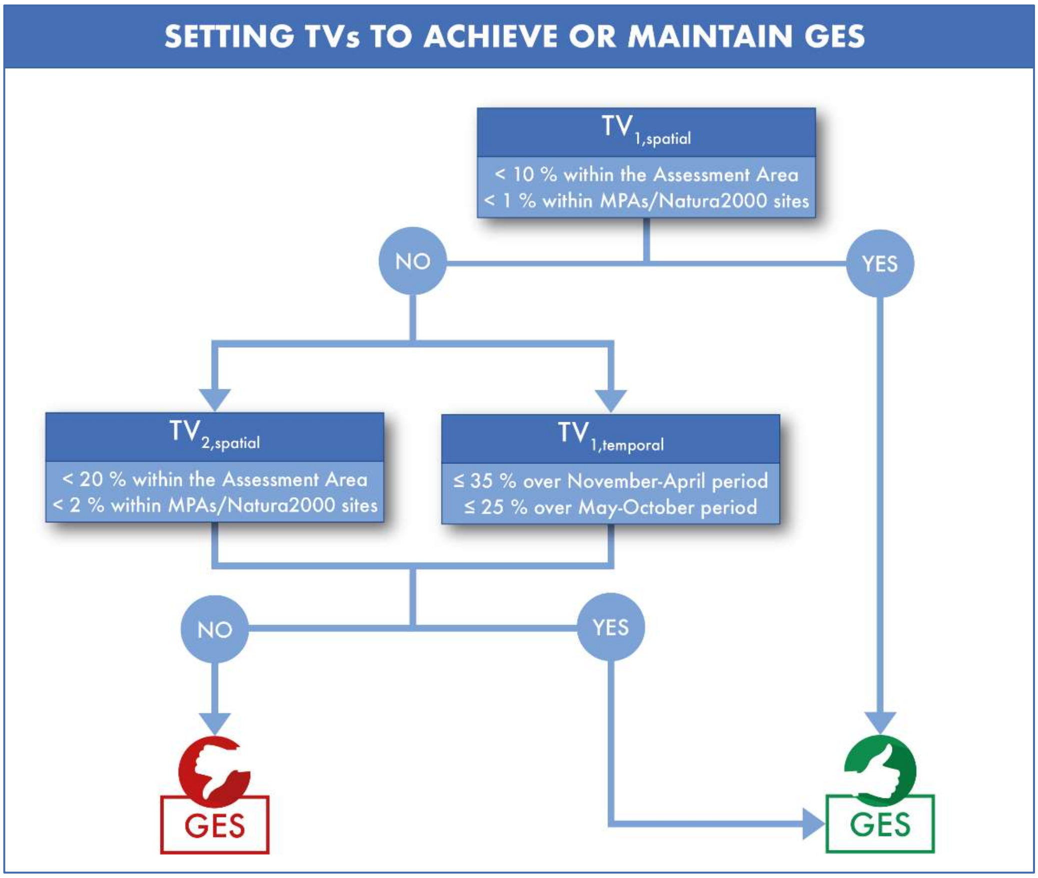

Figure 15. A possible scheme for the definition of TVs for GES.

[2] the noise event duration covers the whole 6 months period

So, following this rationale, the GES could be considered fulfilled if the overall EHAI for the most impacted species is lower than $TV_{1,spatial}$ (e.g., $EHAI_{sp}$ is lower than 10% of the whole assessment area or lower than 1% of any MPA/Natura 2000 areas, included in the assessment area), independently from the Noise duration (DUNE).

When $TV_{1,spatial}$ is exceeded, GES could still be attributed if two conditions are concurrently assessed:

- the ceiling TV2,spatial is not exceeded (e.g., EHAI is lower than 20% over the whole assessment area or lower than 2% of the MPA/Natura 2000 areas) and,
- depending on the period (i.e., Nov-Apr/May-Oct), DUNE does not exceed a TV1,temporal (e.g., DUNE is lower or equal to 35% of days in the Nov-Apr period or DUNE is lower or equal to 25% of days in the May-Oct period).

So, following this tentative hypothetical scheme, given the compliance of EHAIs of the most impacted species with $TV_{1,spatial}$, GES may be attributed without considering $TV_{1,temporal}$. If, instead, EHAI exceeds $TV_{1,spatial}$, there are other two conditions that would be examined to assess if GES has been achieved: a) EHAI should not exceed $TV_{2,spatial}$, and b) DUNE should not exceed $TV_{1,temporal}$ over the Assessment period.

The thresholds described in this example are just tentative and if implemented as any other proposed TV should be validated through dedicated monitoring studies aiming to collect baseline data to fine-tune the thresholds.

5.3 Data availability to test the methodological framework for MED

National research efforts still remain the most detailed requirement for assessing cetacean presence, abundance and distribution. Data from web portals may help and be used to integrate other available data. The European Marine Observation and Data Network (EMODnet) is a network of organisations supported by the EU's integrated maritime policy. EMODnet Physics gateway also contains underwater noise data. The information was collected by OSPAR (North East Atlantic), HELCOM (Baltic Sea) and ACCOBAMS (Mediterranean Sea, Black Sea), and integrated into the EMODnet Physics Impulsive Noise Event Registry. However, there are still areas with large gaps in monitoring, and data are heterogeneous and fragmented (Figure 16).

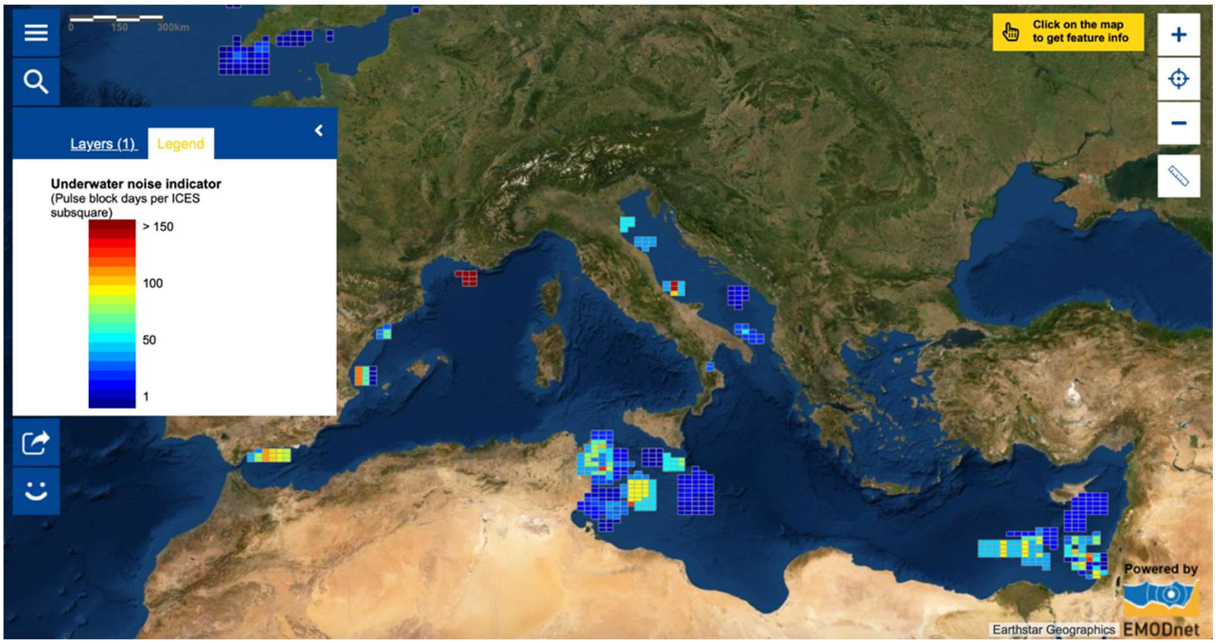

Figure 16. Pulse-block days per ICES unit cell (subsquare) in the MED, as obtained by EMODnet.

The Ocean Biogeographic Information System–Spatial Ecological Analysis of Marine mega-vertebrate Animal Populations (OBIS–SEAMAP; http://seamap. env.duke.edu; Halpin et al., 2006, 2009; Fujioka et al., 2014a, 2014b), a thematic node of OBIS specializing on marine mega-vertebrates, is a tool able to store multiple data types including opportunistic/ad libitum and line transect visual sightings (Figures 17-18), animal tracking data, photo-identification data (sighting history and fin images), PAM data, marine mammal stranding data, etc. These data are brought together into a common, global map based on a coherent, interoperable, and openly accessible information system.

The interest in and resources allocated to conducting systematic monitoring programmes to estimate cetacean density differ by MS or by different subregions. In addition, if monitoring programs exist, the type of monitoring differs, for example as regards the type of survey (i.e., visual survey, acoustics survey, ship based or aerial survey, systematic or opportunistic survey) and the time-period covered (i.e., short- and long- term, summer/winter survey) in different areas, thus rendering the comparison of the results inapplicable.

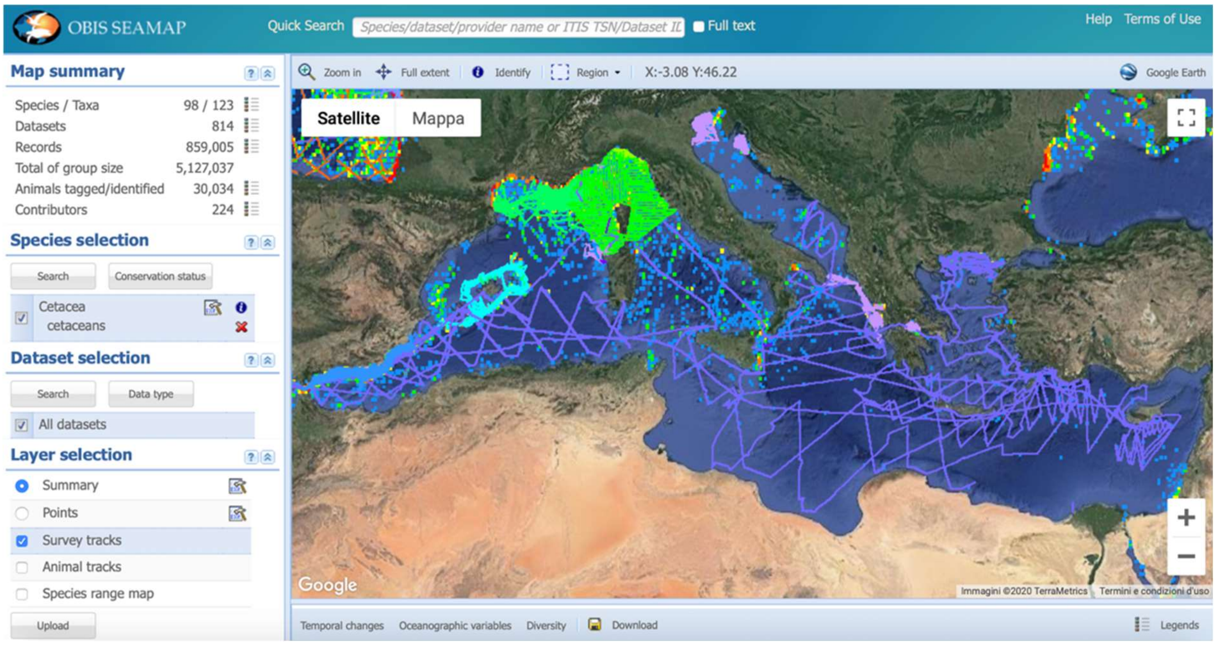

Figure 17. Survey transects conducted in the Mediterranean Sea and presented on the OBIS-SEAMAP web site.

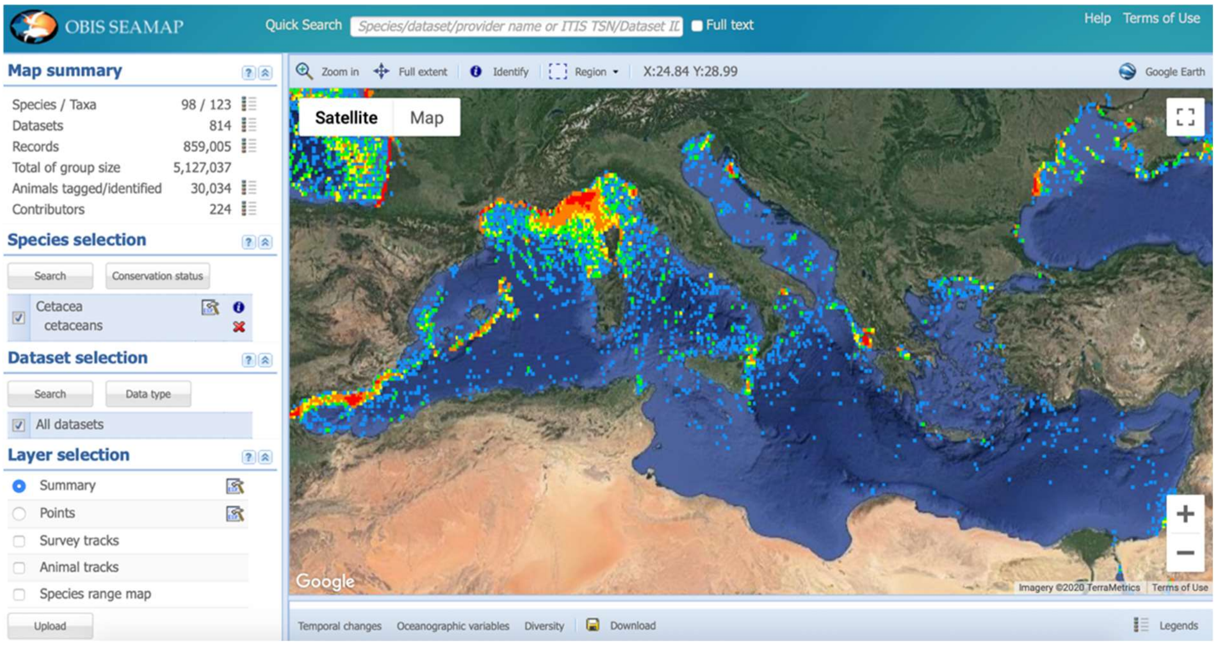

Figure 18. Geographic distribution of cetaceans' observations in the Mediterranean Sea mapped on the OBIS-SEAMAP.

Systematic survey efforts for cetaceans have previously been recognized as heterogeneous across the Mediterranean Sea by Mannocci et al. (2018), who analysed the effort derived from line transect surveys, conducted across the Mediterranean Sea (149,225 km from aerial surveys; 153,256 km ship-based), in order to identify gaps in the geographic, temporal, and environmental coverage of survey effort. As reported by Mannocci et al.(2018), survey programs have been implemented mostly in summer by

European countries in the north-western and central Mediterranean, highlighting the disparity between northern and southern areas of the Mediterranean (Figure 19).

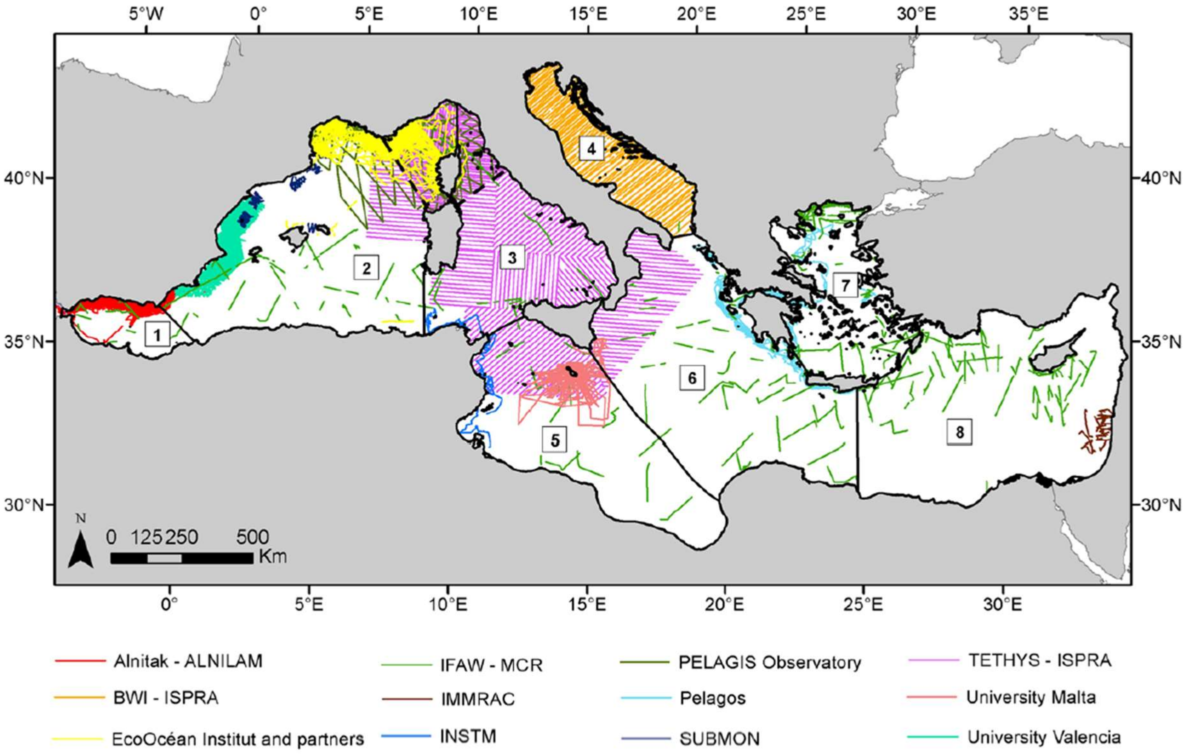

Figure 19. Line transect surveys in the Mediterranean Sea. Colours represent entities responsible for these surveys. Mediterranean subregions following Notarbartolo di Sciara (2016) and UNEP-MAP-RAC/SPA (2010)18,56: (1) Alborán Sea/Strait of Gibraltar, (2) Algero-Provençal Basin, (3) Tyrrhenian Sea/eastern Ligurian Sea, (4) Adriatic Sea, (5) Strait of Sicily/Tunisian Plateau/Gulf of Sirte, (6) Ionian Sea/Central Mediterranean, (7) Aegean Sea, (8) Levantine Sea. The location of the Pelagos Sanctuary is indicated with black dashed lines. Surveying entities: BWI = Blue World Institute of Marine Research and Conservation; ISPRA = Italian National Institute for Environmental Protection and Research; IMMRAC = Israel Marine Mammal Research and Assistance Center; INSTM = Institut National des Sciences et Technologies de la Mer; IFAW = International Fund for Animal Welfare; MCR=Marine Conservation Research. The map was generated with ArcGIS (http:// desktop.arcgis.com/en/) (version 10.2.2). (Mannocci et al., 2018).

To start filling these gaps, the Parties of ACCOBAMS conducted the ACCOBAMS Survey Initiative (ASI) in 2018 (https://accobams.org/asi-data-presentation/) to monitor cetaceans over the entire basin scale during a single set of surveys, which aimed at covering the whole region, where allowed (Figures 20-21).

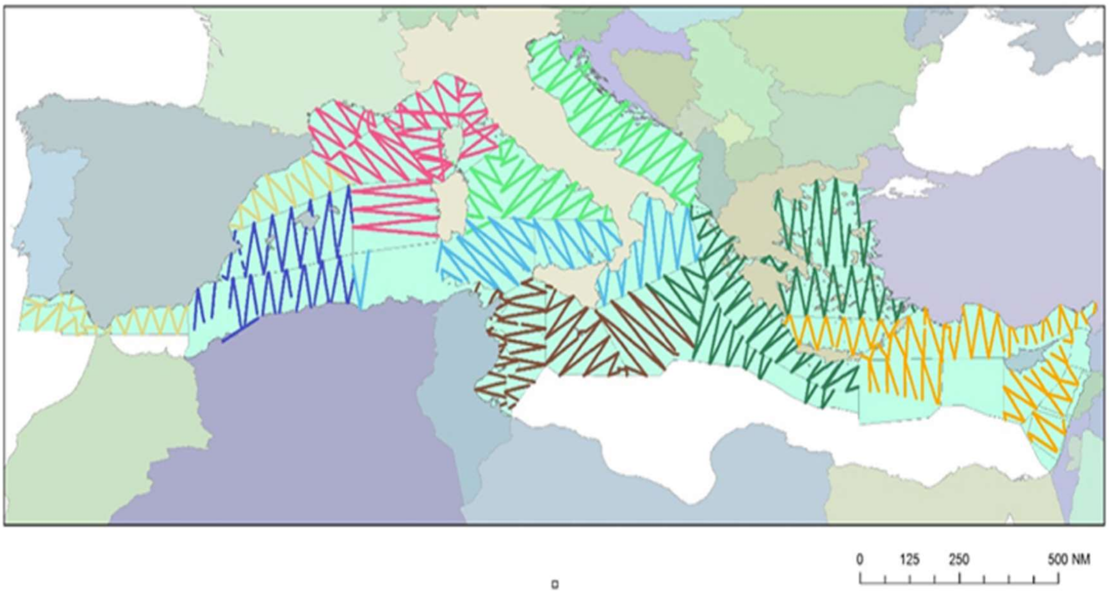

Figure 20. The total effort covered during the aerial survey campaign in summer 2018 (ACCOBAMS Survey Initiative (ASI)).

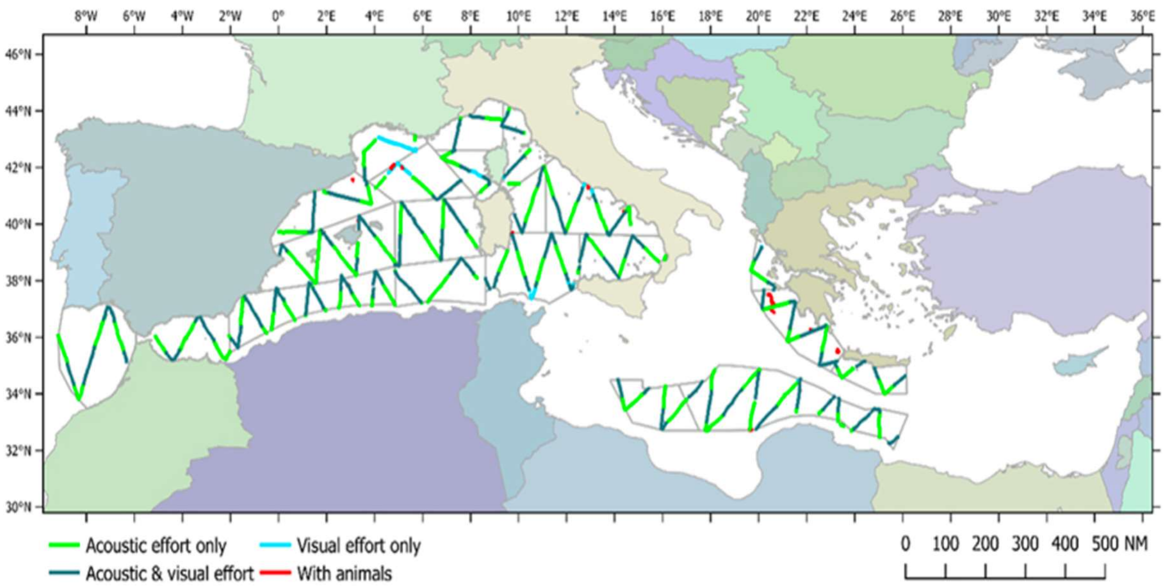

Figure 21. Survey transects conducted by the Song of the Whale research vessel (ACCOBAMS Survey Initiative (ASI)).

The results of this regional survey may be helpful in filling some of the existing data gaps. The ASI results (preliminary results in Figures 22-24) may contribute useful information to facilitate the species or group of species selection according to their distribution at a large spatial scale, thus rendering TVs and GES definition comparable among subregions.

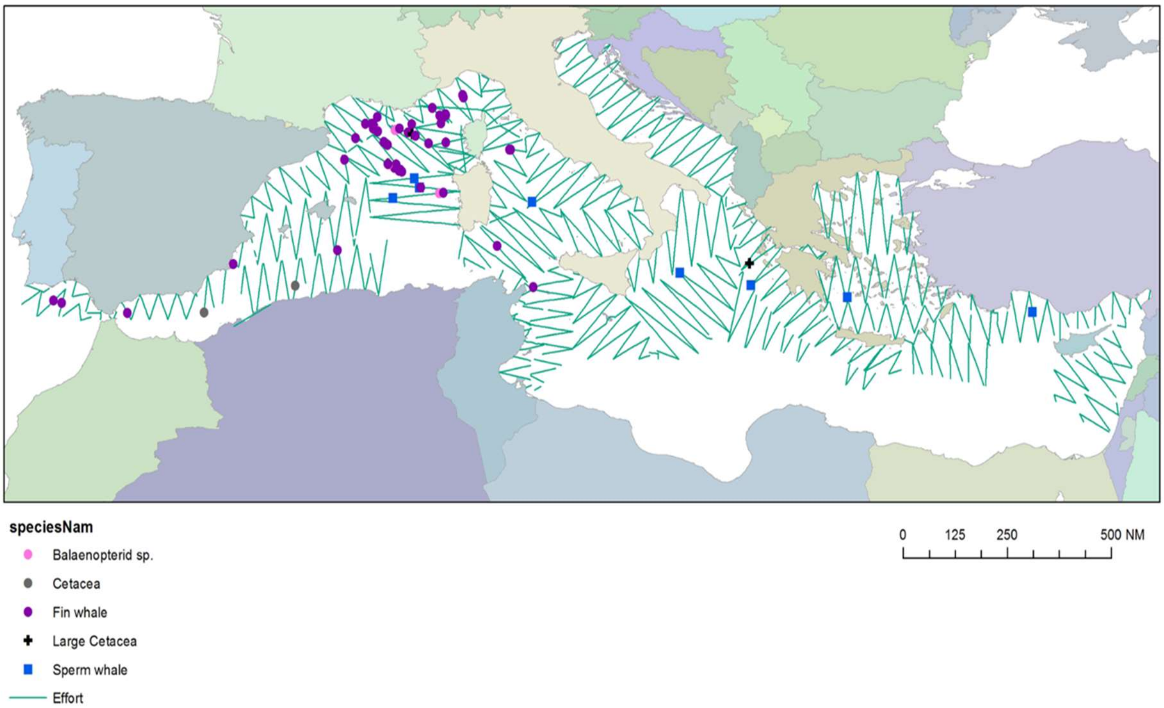

Figure 22. Sightings of large cetacean species during the aerial survey (ACCOBAMS Survey Initiative (ASI)).

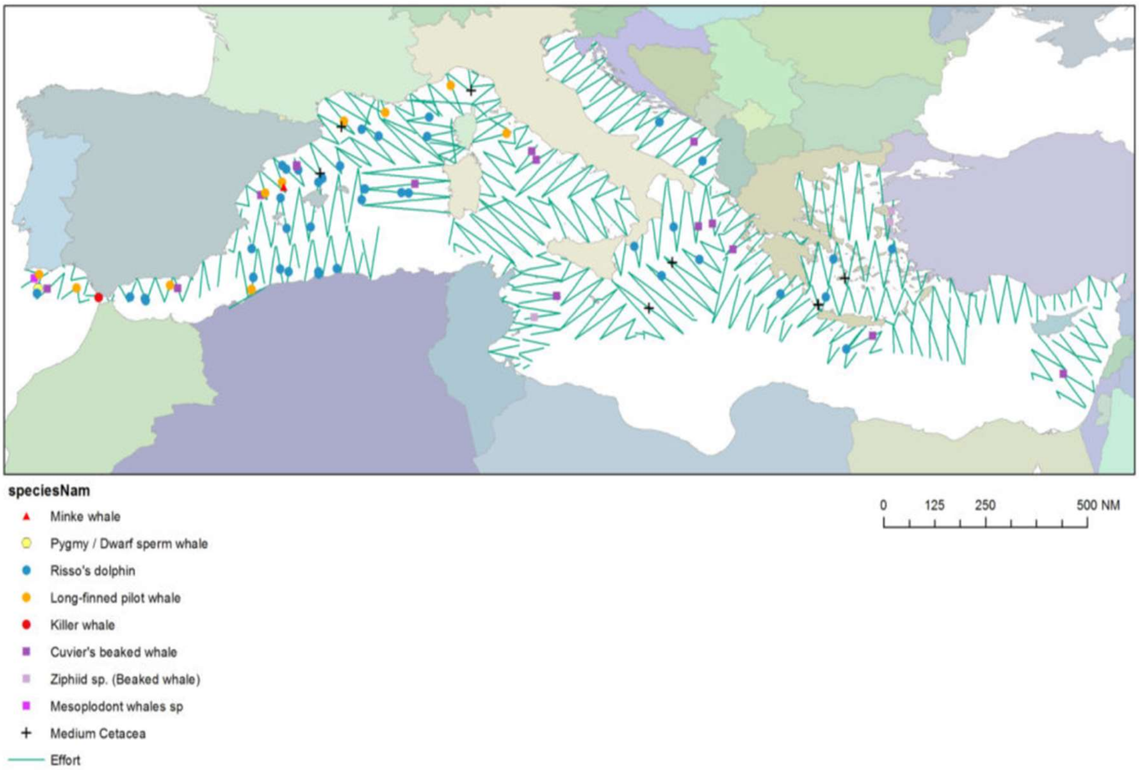

Figure 23. Sightings of medium size cetacean species during the aerial survey (ACCOBAMS Survey Initiative (ASI)).

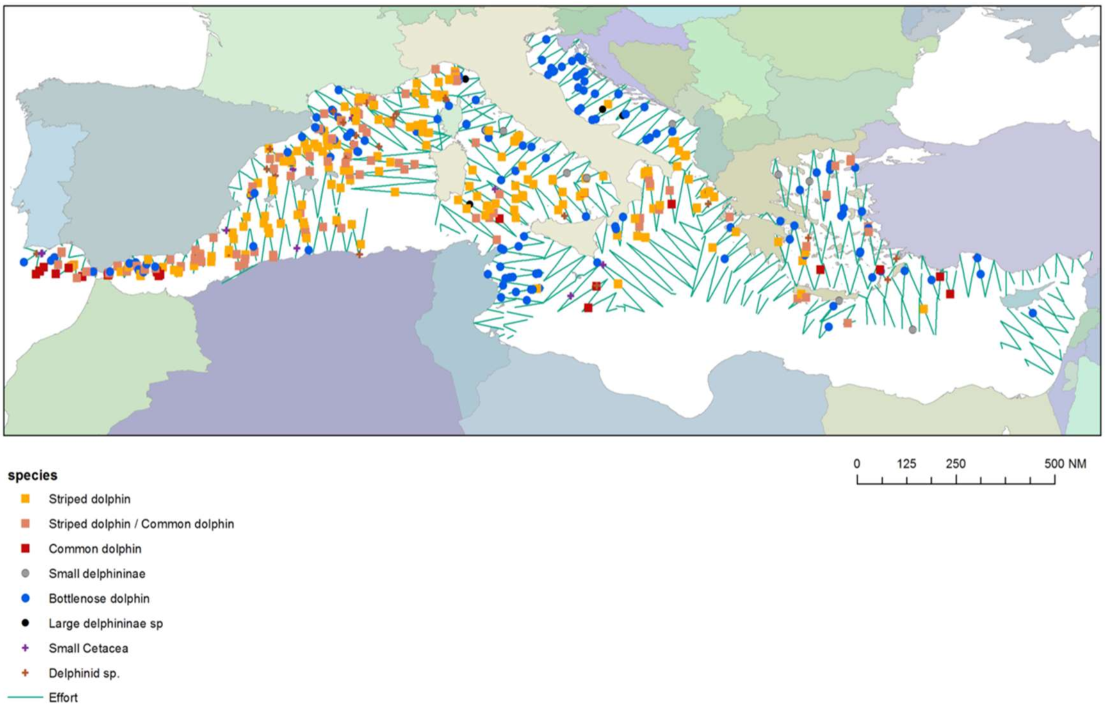

Figure 24. Sightings of small size cetacean species during the aerial survey (ACCOBAMS Survey Initiative (ASI)).

The above results will supplement other available data covering other seasons and local observations, collected by long-term research studies. In particular, long-term studies provide insights about the capability of the species to respond to environmental variability. Studies of this kind are strongly needed to support conservation measures for the species, to improve the knowledge about their distribution, their habitat requirements, their movements, and to monitor the relevant changes due to environmental (e.g., climate change issues) or human drivers, affecting their status and distribution.

5.4 Limitations of the methodology

- The INR-MED, already implemented, needs to be updated for the methodology to be effective;
- Habitat models used to predict PUHA have been developed in the Western Mediterranean Basin, so their predictions may be less accurate concerning the Eastern basin at least for some species (e.g., fin whale);
- Environmental variability may affect the PUHA for some species and its effect can be assessed only based on long-term studies that are not available for the whole MED;
- Noise propagation uncertainties in areas with high heterogeneity in bathymetry and sea bed characteristics;
- Knowledge gaps about species' presence and distribution, which is still quite high in many areas of the Mediterranean, hampers the full validation of the habitat models employed.

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ANNEX I. Considerations about acoustic modelling of INR-MED

The aim of this annex is to point to considerations about acoustic propagation emphasizing their applicability and highlighting the most influential characteristics in the development of the tool (use of external data, computational cost, etc.), including further steps to improve it.

Underwater acoustic propagation models. General considerations

There are several underwater acoustic propagation models with different scopes and fields of application which, due to its different complexity, can be classified into two groups:

- **Robust models**: most of them are based on some analytical approximation of the Helmholtz equation, which describes the amplitude and phase of an acoustic wave in the space of positions and frequencies. Depending on the type of approach carried out, we distinguish the following methods:

    - **Ray-tracing**: model wave fronts as acoustic rays. This approach is strictly valid for high frequencies, but it is computationally quite agile.
    - **Normal modes**: the solution is represented by a series of the product of horizontal functions and vertical functions (eigenfunctions), where the latter satisfy an eigenvalue problem. It is computationally intensive for high frequencies.
    - **Parabolic approximation**: The Helmholtz equation with varying index (elliptic equation) is replaced by a parabolic equation, which is more convenient from a numerical point of view, making the basic assumptions of a large distance between source and receiver and of a small depth of the sound channel compared with the propagation distance. It is a fairly robust model with a high computational cost for high frequencies.
    - **Wavenumber integration**: is basically a numerical implementation of the integral transform technique for horizontally stratified media. The fairly exact field solution is in the form of a spectral (wavenumber) integral of solutions to the depth-separated wave equation, which are evaluated directly by numerical quadrature. For range-dependent environments, however, there are no public models.

Thus, each model is derived from different approximations, and therefore its applicability may vary depending on the frequency used, the depth of the sea and whether there is spatial variability of the sound speed profile at depth (range dependence). Although the capabilities of each model or method depend significantly on the specific algorithm used, certain recommendations for use can be established, which are qualitatively shown in the following table:

Legend: Not valid (red) Very low efficient (orange) Low efficient (yellow) Ideal (green)

Model	Application							
	Shallow waters				Deep waters			
	Low frequency		High frequency		Low frequency		High frequency	
	RI	RD	RI	RD	RI	RD	RI	RD
Ray-tracing	Very low efficient	Not valid	Low efficient	Low efficient	Low efficient	Low efficient	Ideal	Ideal
Normal modes	Ideal	Low efficient	Low efficient	Very low efficient	Ideal	Low efficient	Very low efficient	Not valid
Wavenumber integr.	Ideal	Not valid	Ideal	Not valid	Ideal	Not valid	Ideal	Not valid
Parabolic approxim	Ideal	Ideal	Not valid	Not valid	Low efficient	Ideal	Very low efficient	Very low efficient

The borderlines between "shallow water" and "deep water" as well as "low frequency" and "high frequency" are not strictly determined. However, a separation can be established between shallow and deep waters at 200-500 m, while considering the distinction between low and high frequencies at approximately 1 kHz.

All these models require fairly precise information on environmental characteristics throughout the area where simulation is performed, i.e. on:

- Bathymetry.
- Properties of the seabed.
- Properties of the water column.

In addition, they are models with a relatively high computational cost, at the cost of offering an approximate representation of the underwater acoustic propagation under realistic conditions.

- **Simplified models:** they are a set of analytical approximations or semi-empirical models that allow calculating acoustic propagation in a much less robust way than numerical models but, in general, with a much lower computational cost. Among the great variety of this type of models, the following can be distinguished:
    - **Spherical propagation model:** it propagates the sound as if it were a homogeneous and isotropic medium, without influence from the surface and seabed surfaces, that is, without taking into account the multiple reflections that are produced or the refraction effects derived from the variability of sound propagation with depth. The results often overestimate transmission loss (TL).
    - **Cylindrical propagation model:** it assumes that the acoustic wave propagates with a constant wave front in the water column. The results often overestimate TL.

- **Spherical-cylindrical propagation model:** it is an intermediate propagation model between the previous two, showing TL that are somewhat more in line with the numerical models in general terms. TL versus range can be expressed as A*log(r), with 10<A<20, and taking into account the absorption.
- **Shallow water models:** They consider the transition between spherical and cylindrical propagation, introducing additional empirical coefficients to offer better results in shallow water.
- **Energy models:** They consider the multiple reflections statistically according to the characteristics of the bed.
- **Models based on the image method:** They allow obtaining the acoustic field due to the influence of reflections from the surface and seabed, taking into account its variability, but without taking into account refraction effects.

The main advantages of these models are their low computational cost, as well as the fact that they do not require extensive information on the characteristics of the marine environment, but only average values.

Just as an example, below is shown a comparison of the results of different robust and simplified models for two transects of the Mediterranean taking into account the same source taking into account the properties of the environment from EMODNET:

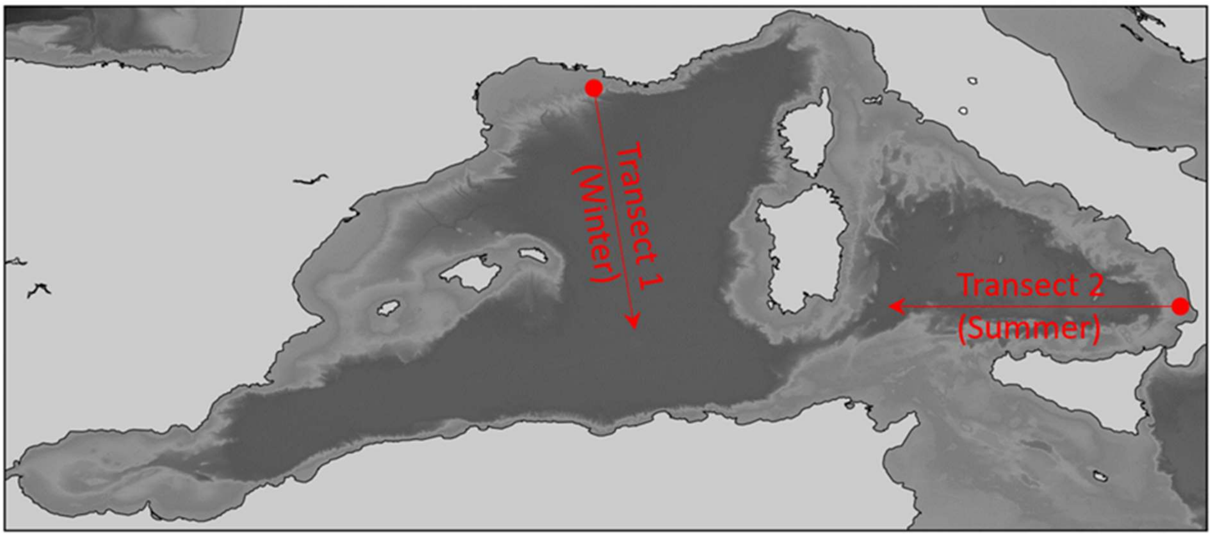

Figure 25. Map with the location of two same sources and propagation transects.

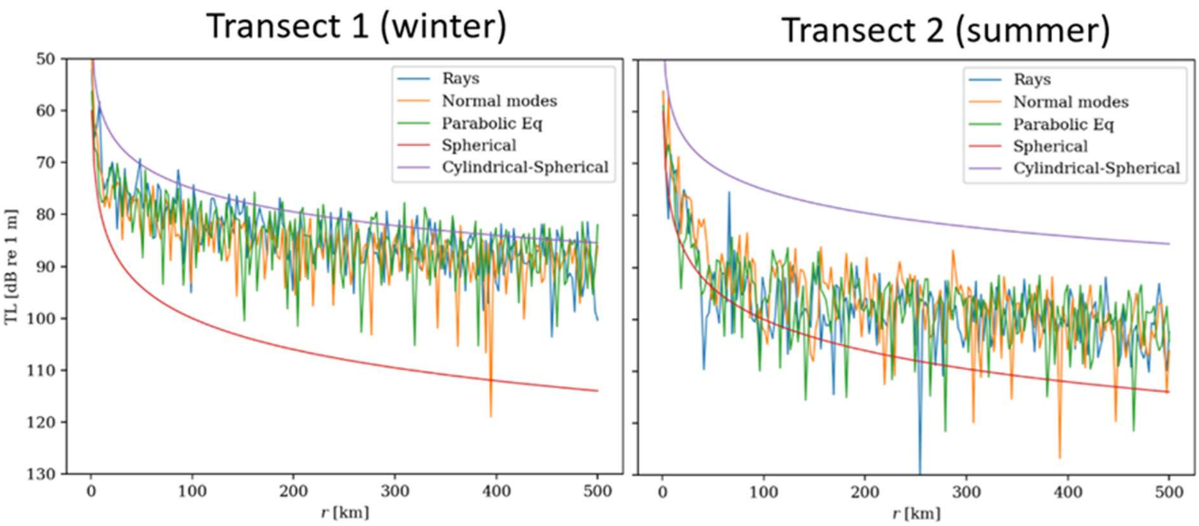

Figure 26. Resulting transmission losses for each transect.

Figure 26 shows that the cylindrical-spherical model (15*log(r)) could be a good upper limit for TL but, depending on the season being considered.

In any case, it should be noted that, for this example, different acoustic propagation models may give different sound pressure levels that could reach differences up to 30 dB in some specific cases.

Propagation models for impulsive noise sources

When creating a sound map, a crucial part is the source level, which will directly affect the resulting values. In addition, impulsive sources are especially difficult to model (spatial extension, directivity pattern, etc.), as can be deduced from the recent efforts found in the bibliography. A quite updated review is given in von Benda-Beckmann et al. (2017). The main impulsive sources addressed as regards underwater noise assessment in MSFD are classified into four distinct groups: sonar and acoustic deterrents, airgun arrays, explosions, and pile driving sources. Each of these types of sources present different characteristics; additionally, sources classified in the same group may further differ in various aspects.

A lot of specific data should be used to rigorously obtain a precise equivalent source level of an impulsive source (Lippert et al., 2016; Ainslie et al., 2019), but this level of detail is usually unknown or hidden from public knowledge, so the four-type classification based on noise event strength is acknowledged as a starting point to model impulsive sources.

Underwater acoustic propagation models in the INR-MED. Solution proposed

Currently, the tool is ready to implement in real time any of the simplified models. However, in order to demonstrate the capability of INR to incorporate propagation models, we opted as a demonstration step of implementation the spherical-cylindrical model, expressing TL as (15*log(r)) for any sources except for the explosions that has been used an specific propagation model for this source[3]. This model seems to offer a compromising (both conservative and realistic) solution between the cylindrical and the spherical model.

Robust models, as mentioned, require information related to the marine environment (bathymetry, sound speed profiles, seabed properties, etc.), that is not currently available in the tool, so they have not been implemented yet.

Regarding the sources, the INR-MED tool allows users to upload data of noise events in which some information regarding the source is required like “position”, “start-end date”, “source type” (the four classes mentioned before), “value code” (as in strength of noise event: very low/low/medium/high/very high) and “data quality”, along with other optional data. Due to the lack of more detailed information regarding the acoustic radiation pattern of the noise events, the sources are considered punctual and omnidirectional.
Thus, based on the information of available sources, this model provides the Sound Pressure Level (SPL) in the frequency range between 10 Hz and 10 kHz.

Feasibility of including different propagation models into the tool

For an increasing complexity of the deployed models in the tool, the next steps could consist of the following:

1**. Incorporation of SEL metrics**. For this, it is necessary to know, not only information on the noise level generated by the source, but also an estimate of the time the source is in operation.

2. **Incorporation of more detailed source data and models**. This would allow a better estimation of the source levels and could be accomplished by providing specific parameters under each type of source.

3. **Incorporation of models that distinguish shallow water from deep water**. Based on the existing bathymetry in the Mediterranean (for example, from EMODNET), establishment of areas where shallow waters are considered compared to those that are not, could allow the tool the capability to automatically choose one analytical or other models based on the specific characteristics.

[3] Chapman, N.R. - Measurement of the waveform parameters of shallow explosive charges, J. Acoust. Soc. Am. 78 (2) 1985

4. **Incorporation of numerical models**. Based on the previous classification, as well as considering the frequency characteristics of the sources, the tool allows incorporating any of the numerical models previously described. To do this, the following information must be included in the tool:

   a. Incorporate bathymetry with precision as required from the models.

   b. Incorporate properties of the seabed.

   c. Incorporate properties of the water column.

5. **Others**. Additional features and models that improve or nuance the acoustic propagation (such as automated selection of the appropriate source and/or propagation model for certain areas and frequency bands of interest, in case that adequate information about the source and 4a, 4b and 4c is provided).

All these characteristics can be implemented in successive improvements of the INR-MED tool, maintaining the same architecture that has been developed in the original tool.