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MASTER THESIS

In the degree course acoustical engineering

Clemens Pitschke

Assessment of continuous Underwater Noise

Using an example of a noise assessment strategy for shipping noise based on effect ranges with regards to animals

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MASTERARBEIT

Bewertung von kontinuierlichem Unterwasserschall

Am Beispiel einer Bewertungsstrategie für Schiffslärm basierend auf Wirkradien in Bezug auf Tiere

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Abstract

Noise in the oceans is a constantly increasing factor. The growing industrialisation due to shipping, offshore wind parks, seismic studies and other anthropogenic noise is putting the eco system under immense stress. The focus of this thesis is on the assessment of continuous underwater noise from ships. Based on existing strategies in air as well as underwater and a comparison of both an alternative strategy for the assessment of continuous noise from ships is given. The concept developed is based on published, scientifically observed responses of animals to ship passes with an indication of an effect range. A model is created to describe the strategy using publicly available data for cargo ships as an example. The results are summarized in maps depicting the affected area for an MRU of the OSPAR II region and the MPA “Borkum Riffgrund”. The strategy is discussed and evaluated on the basis of these results. From this, further improvements and the need for additional information in publicly available data on vessel traffic are derived.

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Glossary

AIS	*Automated Identification System*
BIAS	*Baltic Sea Information on the Acoustic Soundscape*
CB	*critical band*
CR	*critical ratio*
ECHO	*Enhancing Cetacean Habitat and Observation Program*
EEA	*European Environmental Agency*
EMODnet	*European Marine Observation and Data Network*
EMSA	*European Maritime Safety Agency*
GES	*Good Environmental Status*
GIS	*Geographical Information Systems*
ISO	*International Organization for Standardization*
JOMOPANS	*Joint Monitoring Programme for Ambient Noise North Sea*
LF	*low frequency cetacean*
MPA	*marine protected area*
MRU	*marine reporting unit*
MSFD	*Marine Strategy Framework Directive*
PCW	*phocid carnivores in water*
POI	*point of immission*
PSD	*power spectral density*
PTS	*permanent threshold shift*
RL	*received level*
RLS-90	*Richtlinie für den Lärmschutz an Straßen*
SL	*source level*
TTS	*temporary threshold shift*
VHF	*very high frequency cetaceans*
VMS	*Vessel Movement System*
WHO	*World Health Organization*

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1 Introduction

Sound is one of the key stimuli for wildlife underwater. Since soundwaves easily travel long distances underwater and light propagation is limited, the communication and orientation of marine animals is highly adjusted to sound.

Noise in the oceans is a constantly increasing factor. The growing industrialisation due to shipping, offshore wind parks, seismic studies and other anthropogenic noise is putting the eco system under immense stress [13, 41].

Currently states, communities and organisations around the world are developing strategies as well as standards for noise regulation of the maritime environment [4, 24, 28, 36]. The main distinction is made between the assessment of impulsive noise such as pile driving and seismic surveys and continuous noise such as shipping noise or the operation of offshore wind parks. Lucke gives a broad overview on the current status of the different regulations and strategies regarding underwater noise in his presentation [36]. The different approaches are summarized and presented on national as well as international level.

Under the Marine Strategy Framework Directive 2008/56/EC [18] (MSFD) the European commission defines qualitative goals and strategies to achieve and maintain Good Environmental Status (GES). In Annex I of the Document a list of qualitative descriptors for GES is presented. Descriptor 11 focuses on noise and is given as follows: “The Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.“ [18] In the Commission Decision (EU) 2017/848 [19] specific criteria for descriptor 11 are given. These are divided into anthropogenic impulsive (D11C1) and continuous low-frequency sound (D11C2) and are stated in the Annex A (Figure 36)

At the EU level, two documents have recently been published that provide advice to member states and agreements on potential assessment strategies for impulsive noise [6] and continuous noise [55] to reach GES in accordance MSFD.

1.1 Aim of the study

In this master thesis, an overview of current assessment strategies will be given based on the example of two European initiatives for the Baltic Sea and the North Sea region. The focus is set on the assessment of noise from ships (continuous noise).

Since the assessment of airborne noise is quite well developed one should also look for insights in existing strategies and what can be learned or adopted from these. A brief summary and excerpts of the approach in airborne acoustics is to be provided as well as a comparison between airborne and underwater acoustics.

Based on these foundations an alternative concept for assessment of continuous underwater noise will be applied. The indicator for assessing a species is to be based on studies and observations by using an effect range to describe the impact of noise. The concept will be discussed and tested taking an example of shipping noise from cargo ships in a North Sea region with publicly available data from EMODnet [14]. The advantages and disadvantages of this strategy will be discussed. Improvements as well as missing information are discussed thereafter.

1.2 Overview

In chapter 2 the assessment strategies and terminology for airborne sound are presented and summarized. The given examples seek to assess sound sources similar to shipping noise for a later comparison.

In chapter 3 the terminology and approach for underwater acoustics are given alongside bioacoustic foundations important for this thesis. The before mentioned strategies for the Baltic Sea and the North Sea region are presented and discussed briefly. This chapter will conclude with a summary of the similarities and differences in airborne and underwater acoustics.

This leads to chapter 4 with the introduction of an alternative concept for noise assessment of continuous noise from ships. The principles of a simple model for the prediction of shipping noise are outlined. This chapter applies the proposed conceptual and theoretical framework and provides descriptions of the available data and how to interpret these.

In the results and discussion section, chapter 5, the maps which have been generated from the model are presented. The advantages and disadvantages are discussed and the boundaries of the system are outlined

The following chapter 6 states which information may be missing for the concept and what improvements could be made.

The last part of the thesis provides the research conclusion (chapter 7). This final chapter will summarize the advantages and disadvantages of the proposed assessment strategy and give an understanding of the research significance.

2 Assessment of airborne noise

In environmental acoustics the two main tools for assessment are measurements and the prediction/ modelling of sound propagation, with the majority of approaches rooted in measurements. The two tools are also applied as a method of control and verification of each other. The main goal of these methods is to assess the impact of sound on the environment. Usually, the assessment is done separately for different sound sources. The main differentiations are the characteristics of being impulsive (e.g. explosions, construction sites), continuous (e.g. industrial sites, wind farms) or intermittent (traffic noise).

The prevailing method in national and international noise directives, guidelines and laws is the quantitative approach of evaluating the impact of sound based on A-weighted averaged sound pressure levels (L_{Aeq}) [3, 49, 50, 52]. Some countries use a qualitative approach in defining and formulating goals to prevent negative impact of sound without setting specific target values or limits [52]. These methods are often connected, especially in laws and guidelines which are dedicated towards the topic of noise abatement. The main structure of these documents is that a higher goal (e.g. the prevention of unwanted or harmful noise) is presented which is followed by a set of rules and values which should in theory help to achieve the defined higher goal.

The main focus is often on the impact of noise on humans. The basic principles and reactions to sound can also be true for animals, which will be presented through the study of birds and road noise.

In the following chapter the foundations, the basic principles and the most commonly used parameters for noise assessment are outlined and explained.

2.1 Basics

2.1.1 Auditory sensation area of humans

The main foundation for noise assessment is the auditory sensation area of humans. All assessment takes place between the two areas of the hearing threshold, which is the lowest perceivable sound, and the threshold of pain.

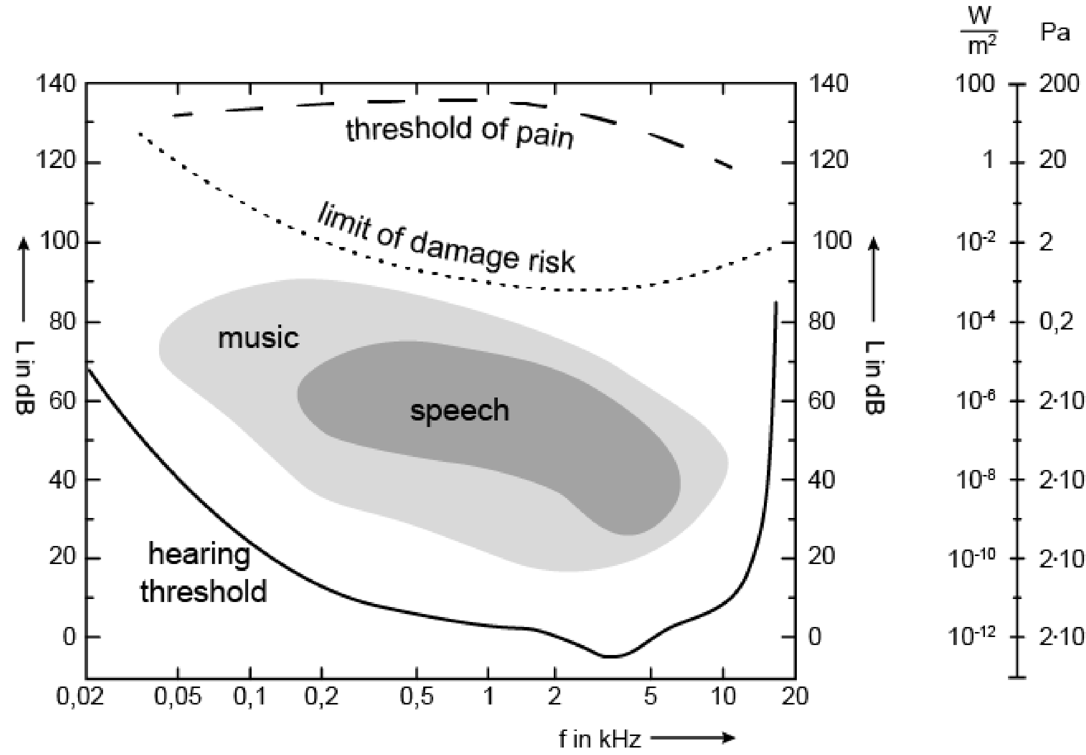


Figure 1: Auditory sensation area adopted from Zwicker [33]

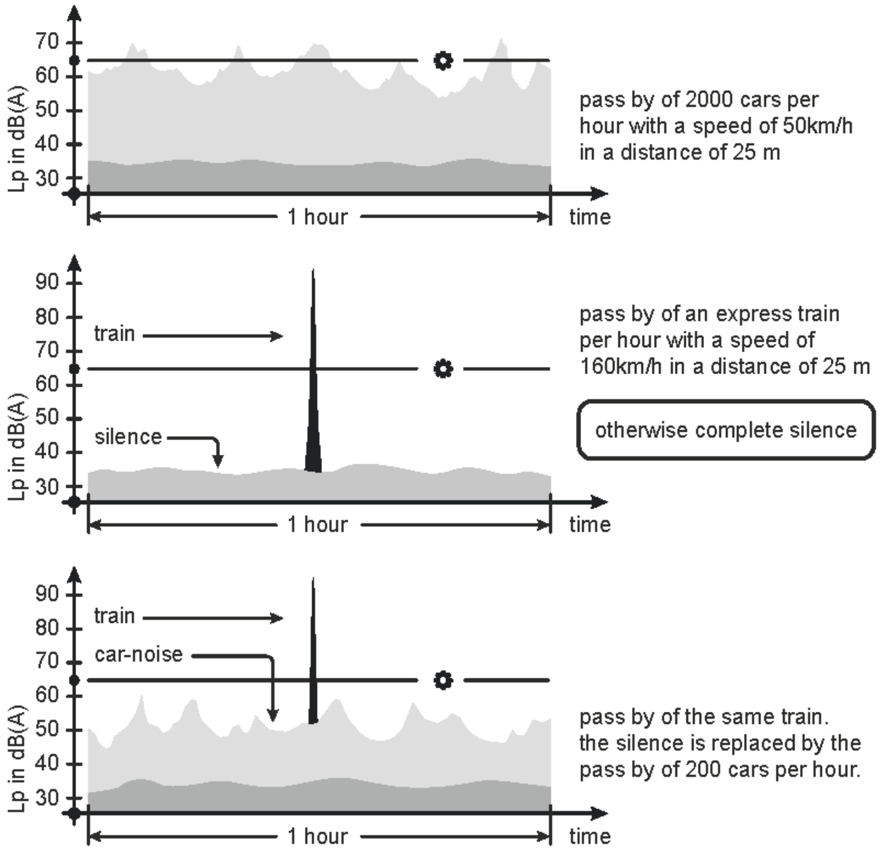
In environmental acoustics the main concern of noise abatement strategies is the prevention of unwanted sound (noise) which could lead to stress, sleep deprivation and long term physiological and psychological effects. This is due to the fact that the sound source is often times in a greater distance to the receiver than in e.g. a workplace environment and thus the received sound pressure levels are often times below the limit of damage risk. Exceptions are for example explosions or the noise from aircrafts at low altitude.

Hearing loss and temporary or permanent threshold shift (TTS and PTS) is mainly evaluated and regulated in workplace environments due to the close proximity of the receiver to the source and thus higher sound pressure levels. More subtle effects like masking or difficulties in concentration are evaluated here as well [7, 48].

2.1.2 Weighting functions and averaged sound pressure levels

Weighting functions have been developed in the first half of the twentieth century [26] to represent the frequency response of human hearing and to be able to give meaningful information in a single value. The weighting functions are derived from the contours of equal loudness [11]. The most common and widely used weighting function is the so-called A-weighting which is derived from the 40 phon contour. In combination with the averaged sound pressure level over a given time, this is the main tool in most noise assessments of airborne sound.

The widely known problem with this method is depicted in the following figure:



The average sound pressure level (⚙) is in all examples the same. In the last example the car-noise adds less than 0,5 dB(A) to the measured value of the express train and by rounding up to full dB the noise doesn't add much to the overall value.

Figure 2: The A-weighted averaged sound pressure level (L_p) and its limits [33]

As shown here the L_{Aeq} for all three events is the same but the perceived loudness by the receiver will be totally different for each event. The common way to compensate this effect is to add surcharges to the averaged values. These are given for impulsive noise, tonal noise or for sounds with information content.

Another way is to use psychoacoustic parameters such as the perceived loudness N in sone, but this is not done very frequently in environmental acoustics since the basis of the regulations and guidelines are mainly limits and indicators derived from sound pressure levels. These limits have been adjusted to match the effect of sound on the receiver as best as possible through several studies and questionnaires and are different for each sound source in question.

An extract of the regulations, standards and guidelines which summarize such findings are given in the next chapters.

2.2 Regulations and guidelines

2.2.1 WHO guidelines and implementation in European countries

In 2018 the World Health Organization (WHO) published their updated environmental noise guidelines for the European region [63]. Herein recommendations for limit values for different kinds of sources or activities are given. The evaluation of noise in environmental acoustics is based on the type of source. The main types are:

- Industrial noise (e.g. factories, construction sites, power plants)
- Traffic noise (road traffic, railway, aircraft)
- Wind turbine noise
- Leisure noise

The differentiation is necessary since all of these sources have different sound characteristics in terms of frequency, loudness and duration (impulsive, continuous, intermittent). The perception and the factor of annoyance is highly dependent on these characteristics. As mentioned before the prevailing method for evaluation is the A-weighted averaged sound pressure level (L_{Aeq}). The given indicators in the WHO directive are also L_{Aeq}. The two most important parameters given here are the L_{den} and the L_{night}. The L_{den} is an average sound pressure level over all days, evenings and nights and is derived from ISO 1996-1 [29]:

- L_{day} is the A-weighted long-term average sound pressure level, determined over all the day periods of a year.
- $L_{evening}$ is the A-weighted long-term average sound pressure level, determined over all the evening periods of a year.
- L_{night} is the A-weighted long-term average sound pressure level, determined over all the night periods of a year.

The evaluation of more noise sensitive times during a day are factored in.

Nusselder and Peeters give an overview of the implementation of these indicator values in existing regulations of European countries in their report [52].

As stated before, these regulations and guidelines are aimed towards the assessment of noise in humans. In the following section an example for regulations and an assessment strategy for bird species is given.

2.2.2 Natura 2000 and the habitats directive

Natura 2000 is an interconnected network of protected areas within the European Union. It is developed under the habitats directive of 1992 [51] with the goal of a transnational conservation of endangered plants, animals and habitats. This applies to land as well as sea areas.

In the science information system of the Federal Agency of Nature Conservation in Germany [21] data and information necessary for the impact assessment of the habitats directive are collected. It gives a broad overview of the protected areas and species as well as detailed information on the management plan for each area and the management for each effect factor (e.g. use of land, light, noise).

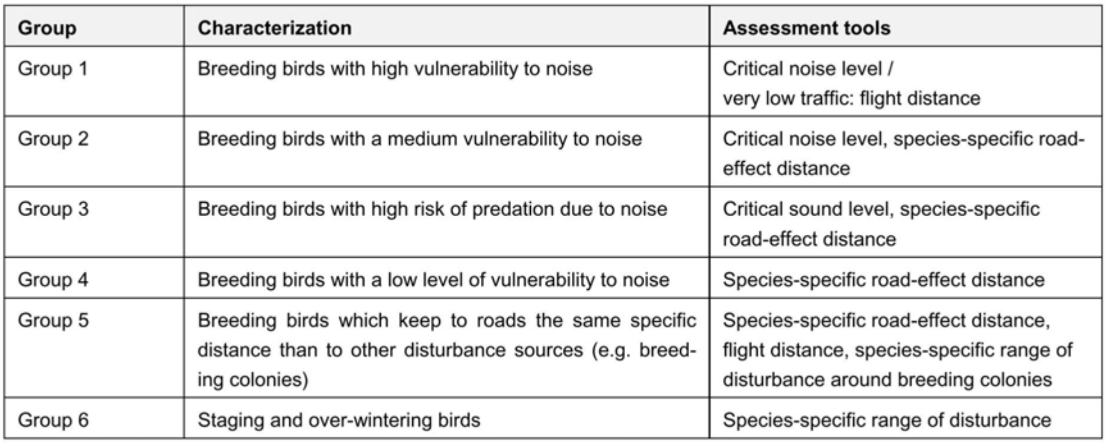
2.2.3 Birds and road noise

The federal ministry of traffic, construction and city development of Germany has developed and released an assessment strategy for the prediction of the impact of road noise on birds which should aid in the appropriate assessment of Natura 2000 sites [2].

It is a comprehensive report with coverage of 202 different breeding bird species and a representative sample of staging species. The report is structured into three parts.

1. Prediction of effects
2. Mitigation measures
3. Compensation

For the prediction of road noise, the established method of the German directive RLS-90 has been utilized as a method of evaluating the sound sources. This is intertwined with the species-specific reactions to traffic, which is one of the major outcomes of the report. Figure 3 shows the classification of the different species and the assessment tools most suitable to assess the impact on each group.



Group	Characterization	Assessment tools
Group 1	Breeding birds with high vulnerability to noise	Critical noise level / very low traffic: flight distance
Group 2	Breeding birds with a medium vulnerability to noise	Critical noise level, species-specific road-effect distance
Group 3	Breeding birds with high risk of predation due to noise	Critical sound level, species-specific road-effect distance
Group 4	Breeding birds with a low level of vulnerability to noise	Species-specific road-effect distance
Group 5	Breeding birds which keep to roads the same specific distance than to other disturbance sources (e.g. breeding colonies)	Species-specific road-effect distance, flight distance, species-specific range of disturbance around breeding colonies
Group 6	Staging and over-wintering birds	Species-specific range of disturbance

Figure 3: Classification of bird species, characterization and applied assessment tools [2]

The values and ranges have been validated by measurements and observations and are summarised in the appendix of the report. The evaluation methods do also include metrics which are not acoustic parameters such as the flight or effect distance which have been obtained from observations.

In step two of the guideline the noise mitigation measures are calculated and evaluated to minimize the impact on the animals and in the last step compensation measurements are discussed and proposed for the different species.

2.3 Calculation, modelling and input data

In this chapter a short overview of the prognosis of traffic noise as a main source of environmental noise is given. The necessary input data and backgrounds for the description of sound sources as well as the calculation of sound propagation are presented. A detailed description of modelling methods is not part of this thesis. The information given here should show how the complex topic of sound propagation is handled in airborne acoustics in relatively simple terms.

2.3.1 Calculation and modelling of traffic noise

The calculation and evaluation of traffic noise is further divided into different types based on their characteristics and impact:

- Road traffic noise (depending on the number and speed of the vehicles and the distance to the road this either resembles intermittent or continuous noise)
- Railroad noise (intermittent noise in close range)
- Air traffic noise (intermittent noise in close range or low frequency continuous noise in greater distances)

When describing the sound emissions from traffic it is either given in terms of an equivalent sound pressure level L_{eq} at a given distance and height in relation to the road/ track or by means of a total sound power level L_{W} or linear sound power level L_{w}'. [45] For the determination of the sound emissions certain input data is necessary:

- Type of vehicles (cars, lorries, motorbikes, passenger trains, cargo trains, express etc.) and number within a certain timeframe (often divided by day and night as described before in chapter 2.2)
- The speed and characteristic (e.g. road junction, number of lanes) for each road or track section and type of vehicle as well as the traffic condition (free flowing or acceleration/ deceleration)
- The type and condition of the road/ track surface as well as the gradient

These monitoring data are mainly obtained from publicly available datasets from mapping services of different states or cities.

In modelling software traffic noise is usually entered as a line source. When calculating the rating level L_{r} at the point of immission (POI) these sources are subdivided into point sources. This procedure is described in the German regulation on traffic noise [3]. The line source is divided into sections with a length of l_{ks}. As a reference value for a suitable length l_{ks} it is proposed to use the half of the path length d_{ks} from the middle of the section to the POI. This concept is shown in Figure 4.

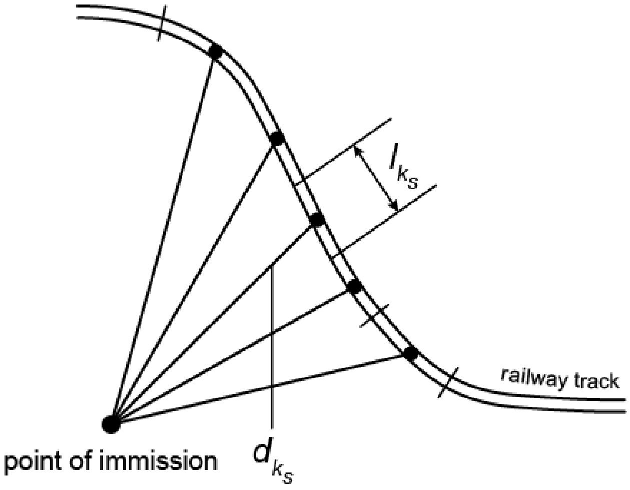


Figure 4: Subdivision of line sources into point sources. [3]

This method generates representative sources for each section of a track in relation to the POI.

2.3.2 Sound propagation in air

To determine the A-weighted sound pressure level caused by a sound source at a specific POI the sound propagation conditions need to be known. The Standard ISO 9613-2 [8] defines the main conditions and terms used for calculation of sound propagation.

If the acoustic emission of a sound source is known, the noise caused at a distance *d* can be calculated. The calculation can be performed dependent on frequency in octave bandwidth. From the octave-band spectrum L_w of a sound power level of a sound source, the expected average sound pressure level in downwind direction $L_f(DW)$ at a distance *d* of the sound source and at the octave band frequency *f* can be calculated according to the following equation:

$$L_f(DW) = L_W + D_C - A_{div} - A_{atm} - A_{gr} - A_{bar} - A_{misc} \qquad 1)$$

With

- D_c – directivity correction
- A_{div} – attenuation due to geometrical divergence
- A_{atm} – attenuation due to atmospheric absorption (at 10 °C and 70 % relative humidity)
- A_{gr} – attenuation due to the ground effect
- A_{bar} – attenuation due to a barrier
- A_{misc} – attenuation due to other miscellaneous effects

In chapter 9 of the standard the restrictions and accuracy of the method is provided. Herein the accuracy is given for a distance of up to 1000 m. Everything above this distance has a higher uncertainty.

As shown here, a lot of site specific and complex factors are compressed into simple to handle quantities.

3 Assessment of underwater noise

In underwater acoustics there are some definitions and terms which are less common in airborne acoustics. The most important ones for this thesis are presented in this chapter.

An overview of current assessment strategies will be given based on the example of two European initiatives for the Baltic Sea and the North Sea region.

The bioacoustic foundations needed when assessing the impact of noise on animals are introduced as well.

The chapter concludes with a comparison between underwater and airborne acoustics.

3.1 Terminology

In recent years standards in underwater acoustics have been developed by the Technical Committee: ISO/TC 43/SC 3 Underwater acoustics to set a scope for a common terminology [30] and the standardization for measurements of shipping noise [9, 10].

The ISO 18405 [30] defines the basic terminology which is important and most commonly applied in underwater acoustics. Terms which are important to the thesis are described hereafter

Source level (SL)

The source level defines the sound pressure which is emitted by a sound source and is defined by ISO as the mean-square sound pressure level at a distance of 1 m from a hypothetical point source in an infinite, uniform, lossless medium. It is regularly expressed in dB and cited with a reference value of $1\mu Pa\ @1m.$.

It is defined as:

$$L_S = 20 \cdot \log_{10}\left(\frac{\sqrt{F_S}}{\sqrt{F_{S0}}}\right) \qquad 2)$$

With $F_{S0} = 1\ \mu Pa^2 m^2$ and F_S being the power quantity source factor defined as:

$$F_S = r^2 \cdot p^2 \qquad 3)$$

With *r* being the distance from the acoustic centre of a source in a specified direction and *p* being the sound pressure in the acoustic far field at that distance.

Remarks:

The source level is comparable to the sound power of airborne acoustics, whereas in the case of an omnidirectional radiator the area of a sphere with a radius of 1 m as well as the acoustic impedance would still have to be taken into account.

The standard series DIN ISO 17208 [9, 10] defines the methodology for measuring the emitted sound from ships and the determination of the source level.

Ambient sound

Ambient sound is described as sound that would be present in the absence of a specified activity. It can either be anthropogenic (e.g. shipping noise at large distances) or natural (e.g. wind, biotic, thermal).

Sound Exposure

Sound exposure is the integral of the square of the sound pressure p over a specified time interval or event, for a specified frequency range.

$$E_{p,T} = \int_{t_1}^{t_2} p^2(t)\, dt \qquad 4)$$

Power spectral density (PSD)

The power spectral density is a generic term in combination with a descriptor (e.g. the mean-square sound pressure) to indicate the type of power-like quantity whose distribution with frequency is described. It is regularly expressed in units of $\mu Pa^2/Hz$.

3.2 Bioacoustics

When assessing noise, it is necessary to have a level of understanding of the auditory needs and functions of the recipient. Hence an overview of the bioacoustic properties and indicators is presented in this chapter.

The effect of sound on animals and their reactions to it vary in relation to the distance of the sound source to the POI. As depicted in Figure 5 the effects can be grouped into 3 Zones.

Zone one can be described as physical effects on animals which could lead to a permanent or temporal threshold shift (PTS or TTS) as well as noise induced trauma or physical harm.

Zone two is the area in which behavioural responses are observable such as flight responses and avoidance but also more subtle reactions such as stress induced higher heart rates and the masking of important communication signals. The effects of zone two cause no direct physical harm but could lead to severe problems in the long term such as decline in population, reduced communication ranges and loss of habitat or a shortened lifespan. When assessing the impact of shipping noise these are the most common effects to be expected.

Zone three should have no effect on animals since the signals are too low for animals to be detected. The transition between Zone 3 and 2 can be also defined as the limit or threshold of hearing.

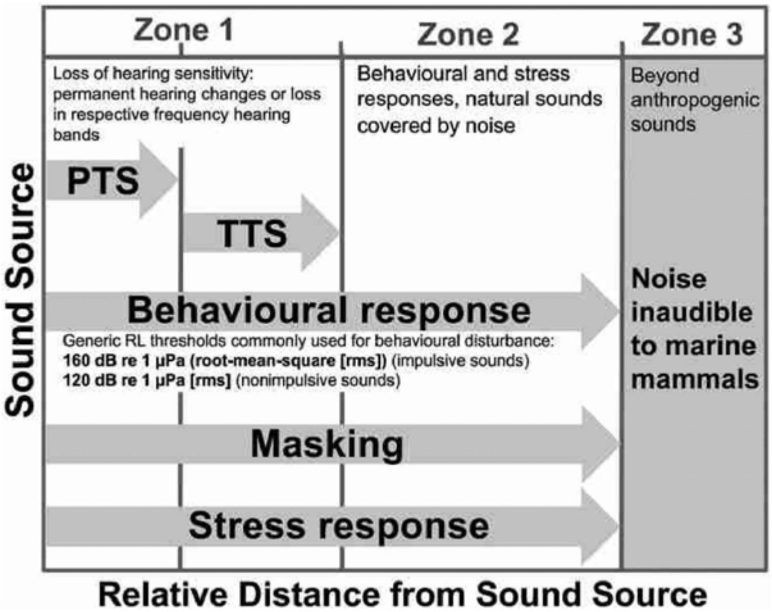


Figure 5:Zones of noise related reactions and effects [23]

3.2.1 Hearing groups, audiograms and weighting functions

As described in chapter 2.1 the foundation for noise assessment is the auditory sensation area. For marine mammal species the audiograms have been summarized by Southall et al. [57]. In this paper the species are divided into hearing groups as presented in Figure 6.

Marine mammal hearing group	Auditory weighting function	Genera (or species) included	Group-specific appendix
Low-frequency cetaceans	LF	Balaenidae (*Balaena*, Eubalaenidae spp.); Balaenopteridae (*Balaenoptera physalus*, *B. musculus*)	1
		Balaenopteridae (*Balaenoptera acutorostrata*, *B. bonaerensis*, *B. borealis*, *B. edeni*, *B. omurai*; *Megaptera novaeangliae*); Neobalenidae (*Caperea*); Eschrichtiidae (*Eschrichtius*)	
High-frequency cetaceans	HF	Physeteridae (*Physeter*); Ziphiidae (*Berardius* spp., *Hyperoodon* spp., *Indopacetus*, *Mesoplodon* spp., *Tasmacetus*, *Ziphius*); Delphinidae (*Orcinus*)	2
		Delphinidae (*Delphinus*, *Feresa*, *Globicephala* spp., *Grampus*, *Lagenodelphis*, *Lagenorhynchus acutus*, *L. albirostris*, *L. obliquidens*, *L. obscurus, Lissodelphis* spp., *Orcaella* spp., *Peponocephala*, *Pseudorca*, *Sotalia* spp., *Sousa* spp., *Stenella* spp., *Steno*, *Tursiops* spp.); Montodontidae (*Delphinapterus*, *Monodon*); Plantanistidae (*Plantanista*)	
Very high-frequency cetaceans	VHF	Delphinidae (*Cephalorhynchus* spp.; *Lagenorhynchus cruciger*, *L. austrailis*); Phocoenidae (*Neophocaena* spp., *Phocoena* spp., *Phocoenoides*); Iniidae (*Inia*); Kogiidae (*Kogia*); Lipotidae (*Lipotes*); Pontoporiidae (*Pontoporia*)	3
Sirenians	SI	Trichechidae (*Trichechus* spp.); Dugongidae (*Dugong*)	4
Phocid carnivores in water Phocid carnivores in air	PCW PCA	Phocidae (*Cystophora*, *Erignathus*, *Halichoerus*, *Histriophoca*, *Hydrurga*, *Leptonychotes*, *Lobodon*, *Mirounga* spp., *Monachus*, *Neomonachus*, *Ommatophoca*, *Pagophilus*, *Phoca* spp., *Pusa* spp.)	5
Other marine carnivores in water Other marine carnivores in air	OCW OCA	Odobenidae (*Odobenus*); Otariidae (*Arctocephalus* spp., *Callorhinus*, *Eumetopias*, *Neophoca*, *Otaria*, *Phocarctos*, *Zalophus* spp.); Ursidae (*Ursus maritimus*); Mustelidae (*Enhydra*, *Lontra feline*)	6

Figure 6: Proposed marine mammal hearing groups, applicable auditory weighting functions, genera or species within each proposed group [57]

The typical mammal species that can be found in the southern North Sea are the harbour porpoise (Phocoena phocoena), harbour seal (Phoca vitulina) and grey seal (Halichoerus grypus). The harbour porpoise belongs to the family of VHF-species and the two seals belong to the hearing group of PCW. The audiograms for these species are depicted in Figure 7. These have been derived from estimates on all available data on individual animals inside each group and can be seen as a best estimate of hearing among each group.

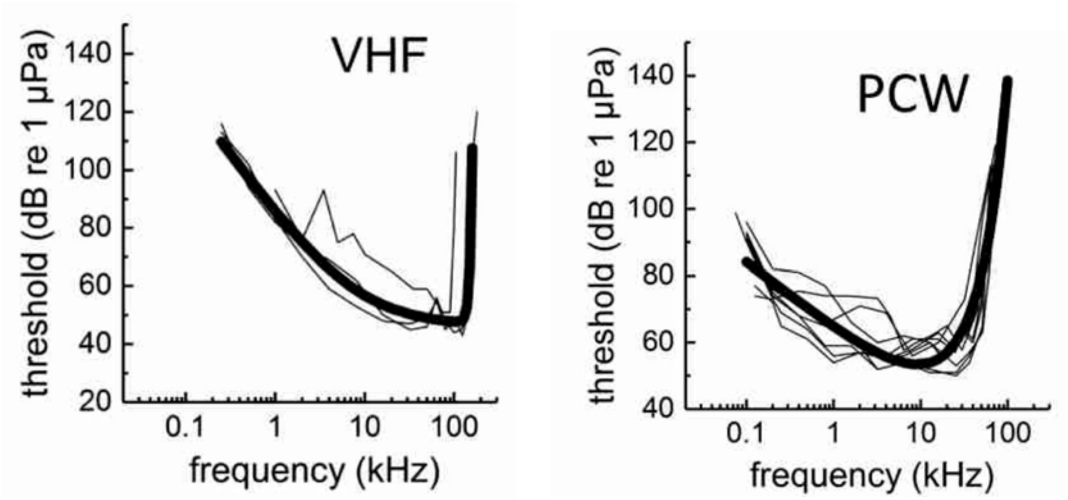


Figure 7: Estimated group audiograms based on original behavioral threshold data for very high-frequency (VHF) cetaceans and phocid carnivores in water [PCW] [57]

When assessing the impact of noise weighting functions may aid in finding values which reflect the perceived sound and effect on animals better than unweighted functions. This is highlighted by the study on the use and development of weighting functions and contours of equal loudness in humans and marine mammals by Houser et al. [26], as well as in the study by Tougard and Dähne [60].

Remark:

The weighting functions may not be easy to obtain or adapt for tonal or impulsive noise. Here it might be more practicable to find surcharges similar to methods used in airborne acoustics described in chapter 2.1.2.

3.2.2 Masking, Critical Ratio and Critical Bandwidth

The effect of masking is categorized into different zones as depicted in Figure 8.

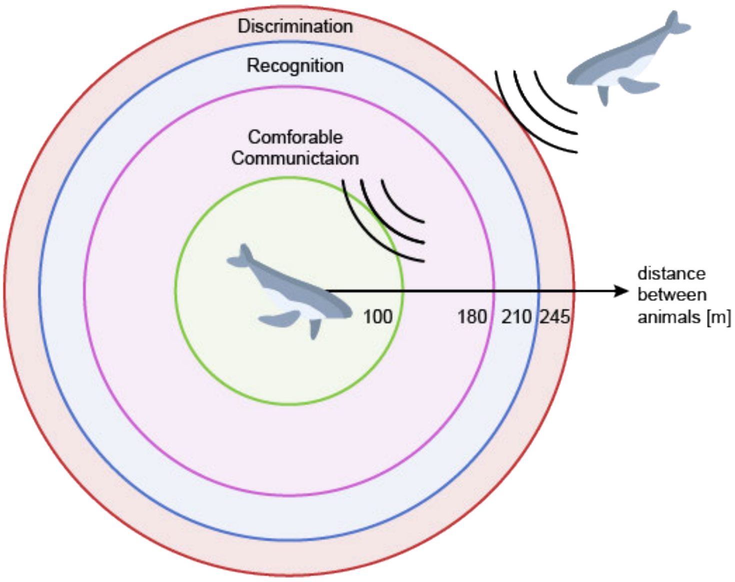


Figure 8: Zones of communication [16]

As pointed out by Erbe et al. [16] the distance of these zones vary with the propagation of sound in water and might translate to large distances depending on the animals in question.

When talking about mere detection of a signal the critical ratio (CR) and critical band (CB) is to be introduced. The CR is the difference between the sound pressure level of a pure tone just audible in the presence of a continuous noise of constant spectral density and the sound pressure spectrum level for that noise expressed in dB. For marine mammals there are some studies on the critical ratios of few individuals [16, 34, 56, 58].

The critical band or auditory filter is an array of bandpass filters that are assumed to exist in the peripheral auditory system [33]. The critical bands are usually summarized in frequency groups which are used in measurements and the evaluation in third octave bands. This is usually derived from human hearing in airborne sound and for a frequency > 500 Hz these filters resemble the human auditory filters quite well. The auditory filters in marine mammals are derived from their critical ratios and can be found in the publication by Erbe et al. [16]. These would be more suitable when assessing animals.

3.3 Assessment tools and strategies

When looking into European waters there are several organisations and countries which have developed strategies for noise assessment and monitoring to implement and develop tools for the evaluation of Good environmental status (GES). EMSA has recently published a paper with an overview of the present state of policy, research and impacts of continuous underwater noise in Europe [5].

In the following section, two strategies developed to assess continuous noise from ships in the north-east Atlantic and the Baltic sea are presented and reviewed.

3.3.1 BIAS

The Baltic Sea Information on the Acoustic Soundscape (BIAS) project has developed a framework for monitoring and assessing continuous underwater noise in the Baltic Sea. It consists of the definition of standards for measurements and signal processing as well as measurements and analysis of the results.

The aim defined in the project is to assess communication loss due to masking and the impact of continuous noise on the population level of an abundant species. The basis for this is a statistical distribution of sound pressure levels extracted from monitoring data and soundscape modelling for the points of each area in between the monitoring positions.

Three approaches have been defined to evaluate GES for different areas of the sea with related criteria.

1. Spatially Sonified Area: “The first criteria is used for evaluating the impact in areas where there is a general need to regulate the noise levels, such as Nature 2000 areas or in areas where no specific sound sensitive species are known to be present.”

2. Temporarily Sonified Area: “The second criteria is used for evaluating the impact on specific species such as cod. The threshold level is set to reflect a sound pressure level that potentially can affect the species. This criterion is used when there is a known threshold level. The threshold can be related to for example masking. Sound pressure levels louder than the threshold would potentially decrease the communication range and hence affect the fitness of the species.”

3. Low Activity Area: “The third criteria is used in areas where it is known that number of ships is low. The assessment can be done by using yearly produced AIS-maps.” [25]

The main output is a soundscape planning tool which generates maps as depicted in Figure 9. Herein the *n*-percentile levels L_n are given for the third octave bands of 63 Hz, 125 Hz, and 2 kHz over the time of a month. The modelling was performed for three different depths.

The frequency bands of 63 Hz and 125 Hz have been selected in accordance to the MSFD descriptor D11C2 [19] (Annex A Figure 36). The 2 kHz third octave band has been introduced to also represent the sound energy introduced by ships in the higher frequencies and to be able to better assess the needs of animals with a higher hearing range. Since the results are given in third octave bands, which are derived from the human auditory system, these do not resemble the auditory filters and bandwidths of animals (as described in chapter 3.2.1). This could lead to a misjudgement in certain frequencies which was also stated by Müller [44].

The input data for the model were derived from the measurements carried out, from information from Automated Identification System (AIS) and Vessel Movement System (VMS) of ships as well as Geographical Information Systems (GIS) for the sound propagation conditions and boundaries such as bathymetry. In addition, detailed information on the development and modelling of the sound sources is given in the report by Jalkanen et al. [31]. Here the sound energy for different types of vessels in the Baltic Sea is summarized and presented in maps (see Figure 37, Annex B).

The modelling and calculation of propagation loss has been carried out for the whole area of the Baltic Sea. This probably leads to a high level of uncertainty in greater distances to the source, similar to the limits described in airborne acoustics (see chapter 2.3.2 and [8]). This adds to the uncertainties which can already be found at the source level. In the Canadian ECHO-program a vast number of measurements for different vessel types was carried out. The data summarized in their report [38] shows large variations of 15-20 dB in certain frequencies from the source levels for each category of ships (cargo, tanker, fishing, etc.).

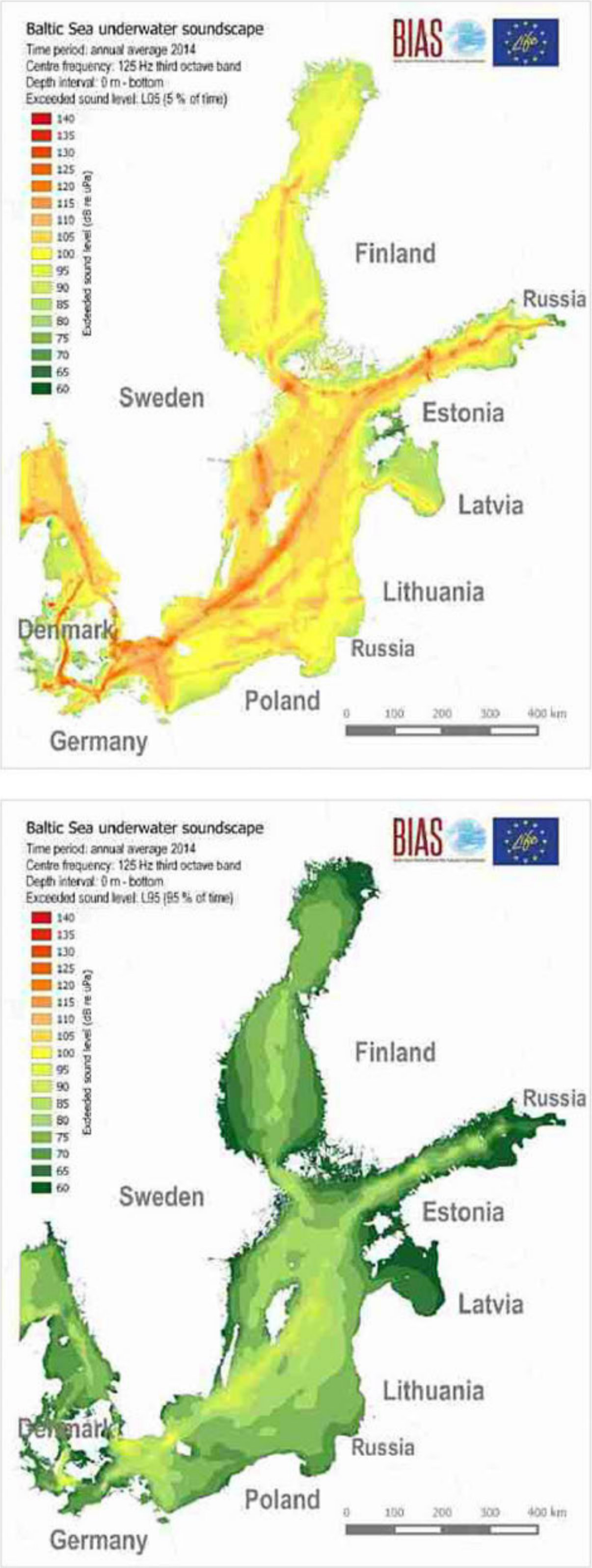


Figure 9: The modelled annual average soundscape for 2014, for the 125 Hz third octave band and over the full depth. (Top figure) Noise levels occurring occasionally (5 % of the year; L05), and (bottom figure) noise levels occurring regularly (95 % of the year; L [47]

3.3.2 JOMOPANS

JOMOPANS is a direct successor to the BIAS project. It is a framework under which tools have been developed for the monitoring and assessment of the North Sea. The work packages are similar to the ones found in BIAS with measurements and data analysis as well as the generation of sound maps for the region. The main difference is, that the frequency range for the sound maps covers the range of the third octave bands of 10 Hz to 20 kHz and different metrics have been introduced to describe and evaluate the soundscape. These will be presented in the following sections. While the frequency range covers a wider range of the overall frequency spectrum, it is still not well suited to assess species in the VHF category, since their hearing is most sensitive at around 100 kHz (see Figure 7). At this point it must also be stated that numerical methods are not well suited for the frequency range and come with a high level of uncertainty due to the short wavelength as well as a high impact of extraneous noise [15].

The input data for the model have been derived from similar sources as in the BIAS project. The shipping routes have been generated from AIS and VMS data with time steps of 10 minutes. The ships have been modelled as omnidirectional sound sources and the positions have been derived from 10-minutes snapshots and an average traveling speed for each category of ship. The results are given in median levels over a period of a month or as annual averages. The calculation is similar in complexity to the BIAS programme and has been carried out for large distances as well. The model of the source levels of ships based on AIS data has been improved using the ECHO data [37].

The main aim defined by JOMOPANS is to evaluate the loss of communication range due to masking. To be able to describe this, the excess level was introduced.

Excess Level

The excess level is described as the exceedance of total noise above natural noise:

$$\Delta L = L_{Total} - L_{Natural} \qquad 5)$$

Where

- L_{Total} represents the sound pressure level at the POI with all sound contributions (shipping, wind, rain, etc.) and is a directly measurable variable.
- L_{Natural} is only the contribution of non-anthropogenic noise.

The excess level in the interpretation of the project JOMOPANS is an instantaneous value, which means that L_{Natural} needs to be known at every timestep.

In Figure 10 a map for the annual median excess level as generated by JOMOPANS is presented.

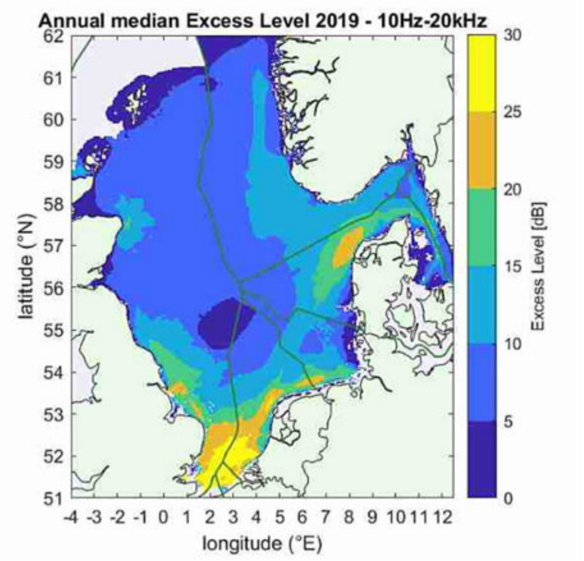


Figure 10: Annual median excess level [32]

Remark:

The Excess Level is effectively a signal to noise ratio that can be taken to describe how the noise of ship traffic masks the natural ambient sound for each time step. However, if this is to be applied as a basis for assessing masking of animal communication, it is unfortunate to apply a constant cut-off threshold for the excess level as was applied in the JOMOPANS project. Short explanation: This would mean that if L_{Natural} is very high, the sound source could also be much louder when the same excess level is applied. However, communication is typically disrupted when background noise is increased.

Dominance

Dominance is defined as the percentage of evaluation time over which the excess level exceeds a certain cut-off value. In the JOMOPANS project it was decided to use the cut-off values of ΔL = 20 dB and ΔL = 6 dB with the aim of assessing communication loss in animals.

Figure 11 gives an example of the generated dominance sound maps.

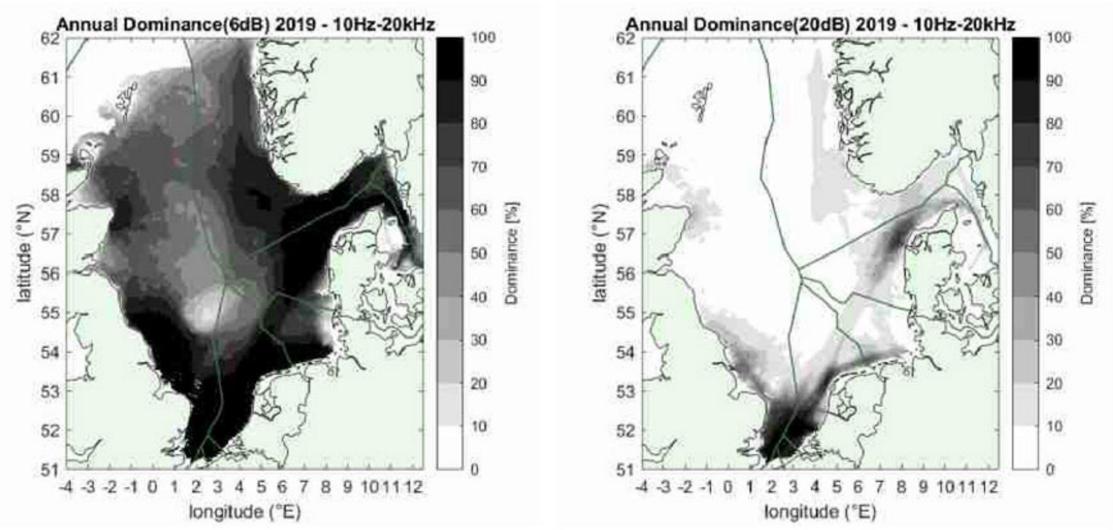


Figure 11: Annual dominance [32]

In Chapter 6.4 of the JOMOPANS paper on the “Guidelines for modelling ocean ambient noise” it is stated that a “6 dB excess level translates into a decrease in maximum communication distance by 50 % and a 20 dB excess translates into a decrease in maximum communication distance by 90 % (see WP7[1] report).” [32]

It is not clear from this statement for which species of animals this is true, since the vocalisation and hearing thresholds for each species are very different.

Furthermore, it is improbable that the loss of communication distance and the impact on the animals is the same for all sea states. If the sea state is low and thus the natural ambient sound is low, the exceedance of 6 dB or 20 dB has a lower impact on the animals than with higher ambient sound. If L_{natural} is high it is already harder for the animals to communicate. If a high ambient noise is exceeded by 6 dB or 20 dB the impact will be more drastic. Figure 38 and Figure 39 in Annex C illustrate this problem for two different species at two different sea states and shipping noise in three different distances to the sound source. As depicted here it is clear that the impact on the animals is highly dependent on their audiogram and the frequencies and source level of their calls.

In order to raise the signal to noise ratio (SNR) animals are also able to raise their volume to a certain extent or alter the duration of their calls and frequency [16]. This is known as the Lombard effect. This however, should not be taken as an excuse for higher sound

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[1] As of today (31.01.2022) the report on WP7 has not jet been published. https://northsearegion.eu/jomopans/publications-presentations-reports/wp7-reports/

levels since this is already a reaction of the animals to noise and the degree to which animals are able to adapt their vocalization also has a limit.

Pressure curves and pressure index

From the before mentioned dominance values pressure curves and pressure indexes are generated as presented in Figure 12 and Figure 13.

The pressure curves show a “cumulative distribution of the percentage of evaluation area as a function of the dominance values”. [32] (% of area in relation to % of time an excess level is exceeded).

The pressure index is “a single number index for the area under the pressure curve, quantifying the percentage of the evaluation area as well as the percentage of the evaluation time interval, in the evaluation frequency band, where the excess level exceeds the specified cut-off value.” [32]

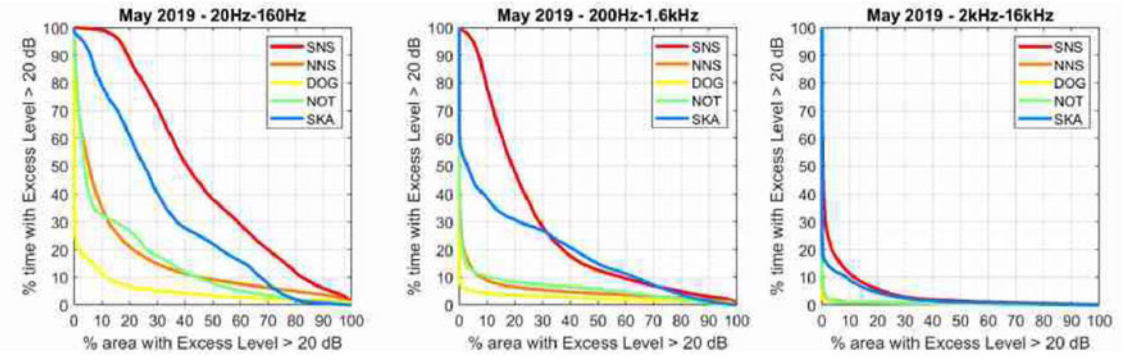

Figure 12: Pressure curves for the five OSPAR subregions for May 2019 and for a cut-off value of excess level of 20 dB [32]

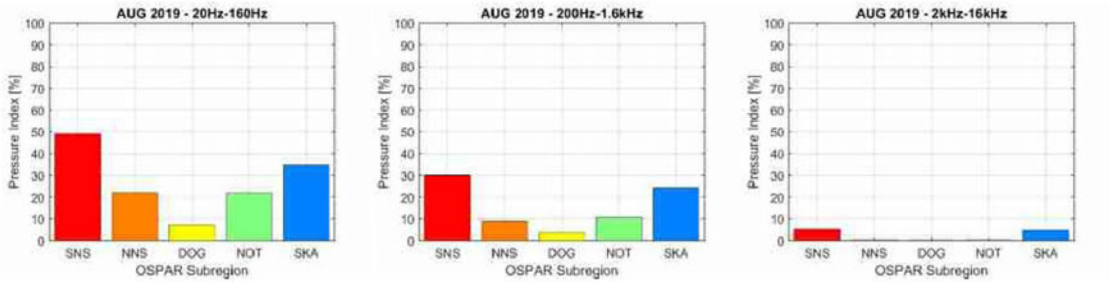

Figure 13: Pressure index for the five OSPAR subregions for May 2019 and for a cut-off value of excess level of 20 dB [32]

These metrics and curves should aid in interpreting the given sound maps and, in applying a single value, the comparison of pressure for certain areas.

3.4 Comparison of airborne and underwater acoustics

To summarize the findings from the previous chapters an overview of the different concepts and parameters in airborne and underwater acoustics is presented.

In the following table the differences between common acoustic variables are given for propagation in water and air.

Table 1: Overview of the differences in common base values in underwater and airborne acoustics as found in [43]

Dimension[2]	Air[2]	Water[2,3]
Speed of sound (m/s)	339	1500
Density (kg m^{-3})	1.23	1.026×10^3
Wave impedance (N s m^{-3})	417	1.539×10^6
Reference Value sound particle velocity (m/s)	5×10^{-8}	10^{-9}
Reference value sound pressure (µPa)	20	1

This already shows that a simple comparison between values in air and water is not possible without conversion.

Next, the differences in classifying the different source types by their characteristics in air and water are shown.

Table 2: Classification of source types in air and water

Source type	Airborne	Waterborne
Impulsive	Explosions, pile driving, gun shot, etc.	Explosions, pile driving, seismic surveys, etc.
Intermittent	Traffic noise	-
Continuous	Industry (pumps, machineries, compressors, etc.), Road noise (high traffic)	ships

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[2] At a temperature of $T = 13\ °C$

[3] At a salinity of $S = 34.75$ ‰

As can be seen here the differentiation of the sources is not explicit and depends on the context.

In underwater noise, ships are put into the category of continuous noise. This may be true from the perspective of the source itself and for areas like harbours and ports as well as areas with a high number of recreational vessels, but is questionable when looking at shipping routes for cargo and other large carrier ships in the open waters. In close range the noise is intermittent from the receivers' point of view. In large distances the low frequency continuous noise is dominant but it is difficult to differentiate between the different sound sources. The best way to manage the low frequency continuous noise would be to find a suitable value of ambient noise and to regulate the sound energy which is introduced into the water by all ships. The previously mentioned sound energy maps (see Figure 37, Annex B) could serve as a starting point. This method is similar to noise allotment in airborne acoustics, where sound power levels are set and divided for different areas of a development plan in order to match the target immission values in the neighbourhood.

Following, a comparison of the tools and parameters used to evaluate and describe the sound sources and impact of noise is given:

As pointed out before the prevailing method for assessment in airborne acoustics is the L_{eq}. This is mainly true for the assessment of the effect of noise on humans. The methods used and presented, alongside the adjustments, have been developed over several decades now and are well documented with a high level of standardization. This is mainly due to the fact that it is easier to assess human beings since the threshold values can be directly evaluated in studies with lots of different participants and direct responses.

In environmental impact studies regarding animals in air the L_{eq} is also used quite frequently. Here the threshold values have been adjusted to the species in question by large scale field studies. In chapter 2.2.3 an example for the assessment of the reaction of birds to road noise has been presented. Beside acoustic metrics this study also utilizes effect ranges and flight distances obtained from observations in dependence which parameters are best suited for each species. This is easier to obtain in air since land is more easily accessible for humans.

When looking into noise assessment of continuous underwater noise the prevailing method is the use of received levels RL with different metrics as either relative or absolute values. The main goal is to assess disturbance or masking as described in the recently published assessment framework on continuous underwater noise by TG Noise [55]. The proposed methods are strictly based on acoustic metrics. Problems in using RL as the main indicator have been described by Gomez et al. [23]. In their study they reviewed studies available from 1971 to 2015 on the behavioural response of wild marine mammals to noise. These show that the reporting of effects and RL in the literature is inconsistent. This is linked to the problem that in underwater acoustics the standardization is not well developed but also to the fact that the accessibility is harder and studies are often limited to a small number of animals. Further it is stated that higher or lower RL do not always correspond to a more or less severe reaction of the animals to noise as often presumed. The study concludes with the proposal of an alternative approach based on a response/ no response rating to predict the impact in terms of habitat loss and degradation.

This approach was considered in the assessment of impulsive noise in water as described by Merchant et al. [42] and implemented in the document of the TG-NOISE on impulsive underwater noise [6] with the use of an effect range.

4 Alternative assessment strategy

From the previously described strategies and suggestions found in the literature the idea of an alternative assessment strategy for shipping noise is derived.

For the assessment of the impact on animals the response/ no response rating as described in the previous chapter is used. This means that if a given threshold value is exceeded the area in the sea is exposed to noise and a reaction from animals is to be expected. With this and additional knowledge of the source level spectra an the applicable propagation law, the exposed area for each sound source (ship) can be calculated. From the input data the information on how many ships are in a certain area can be derived. In the end maps with the overall exposure are generated.

In general all sound sources in an area need to be considered to get a proper description of the soundscape. To illustrate the concept it was decided to only use the data for cargo ships. The input data necessary for the calculation and modelling of the ships are derived from EMODnet [14].

The acoustic situation is assessed for the harbour porpoise, since it is one of the key species in the North Sea [61]. The current strategies and limitations in modelling and measurements in the VHF range make it hard to assess this species properly. A simple observation of reaction responses with reference to ships can be found in the literature described below.

In the following the approach and input data for the strategy are described in greater detail.

4.1 Sound exposure, potential impact and exposed area

The sound exposure *E* can be used to describe the impact of sound on a sea area A_{total} of interest. Since sound pressure represents a spatial quantity the sound exposure must be determined for each position x_i in an area as given in the following formula.

$$E(x_i)_{p,T} = \int_{t_1}^{t_2} p^2(x_i,t)\,dt \qquad 6)$$

with the monitoring time $T = t_2 - t_1$

The potential impact (disturbance, TTS, PTS) on a species of animals can arise from a certain biological threshold value *TV*, e. g. a sound pressure or a (weighted) sound pressure level.

For sound pressure values above this threshold value *TV*, an exposed area E_A can now be described:

$$E_A(x_i)_{p,T} = \int_{t_1}^{t_2} A_S(p^2(x_i,t) > TV) \cdot dt \qquad 7)$$

Where A_S is the affected area as a function in relation to the *TV*.

As a reference value for the exposed area E_A

$$A_{total} \cdot T$$

is being used.

An exposure index *EI* can be introduced

$$EI = \sum_{x_i} \frac{E_A(x_i)_{p,T}}{A_{total} \cdot T} \qquad 8)$$

which is a measure of the exposed area over the observation time *T*. *EI* is zero in case of no impact and a maximum of 1 in case of 100 % exposure (whole time, whole area).

In theory the exposed area can be quantified if the threshold values and the sound emissions of the source (ships) are known. Another way to deduce this is by finding effect ranges from observations of animal behaviour.

Remark:

The severity of the impact is also dependent on the time exposed. This topic is not covered in this thesis.

4.1.1 Effect range and affected area

The effect range is a distance at which a reaction by an animal is to be expected in relation to a source e.g. a ship. As mentioned before this is linked to a threshold value, for an illustration see figure 14.

The affected area A_S for each single source depends on the source level SL of the ship, the propagation loss PL of sound in the specific area and the defined biological threshold value *TV.*

$$A_S = A_S(SL, PL, TV) \tag{9}$$

In the concept presented here, direct acoustic properties are not considered, but observations of noise effects that can be described over a specific distance, in other words an effect range. The area around a source which is affected by sound can thus be simplified for our illustration of the concept:

$$A_S(r) = \pi \cdot r^2$$

Where $A_S$is the area which is affected by a sound source and *r* is the given effect range for a certain species and source level.

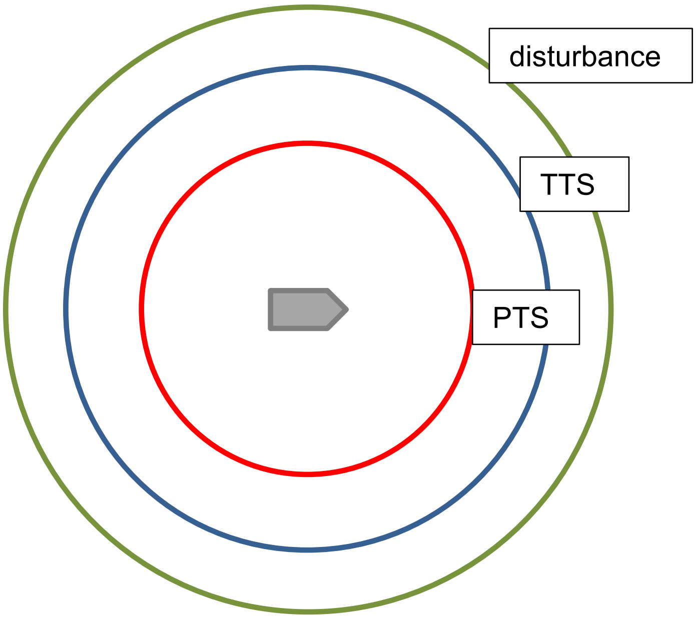

Figure 14: Different effect ranges for certain impacts.

Figure 14 shows the effect ranges for different effects to be evaluated.

4.1.2 Evaluation of a sea area

In the following the concept is explained for the evaluation of a sea area. The area is hereby structured into cells of 1 x 1 km^2. This is derived from the vessel density data from EMODnet since the area and data are also structured into cells by this size. The input data will be explained in more detail in chapter 4.2.1.

If a given sea area is to be assessed with a management or total area of A_{total} the total exposure can be describes as $A_{total} \cdot t_{total}$, where t_{total} is a day.

The relative exposure of a single cell x_c in a management area (A_{total}) can be described as

$$x_c = \frac{E(A_s)}{A_{total} \cdot t_{total}} \qquad 10)$$

The summation of all cells in an area gives us the exposure index for the whole area:

$$EI = \sum_c x_c \qquad 11)$$

This concept is further explained by a simple example:

In a sea area of 100 km^2 (= A_{total}) 24 of the 100 grid cells are exposed with ships for 1 h/day. The area affected by sound from each cell is $A_s = \pi \times (1\text{ km})^2$. So the overall exposure is:

$$EI = \frac{24 \cdot A_s \ \cdot 1\,h}{A_{total} \cdot 24\,h} = \frac{\pi}{100}$$

This can be depicted in a diagram to show the average exposure over a day.

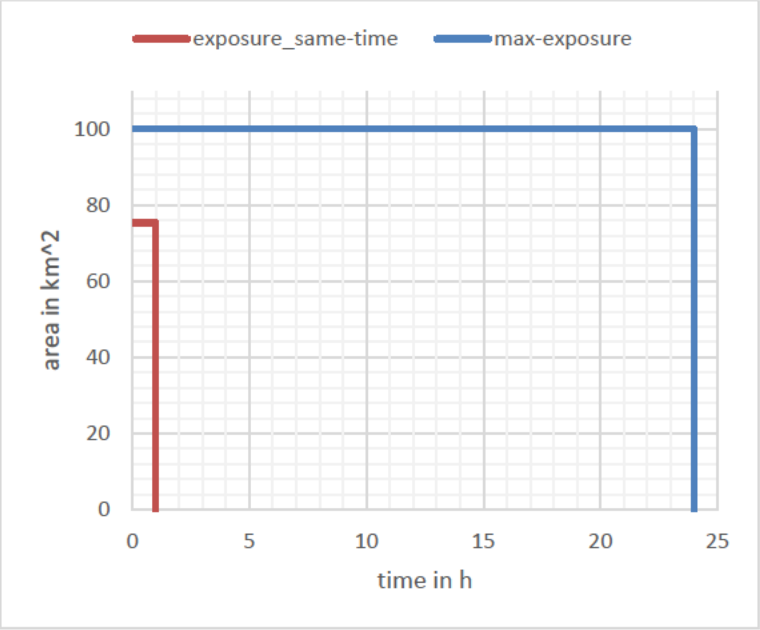

Figure 15: Exposure in a sea area of 100 km^2, all ships at the same time.

In this example all ships are present in the area at the same time.

Therefore this depiction is not explicit and the information we get is the product of the area with the time *A* x t.

If we assume that only one ship is present in the area at any given time and all ships pass the region one after another the exposure curve would result in a low affected area but a long time affected. This would give us the following result:

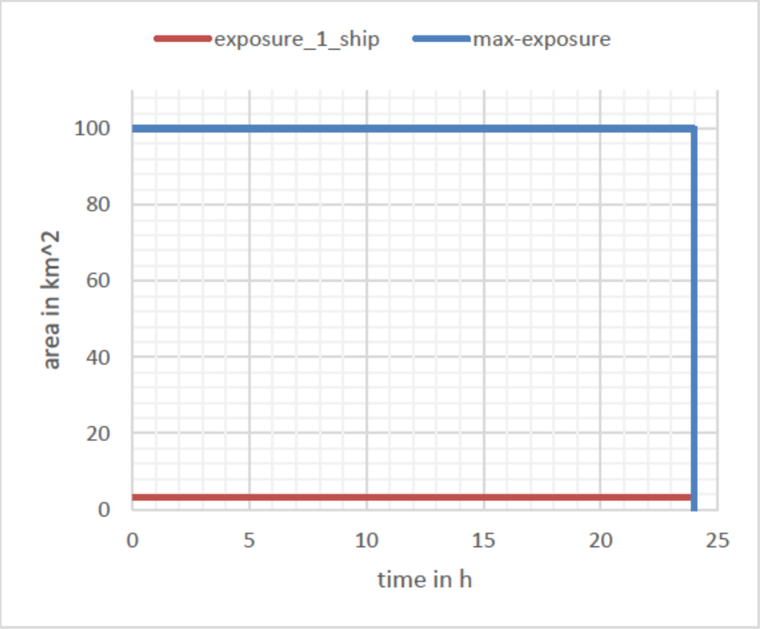

Figure 16: Exposure in a sea area of 100 km^2, one ship at the same time.

These two examples show the extremes, which are not realistic and do not consider the actual simultaneity of ships in a given area.

In the next example, if it is assumed that 5 ships are present in the area at any given time and the ships are traveling with a speed of 10 m/s and pass each cell in a direct line of 1 km, the factors are taken into account for our calculation of the total exposure:

$$EI = \frac{(n_{simul} \cdot A) \cdot \left(\frac{n_{cell}}{n_{simul}} \cdot 1h\right)}{A_{total} \cdot t_{total}}$$

Where:

- n_{simul} is the number of ships which are simultaneously in an area
- n_{cell} is the number of cells with ships

This results in:

$$EI = \frac{(5 \cdot \pi\ km^2) \cdot \left(\frac{24}{5} \cdot 1h\right)}{100km^2 \cdot 24h} = \frac{15.7km^2 \cdot 4.8h}{100km^2 \cdot 24h}$$

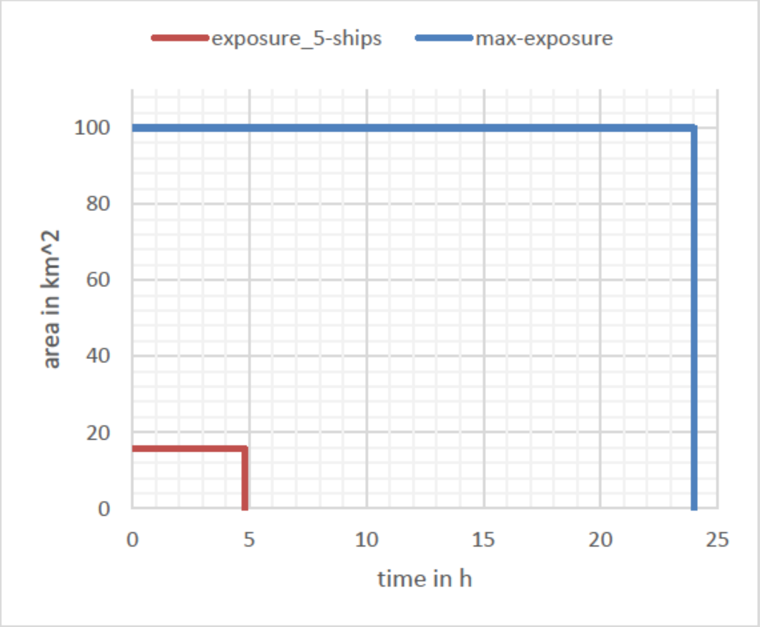

Figure 17: Exposure in a sea area of 100 km^2, 5 ships at the same time with a speed of 10 m/s.

As shown in this example the information about the simultaneity of ships is needed to describe the exposure in a certain area properly.

Furthermore, the topic of speed is also important for the effect range and the affected area. When ships are traveling slower their source level is usually lower and thus the received level will also be lower, which may result in a smaller effect range.

4.2 Input Data for modelling

4.2.1 EMODnet shipping density

The European Marine Observation and Data Network (EMODnet) is a marine data initiative. On their website [14] information on different topics and pressures regarding the use of the ocean are collected and published for public use in a mapping tool with different layers of GIS data. The main data utilized for the modelling in this thesis is on the shipping density.

The datasets which have been generated from AIS data are publicly available and can either be viewed or downloaded from the EMODnet website. For the modelling approach it was decided to use vessel density for cargo ships. Instead of a monthly average which is given from EMODnet, the daily density is used as the reference parameter for the model. This means that the input data from EMODnet is to be divided by the number of days in a month. This was decided because the basis of activity for impulsive noise for underwater sound are also so-called pulse-block-days [6, 42]. Nevertheless, for the assessment of the impact of noise the monthly scale is important, because the sensitive periods for the animals (mating, resting, foraging) should be assessed.

Since density is given in blocks by 1 x 1 km^2 each, the input data are relatively broad. The exact route of a ship can not be derived. Furthermore, there is no information on the average speed of the ships within an area, which is a key factor for the source level of ships.

Following the generation of the shipping density is presented in accordance to EMODnet and EMSA.

Shipping density

Shipping density is a quantity of the number of ships in a given area which is derived from AIS data. There are three main methods to create density values and maps defined by EMODnet [22]. These methods are depicted in the following figures. In EMODnet the area and data provided is divided into grid cells of 1 km^2 (1 km x 1 km).

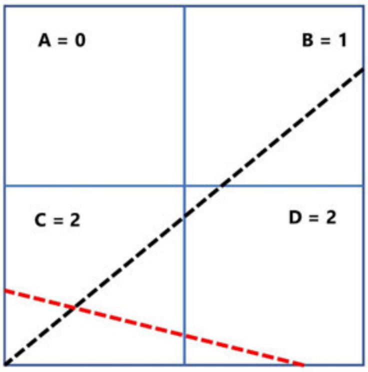

Figure 18: Calculating density based on number of ship tracks [22]

The first and simplest method is calculating the density based on the number of tracks which cross each cell and counting them. As shown in Figure 18 this means that even though the ships only cross the cell for a short amount of the section (section D) it provides the same value as in a section with a long shipping route (section C). EMODnet refers to the result of this method as “ship crossing density” [22].

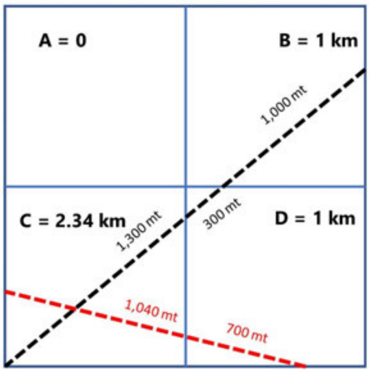

Figure 19: Calculating density based on ship track length [22]

The second method described in the EMODnet document is factoring the length each ship crosses the cells and adding this up. This resulted in the problem, that this is a representation of route length instead of a value of countable objects in an area.

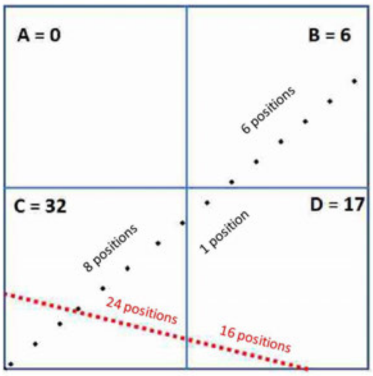

Figure 20: Calculating density from number of AIS positions [22]

The third method takes the number of positions of a ship in the given cell into account. According to EMODnet this represents the true density which is defined herein as “the average instantaneous number of vessels per unit area.” [22]

Vessel density

The third method described was used to derive the parameter of vessel density which is depicted in Figure 21 showing a single ship sailing at different speeds through one cell. The data given herein is derived from the positions of each ship given by its AIS data and generating lines from each point. The duration for each section is processed from the timestamps of each point. The density generated via this method is given as hours per square km per month (h/km^2/month). Therefore, this gives us the average time spent by ships of each category over the duration of a month per cell.

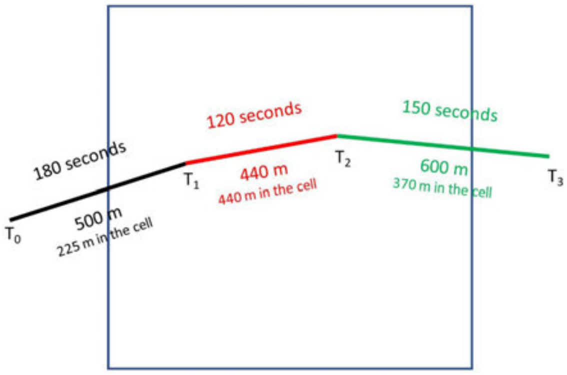

Figure 21: Calculating vessel density in accordance to EMODnet [22]

Route density

On the EMODnet website the second layer of density data available is route density which is provided by EMSA and described in their framework for developing traffic density maps [20]. This is a representation of the first method for calculating density as described by EMODnet and gives the route density as average routes per square km per month or per year.

4.2.2 Species of interest

For the model the effect of noise on harbour porpoise is to be evaluated. The effect range for these animals has been derived from the report by Wisniewska et al. [62], where it is stated that harbour porpoise react to ships at long ranges of 800 to 1000 m. For the modelling approach it was therefore decided to use an effect range $r = 1$ km from the ships. Furthermore, it was assumed that this is the effect range for normal transit conditions with a speed of 18 knots of the ships. If the ships are traveling slower or are anchoring the effect range should be smaller.

Remark: At this point it should be mentioned that for this work the effect range is used for the purpose of a quantitative description of the method. Whether the 1000 m mentioned in the paper justify a general approach needs to be discussed and agreed upon in the bioacoustic community. This master thesis deals exclusively with methods.

4.2.3 Area of interest

The area of interest for which the maps are generated is a marine reporting unit (MRU) of the OSPAR II framework and the marine protected area (MPA) “Borkum Riffgrund” within this subregion. This MPA was chosen since the management plan [1] states that it is a foraging ground for harbour porpoise as well as other marine mammals. The input data of the area for the model have been derived from the EMODnet website [14] and the geospatial data catalogue of the EEA [39].

The Marine Reporting Unit is a Sub-region of the OSPAR II area. This assessment region was chosen because of the important European industrial ports included and therefore the importance of this region for marine trading routes.

4.3 Modelling and generation of maps

Modelling and the generation of the maps was supported by my colleague Ramona Eigenmann at Müller-BBM. Especially the handling and visualization of the GIS data was carried out by her.

For the modelling the subregion is divided into grid cells of 1 x 1 km^2 since the input data is also given in this resolution. For each cell the affected area is modelled from the centre of the cell. The exact position of the ships is not known and can not be derived from the given data. This means that snapshots of each ship position are given here and the effect range is generated around each of these positions.

The density data is transferred into the model and blended with the grid. This is then colour coded for each density group giving an overview of the average affected area and time. The highest value layers depicted above the lower density values.

Modelling is carried out using the software QGIS and ArcGIS[4].

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[4] QGIS Version 3.14; ArcGIS Desktop 10.7.1

5 Results and discussion

In this section a selection of the generated maps as well as the assessment of the exposure is presented. Further maps and histograms for each month are given in Annex D and E.

The results and statements as well as the strength and weaknesses are discussed.

5.1 Generated maps

5.1.1 Maps of the MRU

Figure 22 and Figure 24 show the generated maps for the average density of cargos ships over a day derived from the data for the years 2018 and 2020 and the area which is impacted by shipping noise from cargo ships for the MRU. Figure 23 and Figure 25 present the distribution of the density data. These years have been selected, since the input data show a bigger variation than compared to 2017 and 2019. The years 2017 and 2018 are similar in density and the years 2019 and 2020 are similar, where 2017 and 2018 show higher values than the years 2019 and 2020. It was a bit unexpected to find that 2019 and 2020 are similar in density due to the fact that in 2020 the Covid-19 pandemic impacted the shipping industry and supply chains.

The density data have been divided into classes of steps with a width of 0.05 h for the data below 0.15 h/km^2/month. If the steps would have been wider all the data would have been in the same category and a more distinct differentiation would not be possible.

The classes of 0.151 – 0.35 h/km^2/month have been divided in 0.1 h steps and 0.25 h steps for the class from 0.351 – 0.6 h/km^2. These represent the shipping lanes and since the input data was fewer in numbers the wider grouping was chosen to get a better representation of the lanes.

Everything above a density of 0.6 h/km^2/month are either ships that are anchoring or entering into rivers and ports, with the lowest distribution in this class.

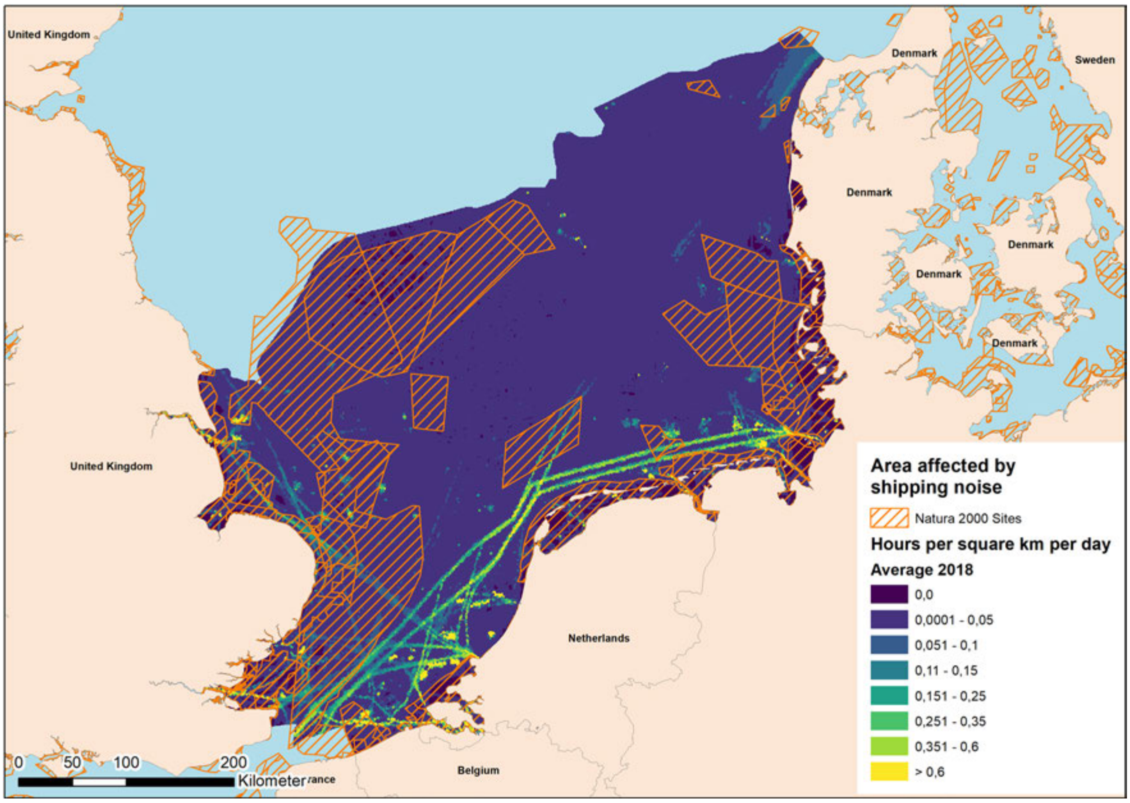


Figure 22: Map of the MRU and the affected area derived from the density average for the year 2018 for cargo ships. (map basis [17, 39, 46])

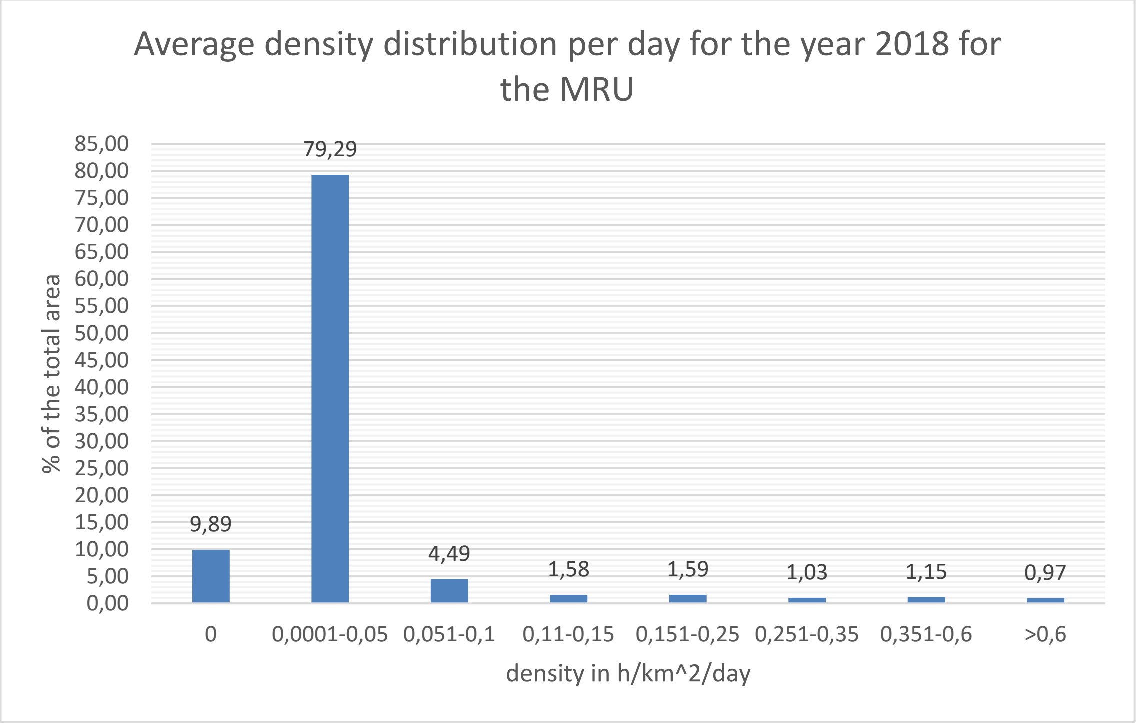


Figure 23: Average daily density distribution for the MRU for the year 2018.

As can be seen from this, most of the area is impacted by ships. There are only 10 % of the area where no ships are present. The largest area is covered only for a short time with cargo ships and is represented by the light blue shading. The shipping routes are represented by the green to yellow lines in the map. There are also some areas where ships are anchoring or waiting to pass into harbours, represented by the bright yellow dots on the maps. If the shipping routes in the northern part of the sea were as centralised as they are along the coastal areas the overall density would be higher but the total affected area would be lower. Therefore this would be an easy method to assess the impact of changing and centralising shipping routes. The question arises if a larger affected area with fewer ships, is more problematic for animals, than a small area with a lot of traffic.

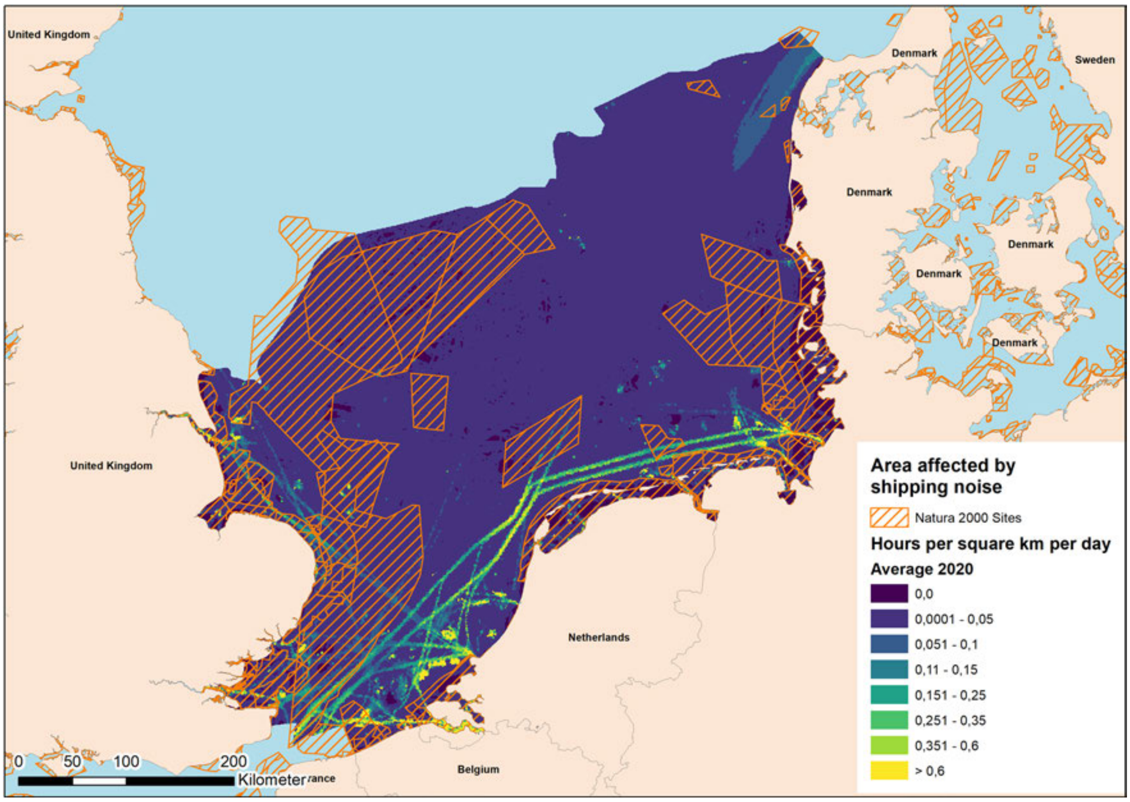


Figure 24: Map of the MRU and the affected area derived from the density average over the year 2020 for cargo ships. (map basis [17, 39, 46])

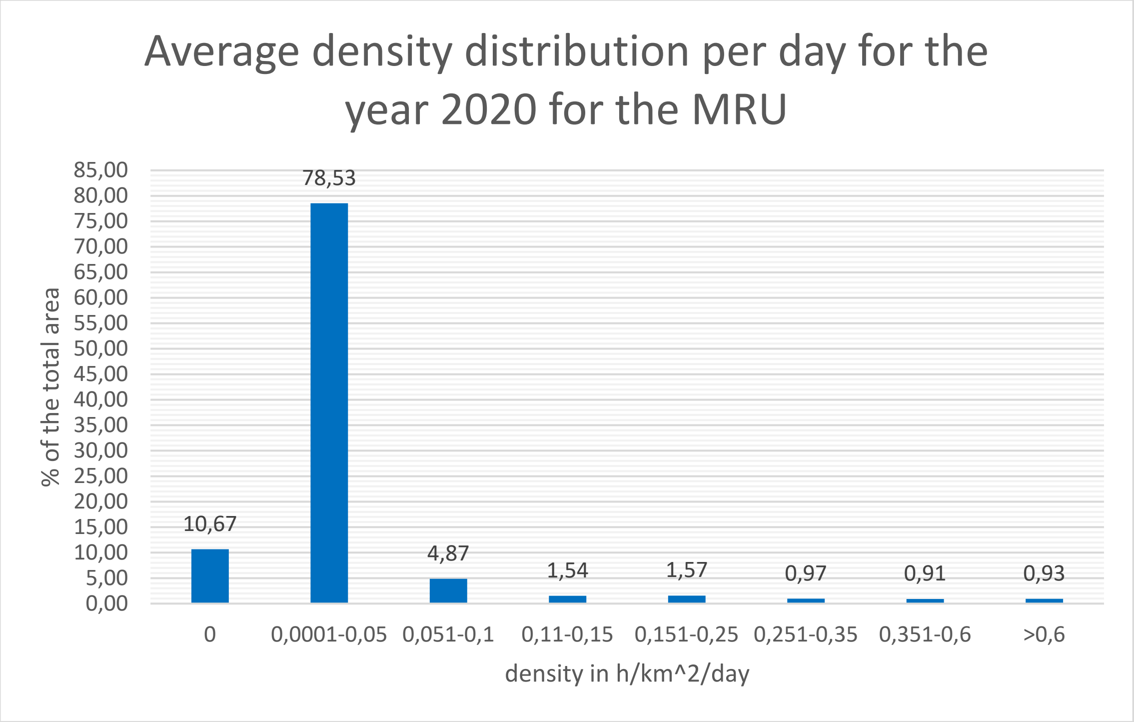


Figure 25: Average daily density distribution for the MRU for the year 2020.

The 2020 map and histogram show that fewer areas are affected overall. The distribution within each density class is similar to 2018.

When reviewing the monthly average as presented in Annex D the distribution of ships and density is different from the yearly average. Overall there are more areas without any shipping traffic in the monthly depictions. The histograms for each quarter of the year show us a lower density in the first and fourth quarter and an overall higher density during the rest of the year. Monthly averages are also important in assessing times of the year where the animals could be more vulnerable. For the harbour porpoise, these could be the months of June to August since they mate from the beginning of July to the end of August and their offspring are being born about 10 to 11 months later. [35]

5.1.2 Maps of the MPA “Borkum Riffgrund”

Figure 26 and Figure 28 show the average density of cargo ships per day derived from the years 2018 and 2020, and the area which is impacted by shipping noise from cargo ships in the MPA. Figure 27 and Figure 28 give the distribution of density for each year.

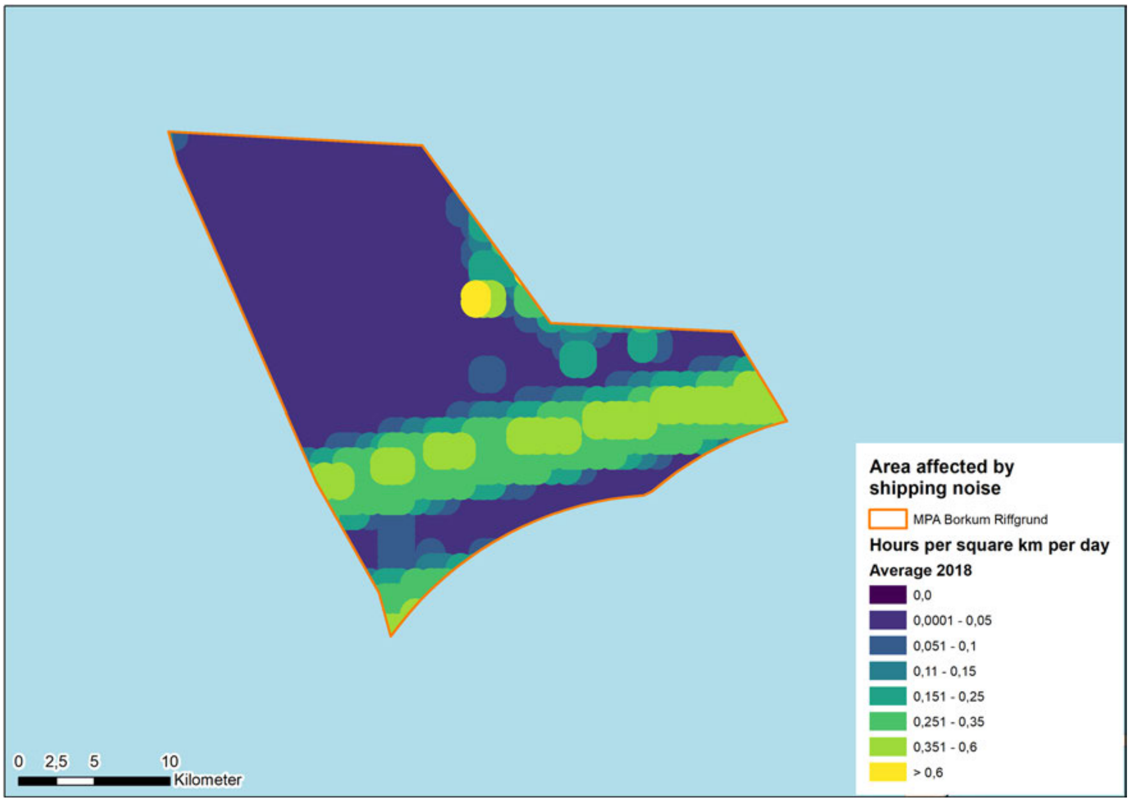


Figure 26: Map of the MPA “Borkum Riffgrund” and the affected area derived from the density average over the year 2018 for cargo ships. (map basis [46])

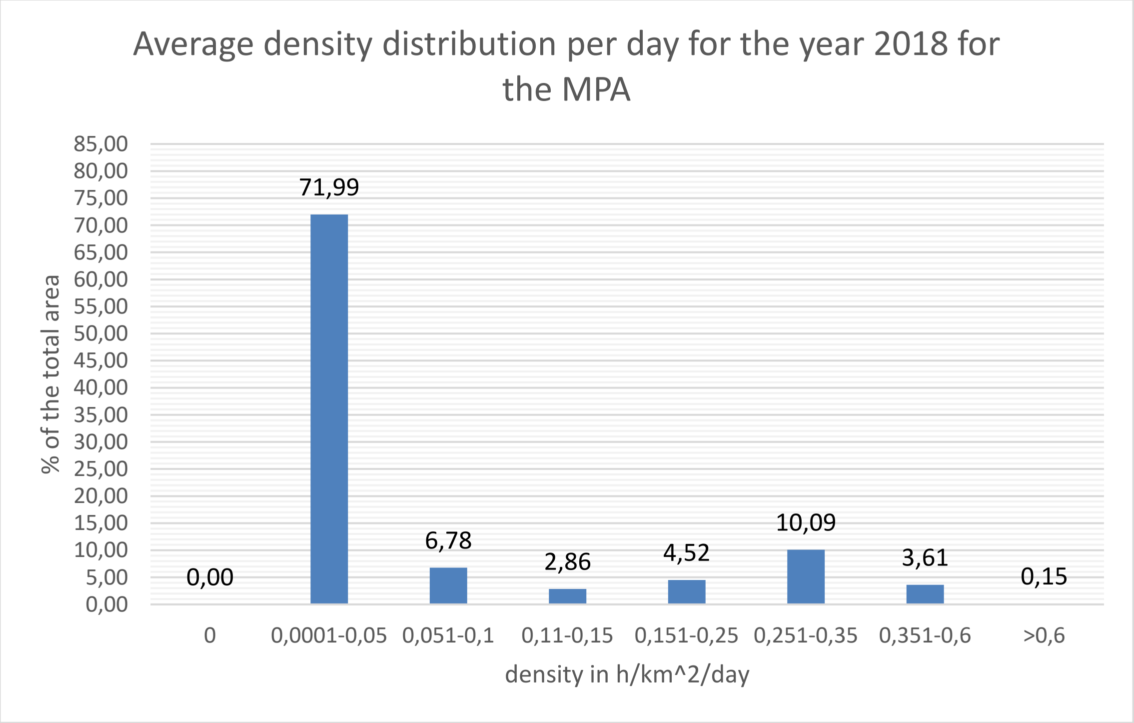


Figure 27: Average daily density distribution for the MPA for the year 2018.

The depicted map and histogram show us that on average the whole area of the MPA is affected by ships for the year 2018. The density distribution is similar to the MRU with a large area only affected for a short time and a higher density in the region of the shipping lane as well as from the neighbouring areas to the northeast.

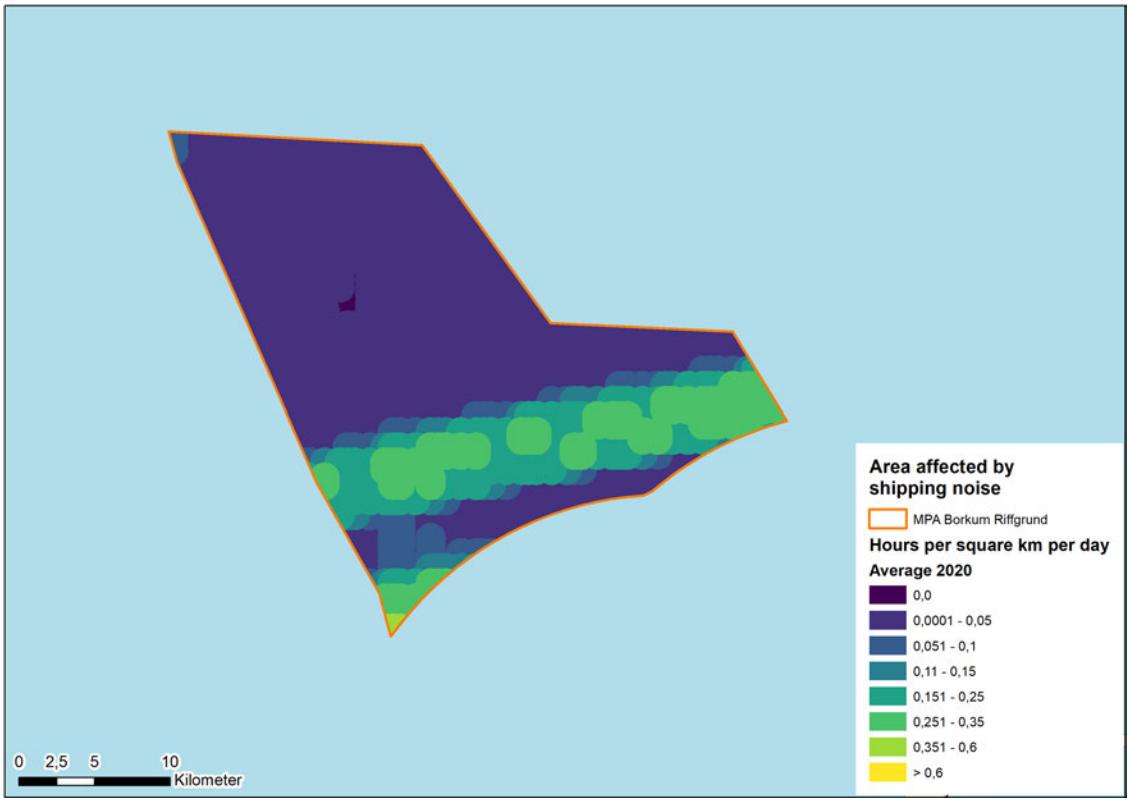


Figure 28: Map of the MPA “Borkum Riffgrund” and the affected area derived from the density average over the year 2020 for cargo ships. (map basis [17, 39, 46])

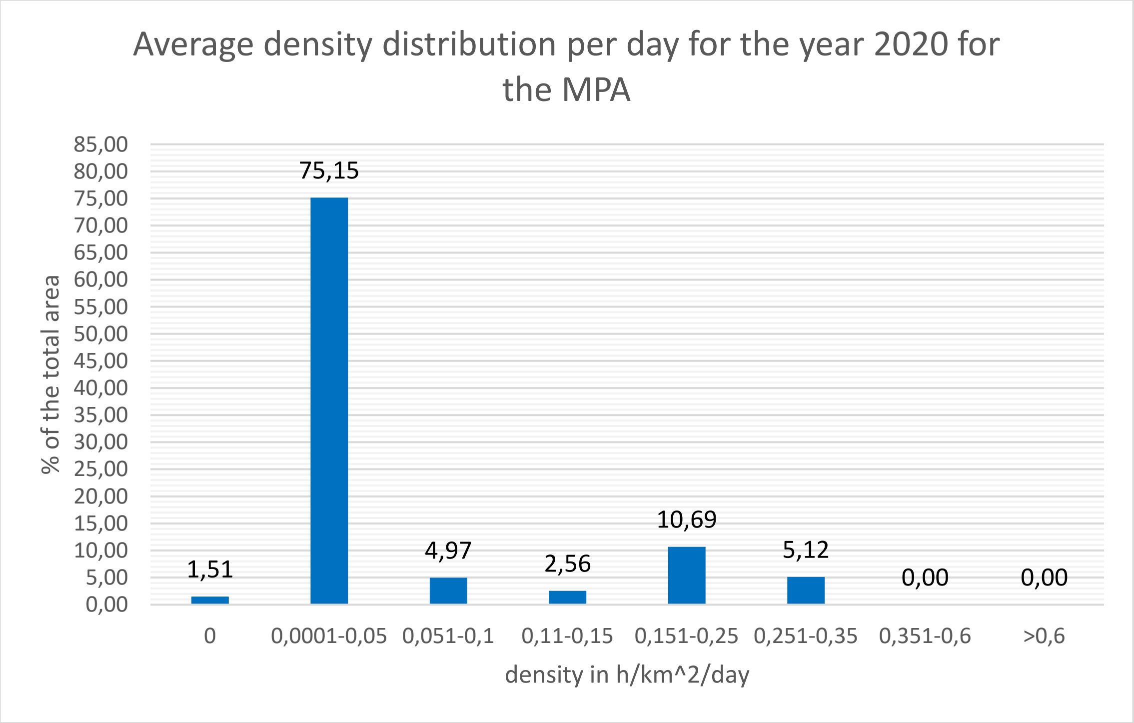


Figure 29: Average daily density distribution for the MPA for the year 2020.

In 2020 the overall affected area is smaller and the density a little lower compared to 2018. There are no high-density values from the neighbouring cells of the MPA.

When looking into the monthly averages as presented in Annex E the density distribution is again quite different to the yearly average. These also show the overall lower density over the course of the year 2020 when compared to 2018.

5.1.3 Discussion of the maps and methods

In general the generated maps are quite simple and straight forward. It is easy to see which areas are affected the most by ships and shipping noise. In a large investigated area like the MRU these give not much more information than the original density maps which can be viewed at the EMODnet website [14]. This is firstly because of the large scale of the MRU and secondly due to the relatively small effect range in our example. The question which arises is what statements can be made about the impact on the animals at such a large scale? In the current analysis there is no information on the distribution of the animals and only the MPAs are an indicator for a habitat or areas of interest.

If the effect range was much larger the affected area would be more obvious on a large scale. This could be the case for animals in the class of PCW or LF, since their hearing is more sensitive in the main frequencies of shipping noise below 1 kHz. This would also mean that the affected areas would overlap each other much more. Where two ships are at a distance to each other which is smaller than 2 x *r,* the sound pressure of both the ships would add up and thus the effect range would probably change. This could also happen with the relatively small effect range used in the depicted example, but is much less likely since cargo ships usually travel at a large distance to each other, at least in open water. When looking into other vessel types that travel at lower distances to each other or are far more frequent, this problem could also arise with relatively narrow effect ranges.

This brings up the question of how to assess different ship types together? Since the effect range will vary between different ship types due to their variation in source level and frequency range, the different classes need to be assessed separately and then added up for the area under consideration. Another way would be to set a standard effect range for ships of similar classes and to give surcharges for the different types of ships which will also depend on the investigated species. This method would be similar to common practices in the assessment of road traffic noise or railway noise in air.

In general, it will be difficult to find an effect range for each ship type and all species from observations. Therefore, it would be difficult to depict the subtle differences. The overall information we get is an average impact. This is also true for the large variation in the source level for each class of ship, since the uncertainties are quite high. A rough assessment with a generalised effect range would probably give the same results as a more differentiated effect range for each class.

In a smaller investigated area like the MPU, the maps give more meaningful information since the affected area can be seen more clearly. With this simple visual cue and the density values, assumptions on the impact or the loss of area in a habitat can probably be made with the aid of biologists or bio-acousticians.

The maps give no information on how many ships are in a certain area at the same time and also no information on which times during the day the ships are underway. This makes it hard to assess the times where animals are more vulnerable to disturbance.

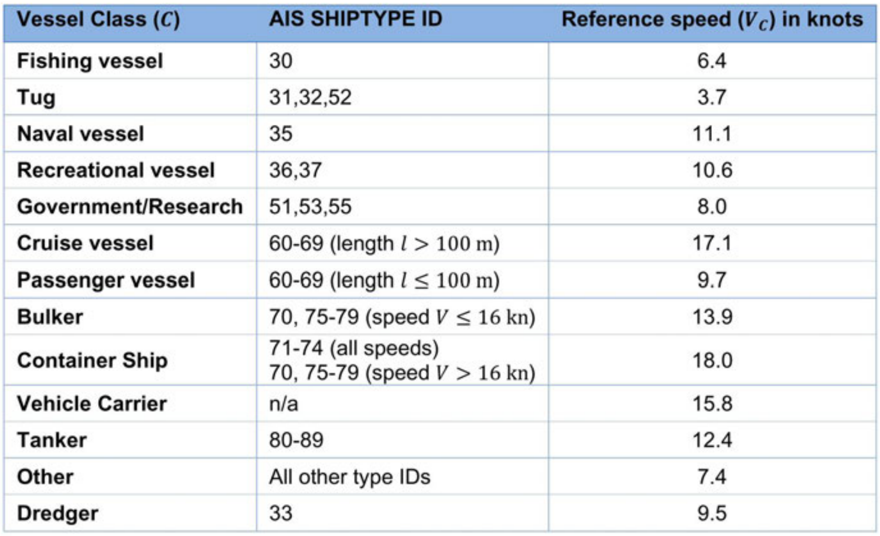
To further evaluate the maps, exposure curves are given and discussed in the following section.

5.2 Exposure curves

To get the exposure curves, it is necessary to make assumptions about the number of ships that are present in a given area at the same time and the average speed at which they are traveling.

The real-time AIS data and position of ships can be viewed on the website of “Marine Traffic” [40]. When looking into the area of the MPA “Borkum Riffgrund”, it is assumed for our calculation that a maximum of 9 ships is present at any given time, which serves as an upper limit. Most of the time traffic seems to be lower in the area.

For the speed of the ships the average data given from JOMOPANS are used with 18 knots (≈9.3 m/s) for container ships as shown in the following figure.



Vessel Class (C)	AIS SHIPTYPE ID	Reference speed (V_C) in knots
Fishing vessel	30	6.4
Tug	31,32,52	3.7
Naval vessel	35	11.1
Recreational vessel	36,37	10.6
Government/Research	51,53,55	8.0
Cruise vessel	60-69 (length $l > 100$ m)	17.1
Passenger vessel	60-69 (length $l \leq 100$ m)	9.7
Bulker	70, 75-79 (speed $V \leq 16$ kn)	13.9
Container Ship	71-74 (all speeds) 70, 75-79 (speed $V > 16$ kn)	18.0
Vehicle Carrier	n/a	15.8
Tanker	80-89	12.4
Other	All other type IDs	7.4
Dredger	33	9.5

Figure 30: ship types and reference speed [32]

The total area of the MPA is given with 625 km^2 as stated in the management plan [1].

With these assumptions for a maximum simultaneity of ships in the MPA and the density data from the maps we get the following exposure curves:

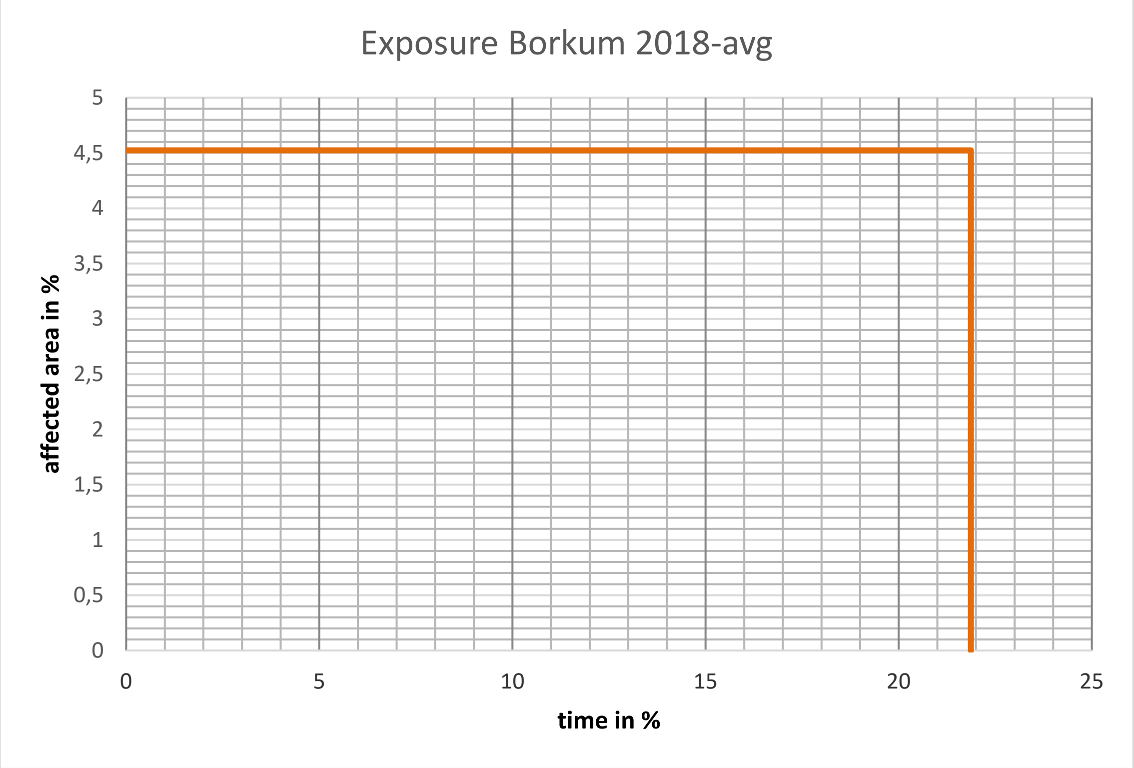


Figure 31: Exposure curve for the MPA "Borkum Riffgrund" for the average per day over the year 2018

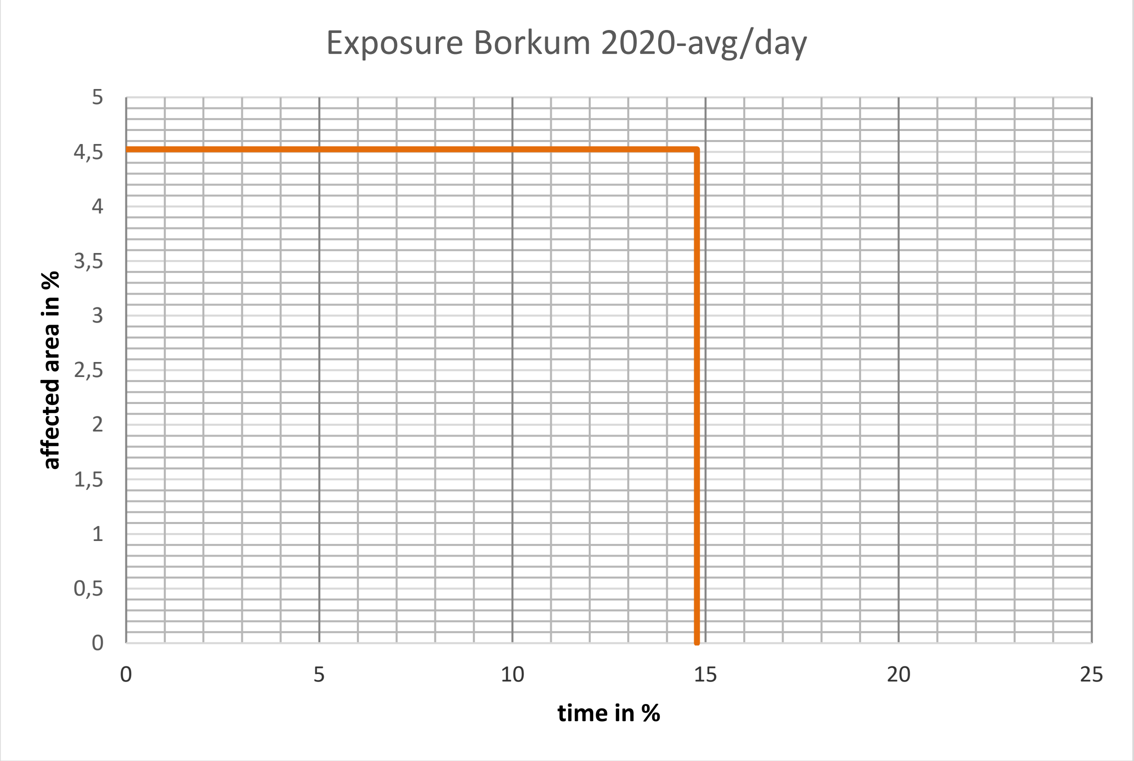


Figure 32: Exposure curve for the MPA "Borkum Riffgrund" for the average per day over the year 2020

These show us that on average about 4.5 % of the area were affected by noise for about 22 % of each day in 2018 and for about 15 % of each day in 2020. The exposure index is *EI* = 0.0099 for 2018 and *EI* = 0.0067 for 2020.

With these graphs it will be possible to evaluate mitigation measures. If the ships travelled slower, the affected time would be longer but the affected area would probably be lower due to a reduced source level. This gives us a simple tool to assess and adjust the measures for each species. It may be possible that for some species time is more crucial and the distance and area at which they are affected by noise does not vary a lot. This should be evaluated by biologists or bio-acousticians.

When applying this method on the whole MRU we will get curves which will not add much information value to the generated sound maps. The whole MRU has a size of about 214,000 km^2. If we assume that 200 ships are present at the same time, we would get the following curve:

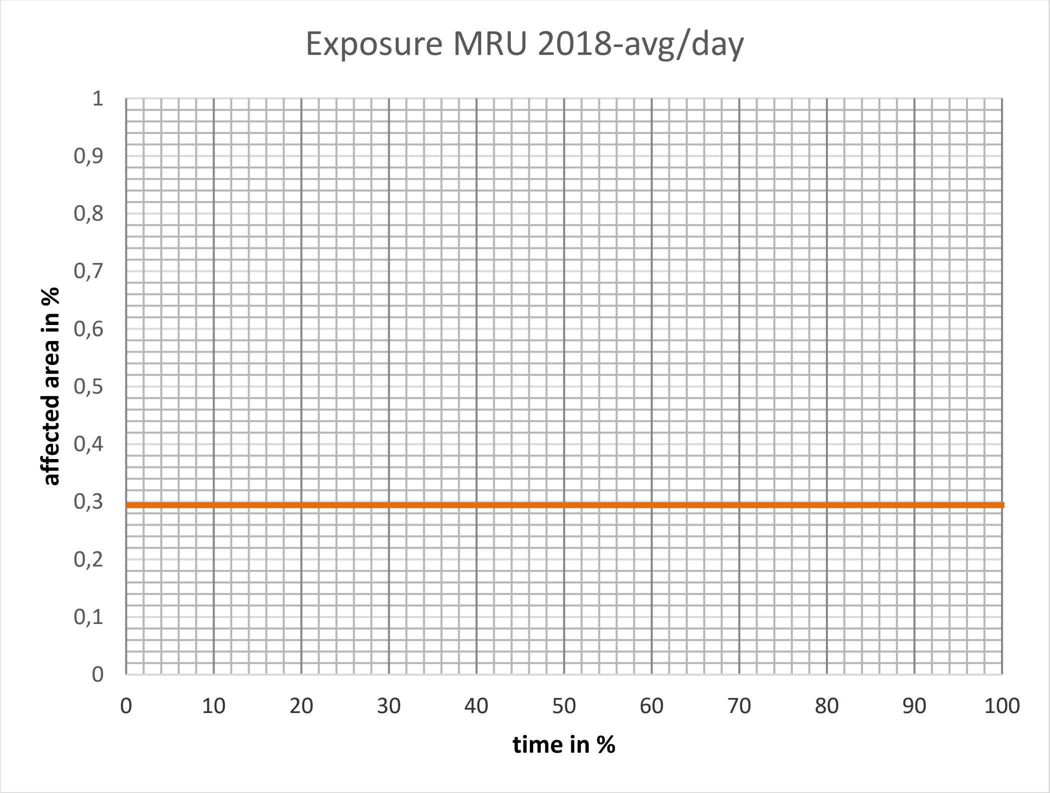


Figure 33: Exposure curve for the MRU for the average per day over the year 2020

In a large investigated area like the MRU the total time of a day is always reached, which is clear from the point that the ships will take more time than a day to travel through the whole area. Therefore, the information we get is that 0.3 % of the whole area is affected for the whole day. In the current stage the strategy generates more detailed information when assessing smaller areas.

6 Suggested improvements

In this chapter suggested improvements and further information needs are presented with regards to the discussion above.

Assessment of large areas

In the previous chapter it has been stated that in the current development stage the strategy gives more detailed information for smaller sea areas. In order to assess a larger area properly it would be beneficial to subdivide the MRU or any other large scale area into smaller grid cells like ICES sub-rectangles [27] and assess these separately. This method has also been proposed by TG Noise in their methodology report [55]. The exposure for each of these grid cells could be determined and thus a better assessment of the severity of the impact of noise in different areas would be possible. This could also be translated back into a map for the whole area with the exposure for each of the grid cells depicted. Further information, like the distribution of animals could also be implemented in such a way.

Below, the map presented in chapter 5.1 for the MRU and the year 2020 is given, with an overlay of the ICES sub-rectangles as an example.

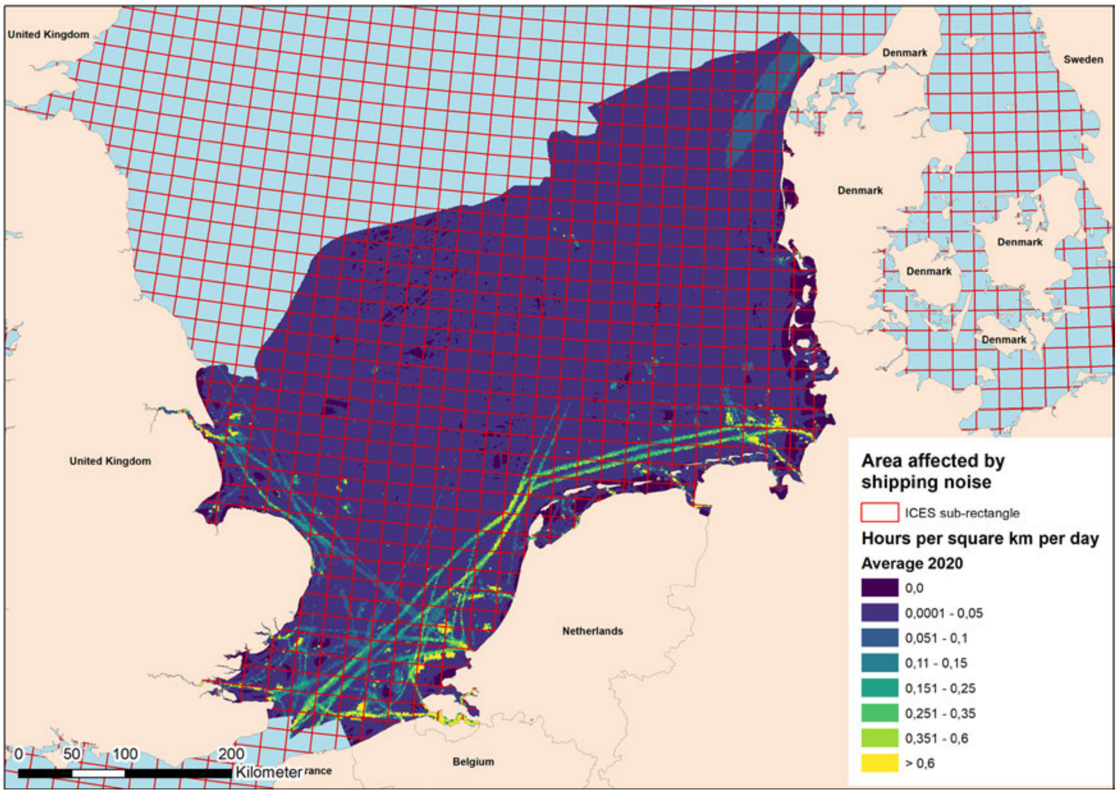


Figure 34: Map of the MRU and the affected area derived from the density average over the year 2020 for cargo ships. With ICES rectangles. (map basis [17, 27, 39, 46])

Simultaneity and average speed of ships

The missing information on the simultaneity and average speed of ships in an area could also be added to the input data. It should be possible to extract the missing data from the original AIS data obtained by EMODnet. The resulting maps would be similar to traffic information systems/ platforms on land, where tracks or roads are subdivided into sections with different speeds and daily densities attributed to these.

In addition to the average quantities already given it would be good to have the maximum and minimum or percentiles for each parameter. With this information an upper and lower limit could be evaluated, which would help to further classify the assessment strategy.

Effect ranges and threshold values for animals

As stated before and summarized by Gomez et al. it would be beneficial "to develop specific look-up tables that provide the best available or precautionary "distance of effect" for a given geographic location, species, sound source, and context of exposure." [23]

In current and past projects such tables and concepts have been developed. In 2019 a report on the noise sensitivity of animals in the Baltic Sea [54] was published. Herein the basic concept of the effects of noise on animals is presented and an overview of the species and their needs and characteristics regarding sound are presented. These findings are summarised in overviews such as Figure 35, as well as tables with more detailed information on the different criteria and references.

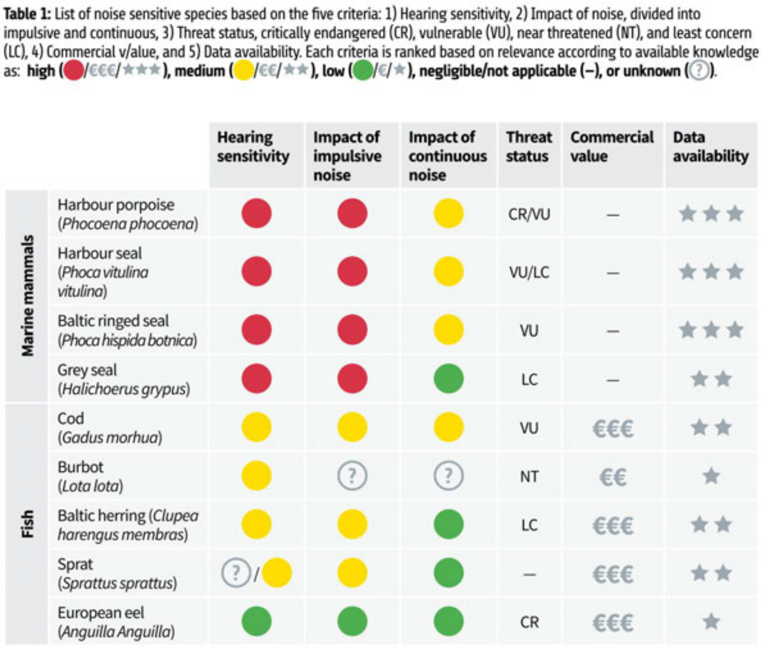


Table 1: List of noise sensitive species based on the five criteria: 1) Hearing sensitivity, 2) Impact of noise, divided into impulsive and continuous, 3) Threat status, critically endangered (CR), vulnerable (VU), near threatened (NT), and least concern (LC), 4) Commercial v/alue, and 5) Data availability. Each criteria is ranked based on relevance according to available knowledge as: **high (🔴/€€€/★★★), medium (🟡/€€/★★), low (🟢/€/★), negligible/not applicable (–), or unknown (?).**

		Hearing sensitivity	Impact of impulsive noise	Impact of continuous noise	Threat status	Commercial value	Data availability
Marine mammals	Harbour porpoise (*Phocoena phocoena*)	🔴	🔴	🟡	CR/VU	–	★★★
	Harbour seal (*Phoca vitulina vitulina*)	🔴	🔴	🟡	VU/LC	–	★★★
	Baltic ringed seal (*Phoca hispida botnica*)	🔴	🔴	🟡	VU	–	★★★
	Grey seal (*Halichoerus grypus*)	🔴	🔴	🟢	LC	–	★★
Fish	Cod (*Gadus morhua*)	🟡	🟡	🟡	VU	€€€	★★
	Burbot (*Lota lota*)	🟡	?	?	NT	€€	★
	Baltic herring (*Clupea harengus membras*)	🟡	🟡	🟢	LC	€€€	★★
	Sprat (*Sprattus sprattus*)	?/🟡	🟡	🟢	–	€€€	★★
	European eel (*Anguilla Anguilla*)	🟢	🟢	🟢	CR	€€€	★

Figure 35: Differentiation of noise sensitive species in the Baltic Sea [54]

A project which is currently running is the SATURN program [53], funded by the EU, with the aim of assessing noise from ships with a clear focus on the effect on animals. The main goals are summarized as follows:

“SATURN will examine; i) which sounds pose the greatest threat to aquatic species and how they are produced and propagated; ii) the short and long-term effects of URN on invertebrates, fish, and marine mammals; and iii) the most promising options for reducing the negative impacts of URN. SATURN will also develop and progress standards for terminology and methodology across all disciplines working on underwater radiated noise, producing recommendations for effective underwater sound management.” [53]

For the strategy proposed in this thesis, it would be important that the documentation of observations on animals is standardized, so that the threshold values and effect distances have a lower level of uncertainty.

Furthermore, it would be helpful if the calculation of propagation loss in water is standardized in a similar way as in air (see chapter 2.3.2). With region specific simplifications for parameters such as bathymetry, salinity, wind etc. calculation and modelling of sound in water would improve significantly in terms of simplicity and need of computing power.

With such standards the model presented in this thesis could be extended. The effect range could thus be obtained from calculations. This would also be beneficial for assessing shipping noise in shallow water and areas with high densities.

7 Conclusion

This thesis aimed to give an example for an alternative assessment strategy for continuous underwater noise. Based on the presentation and review of strategies in air as well as water and a comparison of both, the foundation for the alternative strategy is introduced. The concept focuses on the effect range on animals in relation to ships. Simple observations are used to eliminate uncertainties of the source levels of ships as well as the calculation of propagation loss in water. A simple model is generated to describe the strategy on the example of cargo ships. The results are summarized in maps depicting the affected area for an MRU of the OSPAR II region and the MPA “Borkum Riffgrund”. The strategy is discussed and evaluated on the basis of these results. Further improvements and missing information are outlined.

Overall the presented strategy is a simple tool for the assessment of the disturbance faced by animals. With the effect range based on observations a lot of uncertainties that are present in other strategies are minimized. With the ongoing standardization of underwater noise the strategy can be improved and extended. Furthermore, it is simple to adjust the model to evaluate mitigation measures and future planning regarding shipping routes.

The idea of the effect range can also be implemented in current recommendations regarding continuous underwater noise. Existing databases could be extended to implement the exposure for certain species. This would make the data more accessible to a wider audience.

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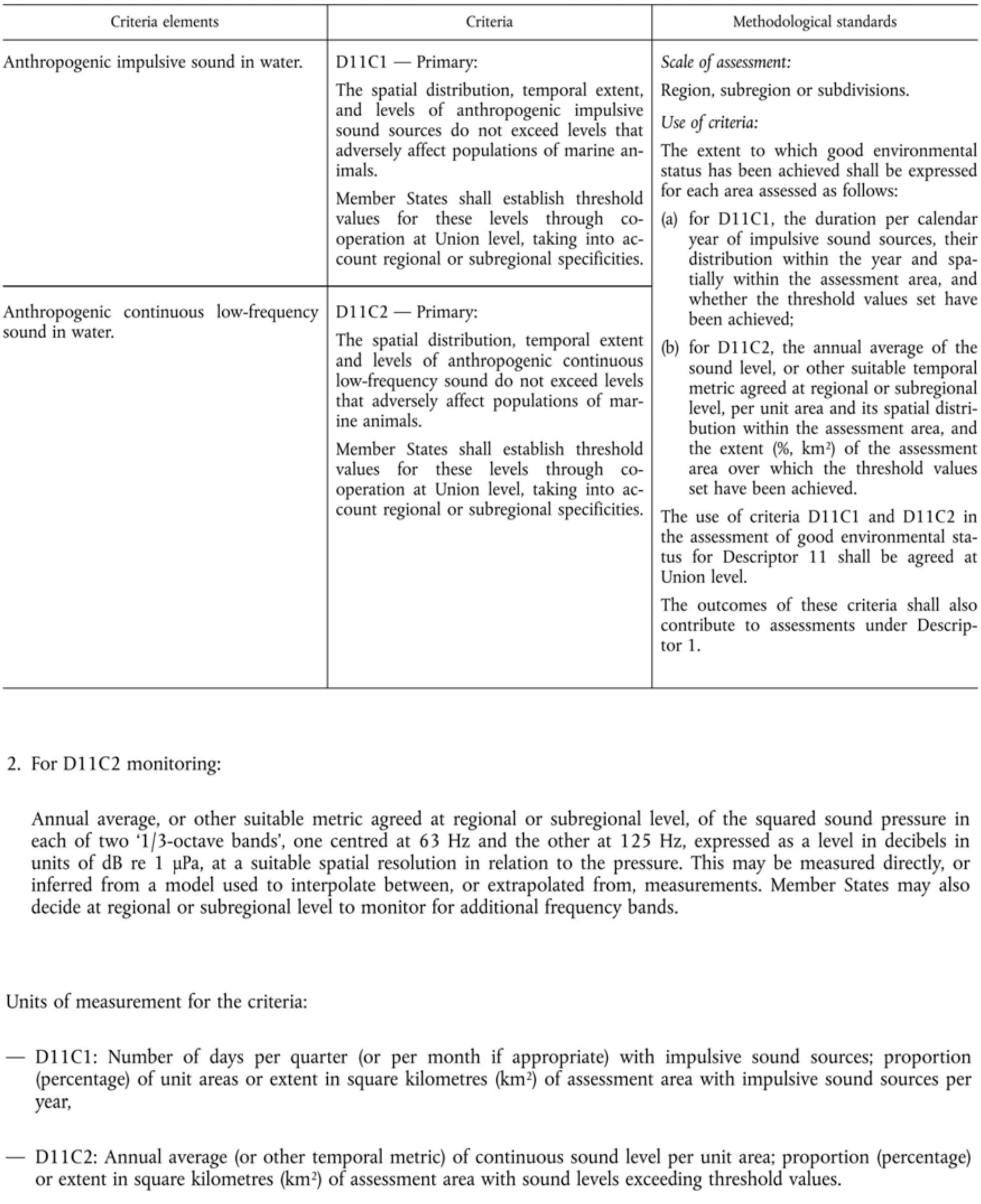
Annex A – MSFD descriptor



Criteria elements	Criteria	Methodological standards
Anthropogenic impulsive sound in water.	D11C1 — Primary: The spatial distribution, temporal extent, and levels of anthropogenic impulsive sound sources do not exceed levels that adversely affect populations of marine animals. Member States shall establish threshold values for these levels through cooperation at Union level, taking into account regional or subregional specificities.	*Scale of assessment:* Region, subregion or subdivisions. *Use of criteria:* The extent to which good environmental status has been achieved shall be expressed for each area assessed as follows: (a) for D11C1, the duration per calendar year of impulsive sound sources, their distribution within the year and spatially within the assessment area, and whether the threshold values set have been achieved; (b) for D11C2, the annual average of the sound level, or other suitable temporal metric agreed at regional or subregional level, per unit area and its spatial distribution within the assessment area, and the extent (%, km²) of the assessment area over which the threshold values set have been achieved. The use of criteria D11C1 and D11C2 in the assessment of good environmental status for Descriptor 11 shall be agreed at Union level. The outcomes of these criteria shall also contribute to assessments under Descriptor 1.
Anthropogenic continuous low-frequency sound in water.	D11C2 — Primary: The spatial distribution, temporal extent and levels of anthropogenic continuous low-frequency sound do not exceed levels that adversely affect populations of marine animals. Member States shall establish threshold values for these levels through cooperation at Union level, taking into account regional or subregional specificities.	

2. For D11C2 monitoring:

Annual average, or other suitable metric agreed at regional or subregional level, of the squared sound pressure in each of two '1/3-octave bands', one centred at 63 Hz and the other at 125 Hz, expressed as a level in decibels in units of dB re 1 µPa, at a suitable spatial resolution in relation to the pressure. This may be measured directly, or inferred from a model used to interpolate between, or extrapolated from, measurements. Member States may also decide at regional or subregional level to monitor for additional frequency bands.

Units of measurement for the criteria:

— D11C1: Number of days per quarter (or per month if appropriate) with impulsive sound sources; proportion (percentage) of unit areas or extent in square kilometres (km²) of assessment area with impulsive sound sources per year,

— D11C2: Annual average (or other temporal metric) of continuous sound level per unit area; proportion (percentage) or extent in square kilometres (km²) of assessment area with sound levels exceeding threshold values.

Figure 36: Extract from Comission Decision (EU) 2017/848 [19]

Annex B – Noise Source Map from BIAS

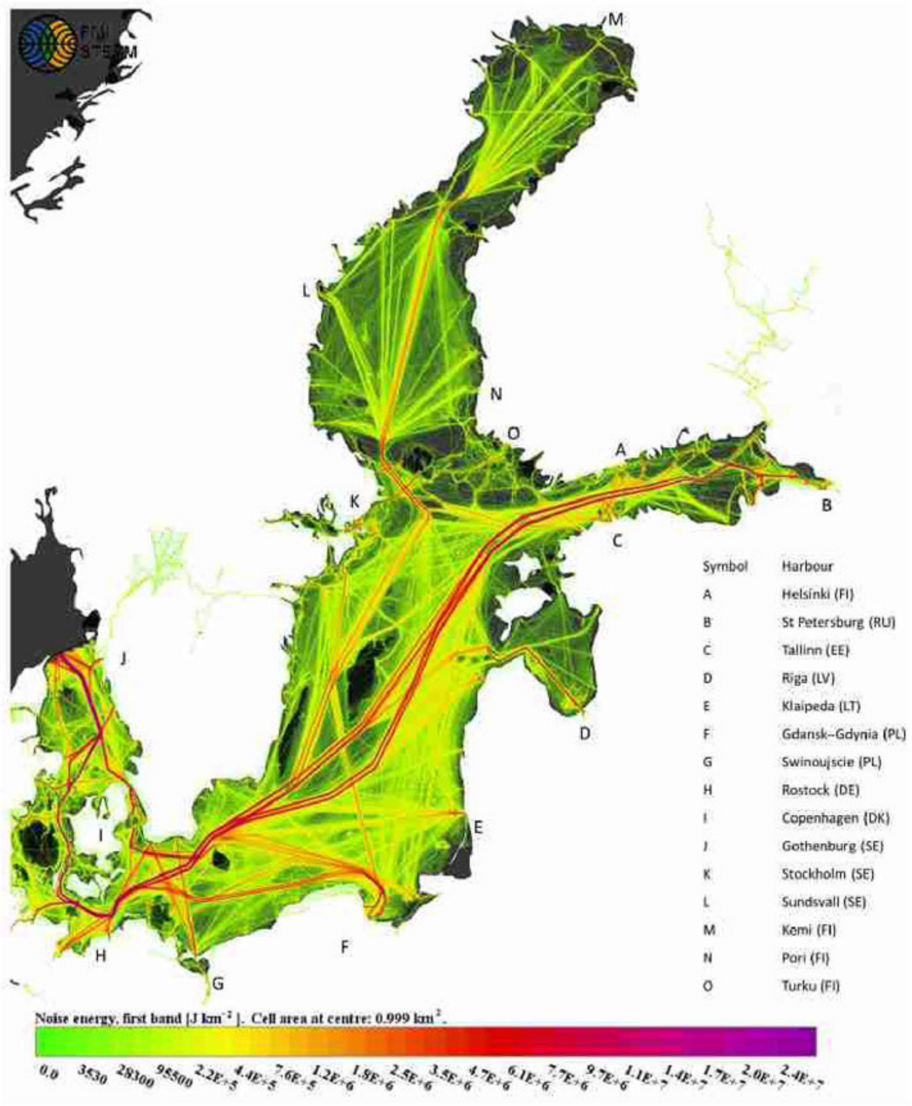


Figure 37: Noise source map for Baltic Sea shipping. This map indicates the sum of sound energy in units of joules per grid cell (cell area 1 km^2) during the year 2015. [31]

Annex C – Comparison of Excess Levels and Audiograms

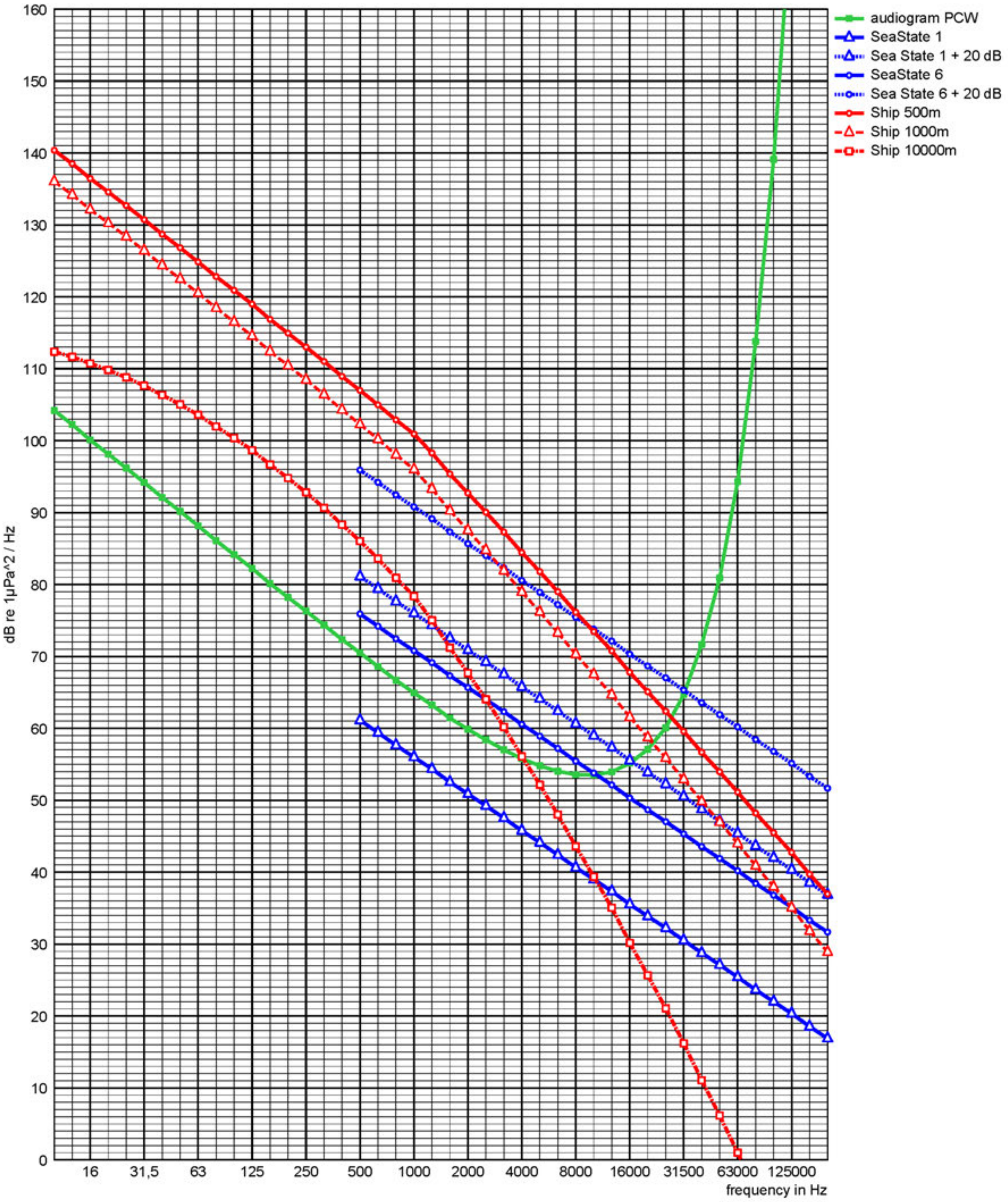


Figure 38: Depiction of the Audiogram of PCW Species derived from [57] in comparison to Sea State 2 and 6 [57] and an excess Level of 20 dB for each Sea State and Shipping Noise in different distances from the Source. SL derived from DNV silent class [12] and calculation of propagation loss in accordance to Thiele [59].

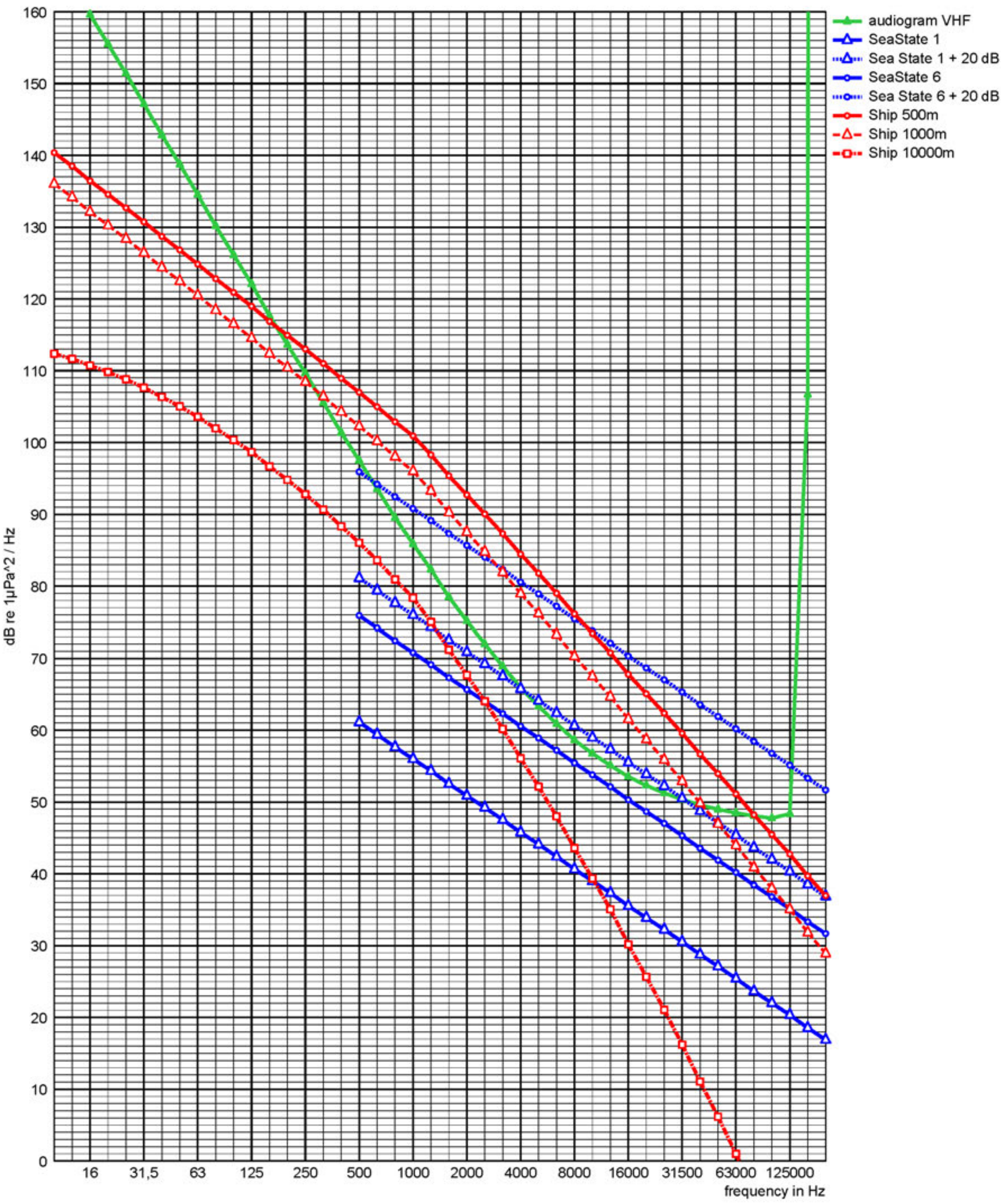


Figure 39: Depiction of the Audiogram of VHF Species derived from [57] in comparison to Sea State 2 and 6 [57] and an excess Level of 20 dB for each Sea State and Shipping Noise in different distances from the Source. SL derived from DNV silent class [12] and calculation of propagation loss in accordance to Thiele [59].

Annex D – Monthly Maps and Histograms MRU

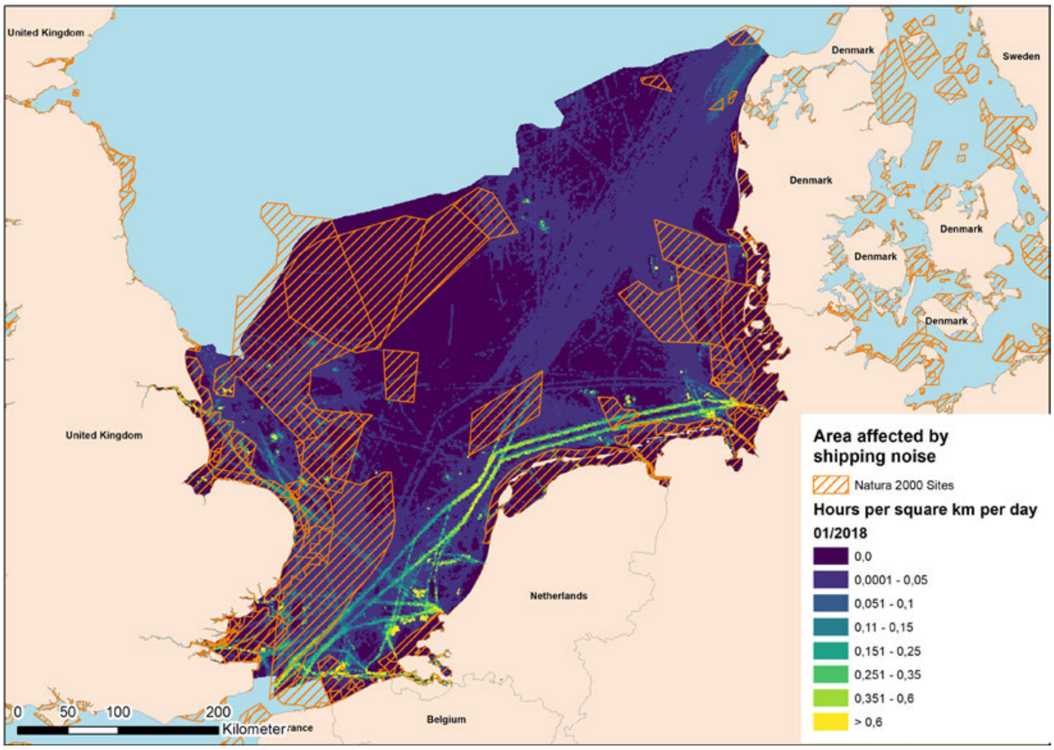


Figure 40: Map of the MRU and the affected area derived from the density average of January 2018 for cargo ships.

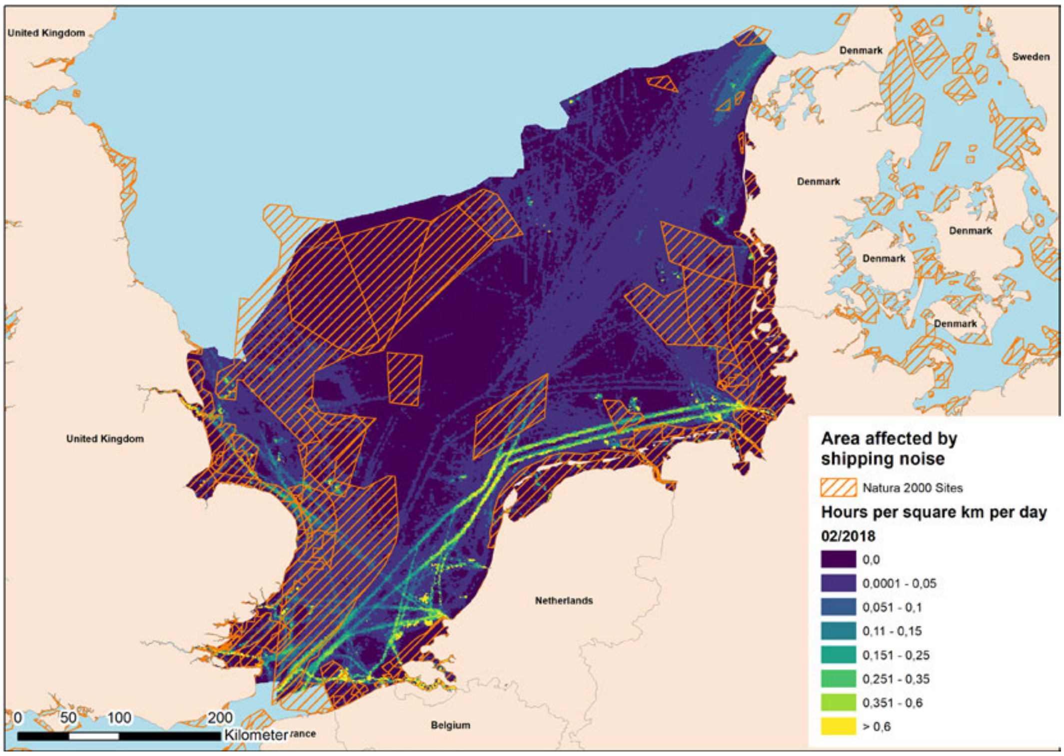


Figure 41: Map of the MRU and the affected area derived from the density average of February 2018 for cargo ships.

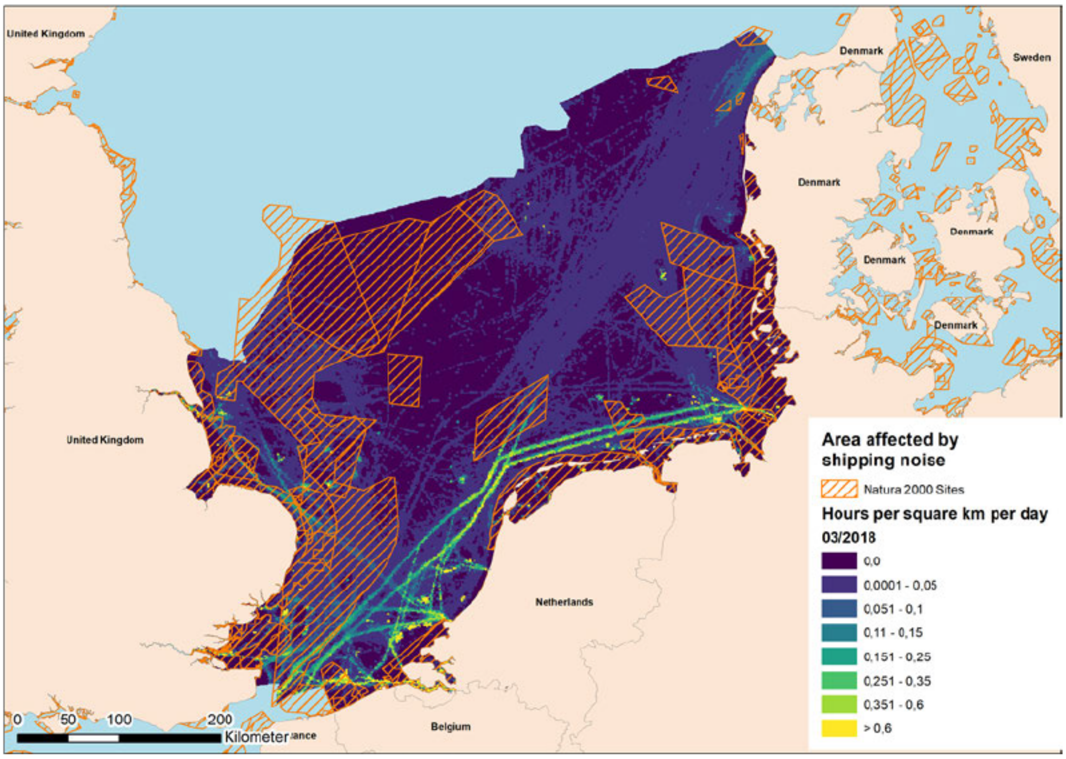


Figure 42: Map of the MRU and the affected area derived from the density average of March 2018 for cargo ships.

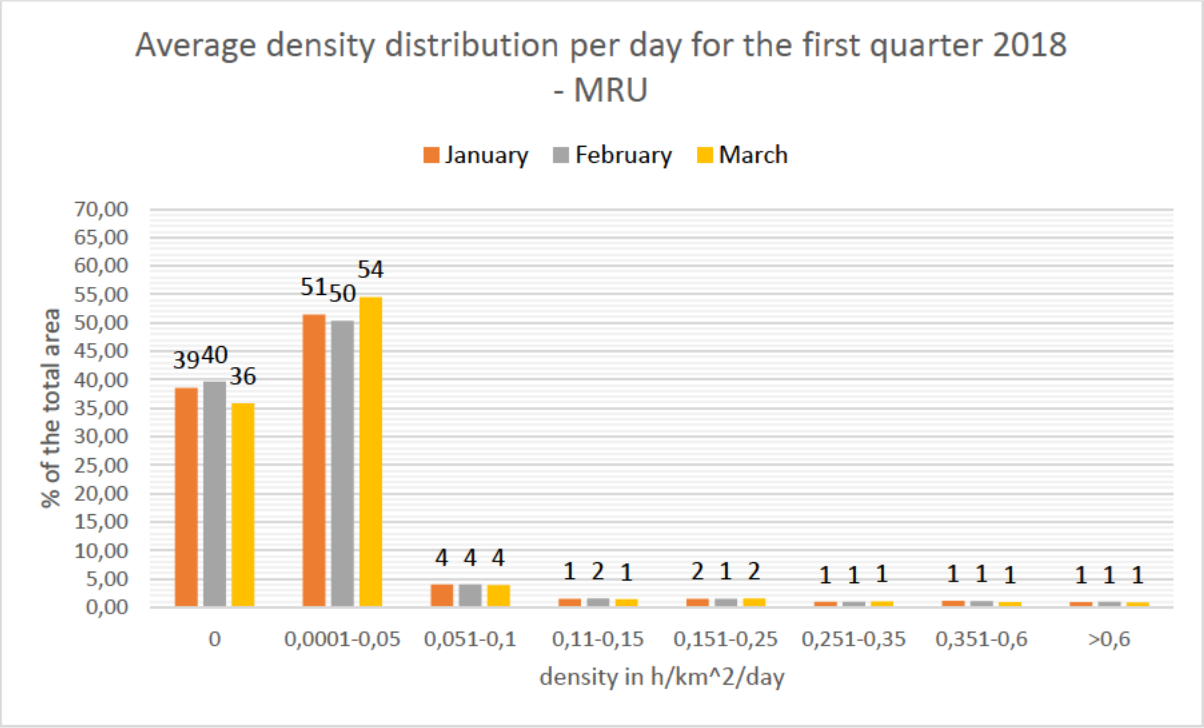


Figure 43: Average daily density distribution for the MRU for the first quarter 2018.

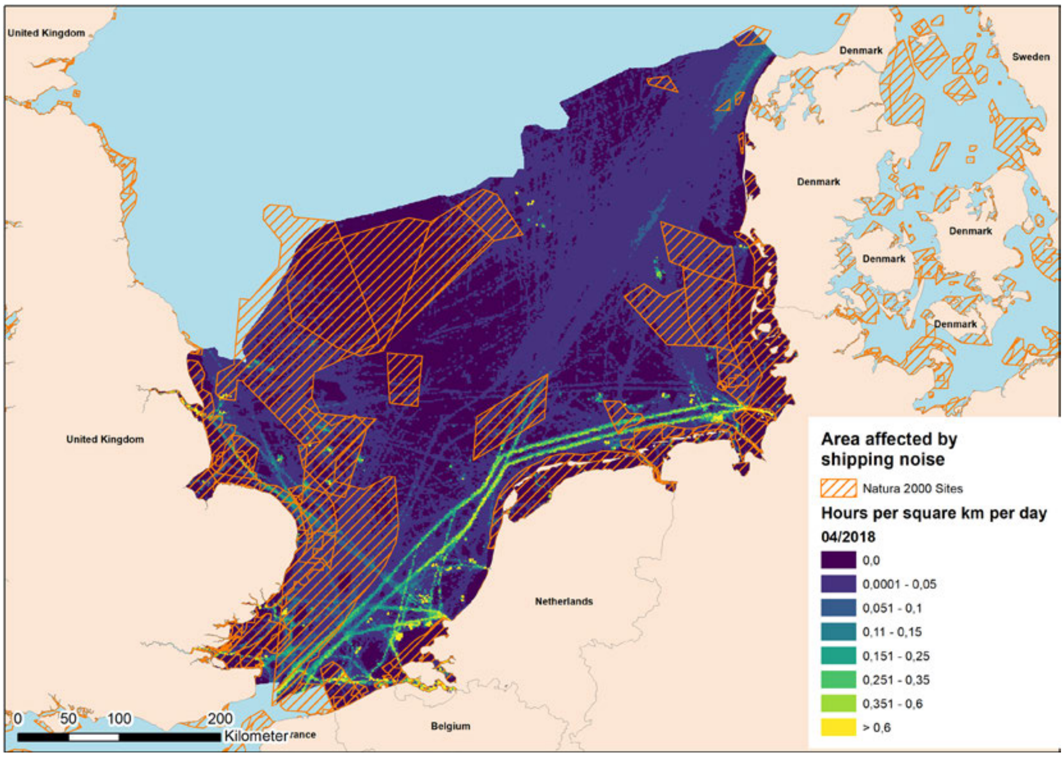


Figure 44: Map of the MRU and the affected area derived from the density average of April 2018 for cargo ships.

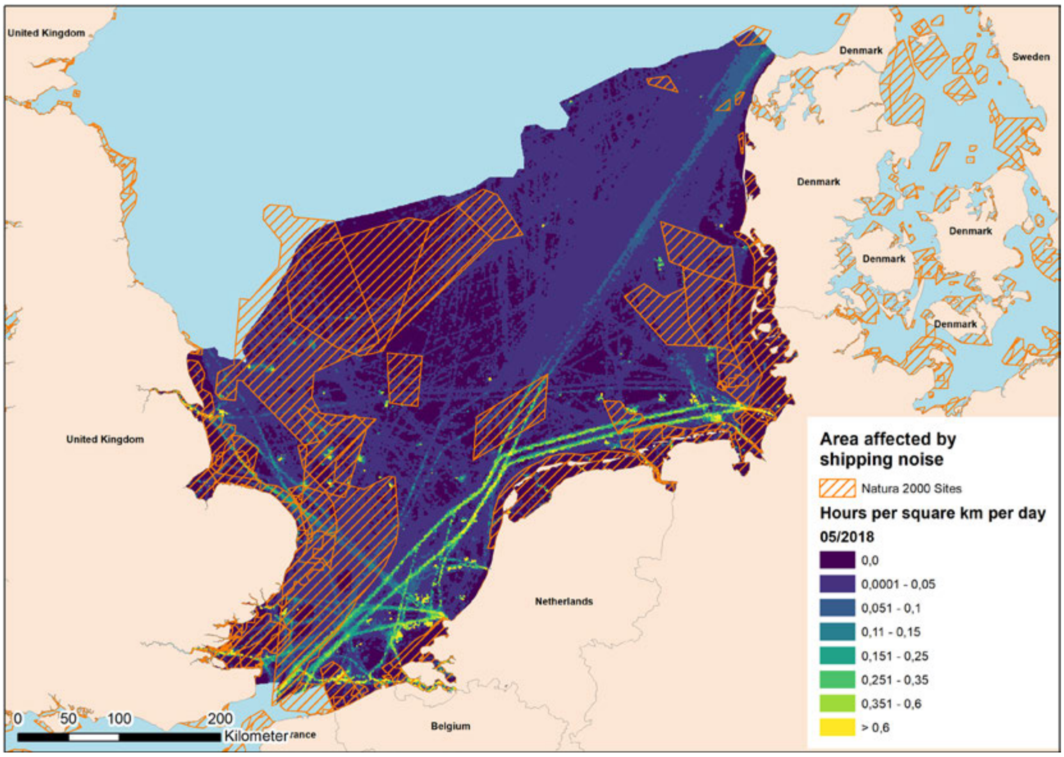


Figure 45: Map of the MRU and the affected area derived from the density average of May 2018 for cargo ships.

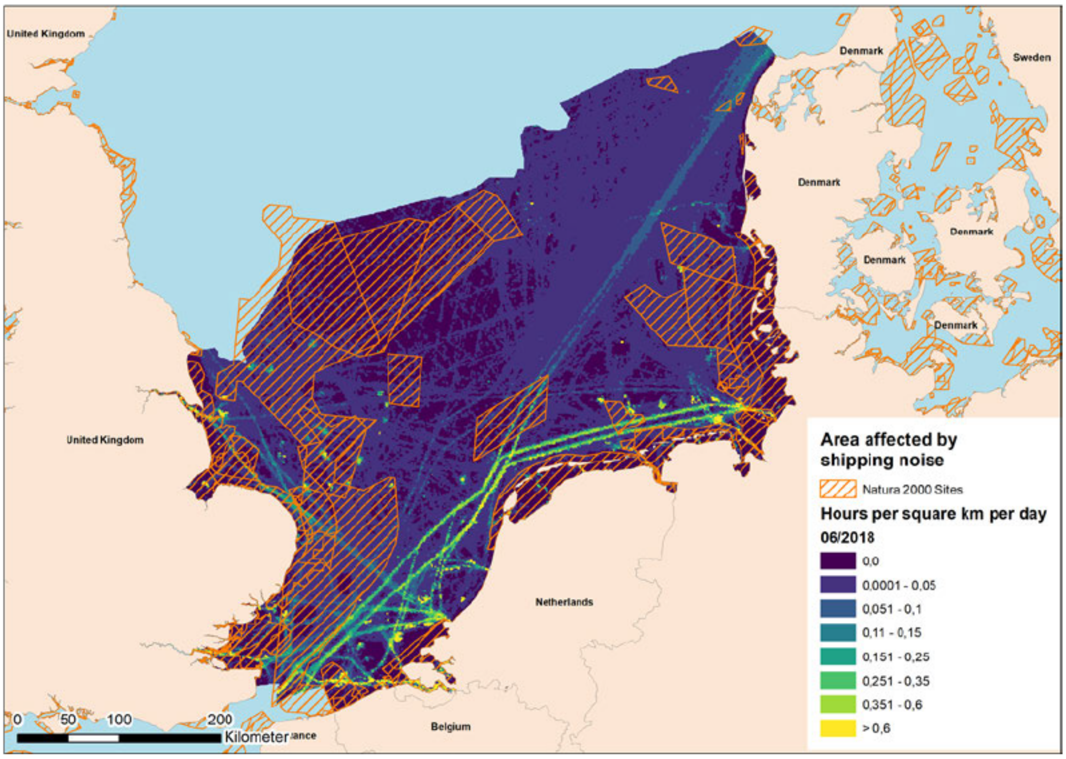


Figure 46: Map of the MRU and the affected area derived from the density average of June 2018 for cargo ships.

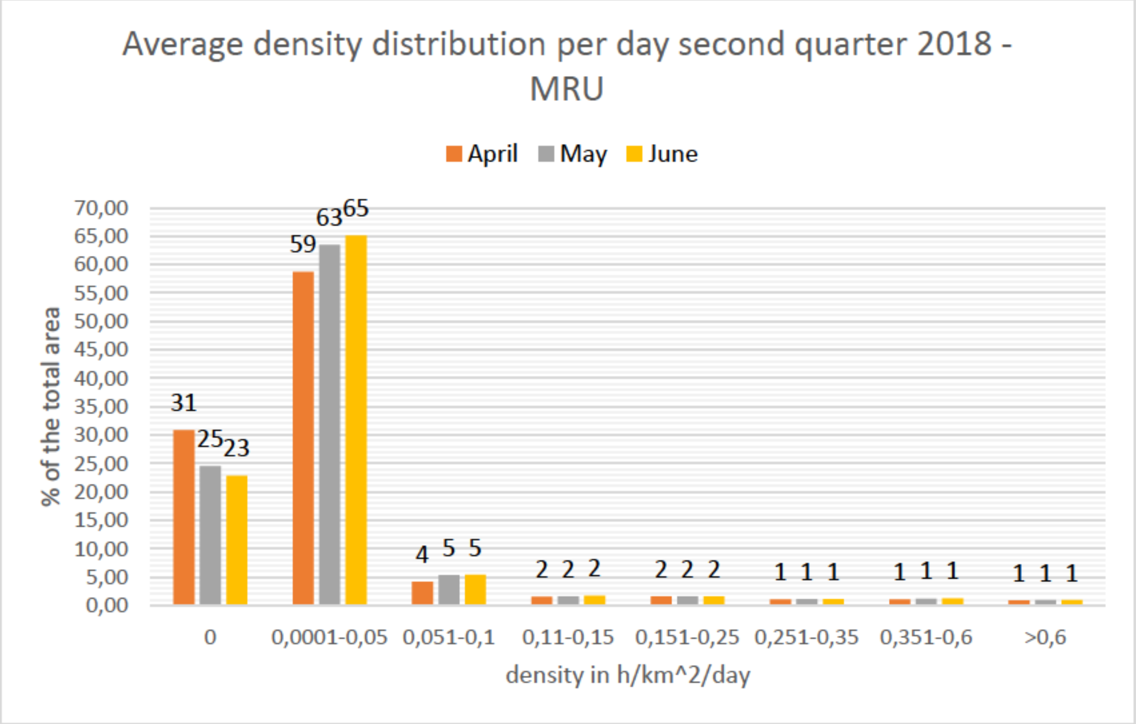


Figure 47: Average daily density distribution for the MRU for the second quarter 2018.

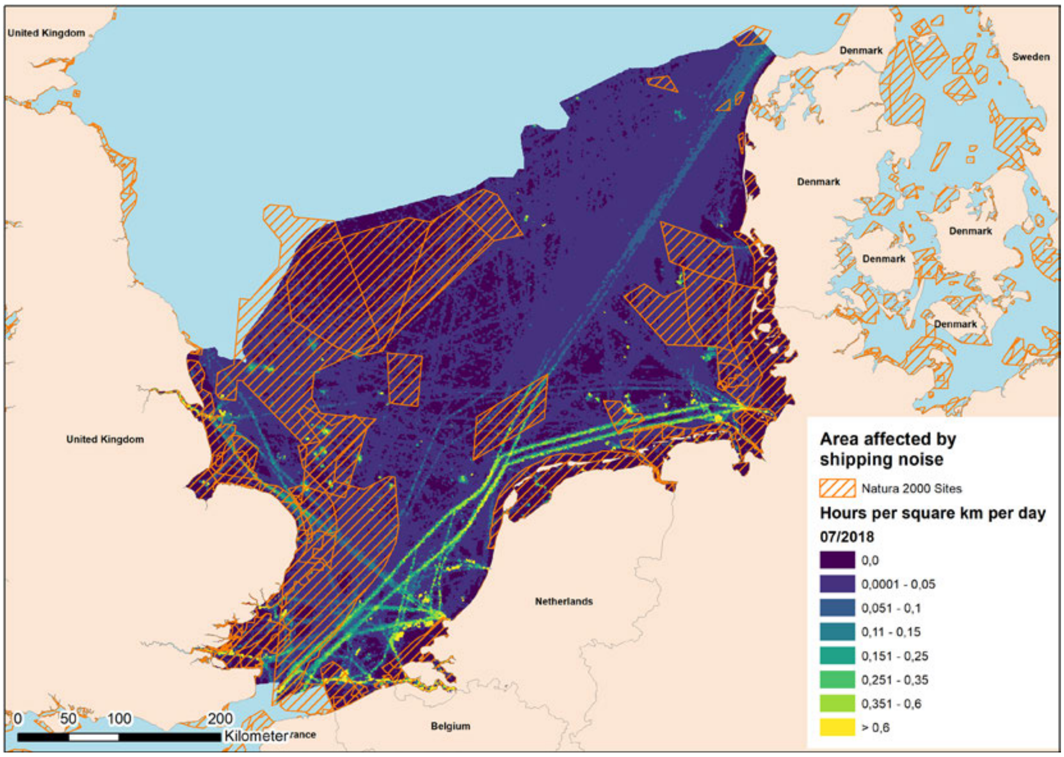


Figure 48: Map of the MRU and the affected area derived from the density average of July 2018 for cargo ships.

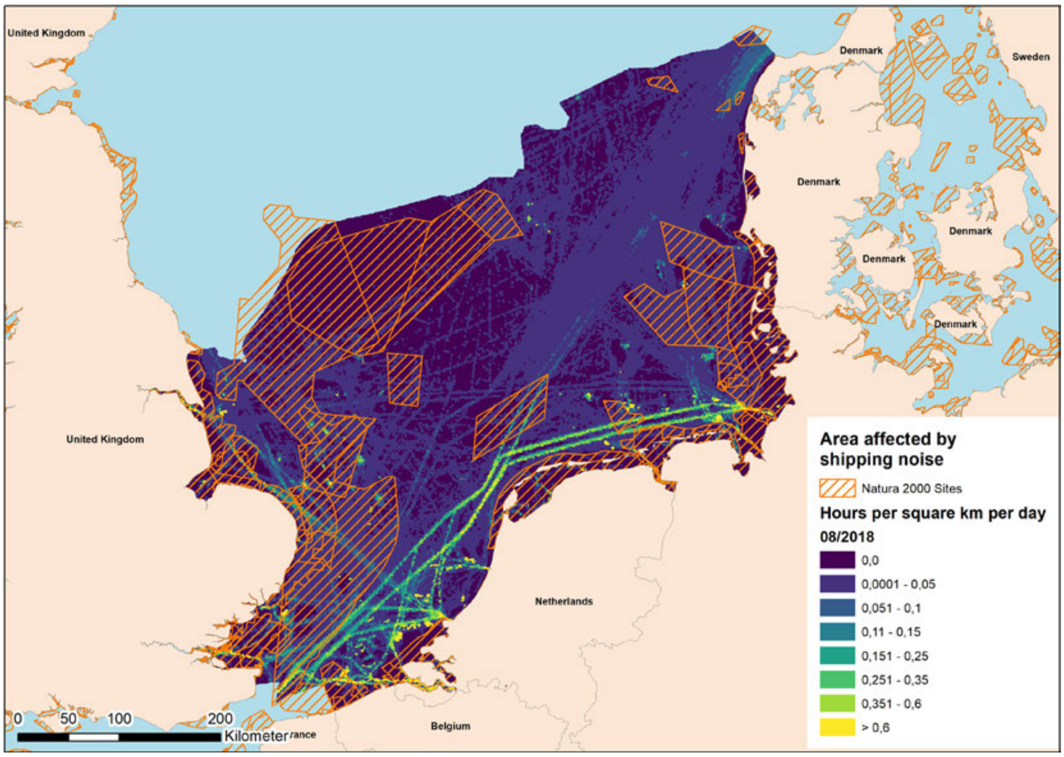


Figure 49: Map of the MRU and the affected area derived from the density average of August 2018 for cargo ships.

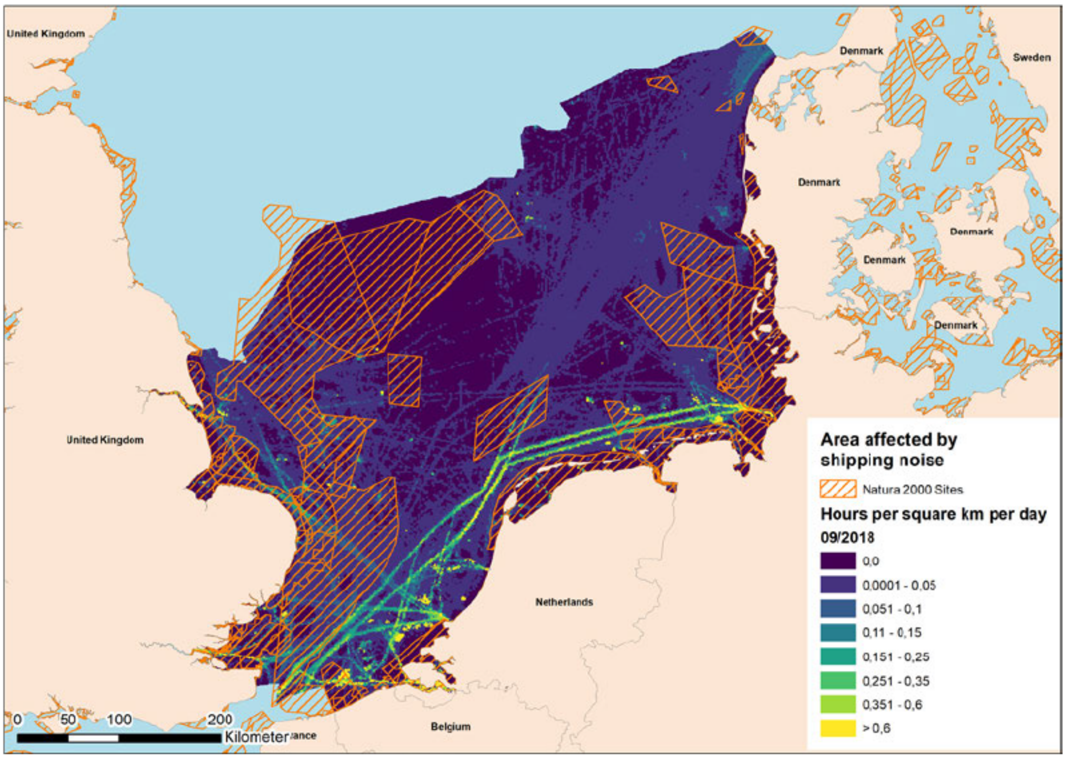


Figure 50: Map of the MRU and the affected area derived from the density average of September 2018 for cargo ships.

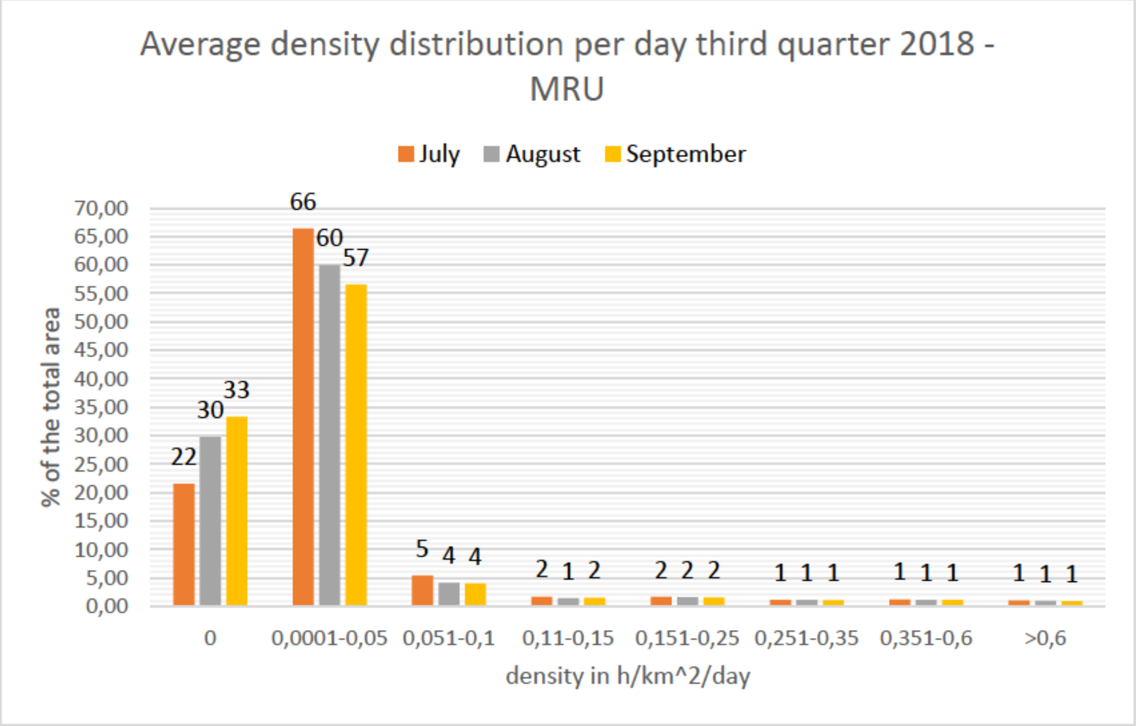


Figure 51: Average daily density distribution for the MRU for the third quarter 2018.

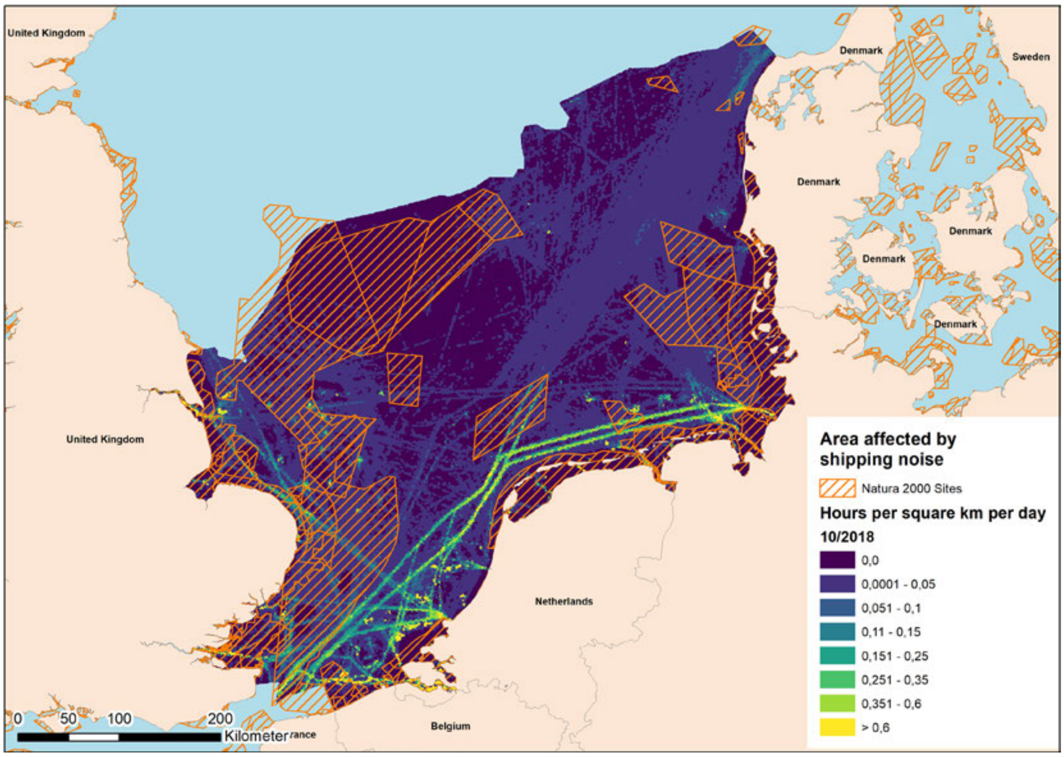


Figure 52: Map of the MRU and the affected area derived from the density average of October 2018 for cargo ships.

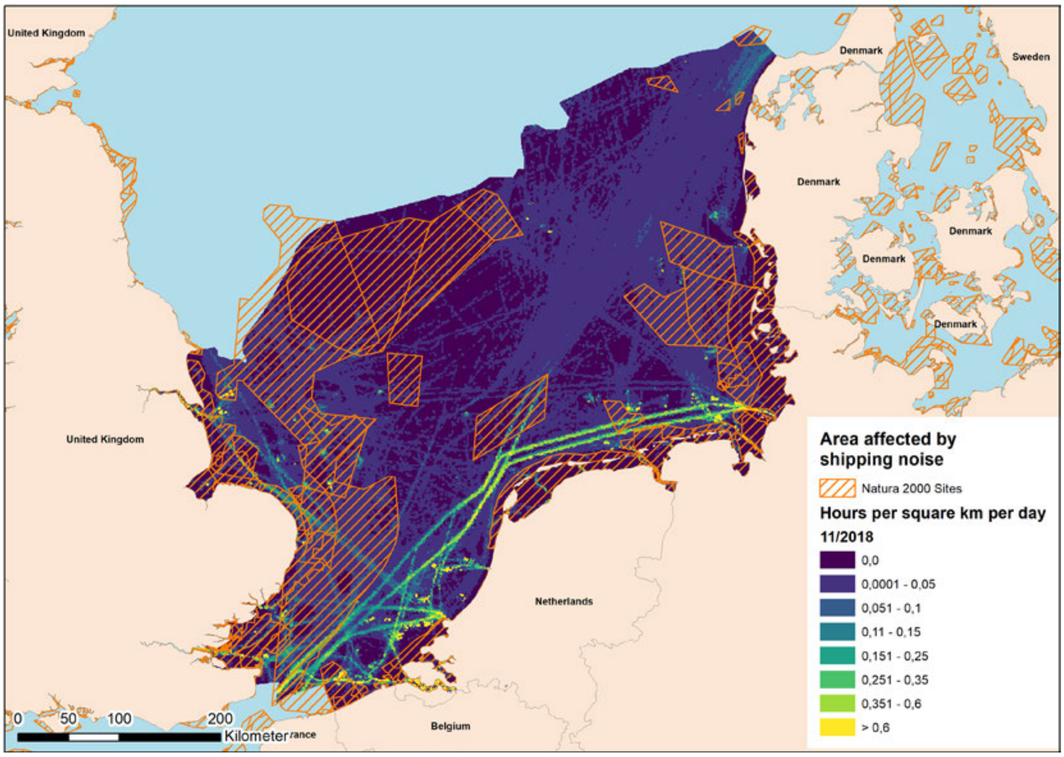


Figure 53: Map of the MRU and the affected area derived from the density average of November 2018 for cargo ships.

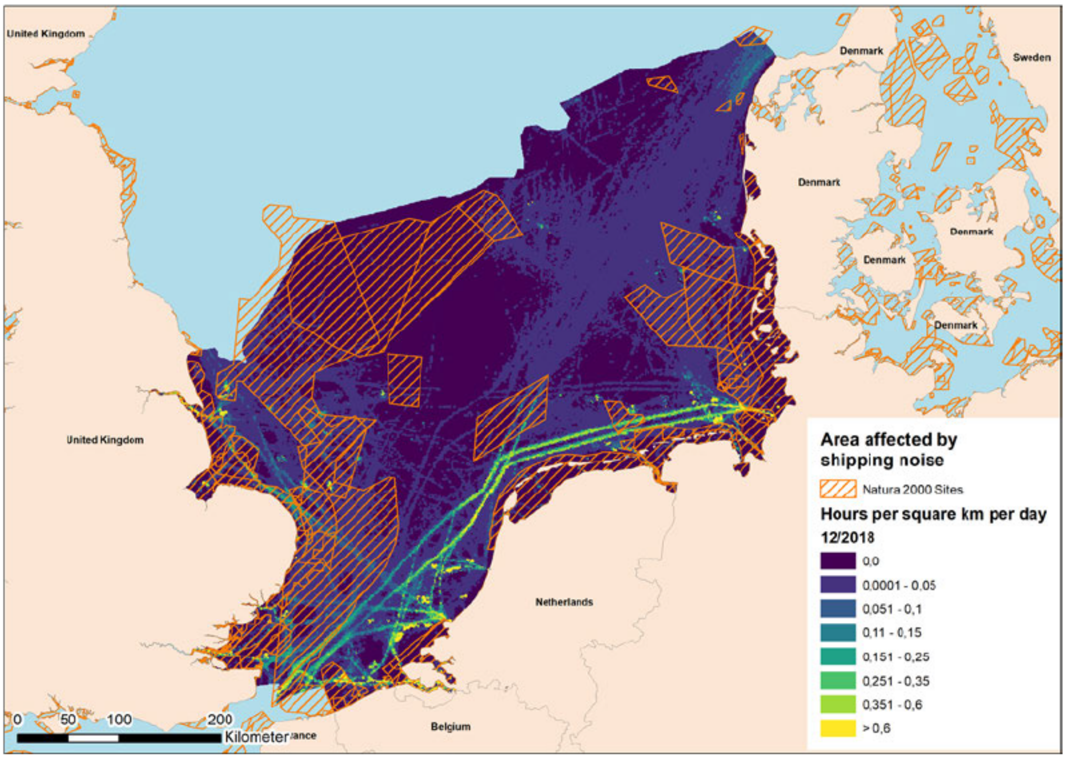


Figure 54: Map of the MRU and the affected area derived from the density average of December 2018 for cargo ships.

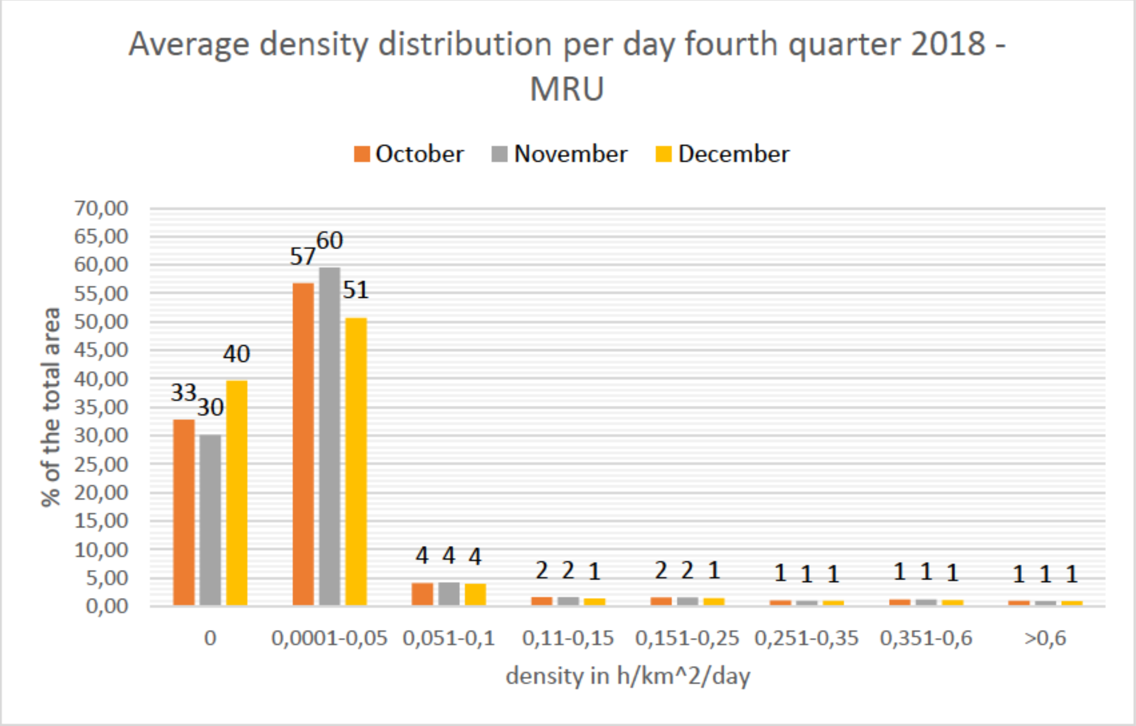


Figure 55: Average daily density distribution for the MRU for the fourth quarter 2018.

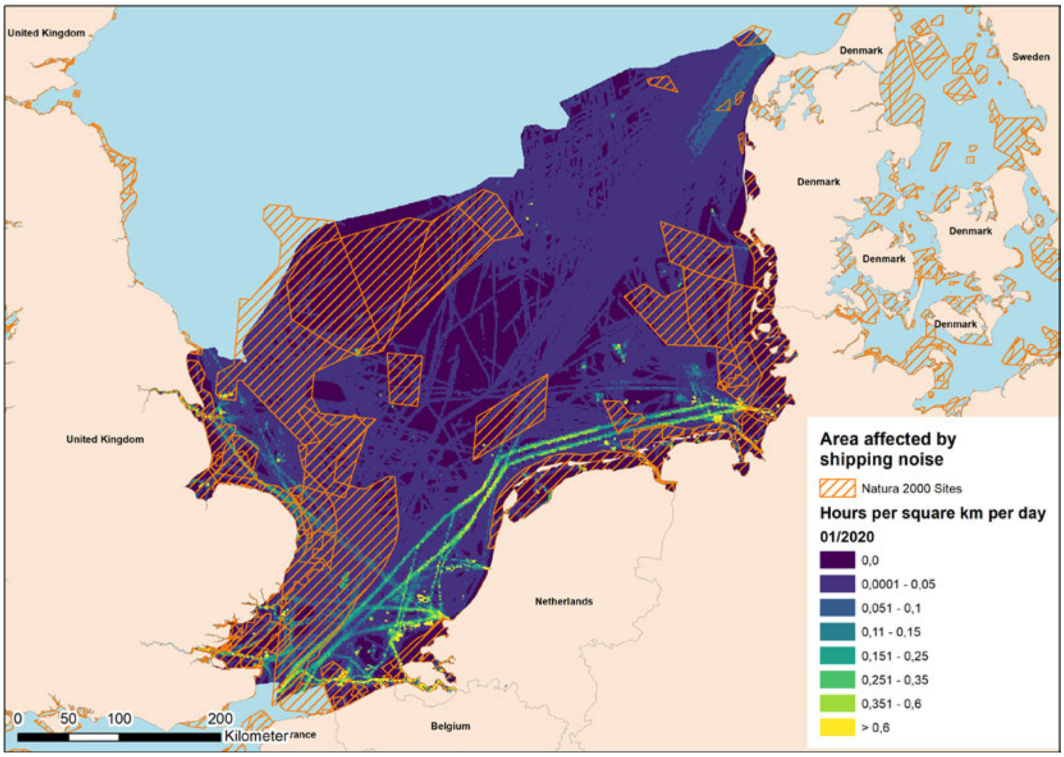


Figure 56: Map of the MRU and the affected area derived from the density average of January 2020 for cargo ships.

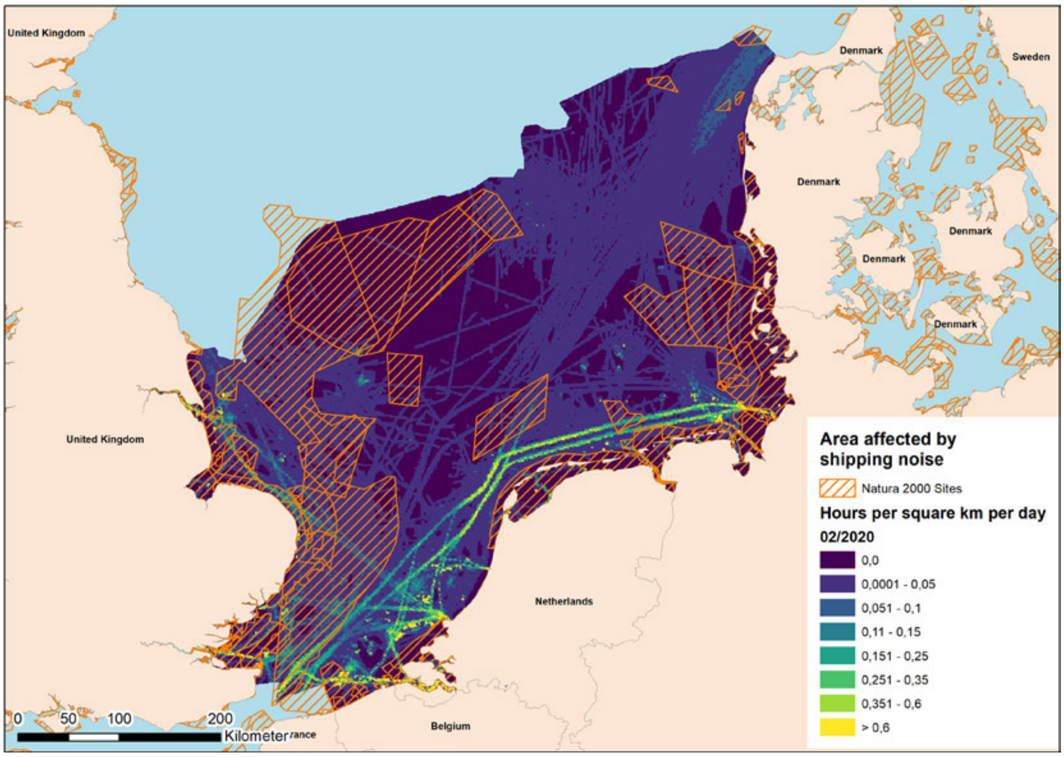


Figure 57: Map of the MRU and the affected area derived from the density average of February 2020 for cargo ships

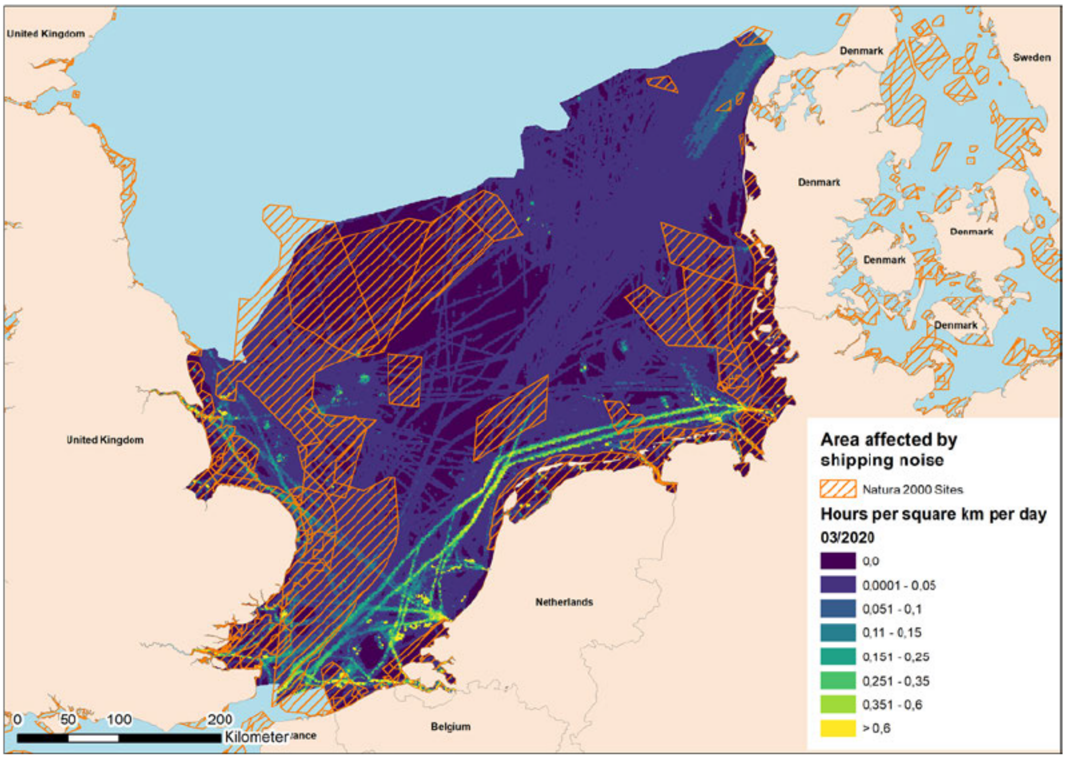


Figure 58: Map of the MRU and the affected area derived from the density average of March 2020 for cargo ships.

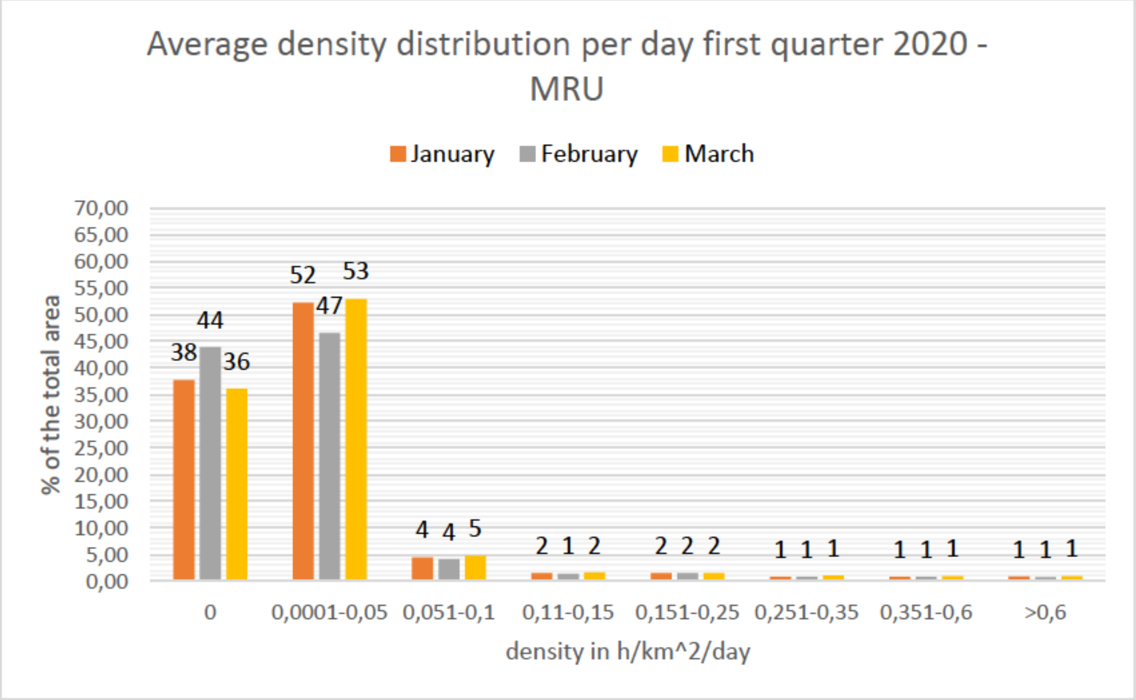


Figure 59: Average daily density distribution for the MRU for the first quarter 2020.

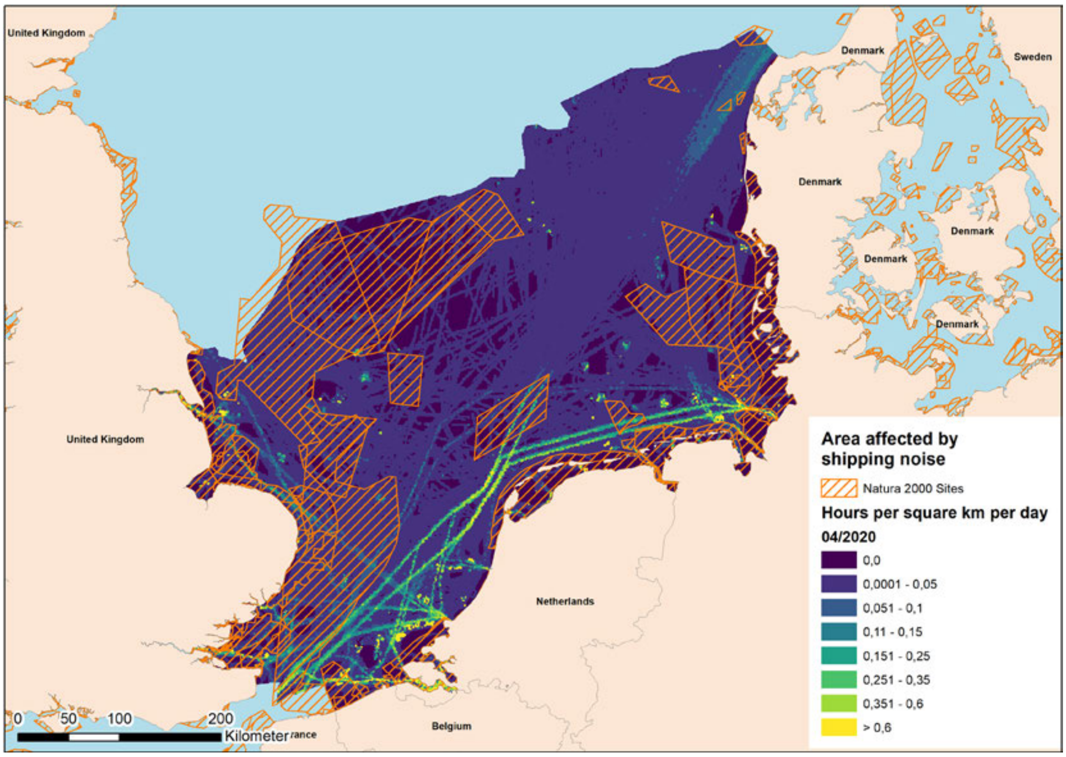


Figure 60: Map of the MRU and the affected area derived from the density average of April 2020 for cargo ships.

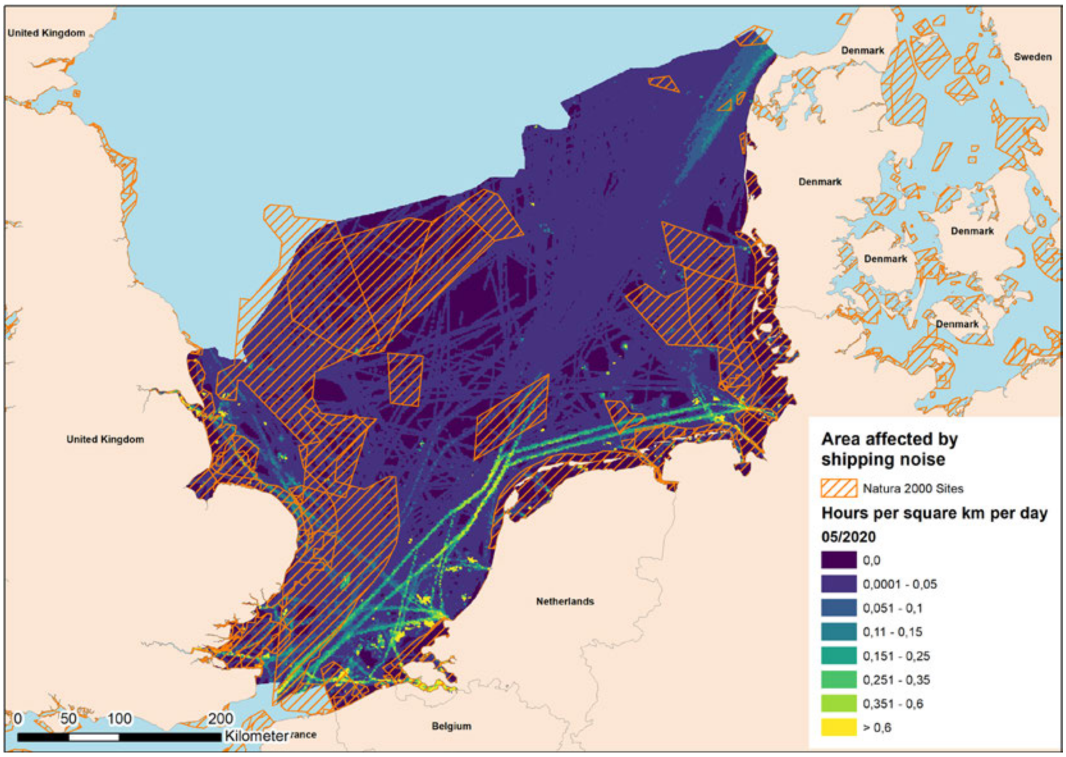


Figure 61: Map of the MRU and the affected area derived from the density average of May 2020 for cargo ships.

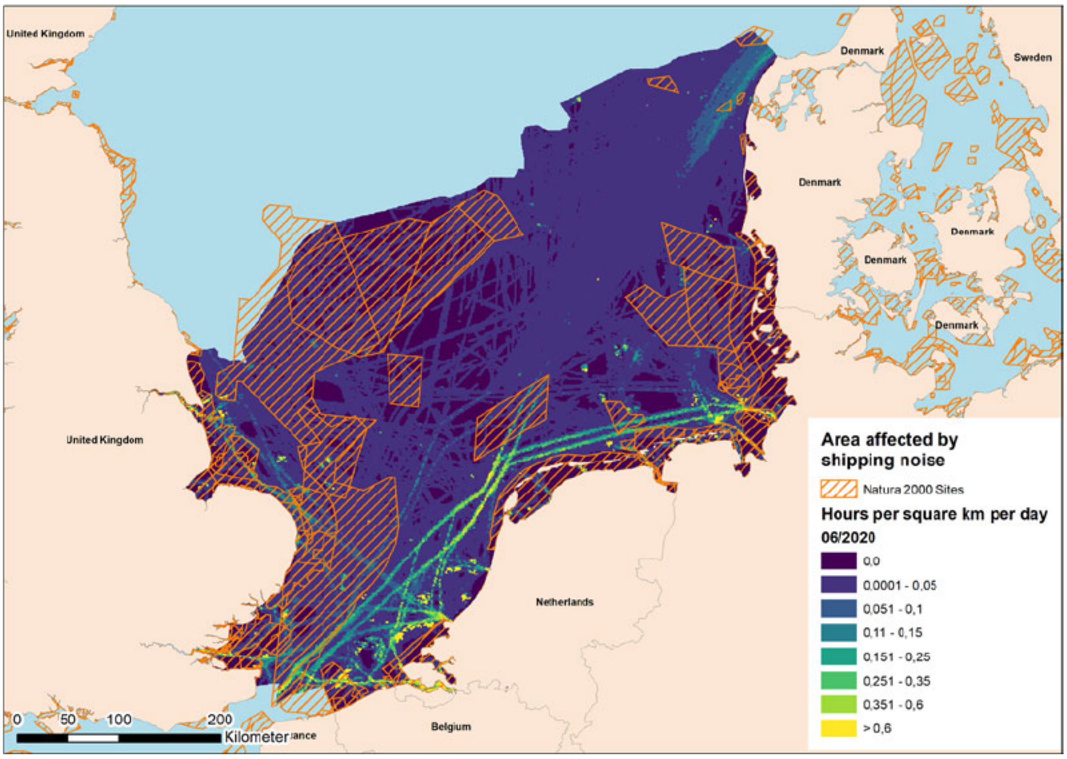


Figure 62: Map of the MRU and the affected area derived from the density average of June 2020 for cargo ships.

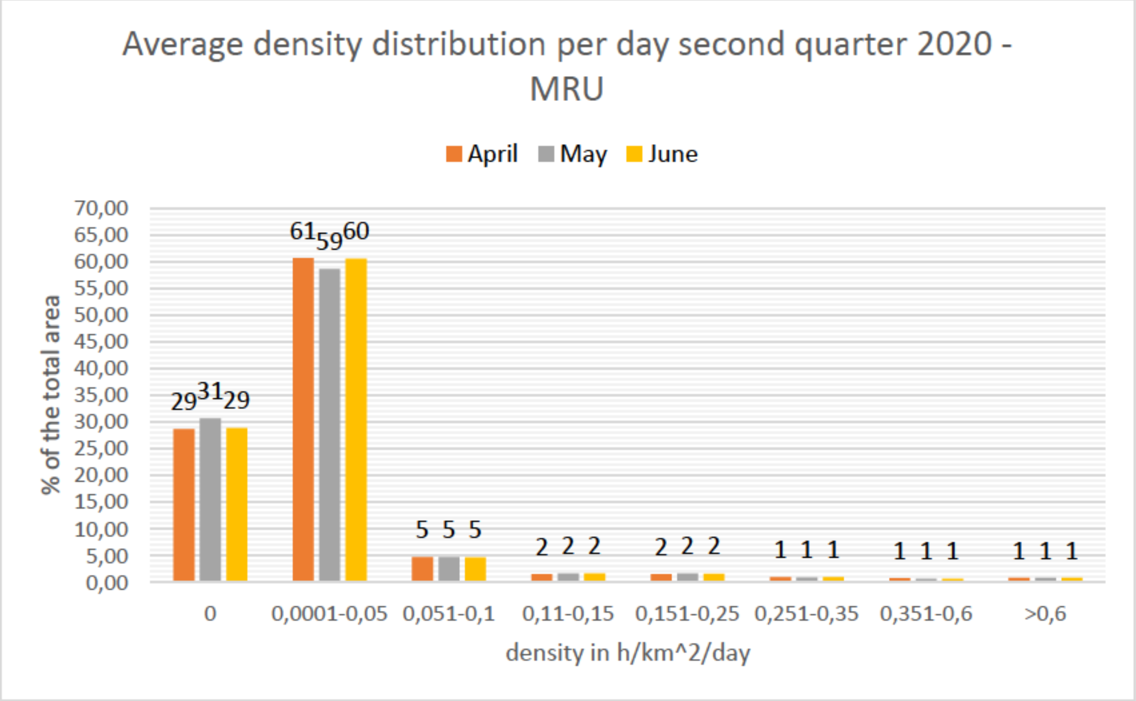


Figure 63: Average daily density distribution for the MRU for the second quarter 2020.

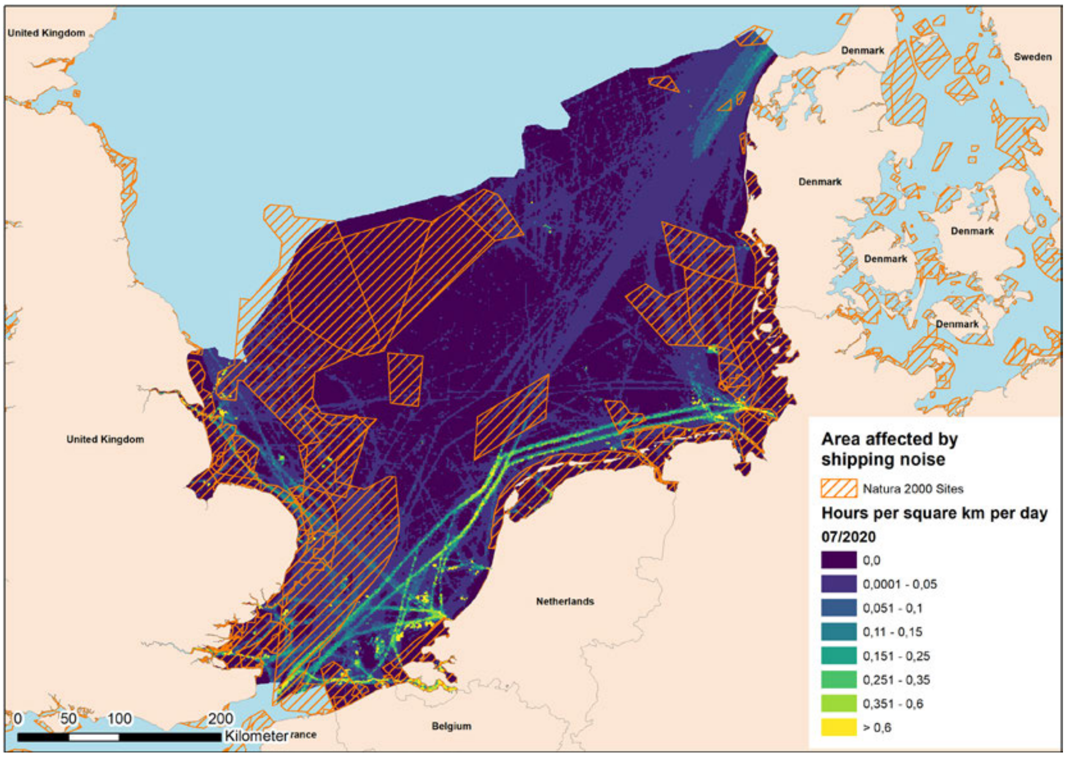


Figure 64: Map of the MRU and the affected area derived from the density average of July 2020 for cargo ships.

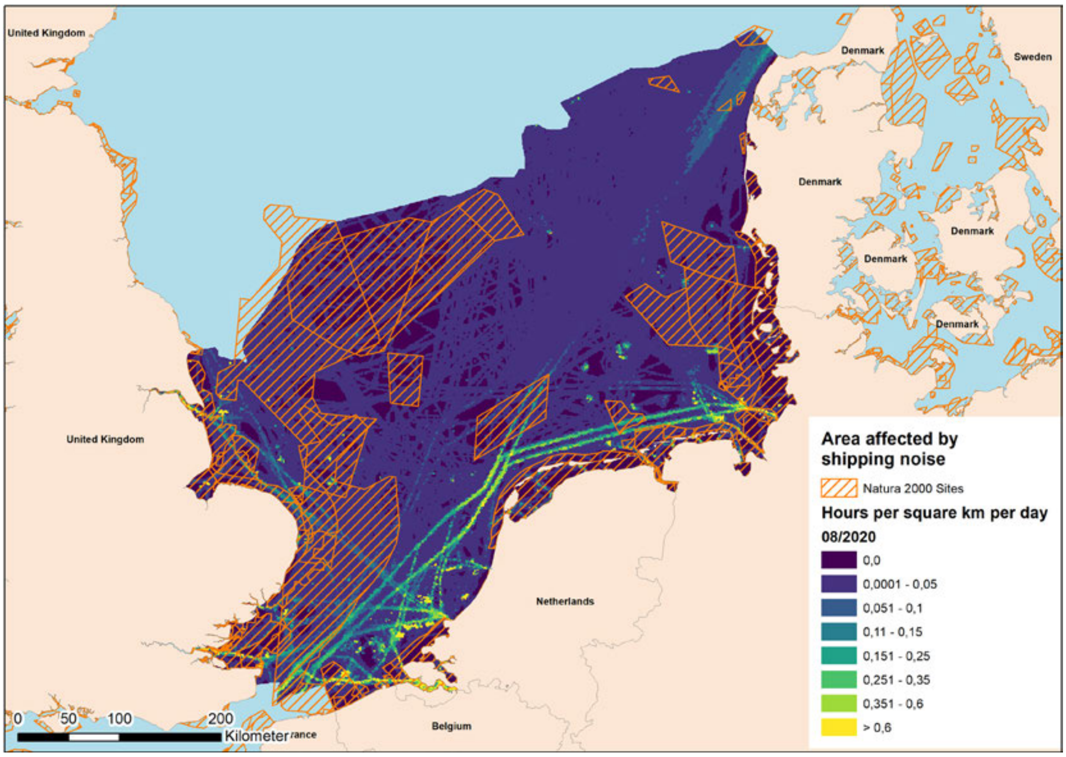


Figure 65: Map of the MRU and the affected area derived from the density average of August 2020 for cargo ships.

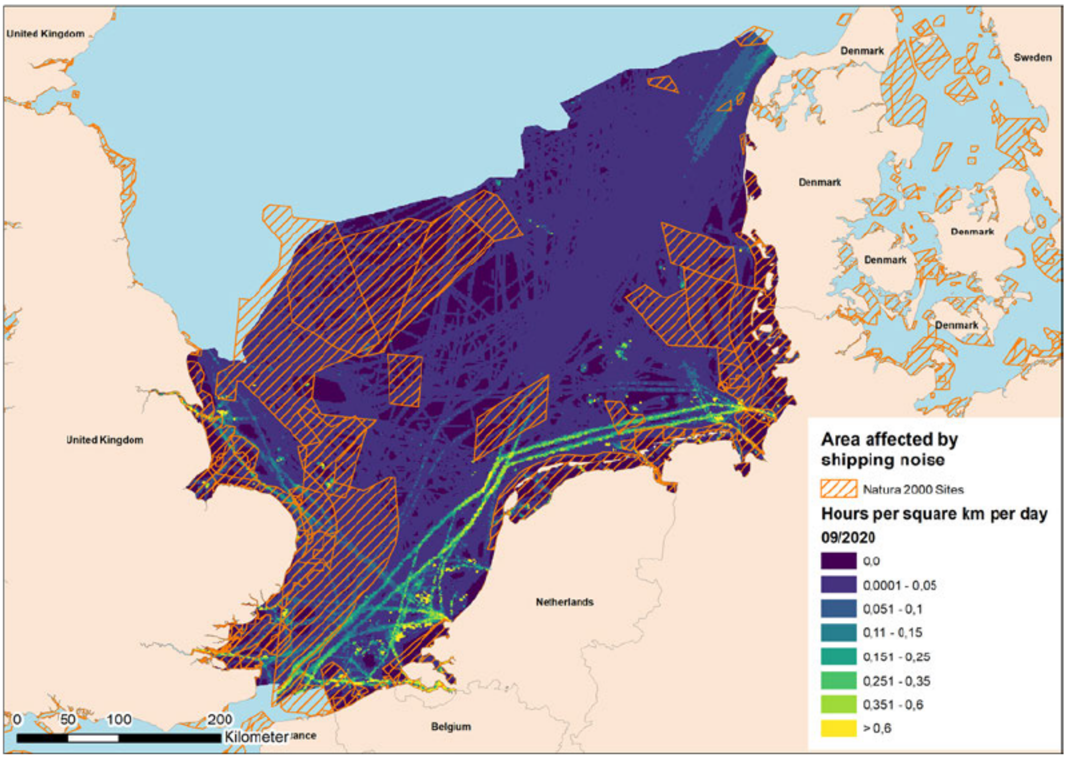


Figure 66: Map of the MRU and the affected area derived from the density average of September 2020 for cargo ships.

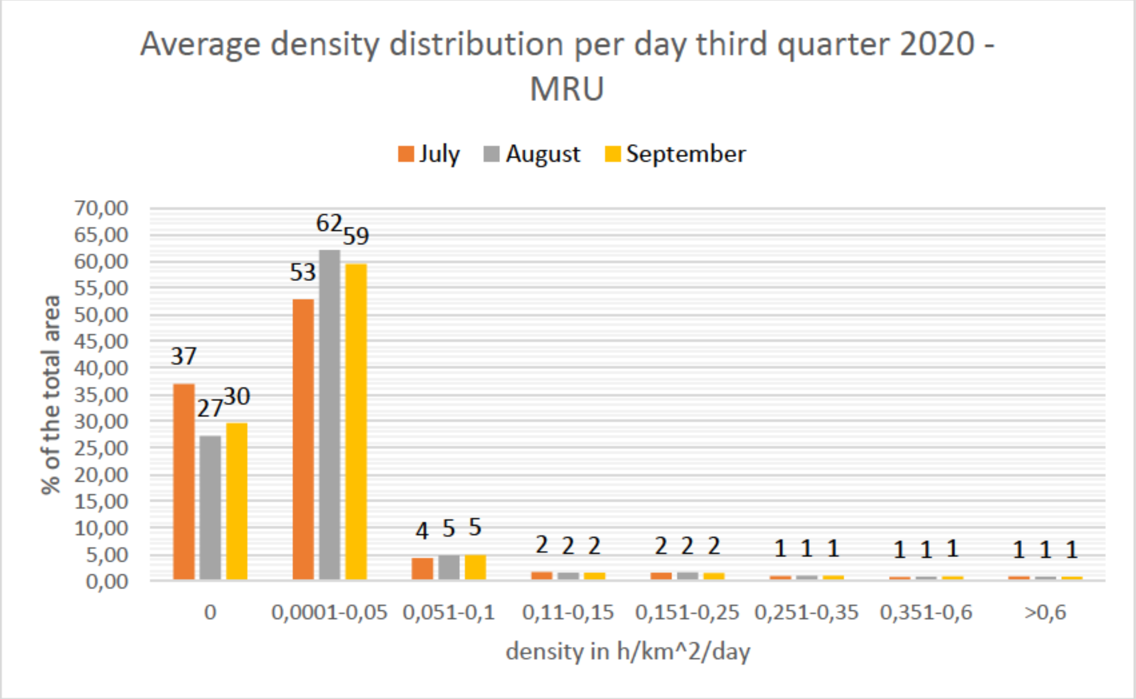


Figure 67: Average daily density distribution for the MRU for the third quarter 2020.

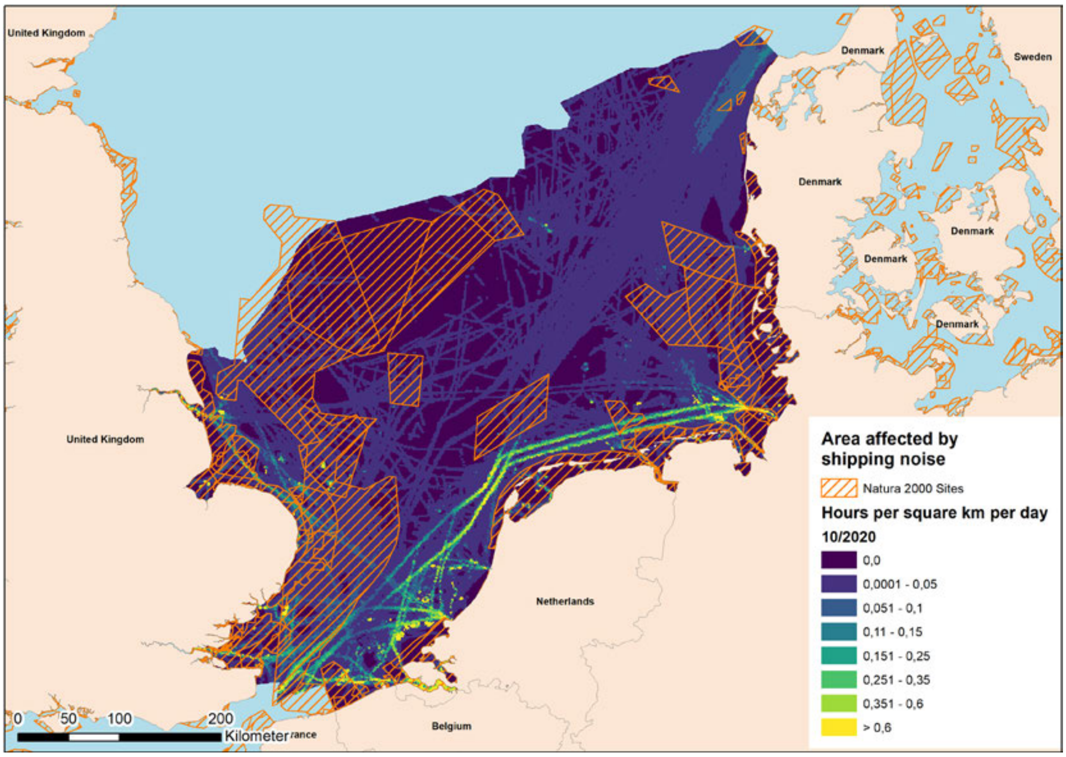


Figure 68: Map of the MRU and the affected area derived from the density average of October 2020 for cargo ships.

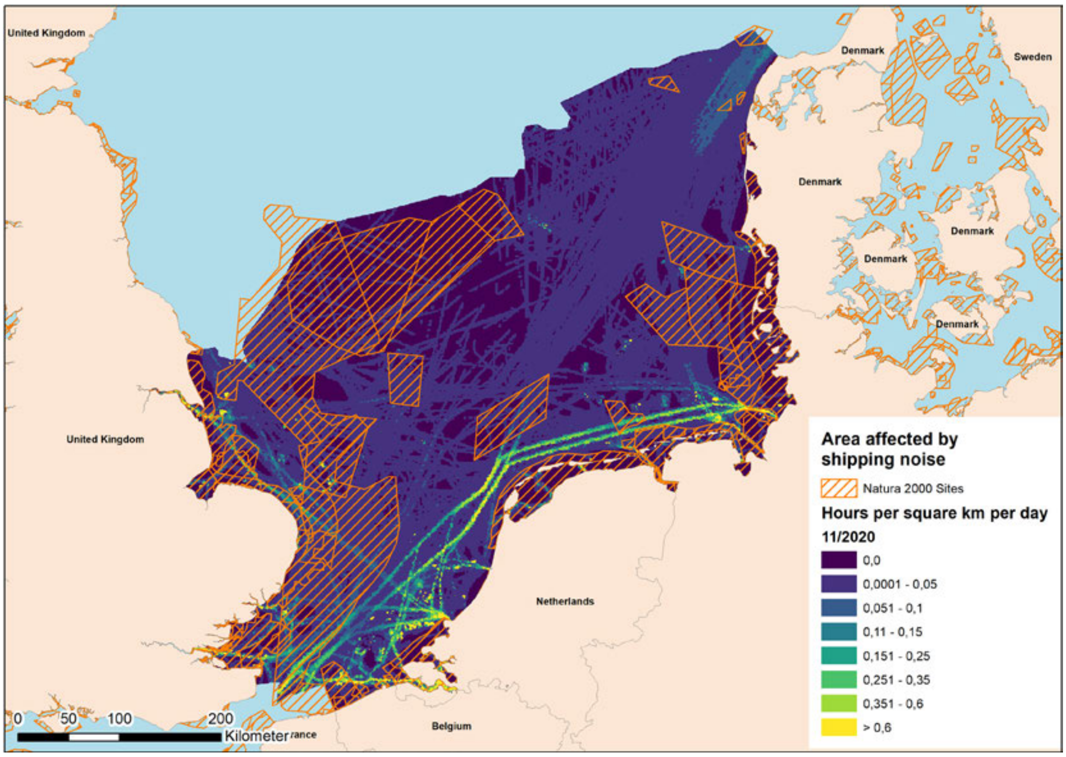


Figure 69: Map of the MRU and the affected area derived from the density average of November 2020 for cargo ships.

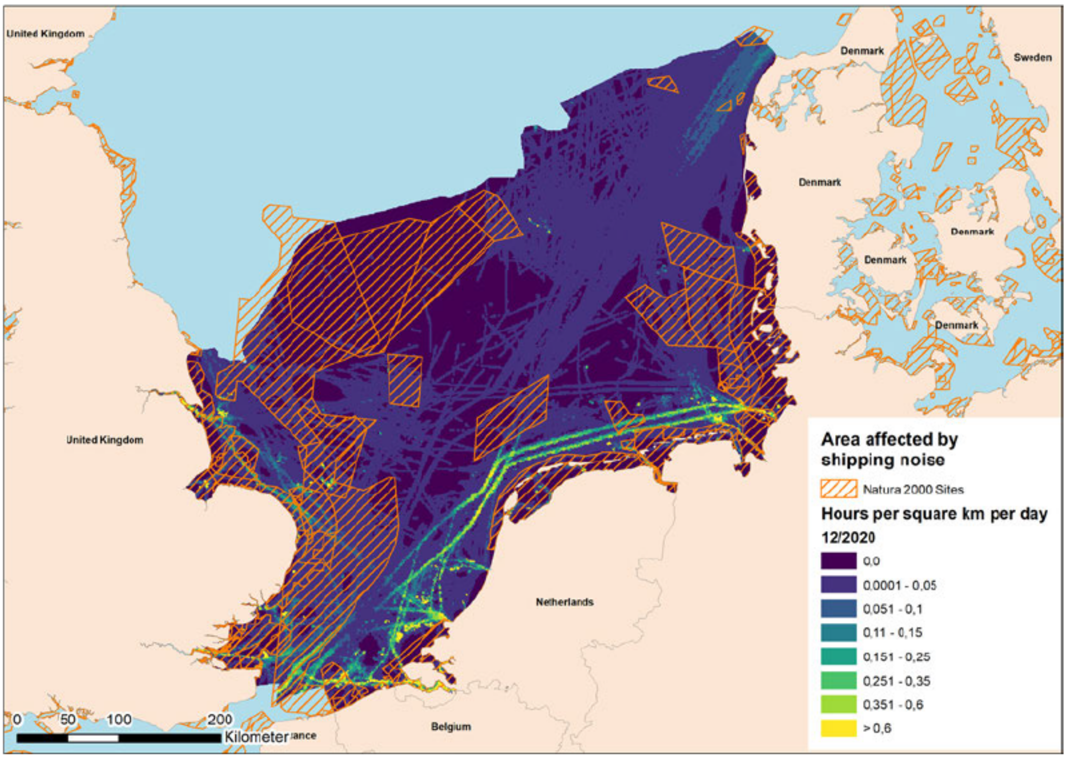


Figure 70: Map of the MRU and the affected area derived from the density average of December 2020 for cargo ships.

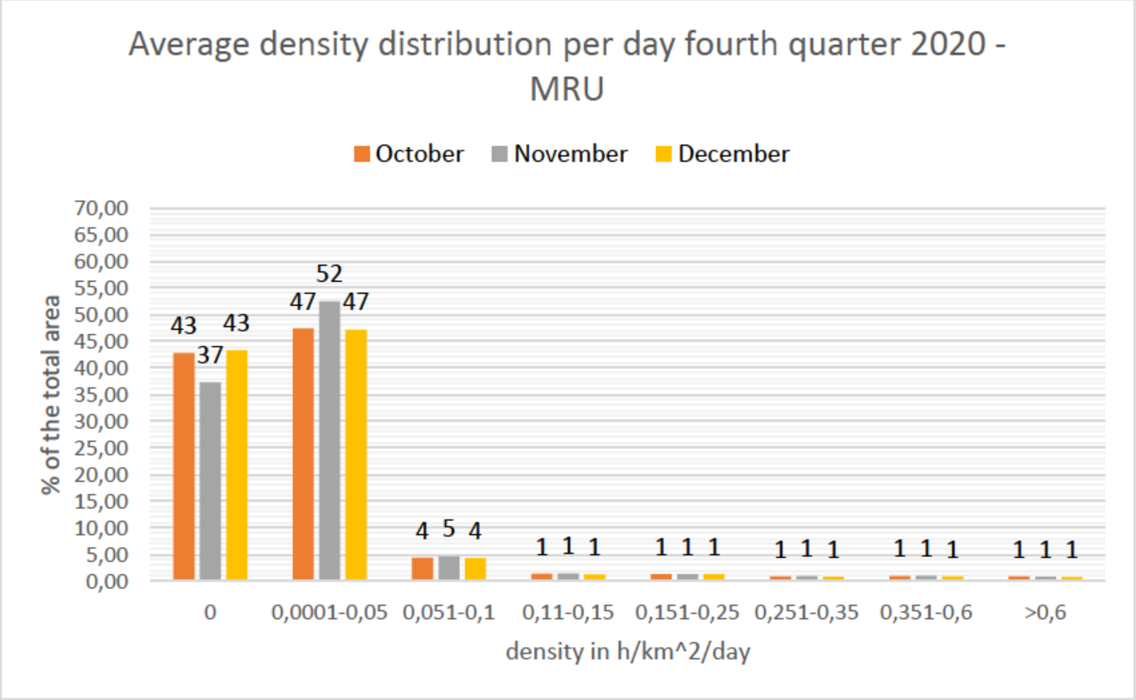


Figure 71: Average daily density distribution for the MRU for the fourth quarter 2020.

Annex E – Monthly Maps and Histograms MPA

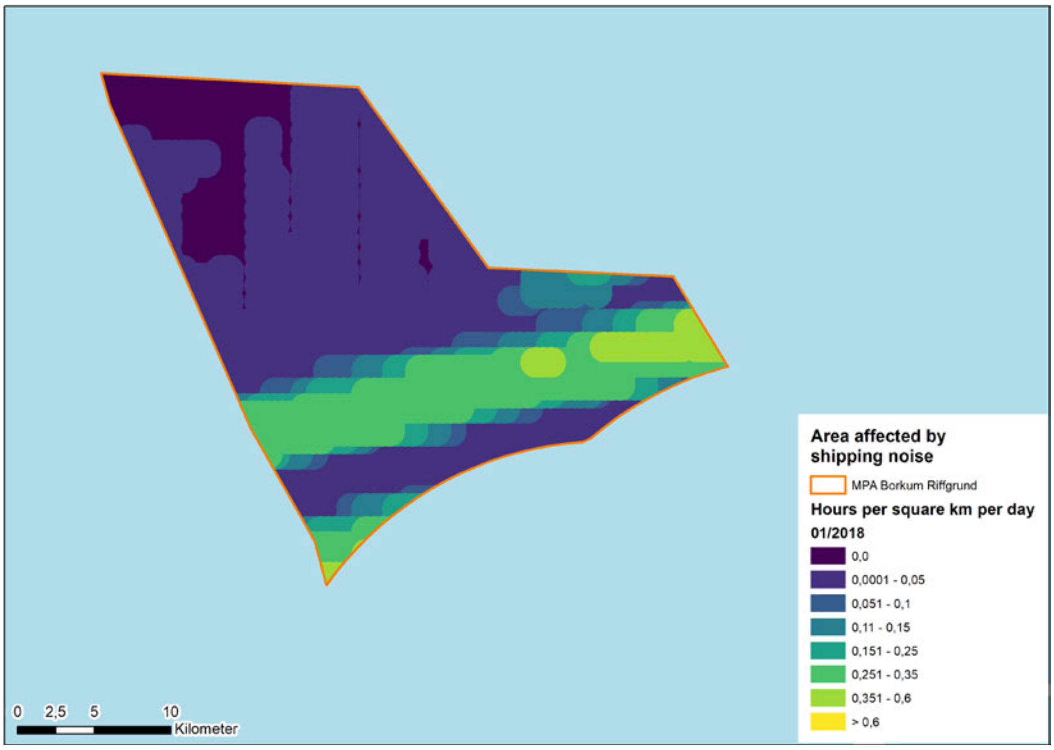


Figure 72: Map of the MPA and the affected area derived from the density average of January 2018 for cargo ships.

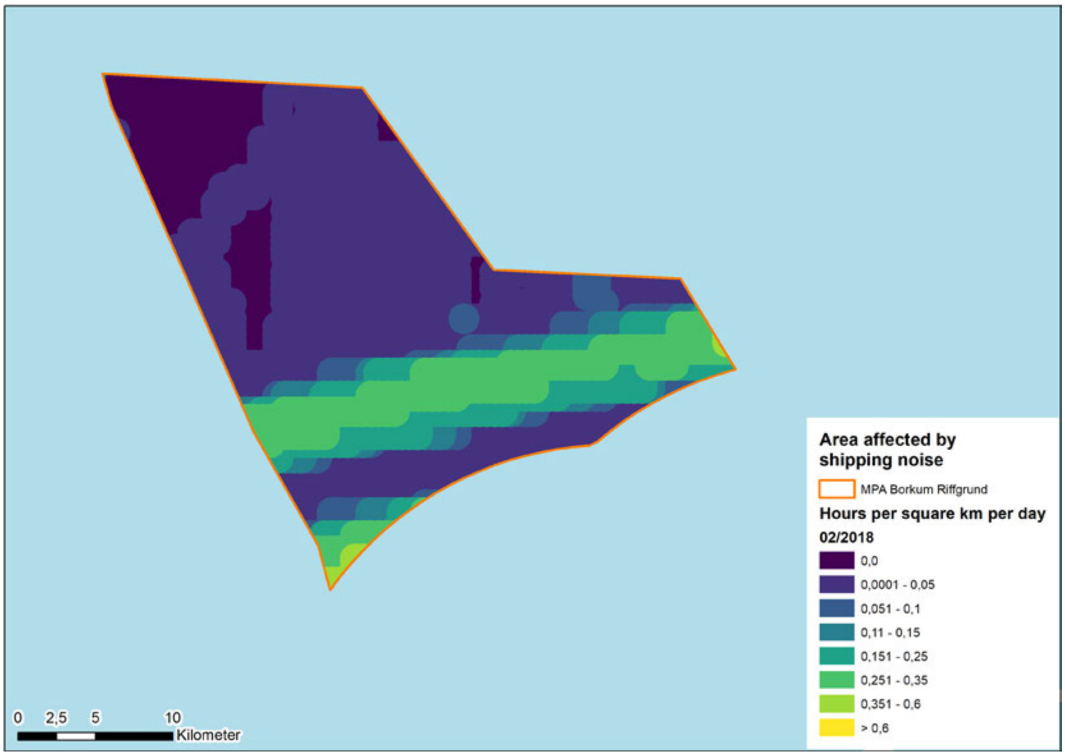


Figure 73: Map of the MPA and the affected area derived from the density average of February 2018 for cargo ships.

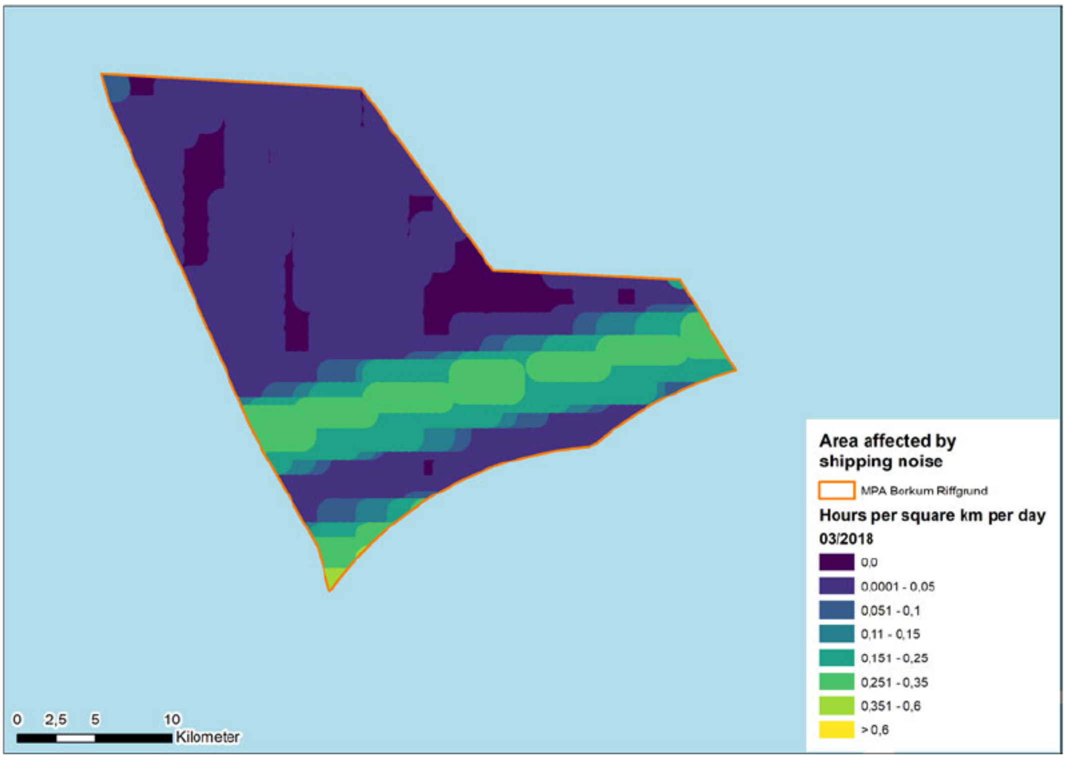


Figure 74: Map of the MPA and the affected area derived from the density average of March 2018 for cargo ships.

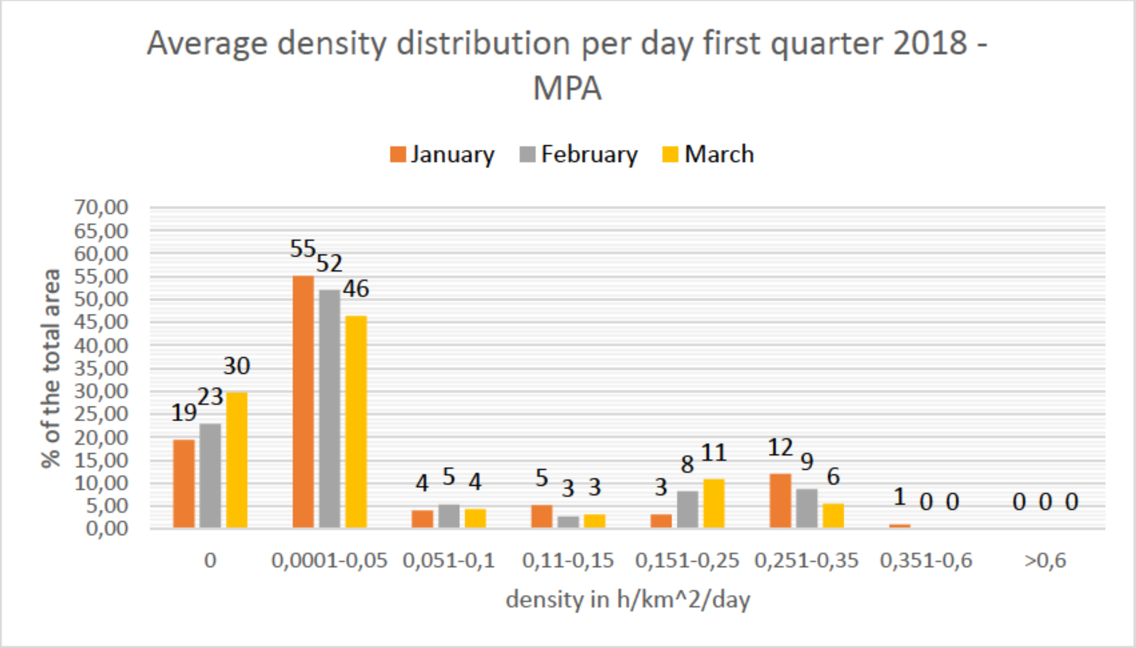


Figure 75: Average daily density distribution for the MPA for the first quarter 2018.

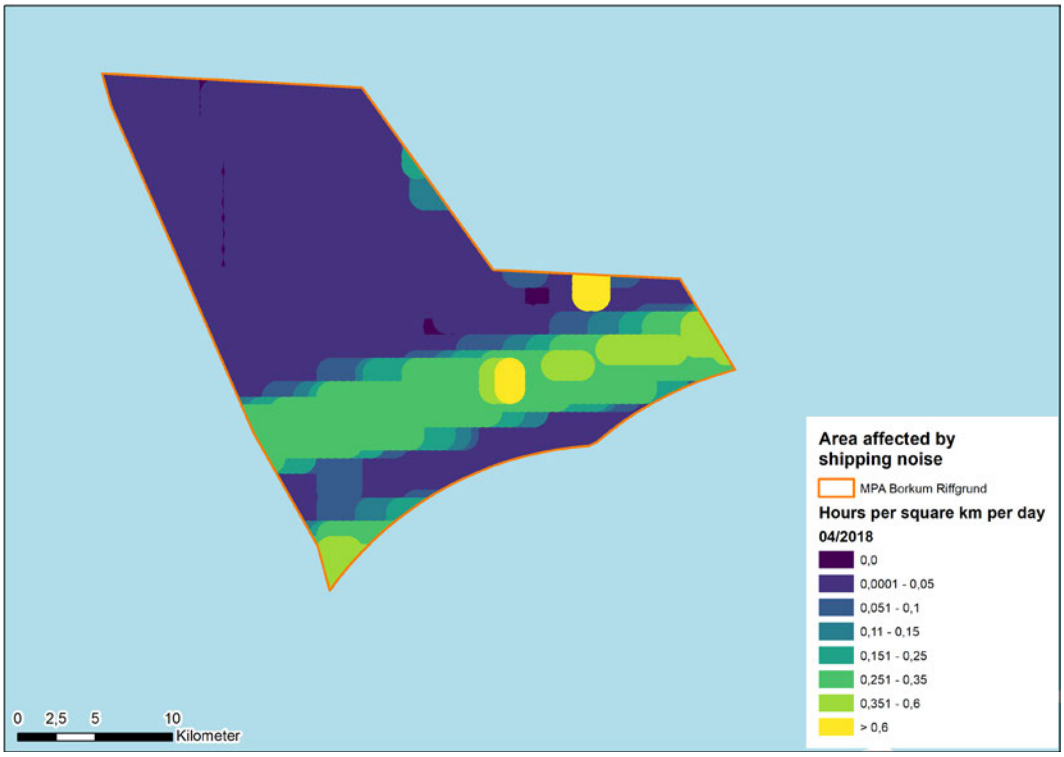


Figure 76: Map of the MPA and the affected area derived from the density average of April 2018 for cargo ships.

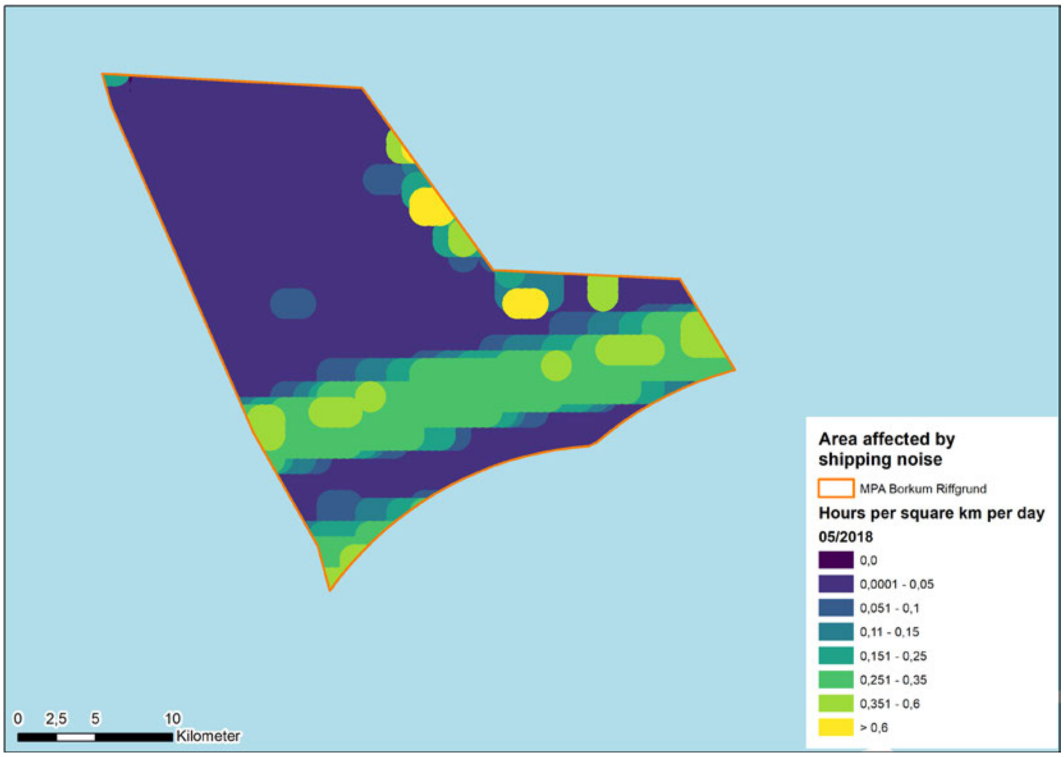


Figure 77: Map of the MPA and the affected area derived from the density average of May 2018 for cargo ships.

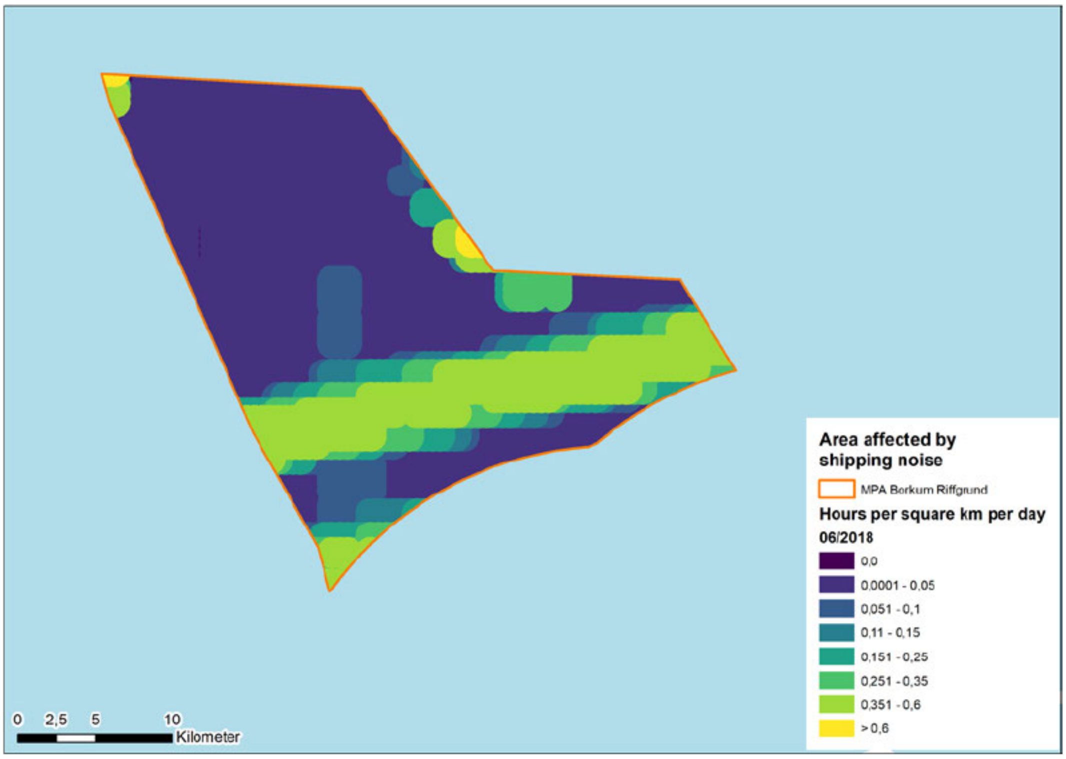


Figure 78: Map of the MPA and the affected area derived from the density average of June 2018 for cargo ships.

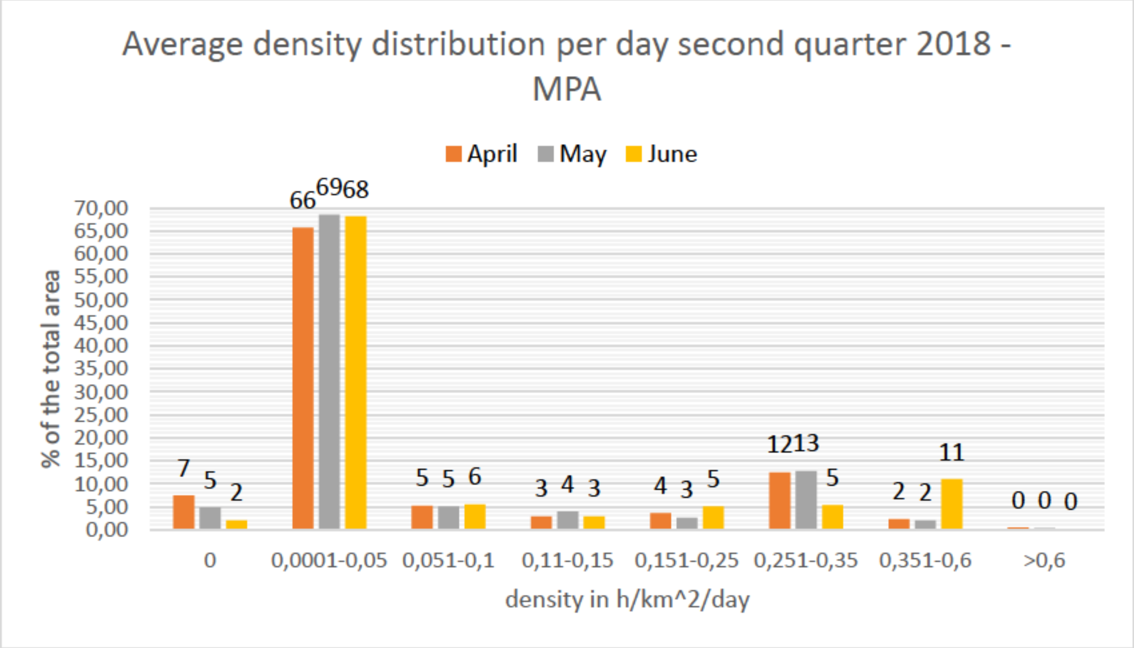


Figure 79: Average daily density distribution for the MPA for the second quarter 2018.

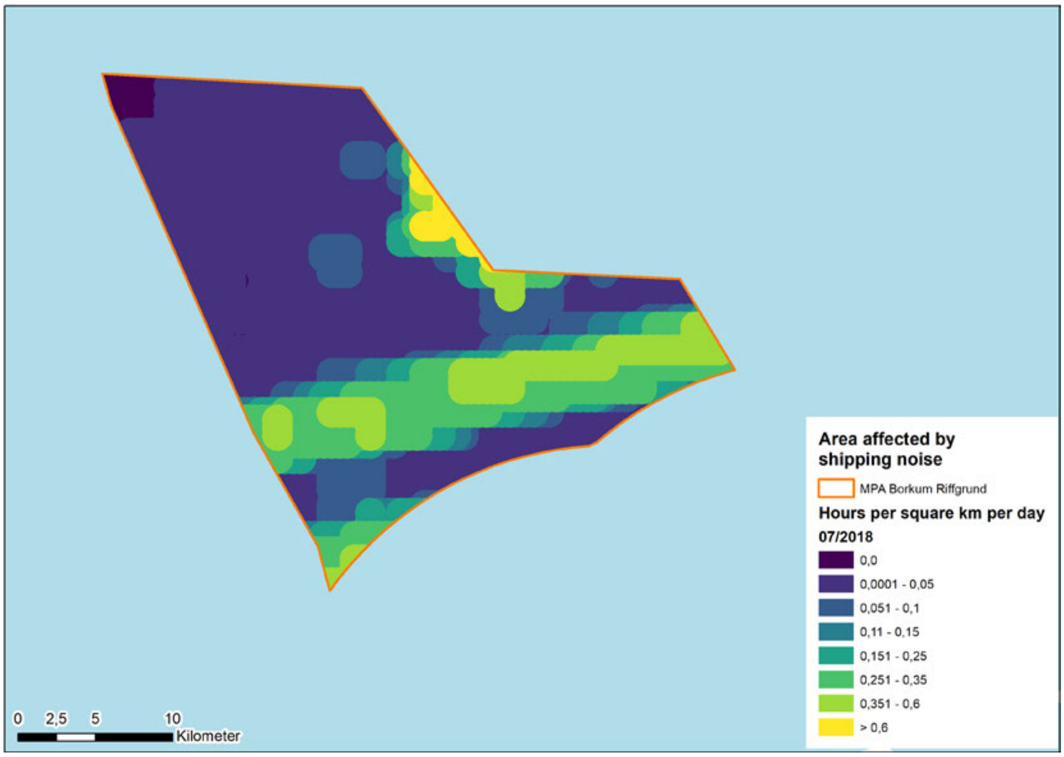


Figure 80: Map of the MPA and the affected area derived from the density average of July 2018 for cargo ships.

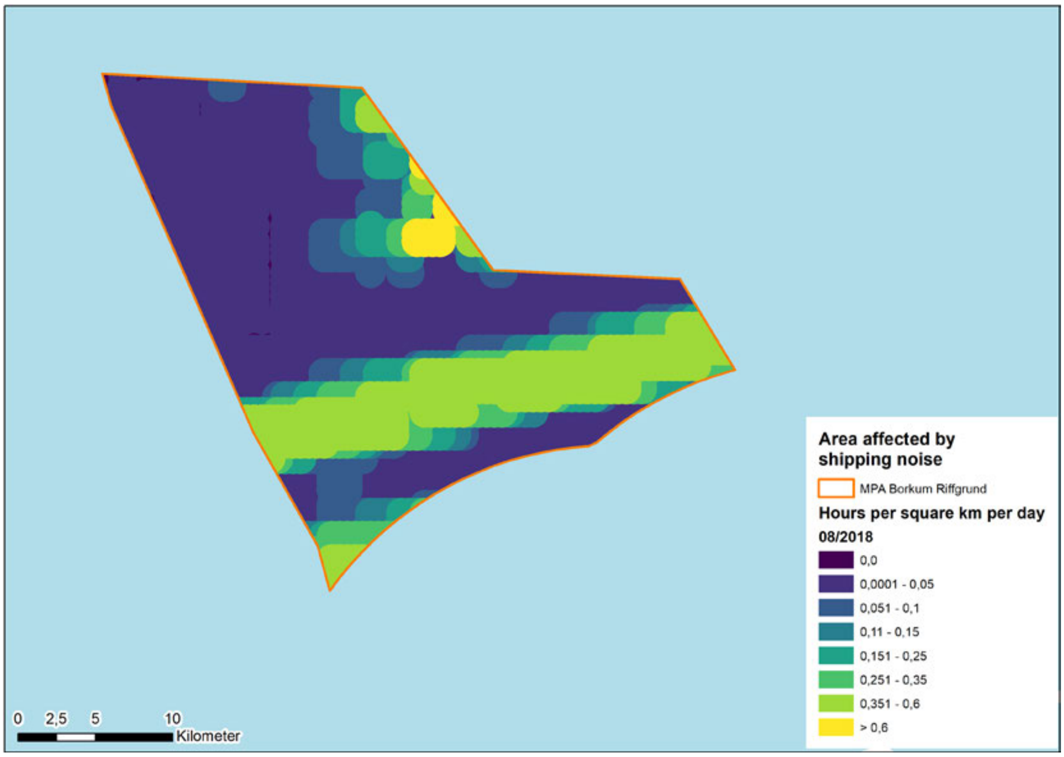


Figure 81: Map of the MPA and the affected area derived from the density average of August 2018 for cargo ships.

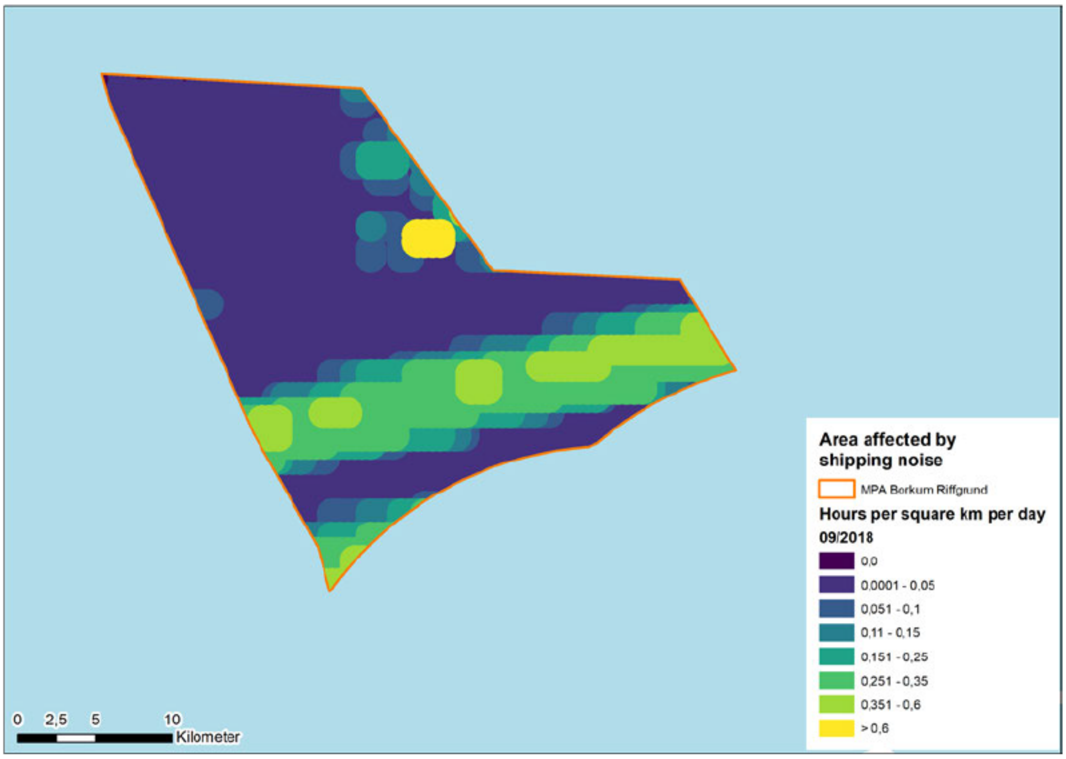


Figure 82: Map of the MPA and the affected area derived from the density average of September 2018 for cargo ships.

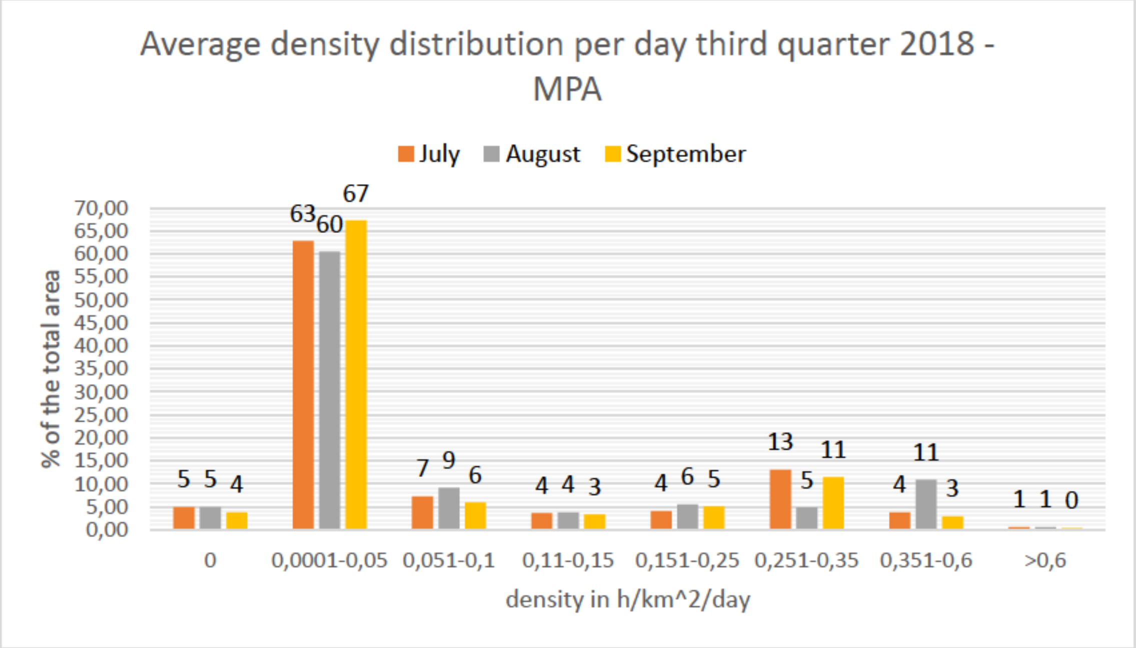


Figure 83: Average daily density distribution for the MPA for the third quarter 2018.

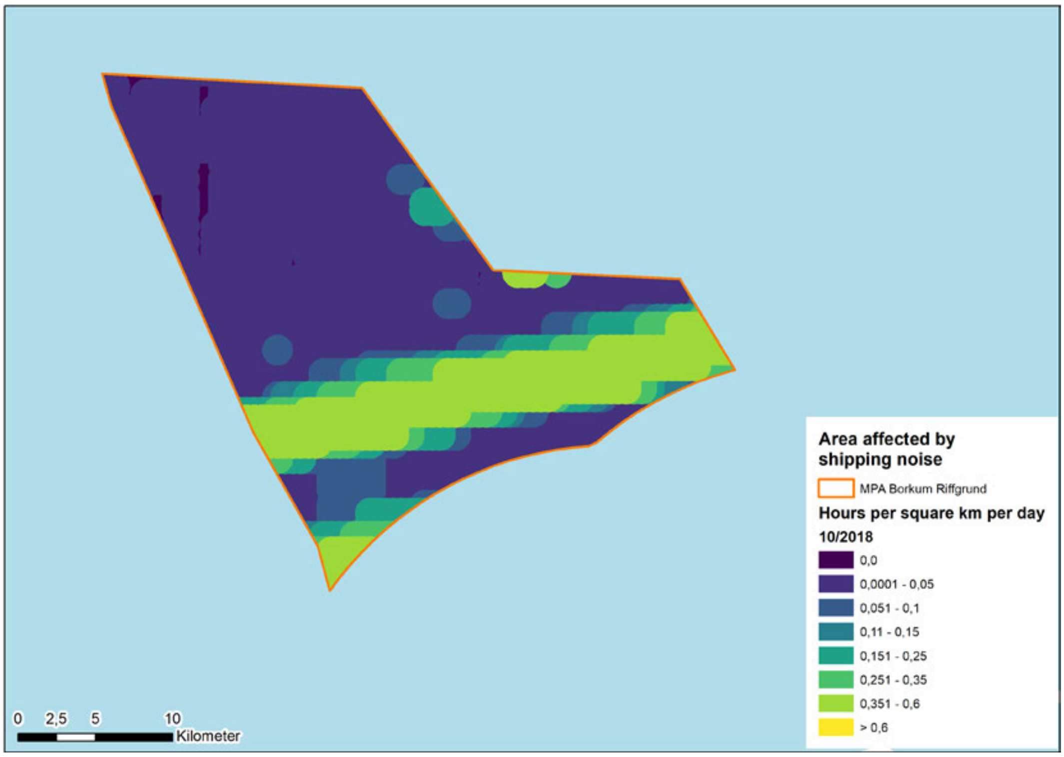


Figure 84 Map of the MPA and the affected area derived from the density average of October 2018 for cargo ships.

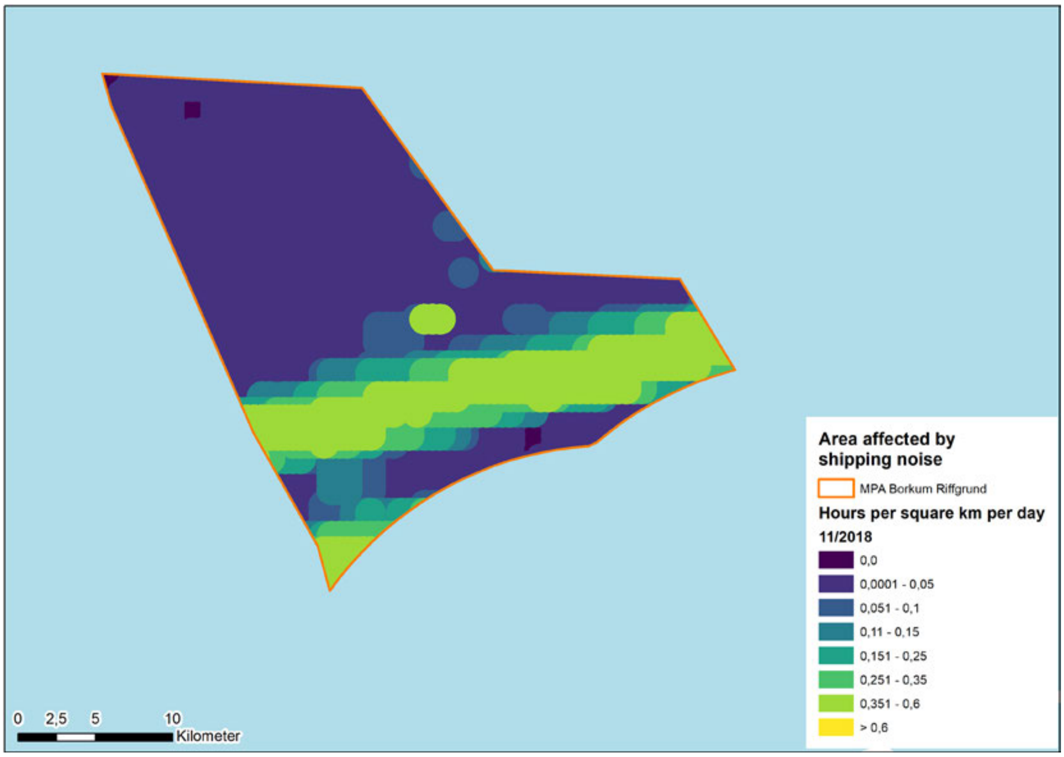


Figure 85: Map of the MPA and the affected area derived from the density average of November 2018 for cargo ships.

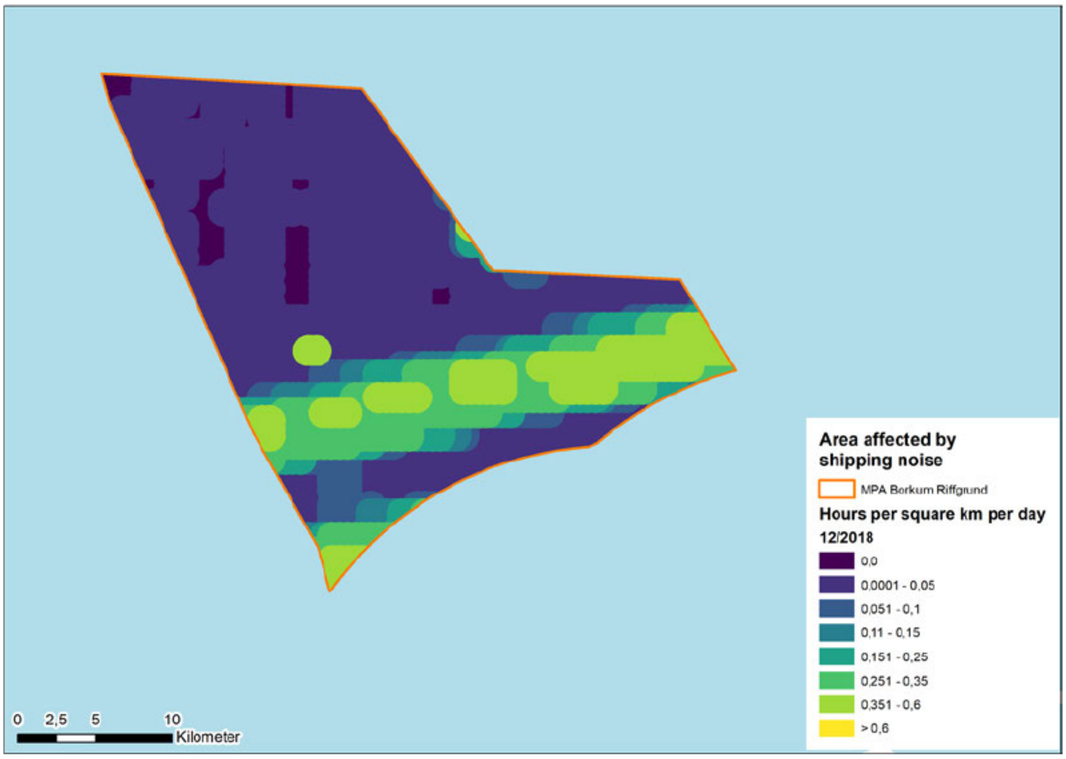


Figure 86: Map of the MPA and the affected area derived from the density average of December 2018 for cargo ships.

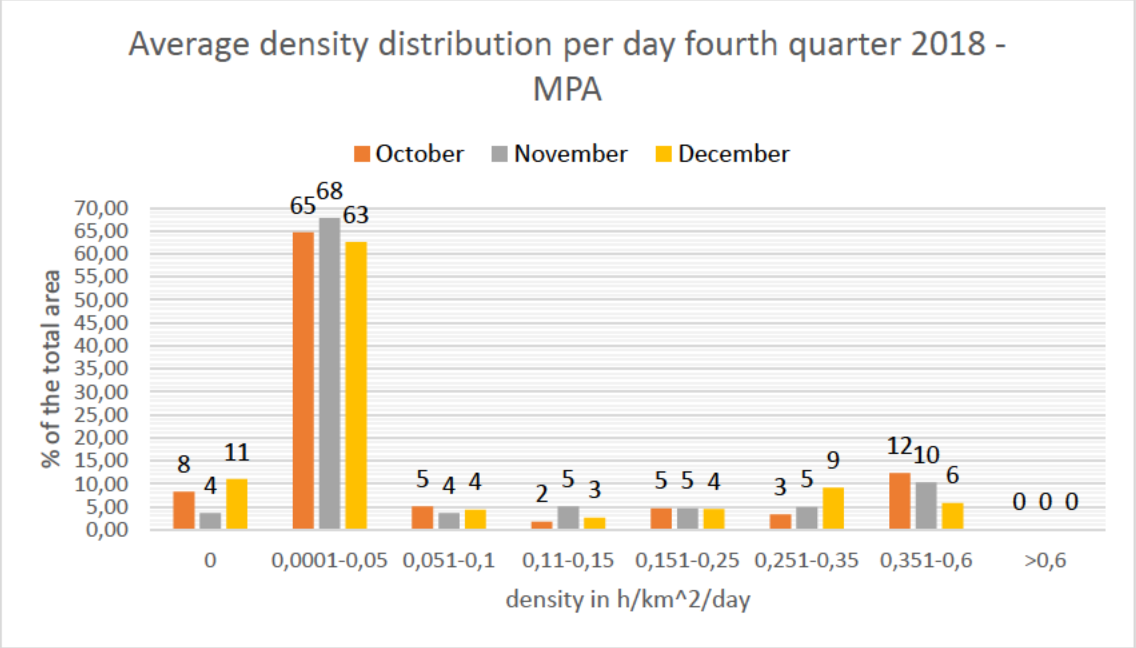


Figure 87: Average daily density distribution for the MPA for the fourth quarter 2018.

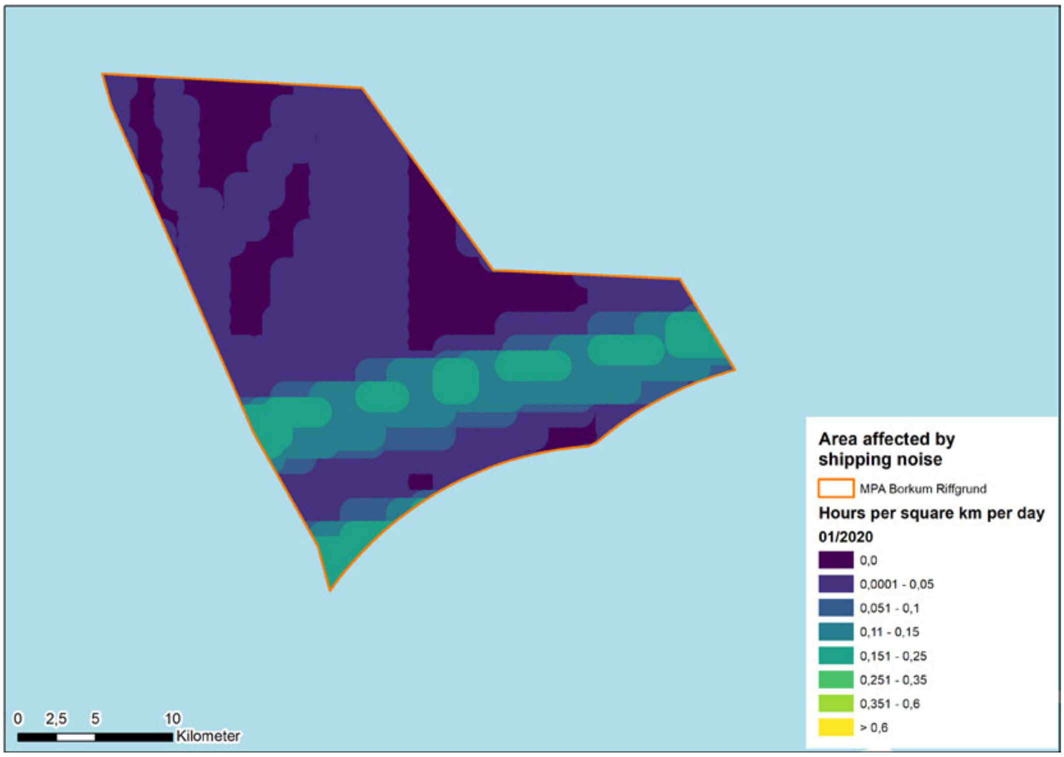


Figure 88: Map of the MPA and the affected area derived from the density average of January 2020 for cargo ships.

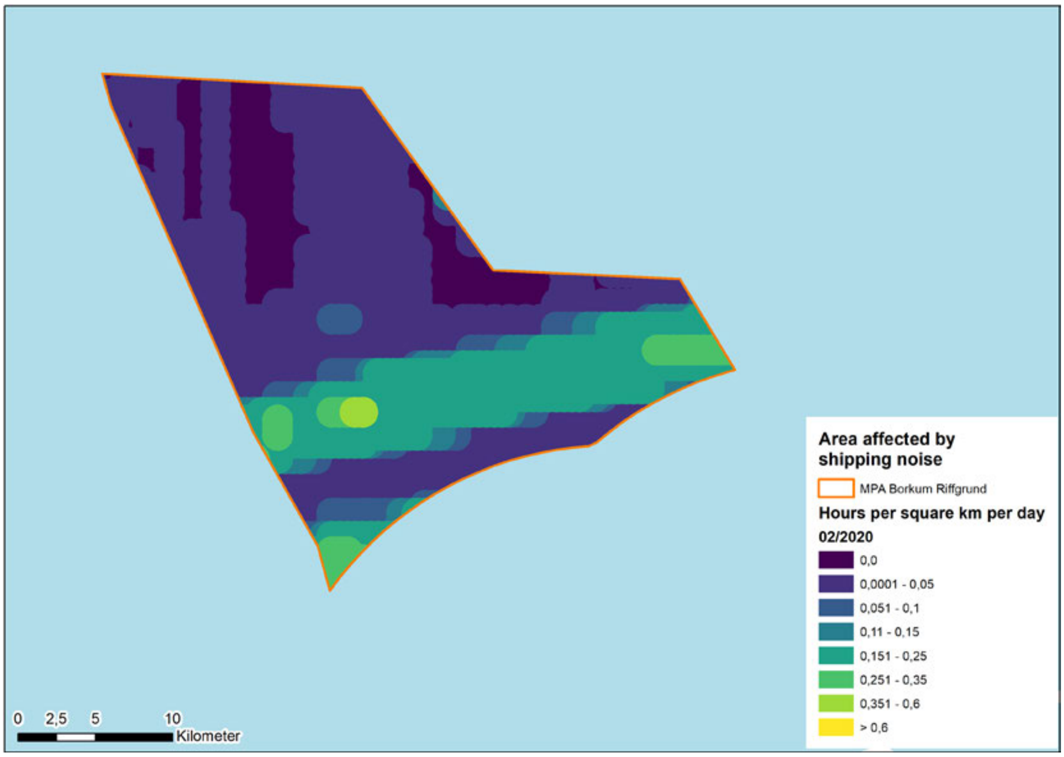


Figure 89: Map of the MPA and the affected area derived from the density average of February 2020 for cargo ships.

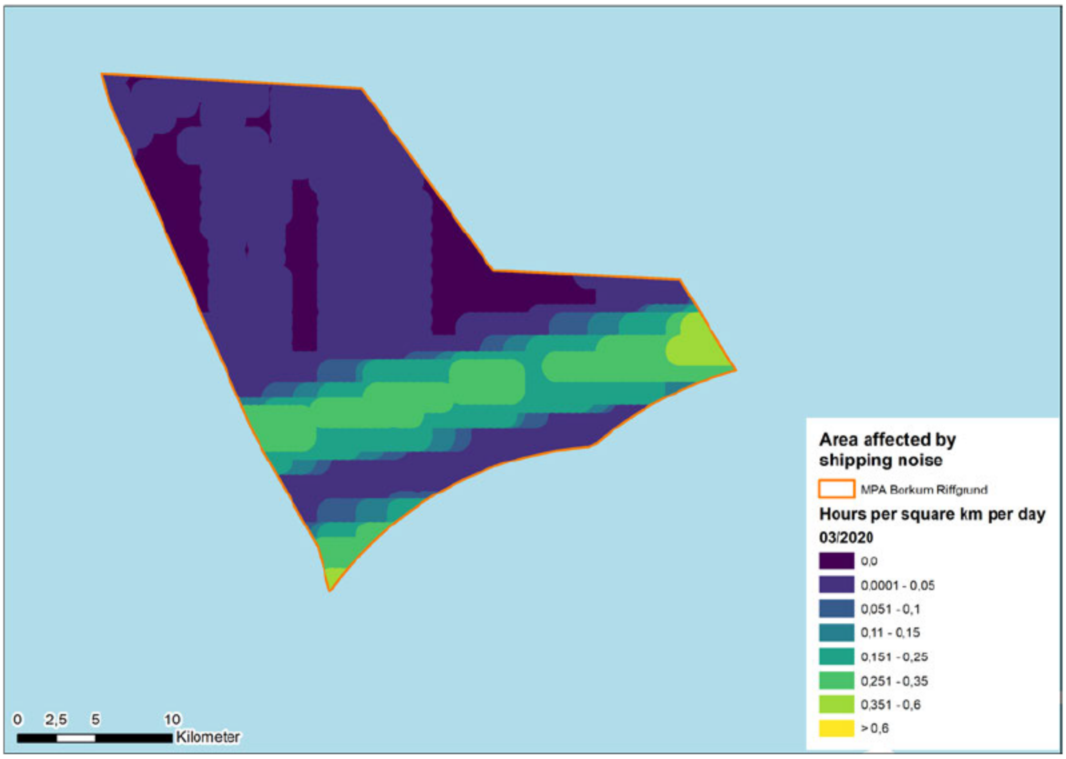


Figure 90: Map of the MPA and the affected area derived from the density average of March 2020 for cargo ships.

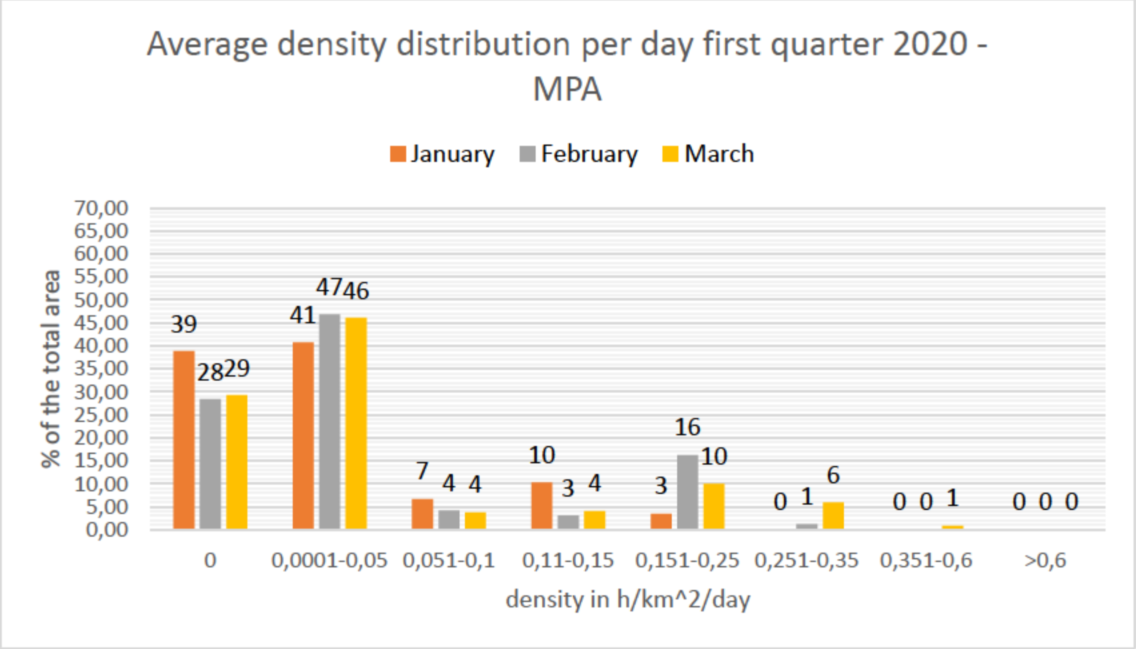


Figure 91: Average daily density distribution for the MPA for the first quarter 2020.

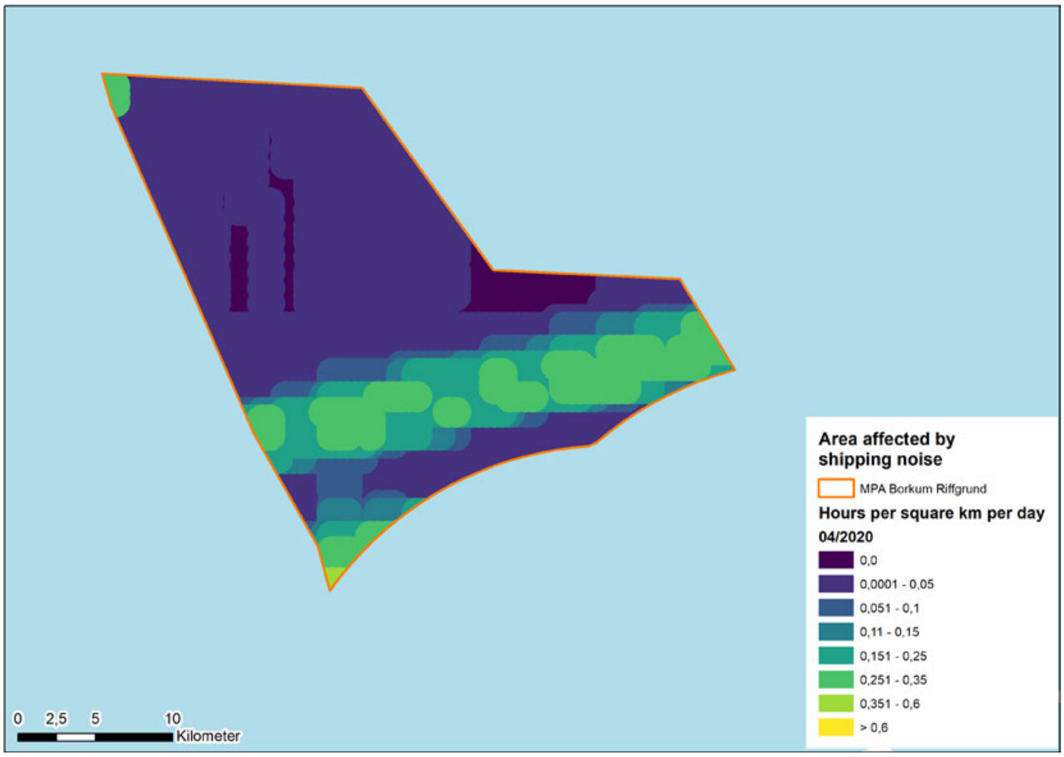


Figure 92: Map of the MPA and the affected area derived from the density average of April 2020 for cargo ships.

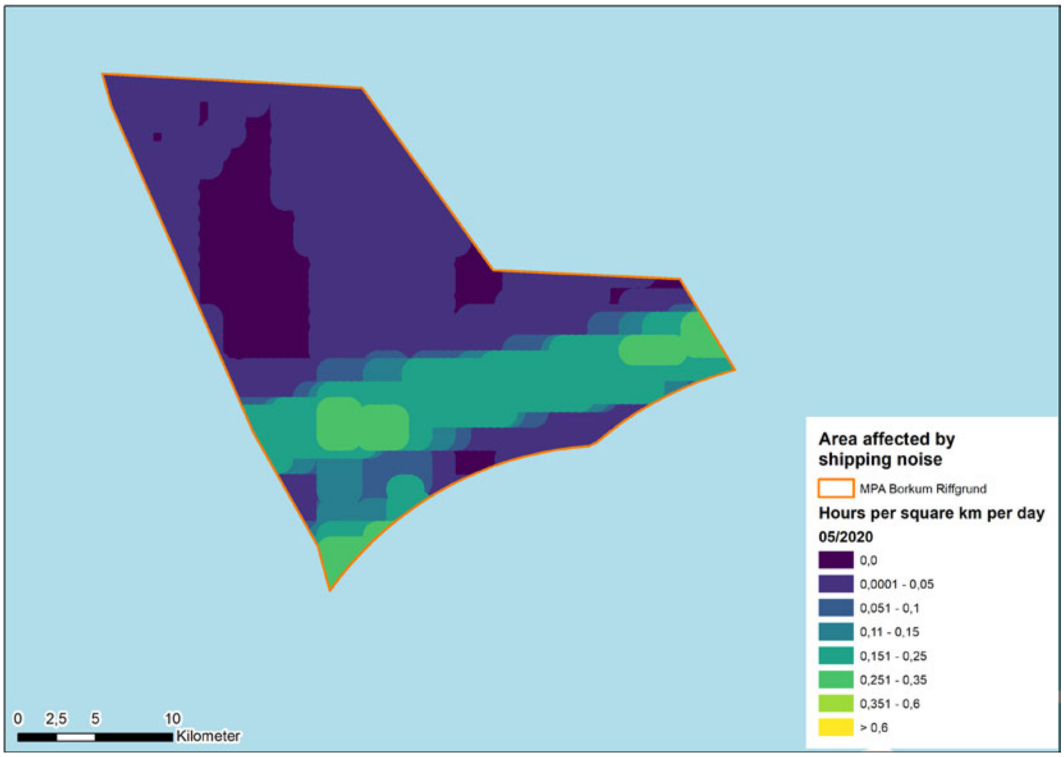


Figure 93: Map of the MPA and the affected area derived from the density average of May 2020 for cargo ships.

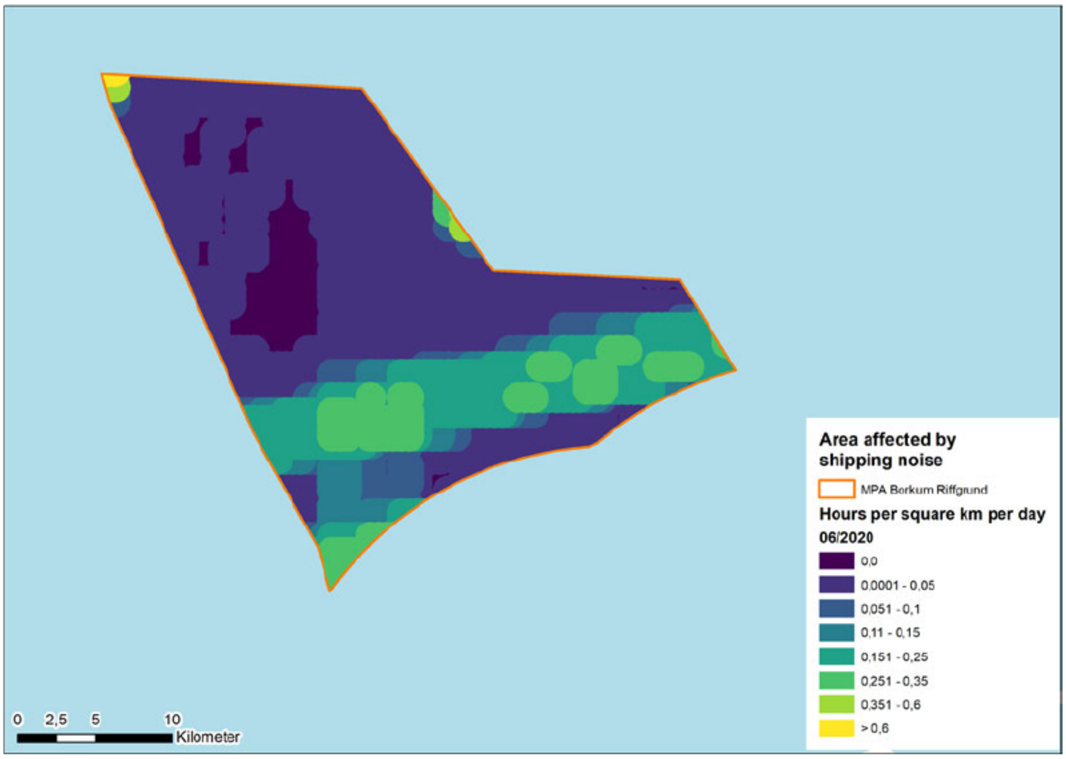


Figure 94: Map of the MPA and the affected area derived from the density average of June 2020 for cargo ships.

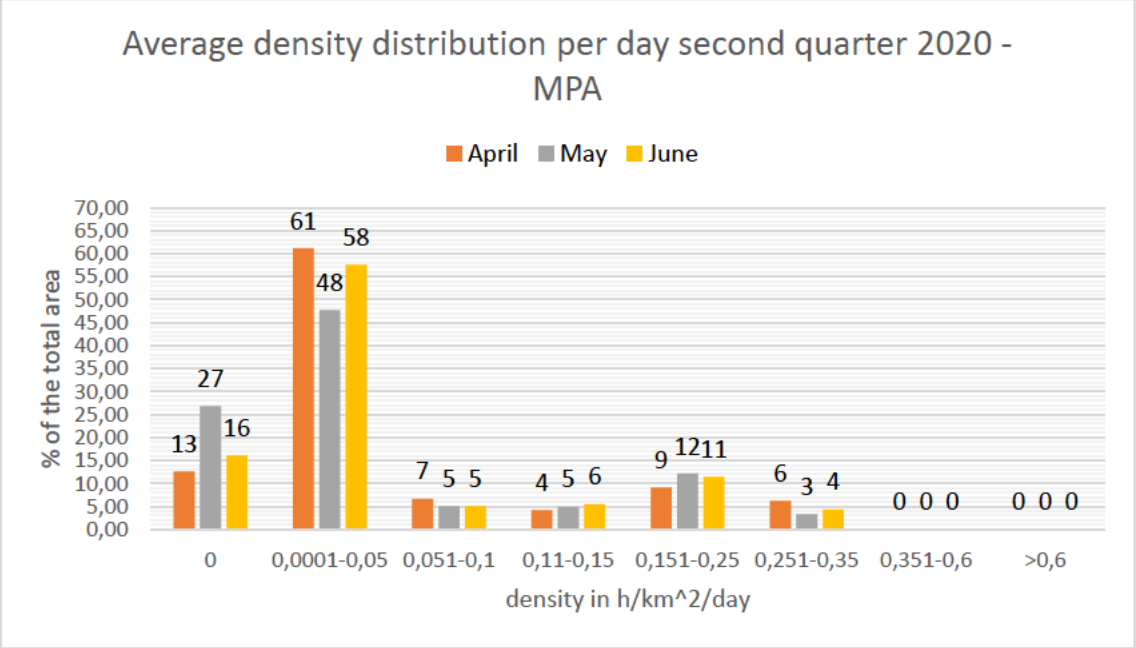


Figure 95: Average daily density distribution for the MPA for the second quarter 2020.

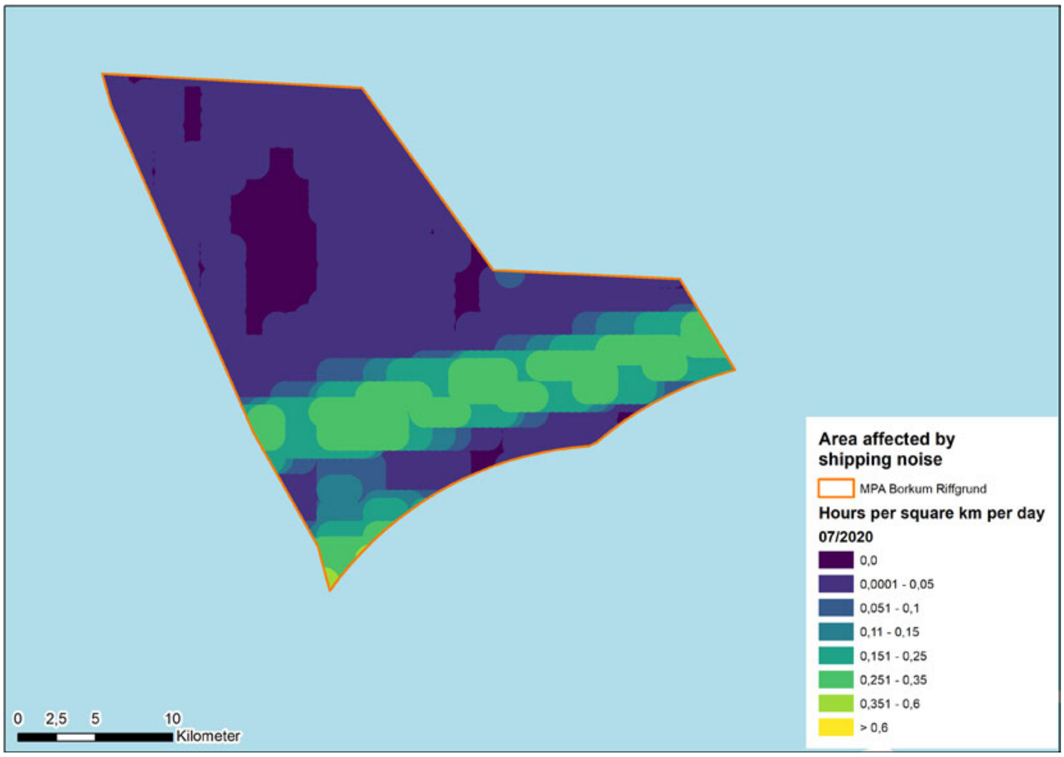


Figure 96: Map of the MPA and the affected area derived from the density average of July 2020 for cargo ships.

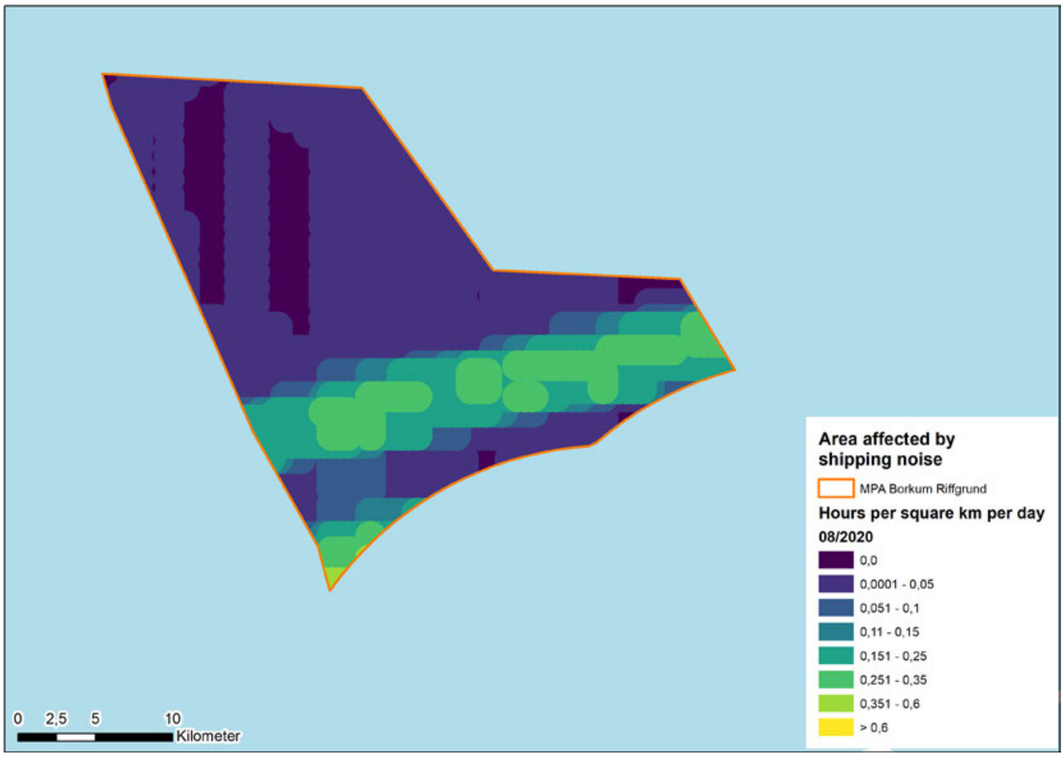


Figure 97: Map of the MPA and the affected area derived from the density average of August 2020 for cargo ships.

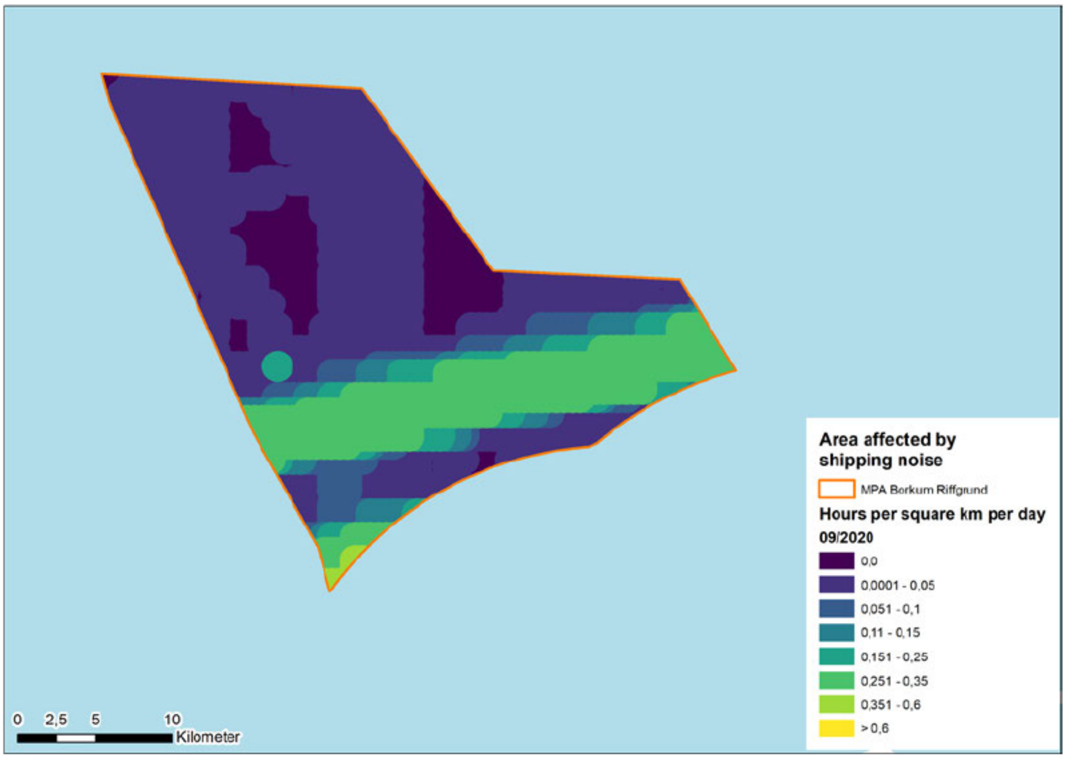


Figure 98: Map of the MPA and the affected area derived from the density average of September 2020 for cargo ships.

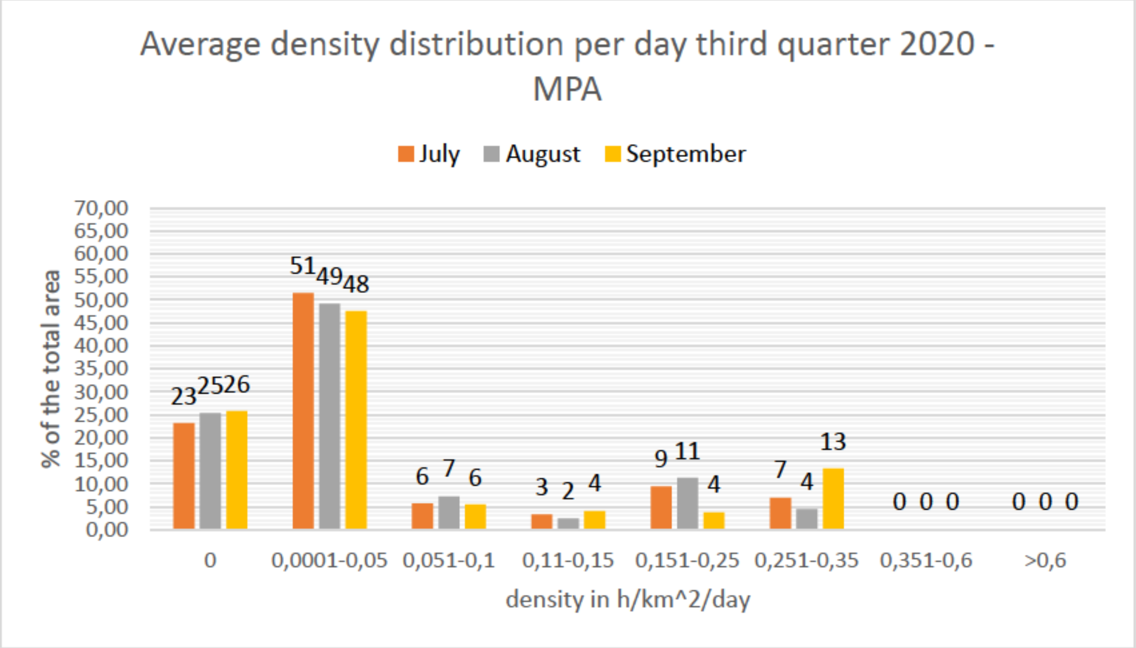


Figure 99: Average daily density distribution for the MPA for the third quarter 2020.

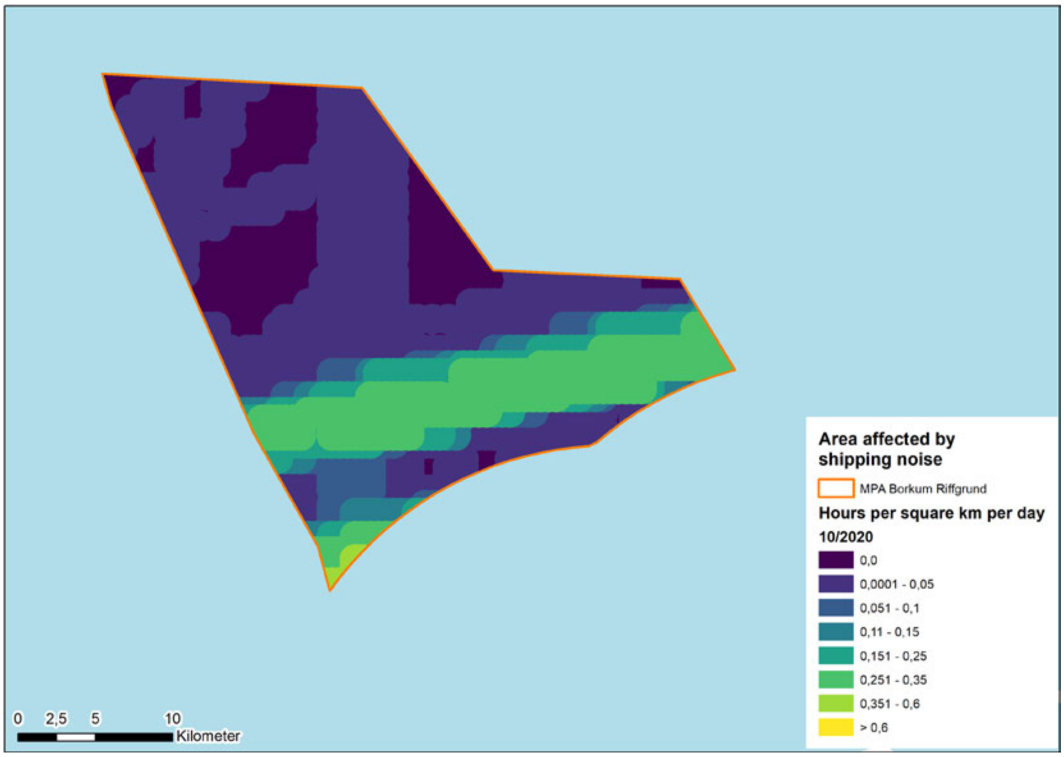


Figure 100: Map of the MPA and the affected area derived from the density average of October 2020 for cargo ships.

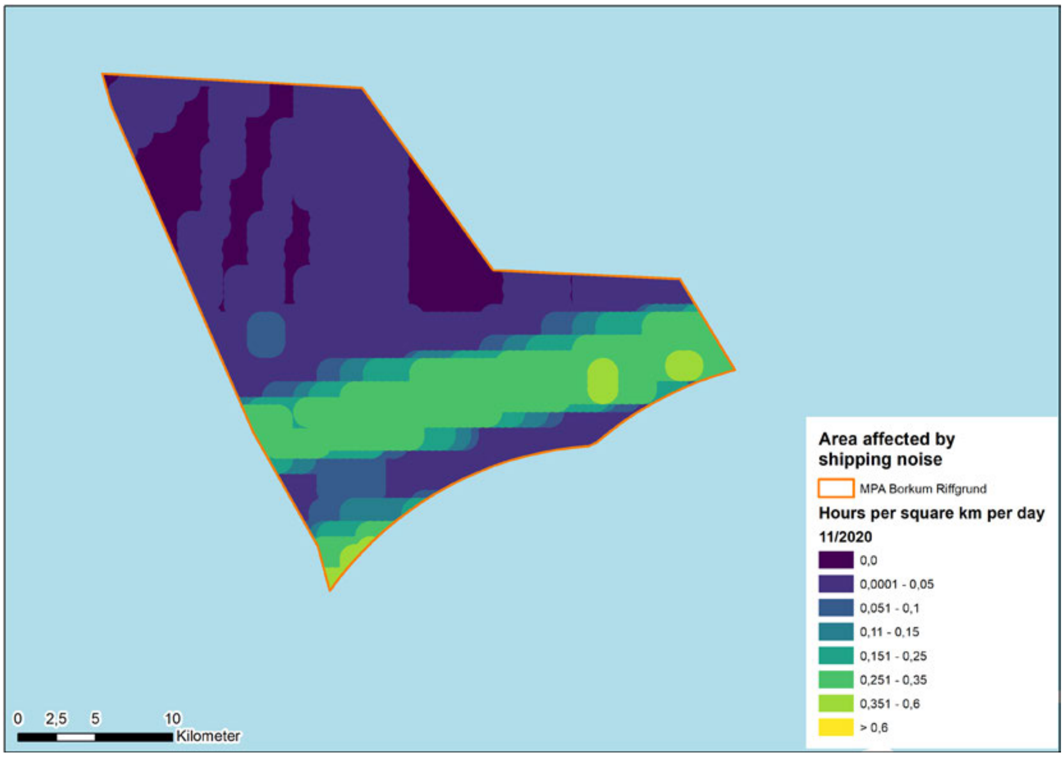


Figure 101: Map of the MPA and the affected area derived from the density average of November 2020 for cargo ships.

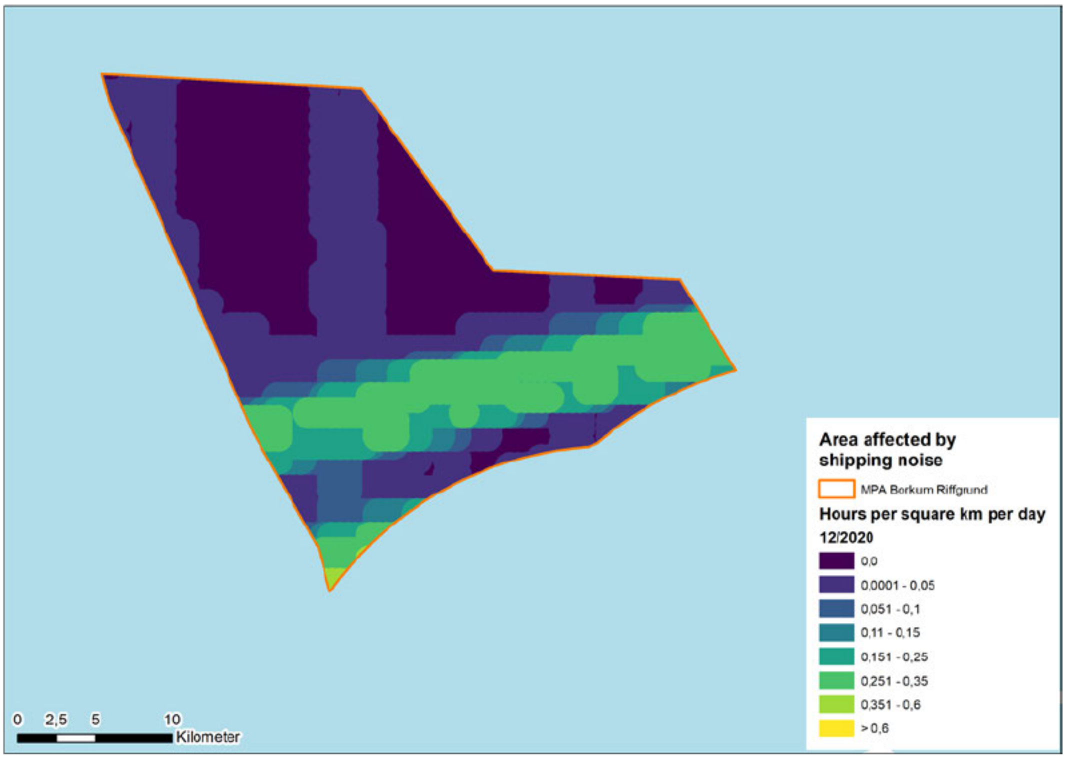


Figure 102: Map of the MPA and the affected area derived from the density average of December 2020 for cargo ships.

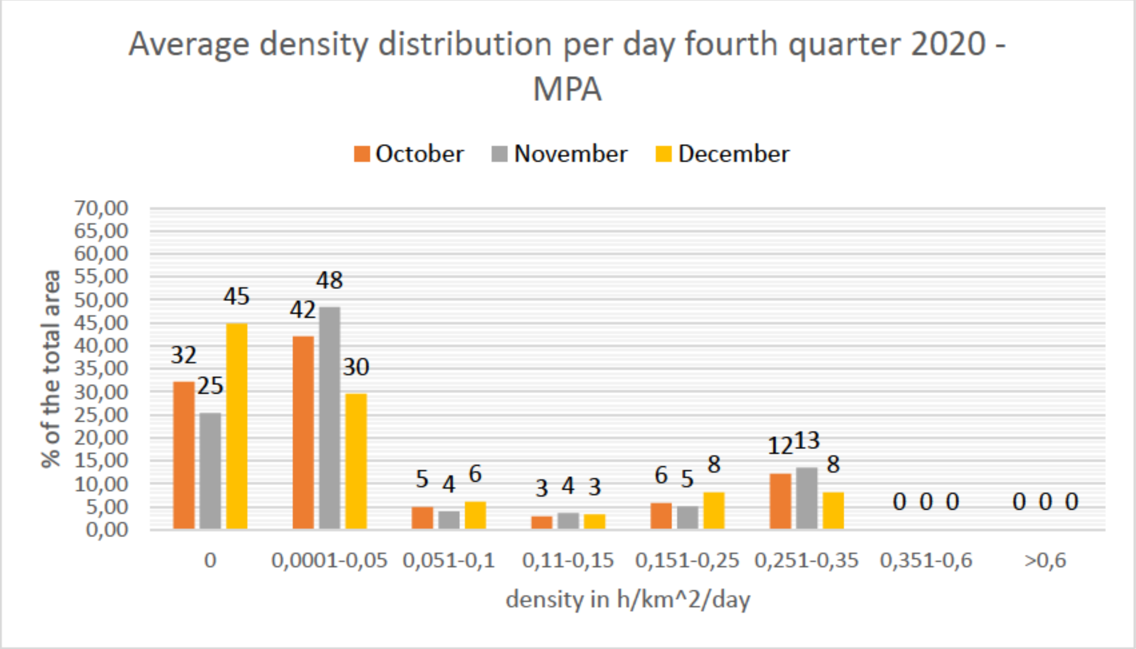


Figure 103: Average daily density distribution for the MPA for the fourth quarter 2020.

Eigenständigkeitserklärung

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[redacted]

Dresden, 31.01.2022 Clemens Pitschke