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Modelled Mapping of Continuous Underwater Noise Generated by Activities

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Modelled Mapping of Continuous Underwater Noise Generated by Activities

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Executive Summary

This report on underwater noise in the South marine plan areas has been prepared by ABP Marine Environmental Research Ltd (ABPmer) on behalf of the Marine Management Organisation (MMO).

Quantification of underwater noise is a current and evolving topic in marine environmental science that is relevant to marine plan policy development. It is recognised that there is currently insufficient data to support a quantitative assessment of underwater noise levels and its impact on the natural environment at marine plan or national scale. This research and development work represents an initial step in addressing the recognised gap in availability of consistent plan scale indicative map(s) of anthropogenic underwater noise distribution and levels to support marine planning.

A data and literature review of academic journals, government, non-government organisations and industry reports identified a wide range of marine noise sources. It found vessel traffic, fishinthis can be presented as g, and dredging to be the principle anthropogenic continuous noise sources relevant to the South plan areas.

Indicative maps can inform sustainable development through improved awareness and consideration of continuous underwater noise in impact assessments, especially in relation to protected and commercially valuable species.

This work resulted in the development of a reusable GIS tool that enables quantitative modelling of underwater noise by taking into consideration relevant quantification and transmission loss concepts. In addition the report identifies the principle sources of continuous anthropogenic marine noise. The report also documents the tool and how it can be used to produce improved indicative maps as new data becomes available.

The GIS tool is based on a simple sound transmission model and produces a grid of annual exposure hours at different sound pressure levels; this can be presented as a spatial map or a frequency histogram for one or more grid cells. It uses noise source values identified in the literature review in combination with Automatic Identification System (AIS) shipping category density data, Electronic Monitoring System (EMS) aggregate dredging data and Vessel Monitoring System (VMS) fishing data which are consistent at the plan scale.

The GIS tool outputs are indicative only and should not be used as a basis for specific environmental impact assessments. There are a number of limitations and caveats associated with the GIS tool output, these relate to output confidence in different conditions and the nature of the available source activity data.

Several recommendations have been made for the further development of the GIS tool, these include updates that would allow the GIS tool to be used beyond the South marine plan areas, and additional work that would most effectively improve accuracy of the output.

1. Introduction

This report has been prepared by ABP Marine Environmental Research Ltd (ABPmer) on behalf of the Marine Management Organisation (MMO). It presents the development of a Geographic Information System (GIS) tool that can produce indicative data for mapping the distribution of anthropogenic continuous underwater noise generated by activities in the south marine plan areas.

This project in part supports the requirement for marine planning to address underwater noise as outlined in the UK Administrations' Marine Policy Statement (MPS). While acknowledging the limits of this project, the data and associated maps produced may inform a range of marine planning and decision making processes, and contribute to facilitating sustainable development in the marine environment.

The modelled underwater noise maps produced by this project may help to improve MMO understanding of underwater noise and may allow marine plans to take account of underwater noise in isolation and as one aspect of the wider cumulative and/or in-combination effects theme as required under the Environmental Impact Assessment (EIA) Directive, Strategic Environment Assessment (SEA) Directive and Article 6(3) of the Habitats Directive.

This project has been developed in the wider context of a number of initiatives that are investigating the issues relating to underwater noise at a European level, including the Marine Strategy Framework Directive (MSFD) (e.g. Van der Graaf *et al*., 2012; Defra, 2014), OSPAR (e.g. OSPAR, 2011), and national initiatives such as the Underwater Sound Forum[1], and widely cited pieces of work such as the National Physical Laboratory (NPL, 2014) and the TNO (2011).

The South Plan Analytical Report[2] identified underwater noise as a current and evolving issue and recognised that there is currently insufficient data to support a quantitative assessment of underwater noise in UK waters and its impact on the natural environment. The development of an initial simple modelled noise map of continuous underwater noise in the context of national and European issues and recommendations will allow marine planning to ensure policies in-development take into account appropriate plan level data. As new and relevant evidence becomes available it is expected that the MMO will incorporate it into its planning and decision making processes.

[1] http://www.oceannet.org/underwater_sound_forum/
[2] https://www.gov.uk/government/publications/south-marine-plan-areas-south-plans-analytical-report

2. Identification of Continuous Noise Sources

A literature review was undertaken to identify and categorise the range of natural ambient and anthropogenic continuous noise sources that are relevant to the south marine plan areas. The literature review presented in this section has drawn on ABPmer's existing in-house library of underwater noise references together with searches using scientific databases and internet search tools such as 'Google Scholar'. The outputs of the literature review have helped to identify significant anthropogenic continuous noise sources in the UK marine area that could be taken into account in a continuous underwater noise mapping GIS tool (see Section 4).

2.1 What is ambient noise?

Underwater noise can occur at many scales in both space and time and may vary with changes in season, location and time of day. Sources of underwater noise may be of short duration (e.g. impulsive such as from seismic surveys and piling for windfarms and platforms, as well as explosions) or be long lasting (e.g. continuous such as dredging, shipping and energy installations) (Dekeling *et al*., 2014a). Impulsive sounds may, however, be repeated at intervals (duty cycle) and such repetition may become 'smeared' with distance and reverberation and become indistinguishable from continuous noise. This study has remained focussed on the anthropogenic continuous sources that are the main contributors to ambient noise. For the purposes of this study, repetitive impulsive sounds have therefore not been included (e.g. percussive piling, blasting, explosives, seismic and geophysical surveys).

Ambient noise is commonly defined as background acoustic noise without distinguishable sources (e.g. Wenz 1962; Urick 1983). This definition, however, has the problem of how to identify distinguishable sources, and how to eliminate them from the measurements. Measurements to characterise the ambient noise in a specific location (i.e. incorporating both natural and anthropogenic sources) are becoming more common as interest grows in the trends in anthropogenic noise in the ocean, for example in response to the MSFD. The EU Technical Sub-Group (TSG) on Noise has thus re-defined ambient noise as follows:

"*All sound except that resulting from the deployment, operation or recovery of the recording equipment and its associated platform, where 'all sound' includes both natural and anthropogenic sounds*" (Dekeling *et al*., 2014a, p 20).

Measurements that characterise the ambient noise at specific locations, and include noise from identifiable sources together with non-identifiable sources, are also sometimes referred to as the local 'soundscape' (NPL, 2014).

Natural and anthropogenic sources contribute to ambient noise. Natural background noise includes wind- and wave-driven turbulence, hydrodynamic noise associated with variable tidal flow conditions, and rainfall. Biological activity (e.g. echo locating marine mammals, snapping shrimp) also contributes to ambient noise.

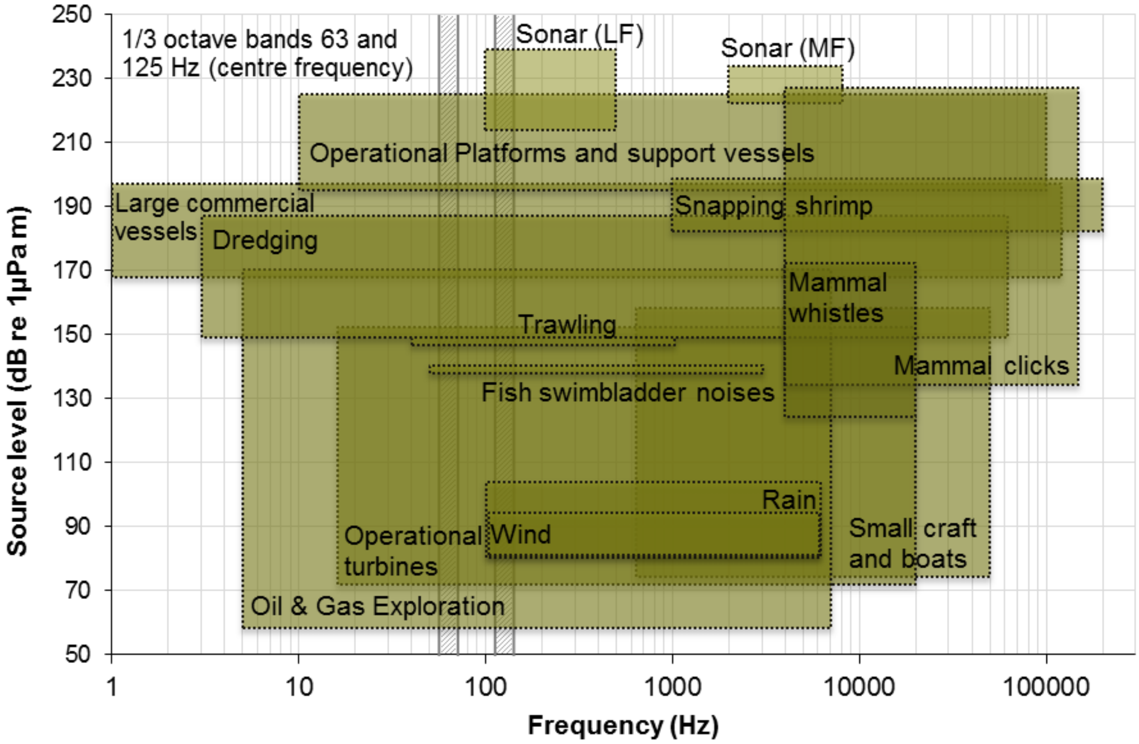
A range of anthropogenic continuous noise sources contribute to ambient noise. These include “traffic noise” generated from commercial shipping and other vessels in transit (e.g. fishing vessels, dredgers), dredging (ports and aggregates), trawling (fishing), sonar (military), drilling (oil and gas production) and recreational vessels (e.g. jet skis and speed boats). The presence of structures in the marine environment can also contribute to ambient noise, such as the operation of offshore wind farms or oil and gas installations.

Ambient noise in the Eastern English Channel (Regional Sea 3[3]) that includes the south marine plan areas, is more variable than in other regional sea areas and is mainly due to distant shipping (Harland *et al*., 2005). The majority of Regional Sea 3 receives high to very high densities of shipping traffic, and has a water depth of less than 60m (DECC, 2009). The coastline is one of the most densely populated in the UK, and adjacent waters are used by a great number of recreational vessels. Additionally, very high levels of fishing activity occur, particularly in inshore waters, with high levels of effort by non-UK vessels also observed in this area. Many dredging licence and application areas are present in the region.

Figure 1 depicts the acoustic properties of anthropogenic and natural noise sources in the ocean as identified in the literature listed in the accompanying Technical Annex document, Table 1. The horizontal axis is frequency in Hertz (Hz). The frequency scale is logarithmic in order to accommodate a spectrum that spans several orders of magnitude. The vertical axis is a measure of the acoustic output of a source, referred to as the source level. This measure, may be considered as a characteristic property of the source itself, independent of the propagation path from source to receiver position The vertical axis is also plotted on a logarithmic decibel (dB) scale, to encompass a very wide span.

[3] Regional Sea boundaries were identified by the Joint Nature Conservation Committee (JNCC, 2004) as an appropriate means of considering the broad scale biogeographical regions within UK waters.

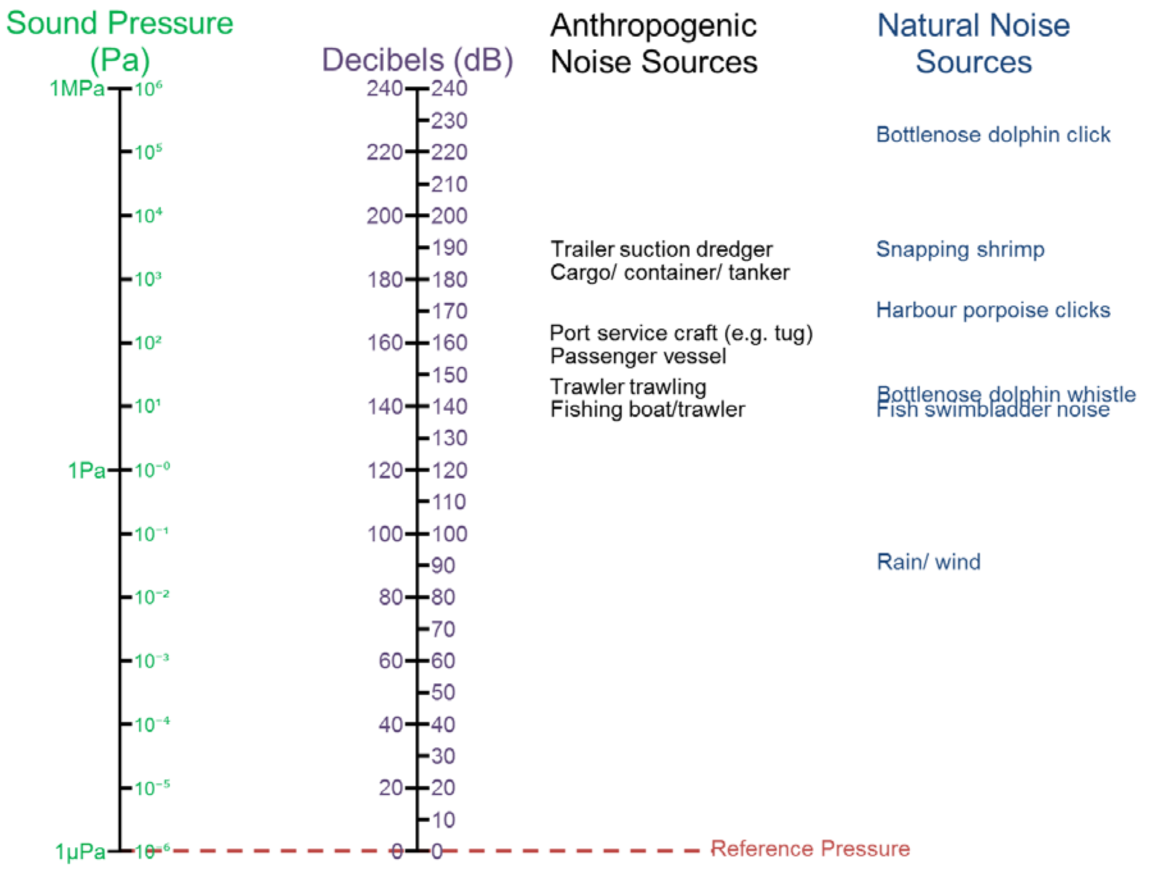
Figure 1: Image showing the range of acoustic properties of anthropogenic and natural noise sources in the ocean.



Ambient noise covers the whole acoustic spectrum from below 1Hz to well over 100kHz (Harland *et al*., 2005). Anthropogenic continuous underwater noise sources are also broadband (i.e. span a wide range of frequencies). For example, shipping noise is most evident at low frequencies below 1kHz (peak in the 50-300Hz frequency range) as a result of machinery. Above 1kHz, the machinery noise diminishes and water displacement noise becomes dominant. This drops below other sources of noise above 20kHz.

Box 1: Loudness and the Decibel Scale.

An important property of sound or noise is its loudness. A loud noise usually has a larger pressure variation and a weak one has smaller pressure variation. Sound can therefore be measured as a change in pressure within the medium, which acts in all directions, described as the sound pressure. Pressure and pressure variations are expressed in Pascal, abbreviated as Pa, which is defined as Newton per square metre (N/m^2). It is not appropriate to express sound or noise in terms of Pa because it would involve dealing with numbers from as small as 0.000001 to as big as 2,000,000. The use of a logarithmic scale, of which the most generally used is the decibel (dB) scale, compresses the range so that it can be easily described. The reference pressure for measurements in air is 20 microPascal (μPa)which was selected on the basis of the human hearing threshold. The reference pressure in water is 1 μPa following the pioneering work on underwater noise that was undertaken by the US Navy in the 1970s[4]. The dB levels for sound in water and in air are therefore not directly comparable. The following chart show how sounds can be expressed both linearly in Pa and logarithmically in decibels (dB).



4 http://resource.npl.co.uk/acoustics/techguides/concepts/spl.html

Higher frequency sounds transmit less well in the deep water marine environment whereas lower frequency sounds can travel a further distance. However, shallow water acts as a high pass filter that allows signals to pass with a frequency higher than a certain cut-off frequency and attenuates signals with frequencies lower than this cut-off frequency. The cut-off frequency increases as the water gets shallower (Harland *et al*., 2005). In this way, distant shipping makes a reduced contribution to ambient noise in very shallow coastal waters.

The MSFD provides a guide for the monitoring of ambient noise as covered by Indicator 11.2.1 on ‘Continuous low frequency sound (ambient noise)’. This indicator is described in the Commission Decision as:

“*Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1μPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate*” (Dekeling *et al*., 2014a, p 5).

Tasker *et al*., (2010) and Van der Graaf *et al*., (2012) provide the background on the concept behind Indicator 11.2.1 on ‘Continuous low frequency sound (ambient noise)’. Further clarification of the terminology included in the indicator is also provided in Van der Graaf *et al*. (2012). This indicator focuses on chronic exposure of marine life to low frequency, anthropogenic ambient noise. The main contributor, in many regions, is noise from commercial shipping, hence the initial choice for an indicator of two frequency bands where the contribution of noise from shipping (relative to other sources, including natural) is likely to be greatest (Dekeling *et al*., 2014a). These frequency bands, however, do not necessarily reflect the maximal spectral levels of all sources of anthropogenic continuous noise.

2.2 Anthropogenic continuous noise sources

A range of anthropogenic continuous noise sources have been collated as part of the literature review and are presented in the accompanying Technical Annex document, Table 1. Information on the noise generated by operational offshore wind farms structures and oil and gas installations has also been collated, while noting that these do not currently occur in the south marine plan areas at present. The full range of noise sources of anthropogenic activities and sub-activities (in brackets) that have been collated are as follows:

- dredging (backhoe dredger, clamshell dredger, cutter suction dredger, suction dredger, trailer suction hopper dredger)[5]
- drilling exploration (drilling production, jack-up, semi-submersible)
- fishing (trawler trawling)
- military (low-frequency sonar, mid-frequency sonar)
- offshore wind (operational turbine)
- oil and gas (operational platform and support vessel)
- recreation (inflatable boat with outboard motor, jet ski, speed boat)

[5] Navigational (non-aggregate) dredging is harder to predict spatially as is this is done on a very much ad-hoc basis.

- shipping (boat, bulk cargo/carrier, container, fishing boat/trawler, oceanographic vessel, offshore oil production vessel, passenger, ship, supertanker, tanker/freighter, tug and barge, vehicle carrier, work boat).

The acoustic properties (i.e. source level and frequency range) of each anthropogenic activity and sub-activity category were collated from scientific literature and published field monitoring reports. The specific source level units that are quoted in the literature were also included the accompanying Technical Annex document, Table 1.

The metric most suitable for continuous noise is considered to be Sound Pressure Level[6] (SPL) which may be written as dB re 1μPa m (NPL, 2014). The constraints and limitations of the range of units and metrics quoted in the literature are discussed further in Section 2.4.

Ship source levels have generally been considered a simple function of ship length and speed (Erbe *et al.*, 2012; 2014). There are a number of studies relating ship noise to speed, however, that did not find evidence for a positive relationship between speed and source levels (e.g. Wales and Heitmeyer, 2002; Heitmeyer *et al*., 2003 cited in Mckenna *et al.*, 2013). The lack of a relationship may be an artefact of combining multiple ship-types into a single regression analysis (Mckenna *et al*., 2012). In addition, propeller cavitation can be a dominant noise source of vessels travelling at moderate to high speeds (Leaper *et al.,* 2014). Under the shipping and recreation category, therefore, any information on vessel length, vessel speeds and engine size/type were collated in separate columns in the accompanying Technical Annex document, Table 1.

Additional information that could potentially support the development of a noise mapping GIS tool was also noted (e.g. water depth, duration, directionality, sediment type, location, local weather conditions, all which influence the propagation of sound). None of this information was used, however, mainly because the information was not always consistently provided. The possibility of applying different noise source levels for vessels that are travelling at lower speeds (e.g. areas subject to speed restrictions) was considered further in Section 4.3.1.

The associated data limitations and/or constraints are also provided in the accompanying Technical Annex document, Table 1. These included whether the data source was peer-reviewed, whether there were any information gaps (e.g. no documented frequency information) or whether any information was potentially incorrect or inaccurate (e.g. if source level units were not properly documented). Any limitations and/or constraints associated with the data formed the basis of assigning a confidence level (high, medium or low) with classification criteria detailed in Table 1. Of the 107 sources of information collated, a total of 33 were considered to have a low confidence and were excluded from further consideration in the model. Exclusions were predominantly sources that lacked both frequency information and were not peer-reviewed.

[6]SPL (in dB) = 10 $\log_{10}$ (P^2/P_0^2) where P is the root mean square sound pressure and P_0 is the reference pressure. The reference pressure in underwater acoustics is defined as 1 microPascal (μPa).

Table 1: Criteria used to assign confidence level to data sources.

Confidence level	Criteria
High	Measurement data that are from a peer-reviewed journal and/or published book.
Medium	Measurement data that are not from a peer-reviewed journal and/or published book. Modelled data from a peer-reviewed journal and/or published book.
Low	Measurement and/or modelled data that are not from a peer-reviewed journal and/or published book. No documented frequency information. Source level units are not properly documented. Original data source is not referenced.

Table 2 provides a summary of typical average (arithmetic mean and median) and worst case maximum acoustic properties of each of the anthropogenic activity and sub-activity source categories. In this table, only those information sources from Table 1 in the accompanying Technical Annex document that have a moderate or high confidence level are included. Despite this, there was a wide (usually several orders of magnitude) variation in source levels indicating a high level uncertainty. This variation may be due to varying monitoring techniques, as well as different theoretical or empirical propagation models being applied to estimate the level of noise at the source (i.e. source level). There can also be a large (over two orders of magnitude) variability in source levels of individual vessels associated with operational conditions (e.g. speed), ship design characteristics (e.g. size) and oceanographic setting (e.g. wave height) (McKenna *et al*., 2013). It is possible that the wide diversity in source levels within the sub-activity categories might be improved by further sub-division. For example, some of the variability could be attributed to certain characteristics of the noise source (e.g. material dredged versus a dredger's engine power).There is insufficient information documented in the literature, however, to be able to do this in any standard or consistent manner.

Large commercial vessels (e.g. cargo ships, container ships, supertankers) produce relatively loud noise (169-198dB re 1µPa m) of predominately low frequency (less than 1,000Hz). Although the exact characteristics depend on vessel type, size and operational mode, the strongest energy occurs below 1,000Hz. Small craft and boats (e.g., outboard powered inflatables, jet skis, speed boats and work boats) produce lower levels of noise (75-159dB re 1µPa m), and the output characteristics are highly dependent on speed and other operational characteristics (Richardson *et al*., 1995 cited in OSPAR, 2009). Many of these sources have greater sound energy in higher frequency bands (i.e. above 1,000Hz) than large ships.

Dredging activities emit moderate levels of noise (150-188dB re 1µPa m) at relatively low frequencies (less than 500Hz). There are various potential sources depending on the type of dredger (see Thomsen *et al*., 2009; CEDA, 2011; WODA, 2013). Military activities, namely sonar (low- and mid-frequency), have the potential to generate large noise sources (215-267dB re 1µPa m) in the marine environment (WDCS, 2003; OSPAR, 2009). Oil and gas exploration activities, including drilling production and jack-ups, generate relatively low levels of noise (59-171dB re 1µPa m) of low frequency (less than 250Hz) (Evans, 1996 cited in Evans, 2003).

Noise levels from operational offshore wind farms are relatively low (73-153dB re 1µPa m) and most prominent in the lower frequency range (less than 400Hz) (Thomsen *et al*., 2006; Nedwell and Howell, 2004). Oil and gas installations can generate relatively loud sources of noise (196-226dB re 1µPa m) associated with lower frequencies (100-300Hz). Sound fields around oil and gas rigs are associated with the conduction of sound from machinery on the platform into the water column and the noise generated from any support vessels.

Table 2: Typical and worst case acoustic properties of anthropogenic continuous noise sources.

Activity	Sub-activity	Source level (dB re 1µPa m)				Frequency (Hz)		Number of literature sources (number of data points)
		Range	Typical (average)		Worst case (maximum)	Range	Peak	
			Mean	Median				
Dredging	Backhoe dredger	163-186	178	175	186	3->20,000	35-500	3 (4)
Dredging	Clamshell dredger	150-162	158	158	162	10-1,000		1 (2)
Dredging	Cutter Suction Dredger	160-185	178	177	185	10->20,000	100-500	2 (4)
Dredging	Suction dredger	160	160	160	160	ND	380	1 (1)
Dredging	Trailer Suction Hopper Dredger	184-188	187	187	188	30-63,000	40-500	3 (5)
Drilling Exploration	Drilling production	163	163	163	163	ND	250	1 (1)
Drilling Exploration	Jack-up	59-127	118	85	127	5-7,070	16	2 (3)
Drilling Exploration	Semi-submersible	167-171	169	169	171	16-200	ND	1 (2)
Fishing	Trawler trawling	147	147	147	147	40-1,000	100	1 (1)
Military	Low-frequency sonar	215-240	235	235	240	100-500	ND	2 (3)
Military	Mid- frequency sonar	223-235	233	235	235	2,000-8,200	3,500	1 (3)
Offshore wind	Operational turbine	73-153	145	142	153	16-20,000	16-400	3 (5)
Oil and gas	Operational platform and support vessel	196-226	220	220	226	10-100,000	100-300	2 (2)
Recreation	Inflatable	105-156	148	147	156	800-20,000	6300	3 (4)

Activity	Sub-activity	Source level (dB re 1µPa m)				Frequency (Hz)		Number of literature sources (number of data points)
		Range	Typical (average)		Worst case (maximum)	Range	Peak	
			Mean	Median				
Recreation	Jet ski	75-125	119	119	125	800-50,000	ND	2 (4)
Recreation	Speed boat	110-156	147	130	156	630-20,000	630	2 (3)
Shipping	Boat	157-164	161	160	164	10->10,000	60-500	2 (3)
Shipping	Bulk cargo/carrier	175-192	186	184	192	10-40,000	20-1,000	5 (9)
Shipping	Container	169-198	186	181	198	1-120,000	8-33	8 (11)
Shipping	Fishing boat/trawler	110-158	150	143	158	100-20,000	ND	3 (4)
Shipping	Oceanographic vessel	170-230	224	224	230	<100	ND	1 (2)
Shipping	Offshore oil production vessel	174-183	180	180	183	20-2,500	ND	1 (2)
Shipping	Passenger	154-155	155	155	155	1-120,000	ND	1 (2)
Shipping	Ship (e.g. merchant vessel)	160-191	185	181	191	10->10,000	60-120	4 (5)
Shipping	Supertanker	180-190	188	189	190	<500	7-8	5 (6)
Shipping	Tanker/freighter	169-185	179	178	185	ND	20-1,000	7 (8)
Shipping	Tug and barge	161-171	167	166	171	45-7,070	37-5,000	5 (5)
Shipping	Vehicle carrier	178-182	180	180	182	ND	20-1,000	1 (2)
Shipping	Workboat	159	159	159	159	ND	630	1 (1)

ND - no data provided in the literature. This is due to the lack of a standard approach for quoting underwater noise measurement data prior to recent guidance (e.g. TNO, 2011; NPL, 2014).

2.3 Natural ambient noise

A brief review of sources of natural noise has also been undertaken in parallel to the review of anthropogenic sources to provide context, the sources are recorded in the accompanying Technical Annex document, Table 3. The sources of natural noise that have been collated are as follows:

- ambient
- bottlenose dolphin (clicks, whistles)
- fish[7] (swimbladder noise)
- harbour porpoise (clicks)
- invertebrates (snapping shrimp[8])
- weather (lightning, rain, storm, wind).

Ambient noise measurements were available in the literature from open coastal waters (e.g. Hastings Shingle Bank and Cook Inlet, Alaska) and a shallow, constrained estuary (Southampton Water). These measurements ranged from 60dB re 1µPa m at Cook Inlet to 141dB re 1µPa m in Southampton Water. The high measurement at Southampton Water was taken at Dock Head which is adjacent to a working dock. Cook Inlet is a very remote location and considered more likely to be representative of 'natural' ambient noise.

There are various potential sources of biological activity in the UK marine area that contribute to ambient noise. Echo locating marine mammals (e.g. bottlenose dolphin (*Tursiops truncates*), harbour porpoise (*Phocoena phocoena*)) generate very loud sources of noise (up to 228dB re 1µPa m) at very high frequencies (more than 110,000Hz). Snapping shrimp also produce loud noise in the mid-frequency range (2,000-5,000Hz) (Au and Banks, 1998 cited in CEDA, 2011). Fish (unknown species) can produce swimbladder sounds (140dB re 1µPa m) at relatively low frequencies (less than 3,000Hz) (Battele, 2004).

Weather also has an influence on ambient noise. Heavy rainfall generates significantly louder noise (105dB re 1µPa m) than light rainfall (81dB re 1µPa m) although both produce noise at similar and relatively high frequencies (10,000Hz) (Malme *et al*., 1989). High wind speeds also produce louder noise (95dB re 1µPa m) than low wind speeds (82dB re 1µPa m) at similar frequencies to traffic noise (circa 1,000Hz). Lightning strikes are likely to generate very loud sources of noise in the marine environment if they hit the water surface (250dB re 1µPa m) (Battele, 2004). However, a low confidence has been assigned to this reported value as it did not include any documented frequency information. It should be noted that the natural ambient noise information has been included to provide context and has not been applied within the noise modelling process.

[7] Fish species is not provided in the literature source (Battele, 2004).
[8] This is the only invertebrate that has been identified in the literature review.

2.4 Challenges and limitations

Historically, there has been a lack of standardised protocols and associated terminology for measuring and describing underwater noise. A number of initiatives have investigated these issues, including the MSFD and OSPAR at a European level and the Underwater Sound Forum at a national level. Recent best practice guidance has also been published that includes advice on the appropriate metrics for reporting underwater noise measurements (TNO 2011; NPL, 2014). Information of source characteristics was therefore generally incomplete or incorrectly referenced in the historical sources that have been reviewed as part of this study. This can make comparisons across studies sometimes difficult.

Source levels were generally quoted in the literature using the SI convention (i.e. dB re 1µPa m). However, there were three separate literature sources that did not properly document source levels units and provided no distance from the source (i.e. dB re 1µPa). A low confidence was assigned to these data sources and they were not considered further in the study.

The metrics underpinning the quoted source levels were rarely provided in the literature. The metric considered most suitable for continuous noise (including ambient noise) is Sound Pressure Level (SPL) (NPL, 2014). This is a time-averaged quantity and is most commonly understood as a root mean square[9] (RMS) sound pressure value. The averaging time used in the calculation of the values of SPL should be stated but this was not clearly documented in any of the literature. Where continuous noise also contains transient or pulsed sounds from specific events, the metrics used for pulsed sounds should be used to describe these specific events (NPL, 2014). Zero to peak[10] (0-pk) or peak to peak[11] (pk-pk) sound pressure were sometimes used in the literature to describe pulsed anthropogenic sources, (e.g. echo sounders, blasting, sonar and airgun arrays).

One data source (WODA, 2013), only quoted energy source levels expressed in units of dB re 1µPa^2 m^2. This is the source output metric specified in MSFD Descriptor 11, Indicator 11.1.1 on 'Distribution in time and place of loud, low and mid frequency impulsive sounds'. This indicator is described in the Commission Decision as:

"*Proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level (in dB re 1µPa^2 s) or as peak sound pressure level (in dB re 1µPa peak) at one metre, measured over the frequency band 10 Hz to 10 kHz.*" (Dekeling *et al*., 2014a, p 5).

[9] The square root of the mean square pressure, where the mean square pressure is the time integral of squared sound pressure over a specified time interval divided by the duration of the time interval.
[10] The maximum sound pressure during a stated time interval. A peak sound pressure may arise from a positive or negative sound pressure.
[11] The sum of the peak compressional pressure and the peak rarefactional pressure during a stated time interval.

This source output metric is therefore not considered appropriate to use for continuous noise. However, given that the values are comparable (in relative terms) to SPL, they have not been omitted from this study.

Source level is calculated by measuring the SPL in the acoustic far-field[12] of the source, in a specified direction, and propagating the value back to the reference distance of 1 m from the acoustic centre of the source using an appropriate propagation model (NPL, 2014). The source level is therefore not a directly measurable quantity but is derived from measurements of received sound at some distance away from the source. The propagation model used to back-calculate the source level was rarely provided in the literature and therefore will account for some of the variability in the quoted source levels.

The majority of studies that were reviewed were published in non-refereed sources. This made it difficult to have sufficient confidence in the data and information. Only peer-reviewed journal papers and/or published books were therefore assigned a ‘high’ confidence level (Table 1).

[12] A region, distant from a sound source, where the SPL is spreading spherically (i.e. the SPL decreases 6dB with each doubling of distance from the source).

3. Review of Underwater Noise Propagation Models

To produce a GIS tool that can map the modelled propagation of anthropogenic continuous underwater noise, the principle factors influencing the propagation of underwater noise and possible approaches to modelling noise propagation were reviewed in this section. An appropriate and pragmatic propagation model was selected to meet the aims of the project and is presented in this section.

3.1 Noise propagation

The process of noise travelling through a medium is referred to as noise propagation. The propagation of underwater noise produced by various ambient noise sources is a very complex process (Harland and Richards, 2006). The factors that influence the propagation of noise in the ocean and contribute to propagation (or transmission) loss[13] broadly include the following (NPL, 2014):

- the reduction (or attenuation) of sound away from the source due to geometrical spreading
- absorption[14] of the sound by the sea-water and the seabed
- the interaction with the sea-surface (reflection and scattering)
- the interaction with (and transmission through) the seabed
- the refraction of the sound due to the sound speed gradient
- the bathymetry (water depth) between source and receiver positions
- source and receiver depth.

Density and elasticity influence the speed of sound in water (Coates, 2006). Density is the tendency of the water to possess inertia (i.e. to resist motion) and elasticity is the reluctance the water has to being distorted (i.e. compressed or rarified[15]).

The path followed by the sound waves can deviate markedly from a straight line due to changes in speed of sound brought about by variations in temperature, salinity (or conductivity) and pressure (or depth). There are many equations predicting sound speed from temperature, salinity and depth. In seawater the speed of sound increases by about 3.2ms^{-1} for each 1°C increase in temperature and 1.2ms^{-1} for each 1psu increase in salinity (Coates, 2006). The speed of sound also increases by approximately 0.017ms^{-1} per metre increase in depth (Coates, 2006).

The density and elasticity structuring of seawater is most marked in the vertical dimension, causing sound to be refracted upwards or downwards, depending on the sound speed gradient, but horizontal structuring can also be encountered. As sound is refracted up or down it may interact with the sea surface and the seabed by reflection and scattering. Interaction with the seabed may also result in transmission of sound (NPL, 2014). For example sound may travel sideways through the rocks of the seabed, re-emerging back into the water at a distance (Nedwell and Edwards,

[13] The reduction in signal as sound propagates from source to receiver.
[14] Frictional conversion of sound into heat during propagation.
[15] To expand or enlarge without adding any new matter.

2004). Absorption of sound by the seawater and the seabed further distorts the impulse.

Sound may also be carried with little loss to great distance by being trapped in sound channels created by specific combinations of temperature, salinity and pressure. The level of signal arriving at a distant point is therefore a complex sum of many paths that may or may not interact with the seabed and sea surface (Harland *et al*., 2005).

In shallow water around the UK coast, the sound speed is less likely to vary strongly with depth due to the shallow conditions and the often rapid tidal flow, which often leads to a mixed isothermal water column (NPL, 2014). Variations of salinity are generally very small, except perhaps at the mouth of major rivers. Temperature variations are therefore considered to have the most significant effect on the path followed by the sound waves in UK coastal waters. When the sea surface heats up, it introduces a temperature gradient close to the sea surface that causes downwards refraction as sound travels faster in the warmer upper water column (Harland *et al*., 2005). The downwards refraction leads to increased propagation loss. Propagation loss therefore varies on a diurnal and annual basis, as air temperature variations throughout the day and year result in the warming and cooling of water. A period of sustained strong wind can also disrupt the temperature structuring.

Seabed sediment type and roughness can also affect propagation loss due to differences in reflective properties and scattering (Harland and Richards, 2006). Softer sediment types (e.g. silts, mud) are less reflective than harder sediment types (e.g. sand, rock), and increased seabed roughness increase the degree of scattering. Similarly, waves on the surface can affect propagation loss by scattering the sound interacting with the surface rather than just reflecting it (Harland and Richards, 2006). Suspended sediments or microbubbles from wave entrainment can also cause additional propagation loss by absorption, scattering and changes in speed of sound.

A further consideration is that the propagation of noise is frequency dependent. In deep water, higher frequency sounds transmit less well whereas lower frequency sounds can travel a further distance. However, low frequency sounds do not propagate as well as high frequency sounds in shallow water due to the wave-guide effect (i.e. where the wavelength is of a similar magnitude to the water depth) (NPL, 2014). This effect means that there will be a lower cut-off frequency at a particular depth, below which sound waves will not propagate well. Any sound at frequencies below the cut off will not be able to propagate far because the grazing angle of the sound wave exceeds the critical angle and it loses energy very quickly through multiple reflections between the surface and bottom with limited horizontal propagation (NPL, 2014).

3.2 Simple models of propagation or transmission loss

An observer moving away from the source will typically measure gradually decreasing sound pressure levels which are referred to as received levels. In complex bathymetric domains or at relatively low frequencies, however, a more complex relationship between received level and range is likely to occur.

As discussed in Section 3.1, the propagation of noise is very complex and therefore predicting the received levels at distance from a source is extremely difficult. Use is generally made of theoretical models or empirical models based on field measurements (Nedwell and Edwards, 2004).

A simple model of noise propagation is:

Equation 1: Simple sound propagation model.

$$RL = SL - TL$$

where RL is the received level, SL is the source level and TL is the transmission loss.

The geometrical spreading of sound away from a source is a major component of transmission loss and is represented by:

Equation 2: Geometric spreading model.

$$TL = N\, log_{10}(R)$$

where N is the attenuation coefficient and R is the distance in metres from the source to the receiver. However, this equation generally represents a simplistic model of propagation loss except in certain idealised scenarios. For example, it does not take into account the refraction that occurs because of the dependence of sound speed on depth. To account for the complex interactions between sound waves and the seabed, water column, and sea surface, a more sophisticated model which incorporates these factors is generally required. Such models are computationally intensive and demand detailed knowledge of environmental parameters, which is why a simplified approach is advocated for this study (see Section 3.4).

Combining Equations 1 and 2 enable the received level (RL) to be easily calculated at varying distances from the source:

Equation 3: Expanded simple model.

$$RL = SL - N\, log_{10}(R)$$

Spherical (or geometric) spreading applies when sound propagates uniformly in all directions (i.e. free-field) with no refraction or reflection from boundaries (i.e. the sediment or water surface) and is denoted by an attenuation coefficient, N equal to 20. Spherical spreading results in a general 6dB decrease in the intensity of the sound per doubling of distance. This model is considered most appropriate at short ranges (where R is comparable with, or less than the water depth), and/or in deeper water (greater than 2,000m) or where the seabed is highly absorptive (e.g. mud) (Richards *et al.*, 2007). At low frequencies, spherical spreading will only typically be applicable in deep water (Coates, 2006). At very high frequencies, this relationship may also be evident in shallow water.

Cylindrical spreading applies when the propagation of sound is constrained by the water surface and the seabed, and is defined by N equal to 10. This results in a general 3dB reduction in sound intensity per doubling of distance. Cylindrical spreading is usually assumed for shallow water, where water depth is less than R. Transmission loss for cylindrical spreading is less than for spherical spreading at a given distance, R. Therefore, according to the spreading law, a noise source generated in shallow coastal waters or estuaries travels twice the distance of an equal noise source in the open ocean (WDCS, 2003).

Reflections from the sediment or water surface can reduce spreading considerably in shallow water. These reflections are very complex and difficult to define. Since sound energy is not perfectly contained by reflection and refraction, and since sound penetration into the seabed at low frequencies is quite good, cylindrical spreading tends to underestimate the degree of transmission loss. A practical spreading loss model, intermediate between spherical and cylindrical spreading, denoted by N equal to 15, is thus often invoked for “first-cut” calculations in acoustics (Coates, 2006). Richards *et al*. (2007) also describe an alternate spreading regime where N is equal to 17 which is considered appropriate for longer ranges (i.e. ranges equal to several water depths), and/or in shallower water or where the seabed is more reflective (e.g. sand or rock). Empirical data indicate that in shallow coastal waters, underwater noise transmission loss is close to spherical spreading where N is equal to 20 (Nedwell and Howell, 2004). In summary, N should either be chosen from an empirical fit where data are available, or set to be equal to 15 to provide a pragmatic representation of shallow water environments.

3.2.1 Other factors that influence propagation of noise

It would be possible to include a coefficient for absorption (α) in a simple spreading model as follows:

Equation 4: Geometric spreading and absorption model.

$$TL = N\, log_{10}(R) - \alpha R$$

where α is a coefficient for the absorption of noise in water and boundaries (i.e. the sediment or water surface) in dB m^{-1}. An approximation for absorption losses in water is provided by:

Equation 5: Absorption loss.

$$\alpha = 0.036\ \times f1.5$$

where *f* is the frequency in kilohertz (kHz) (Richardson *et al*., 1995).

The propagation of noise is also related to bathymetry and bottom substrate type (see Section 3.1). Medium sand, for example, is a better reflector of sound than clay, silt or gravel which are considered poor reflectors of sound (Dekeling *et al*., 2014b). These terms can be included in a simplified manner to a shallow water propagation model by:

Equation 6: Practical spreading, bathymetry and bottom type model.

$$TL = 15\, log_{10}(R) + 5\, log_{10}\left(\frac{\eta\, H}{\pi\, Rref}\right)$$

where η is the reflection loss gradient (0.25 is representative of sand), H is the water depth, π is 3.14 (Pi to the nearest 2 decimal places) and Rref is 1m, which are dependent on the attenuation coefficient, N=15 (Dekeling *et al*., 2014b).

3.3 More complex models

The wave equation describing the propagation of an acoustic field is often difficult to solve in real-world situations (NPL, 2014). Despite these difficulties, it is possible to make accurate estimates of the propagation of noise if sufficient information is available about the environment. A sophisticated model will make use of information about the water column itself (e.g. sound speed profile, absorption, and bathymetry), seabed (e.g. sound speed, density, and absorption), sea surface (e.g. roughness, bubble presence) and the depths of source and receiver.

Models are generally categorised as range independent (the input parameters are kept fixed), and range dependent (input parameters such as water depth and sound speed are allowed to vary with range from the source), the latter being the preferred choice when the bathymetry or water column conditions change along the propagation path. The boundary conditions used and the modelling regime to be considered logically lead to one or other solution to the wave equation and this has given rise to a number of classes of models that employ similar techniques. The models may be categorised generally into a number of classes (Jensen *et al*., 2000; Weston, 1976 cited in NPL, 2014):

- ray tracing models
- normal mode models
- parabolic equation model
- wavenumber integration models
- energy flux models.

Each set of solutions are valid and computationally efficient over a limited frequency, depth and range regime. For instance, ray theory is most suited to short range and high frequency scenarios while normal mode and parabolic equation are applied to long range and low frequency models. Full-field models are applicable to many scenarios but are often computationally intensive and require a high level of user-experience to ensure that the mathematical iterative processes have reached convergence. In general, more sophisticated models operate at narrowband frequencies and do not therefore easily lend themselves to applications involving broadband noise sources.

Although it is possible to obtain good resolution in range from the source and depth in the water column, more complex models are not usually fully three-dimensional, but are instead formed of a series of two-dimensional slices through the water column (range versus depth) at a succession of bearings. There are very few models that can cope with horizontal spreading due to refraction, diffraction or reflection, and none that are readily available (NPL, 2014).

3.4 Recommended propagation model

The following practical spreading loss model has been used in the noise mapping tool that has been developed as part of this project:

Equation 7: Practical spreading model.

$$TL = 15\, log_{10}(R)$$

The main reason for choosing this simple approach is that sophisticated modelling that account for complex interactions with the environment presents computational challenges and demand detailed knowledge of environmental parameters that cannot be resolved in the timescale of the project. Furthermore, given the limitations of the model input data (Section 2.4) and the high level nature of this project, the use of more complex modelling techniques is not considered to be appropriate. Based on these considerations and the limited range of simple models available, the practical spreading model (Equation 7) provides a pragmatic estimate of transmission loss and is necessarily easy and quick to incorporate into the noise mapping model.

It was not considered relevant to include absorption losses in the model as these are negligible at low frequencies (<1 kHz) and short ranges[16] (Dekeling, 2014b). It is also not considered necessary to include bathymetry or bottom substrate type terms as described above in Equation 6 - practical spreading, bathymetry and bottom type model. These factors do not influence transmission loss enough to justify the additional effort and equate to a change in received level of approximately 1dB from that predicted by geometric spreading alone under conditions prevalent in the south marine plan areas[17].

[16] At 1kHz, absorption is less than 0.1 dB/km, see http://resource.npl.co.uk/acoustics/techguides/seaabsorp

[17] Assuming the reflection loss gradient η is 0.25 which is representative of highly reflective substrate (i.e. sand) as a conservative input value, and water depth H is between 1 and 60 metres.

4. A Continuous Underwater Noise Mapping GIS Tool

Relevant anthropogenic continuous noise sources and the recommended propagation model (Equation 7) have been used to develop a mapping tool in GIS. The assumptions that have been made to represent these noise sources in the GIS tool are presented in this section.

4.1 Anthropogenic continuous noise sources included in GIS tool

It is important that the study remains focussed on the anthropogenic continuous noise sources that are the main contributors to ambient noise. A high level screening exercise was therefore undertaken to determine the sources that should be “screened in” to the study (i.e. included in the noise mapping GIS tool). The outcomes of this process are summarised below.

All anthropogenic sources of continuous noise that were identified in the literature review were generally found to be louder than natural sources of noise (Section 2). All these anthropogenic sources are therefore potentially a significant contributor to ambient noise and have remained in the study on the basis that they are greater than natural ambient noise.

Mid-frequency sonar used by military is well outside of the frequency range of interest under the MSFD indicator for ambient noise. Mid-frequency sonar operates at approximately 2,000-8,200Hz whereas the frequency bands of interest under the MSFD indicator are 1/3 octave bands 63Hz and 125Hz (centre frequency). It was therefore not considered a relevant noise source and has been screened out of the study.

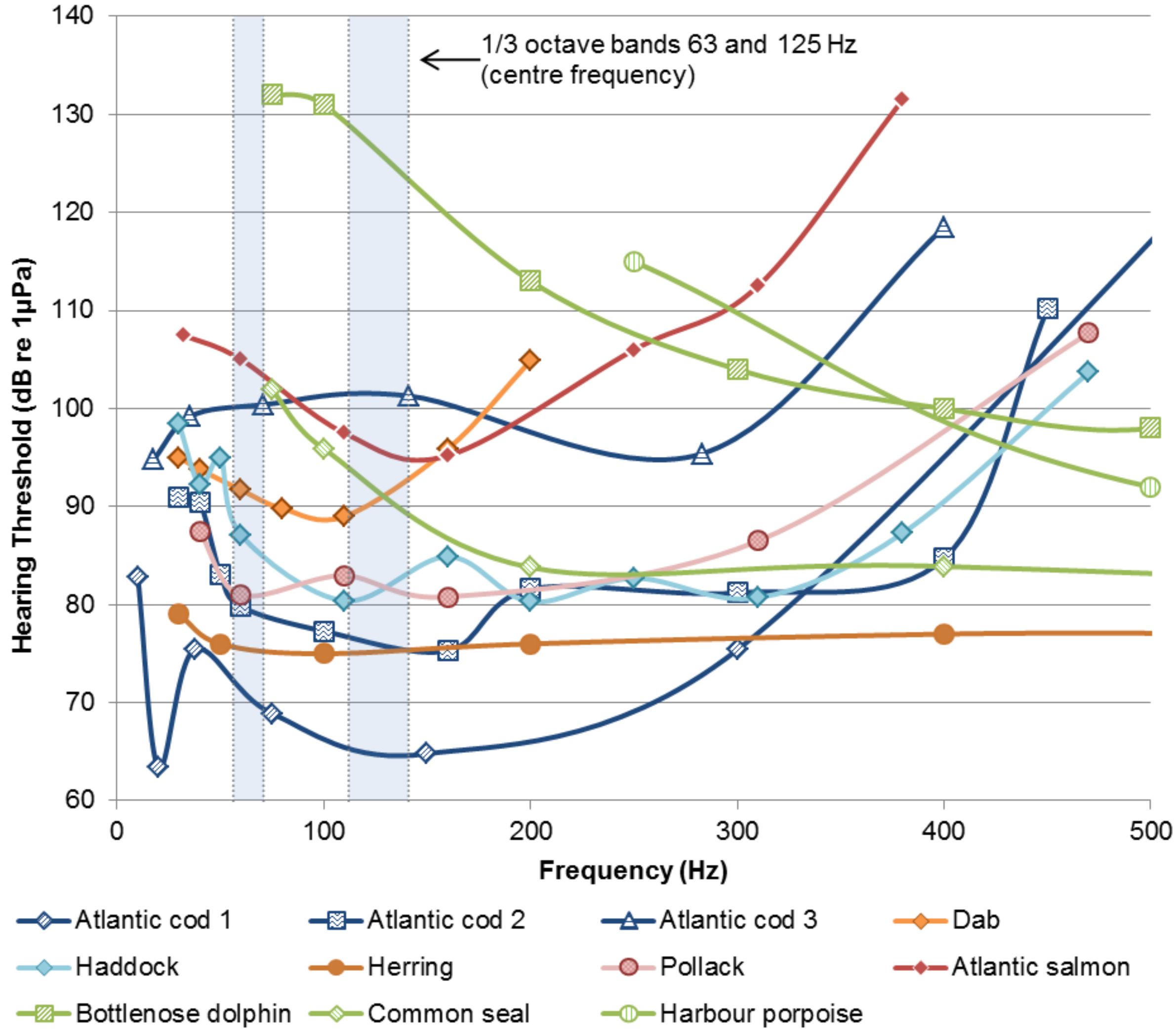
Low-frequency sonar could potentially be a significant contributor to ambient noise at the lower frequency range of interest for this study. However, there is no publically available spatiotemporal information on this military activity and therefore it is not possible to determine the likely duration or accurately map the location of this source of noise. For this reason, at present it is not possible to include this activity in the underwater noise mapping tool that has been developed as part of this study. Regardless, it is arguable whether sonar noise sources could be considered in the category of impulsive noise rather than a continuous source of noise for the purposes of this study.

Smaller craft and boats (e.g. jet skis, speed boats and work boats) generate lower sources of noise at generally higher frequencies relative to commercial shipping which are outside the frequency range of interest under the MSFD indicator for ambient noise. Despite this, they are more likely to dominate ambient noise in quieter areas and may pose a significant localised concern. However, the spatiotemporal data available on these sources are considered to be of low quality. The AIS data for Recreational and High Speed Craft Ship Type Groups are not representative of these types of vessels given that they are not required to carry a AIS receiver and the very small proportion of vessels that do, do not always have them switched on or properly set up to record information. It is therefore not considered appropriate to incorporate these sources into the GIS tool.

4.2 Anthropogenic noise and ecological sensitivity

To provide additional ecological context, this section relates the anthropogenic noise sources identified in the literature review with the hearing sensitivity of marine fauna found in UK waters. This highlights the potential for anthropogenic continuous noise to produce a response (physiological, behavioural and/or masking effect). This has involved collating hearing threshold data from published peer reviewed audiograms[18] of a range of marine species that occur in UK waters. This audiogram data are summarised in Figure 2 and the source data can be found in Table 4 in the accompanying Technical Annex document.

Figure 2: Published audiograms of UK marine species in relation to 1/3 octave bands 63 and 125Hz (centre frequency).



[18] An audiogram is a hearing curve that depicts the frequency dependent hearing sensitivity or hearing threshold of a species, which in fish and marine mammals usually exhibits a U-shaped form. The hearing threshold increases (i.e. hearing sensitivity reduces) for frequencies outside those optimal for those species.

Fish are sensitive to noise at lower frequencies (less than 500Hz), with some species having particularly acute hearing such as Atlantic cod (*Gadus morhua*) and herring (*Clupea harengus*). Marine mammals are more sensitive at higher frequencies and generally have a wider range of hearing than fish (i.e. their hearing ability spans a larger range of frequencies).

Atlantic cod has the lowest published hearing threshold (69dB re 1µPa m) between 63Hz and 125Hz. It is important to recognise, however, the large variability in hearing sensitivity reported for this fish species alone. Three separate studies report a minimum hearing threshold between 63Hz and 125Hz for this species ranging from 69dB re 1µPa m to 100dB re 1µPa m, which corresponds to three orders of magnitude difference. This may in part be due to the inherent challenges and limitations associated with undertaking controlled laboratory experiments in a tank, the varying methods applied, as well as intra species specific differences in hearing ability.

The source levels of each anthropogenic continuous noise category have been compared to the corresponding hearing threshold of marine species at 1/3 octave bands 63 and 125Hz (centre frequency). These frequencies, which are shown as a blue shaded area on the graph in Figure 2, have been selected to coincide with the MSFD indicator for ambient noise (Section 2.1). Peak source levels of all anthropogenic ambient noise categories have been assumed to occur at these 1/3 octave frequency bands (see Section 4.4.3). The typical (mean and median) and worst case (maximum) source levels of all anthropogenic noise categories are above the hearing thresholds for marine species identified in the literature. This indicates that all these noise sources would be detected (i.e. heard) by hearing sensitive marine species.

The zone of responsiveness is the area within which a species reacts behaviourally to the noise. An intense noise may elicit a strong behavioural avoidance. Reactions to less intense noises may be evidenced by altered but less obvious movement patterns. Individuals within a species may react differently based upon the status of their auditory capability, their behavioural state (e.g. reproductive condition, life-cycle stage, etc.) or their physical surroundings (e.g. open deep water versus confined and shallow estuary) (WODA, 2013).

Lower levels of noise may result in masking effects i.e. interference with the detection of biologically relevant communication signals such as echolocation clicks or social signals. Masking has been shown in acoustic signals used for communication among marine mammals (see Clark *et al.,* 2009) and also fish (Holt and Johnston, 2014; Radford *et al*., 2014). Masking may in some cases hinder echolocation of prey or detection of predators. If the signal-to-noise ratio prevents detection of subtle or even prominent pieces of information, inappropriate or ineffective responses may be shown by the receiving organism.

Furthermore, it is important to note that physiological effects are related to the dose of exposure, which involves the duration of impact (Southall *et al*., 2007; Kastelein *et al.*, 2012). Consequently, physiological effects can potentially occur at lower noise levels that do not cause a behavioural response[19] when the animals are exposed for a long period.

Given the broad spatial influence of anthropogenic continuous noise and the lack of ecological sensitivity data, it would be precautionary to assume that all identified categories are potentially ecologically relevant and should ideally be included in the GIS tool where possible. This allows for less well understood noise impacts that do not necessarily result in behavioural or physiological modification such as communication masking.

4.3 Spatial data for relevant anthropogenic activities

Spatial data layers that provide information on both the location and intensity of relevant anthropogenic activities in the south marine plan areas have been identified and sourced. The following spatial data layers are proposed to be used in the GIS tool to represent the spatiotemporal distribution of anthropogenic activities:

- automatic Identification System (AIS) shipping data
- electronic Monitoring System (EMS) aggregate dredging data
- vessel Monitoring System (VMS) fishing data.

The literature review identified considerable variability in the source levels of different anthropogenic sources of continuous underwater noise (see Section 2.2, Table 2). For example, the reported source levels of a backhoe dredger ranged from 163 to 186dB re 1µPa m, corresponding to over two orders of magnitude difference[20].

For the purposes of this study, in order to determine annual changes in anthropogenic continuous noise, it is considered most appropriate for the GIS tool to characterise noise sources using typical source levels. The average (mean and median[21]) varies with noise source (see Table 2). As a general pragmatic approach the arithmetic mean has been used to represent typical source levels in the GIS tool.

It is recognised that using the mean as opposed to the median may potentially skew the output in some cases. For example, the mean source level for the fishing boat/trawler sub-activity (139dB re 1µPa m) will potentially underestimate actual noise source levels given that the median (143dB re 1µPa m) is slightly higher. However, in the majority of cases the mean and median were very similar (see Table 2) and given the low number of source level data points for most categories, the mean was considered the most generic and appropriate statistic at this stage. The GIS tool can also be used to characterise worst case (maximum) source levels by category to allow for flexibility in marine planning decisions in the future.

[19] A mild behavioural response is considered to be a sudden change in swimming direction or erratic movements by a minority of the population.
[20] A change in noise level by 10dB corresponds to a change in power (or energy) by a factor of 10. A change in noise level by 3dB corresponds to a doubling of power.
[21] The mode is the value that occurs most often in a given list of numbers. Given the low number of data sources for the majority of source level categories, numbers are rarely repeated so mode was not considered an appropriate statistic for this application.

The source levels that have been collated as part of the literature review and are considered to best represent the various spatial data layers that have been used in the GIS tool are summarised in Table 3. The following sections provide a more detailed explanation for the derived source levels.

Table 3: Typical and worst case source levels that have been used to represent spatial data layers in GIS tool.

Spatial data layer	Sub-activity	Typical source level (dB re 1μPa m)	Worst case source level (dB re 1μPa m)	Commentary
AIS Ship Type Group: Cargo	Bulk cargo/carrier Container Vehicle carrier	185	198	The typical source levels of these sub-activity categories are very similar (Table 2). In the absence of information on the proportion of each vessel type represented by the AIS Ship Type Group, the mean source level of all vessel types has been used to characterise typical source levels.
AIS Ship Type Group: Tanker	Supertanker Tanker/freighter	184	190	The typical source levels of supertankers and tanker/freighters vary by an order of magnitude (Table 2). Furthermore, supertankers are likely to comprise a smaller proportion of the population compared to tanker/freighters. The mean that has been used to represent typical source levels is therefore likely to overestimate the levels of noise for this AIS Ship Type Group in the GIS tool.
AIS Ship Type Group: Vessels engaged in dredging or underwater operations	Backhoe dredger Clamshell dredger Cutter suction dredger Suction dredger Trailer suction hopper dredger	181	180	The source levels of a range of dredgers engaged in dredging have been used to represent this AIS Ship Type Group. Typical source levels of these dredgers span three orders of magnitude (Table 2). There is no available source level information on transiting dredgers, although it is likely that levels generated by dredgers engaged in dredging are higher compared to those in transit. Furthermore, the spatiotemporal distribution of dredgers in transit compared to those in operation is unknown. Therefore the mean value that has been applied to represent typical source levels is likely to potentially overestimate the levels of noise for this Ship Type Group in the GIS tool.
AIS Ship Type	Passenger	155	155	The typical and worst case source levels for this sub-

Spatial data layer	Sub-activity	Typical source level (dB re 1μPa m)	Worst case source level (dB re 1μPa m)	Commentary
Group: Passenger				activity category are represented by a high speed ferry. There are no known measurements for large ferries or cruise ships available in the literature. Typical source levels are therefore considered likely to underestimate the levels of noise for this AIS Ship Type Group in the GIS tool.
AIS Ship Type Group: Fishing vessels	Fishing boat/trawler	150	158	The mean source level for this sub-activity category is slightly lower than the median source level (Table 2). Using the mean to characterise typical source levels is therefore likely to marginally underestimate noise levels for this AIS Ship Type Group in the GIS tool.
AIS Ship Type Group: Port service craft	Tug and barge Workboat	166	171	The typical source levels of these sub-activity categories are broadly similar (Table 2). In the absence of information on the proportion of each vessel type represented by the AIS Ship Type Group, the mean source level of all vessel types has been used to characterise typical source levels.
EMS aggregate dredging	Trailer suction hopper dredger	187	188	The mean and median source levels of this type of dredger are the same and therefore the mean is considered a good representation of the typical levels to use for the EMS data in the GIS tool.
VMS fishing data	Trawler trawling	147	147	One single measurement of a trawler trawling has been used to represent the mobile fishing gear category of the VMS data in the GIS tool. This is likely to slightly overestimate the levels of noise generated by fishing activities in the GIS model tool given that some mobile gears do not interact with the seabed and are therefore likely to produce lower levels of noise than benthic trawling (e.g. pelagic gears).

4.3.1 AIS shipping data

AIS density grid data contain the weekly average number of vessel transits (based on 6 weeks of 2012 data) per grid cell for each Ship Type Group (MMO, 2014). The Ship Type Groups are as follows:

0 – Unknown Vessels
1 – Non-Port service craft
2 – Port service craft
3 – Vessels engaged in dredging or underwater operations
4 – High Speed Craft
5 – Military or Law enforcement
6 – Passenger
7 – Cargo
8 – Tankers
9 – Fishing vessels
10 – Recreational.

The bulk cargo/carrier, container and vehicle carrier sub-activity categories are considered to align with the Ship Type Group: Cargo (Container, Bulk, Roll-on-Roll-off, etc.). An arithmetic mean of the typical (mean) and worst case (maximum) source levels identified for each of these vessel types has been assumed to represent source levels for this Ship Type Group (Table 3). Based on the values provided in Table 2 this would equate to typical and worst case source levels of 182dB re 1µPa m and 191dB re 1µPa m respectively for this Ship Type Group. This approach will skew the outputs of the GIS tool if the actual population is represented by, for example, a large proportion of container vessels compared to cargo/carrier and vehicle carriers. However, in the absence of detailed information on the exact proportion of each vessel type included in this Ship Type Group, the mean of all vessel types is considered a pragmatic approach for this study.

Both supertankers and tanker/freighter sub- activity categories are considered to be represented by the Ship Type Group: Tanker (oil, bunker, gas). Based on the values provided in Table 2, the typical and worst case source levels for this Ship Type Group are 182dB re 1µPa m and 188dB re 1µPa m respectively (Table 3). There is an order of magnitude difference between the mean noise of supertankers (187dB re 1µPa m) and that of tanker/freighters (177dB re 1µPa m). Furthermore, it is considered likely that supertankers are a smaller proportion of the population compared to tanker/freighters and therefore this average is likely to slightly overestimate the levels of noise for this category in the GIS tool. However, in the absence of evidence about the actual population, the mean of both these sources has been used to represent the average source levels of this Ship Type Group.

All the different types of dredgers identified in the literature review are considered to be represented by the Ship Type Group: Vessels engaged in dredging or underwater operations. The typical and worst case source levels of all these dredgers dredging are 170dB re 1µPa m and 176dB re 1µPa m respectively. These source levels have been used to characterise this AIS Ship Type Group given that the actual structure and variability in the population is unknown.

It is important to note that this Ship Type Group includes both transiting dredgers as well as operational dredgers that are actively dredging material. However, there is no available source level information on transiting dredgers, and the spatiotemporal distribution of dredgers in transit compared to those in operation is unknown. Therefore as a worst case approach has been taken which uses the sound levels generated by dredgers engaged in dredging (which are likely to be higher compared to those in transit) at all times including when they are in transit. This is likely to overestimate the noise level outputs for this Ship Type Group, however, in the absence of the necessary information on spatial activity distribution this approach is considered to be the most practical way forward.

Two source level measurements for a high speed ferry are available in the literature and the mean and maximum of these (155dB re 1µPa m) has been used to represent Ship Type Group: Passenger (Table 3). No measurements for large ferries or cruise ships could be found and therefore this estimate is likely to result in noise outputs that are potentially an underestimate of the typical levels generated by this Ship Type Group.

The mean and maximum of all the available source level measurements of fishing boats and/or trawlers in transit (139dB re 1µPa m and 158dB re 1µPa m respectively) has been used to represent typical and worst case noise levels for the Ship Type Group: Fishing vessels (Table 3). Fishing vessels that are in the process of fishing (trawling) are being represented by VMS fishing data (Section 4.3.3).

The tug and barge and workboat sub-activities are considered to be represented by the Ship Type Group: Port service craft. The mean and maximum source levels of these two sub-activities (163dB re 1µPa m and 165dB re 1µPa m respectively) have been used in the GIS tool for this Ship Type Group (Table 3). The proportion of tug and barges versus workboats that are represented by the AIS data is unknown and therefore the mean is considered adequately representative in the absence of this information.

Based on the information collated as part of the literature review, it would be possible to apply different source levels to the Ship Type Group: Cargo (Container, Bulk, Roll-on Roll-off, etc.) that crudely represent low speeds in areas where there are speed restrictions and high speeds outside of these areas. Evidence suggests that there is around a 10dB difference between container and bulk cargo ships travelling at low speed and high speed. Leaper *et al.* (2014) provide a review of the relationship between noise and vessel speed, concluding that despite considerable uncertainty, the generalised model suggested by Ross (1976) is most likely to be the most applicable.

Using an average source level would therefore over and underestimate the actual source levels when vessels are transiting at low and high speeds respectively. However, areas subject to speed restrictions are highly site specific and are not necessarily applied to all harbour areas in the UK. There are no existing spatial data layers that represent such information and therefore it has not been possible to apply different source levels for vessels transiting at low versus high speed as part of this study.

4.3.2 EMS aggregate dredging data

The EMS aggregate dredging data for 2012 have been obtained from The Crown Estate. These data provide the location and intensity of dredging effort in hours (The Crown Estate and BMAPA, 2013). All forms of dredging, including aggregate and navigational dredging, and also the movement of dredgers in transit, are already represented in the AIS Ship Type Group: Vessels engaged in dredging or underwater operations (Section 4.3.1). For only those model grid cells containing EMS data it is proposed to substitute this information in preference to AIS data as the AIS data under-records aggregate dredging activity. A trailer suction hopper dredger is used in marine aggregate extraction. The mean and maximum source levels of this type of dredger (187dB re 1µPa m and 188dB re 1µPa m respectively) have been used in the GIS tool to represent typical and worst case noise levels for the EMS data (Table 3).

4.3.3 VMS fishing data

VMS fishing data have been sourced for 2011. This year differs from the AIS and EMS spatial data layers (which were obtained for 2012). Core fishing areas of activity appear to experience relatively stable levels of activity, while fringe areas show greater spatial-temporal variability in activity levels (Stelzenmüller, 2008; Jennings *et al*., 2012). Using AIS and VMS from 2012 and 2011 respectively is therefore not considered a significant issue for the current proof of concept of the GIS tool.

These data provide position information and vessel fishing activity data for fishing vessels greater than 15m length (MMO, 2013). The mobile fishing gear category is proposed to be used to represent the noise generated by trawling activity. In this way, all mobile gears will be assumed to have the same source level as the single noise measurement available in the literature for trawling (147dB re 1µPa m, see Table 3). This will slightly overestimate the levels of noise generated by fishing activities in the GIS tool given that some mobile gears do not interact with the seabed and are therefore likely to produce lower levels of noise than trawling (e.g. pelagic gears).

Other GIS spatial layers of fishing activities have been considered for this study. Fishermap provides information on fishing vessels less than 15m length (MMO, 2013) but does not include information on effort and thus cannot be easily incorporated into the model. Inshore Fisheries and Conservation Authority (IFCA) sightings data also provide additional information on observed fishing locations of vessels (Cefas, 2010; Breen *et al*., 2014)) but again does not include information on effort and therefore cannot easily be incorporated into the model. It has therefore not been possible to include either of these spatial layers in the GIS tool at this stage.

4.4 GIS tool assumptions

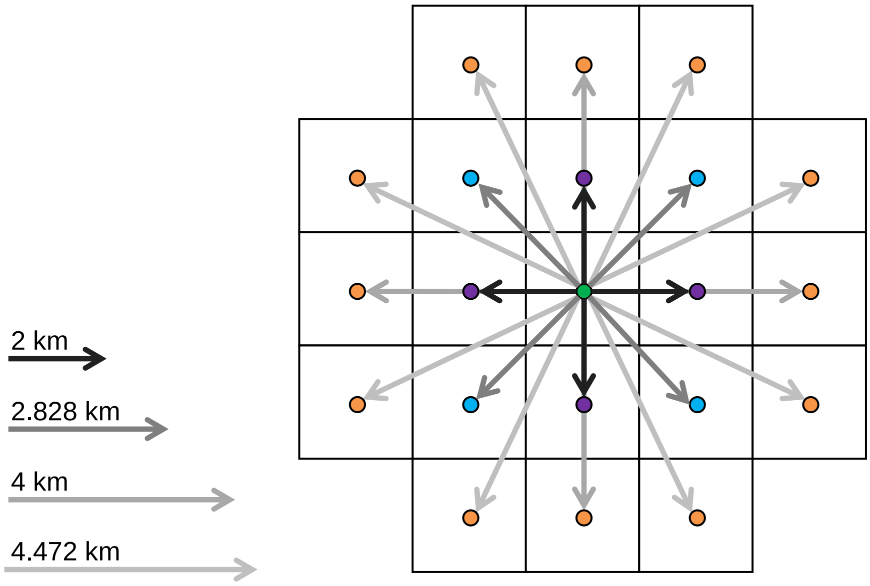
The following sections describe the assumptions that are proposed to be applied for representing anthropogenic continuous underwater noise in the GIS tool. A diagrammatic representation of the GIS tool is provided in Section 3 of the accompanying Technical Annex document.

4.4.1 Output grid size

A GIS tool based on the 2km x 2km density grid used in the Mapping UK Shipping Density and Routes from Automatic Information System (AIS) Project MMO1066 (MMO, 2014) has been developed. Noise sources occurring in a particular grid cell were assumed to be located in the centre of that cell and noise is assumed to propagate outwards from that central point to neighbouring cells (Figure 3). Assuming that the noise source occurs at the boundaries of the cell would artificially overestimate noise in that cell and was therefore not considered a realistic representation for the purposes of this study.

Figure 3 provides a simple illustration of how the propagation of noise from a single cell has been represented in the GIS tool. The black boxes represent the 2km x 2km grid and grey arrows represent the linear propagation of noise from a source in the centre of the middle grid cell (green). The centre of neighbouring adjacent grid cells is represented in purple, the centre of neighbouring diagonal grid cells is represented in blue and the centre of the outer neighbouring cells are represented in orange. Further propagation into more distant cells is not considered practical for the GIS tool application given computational processing constraints and the properties of the simple underlying propagation model.

Figure 3: Simple representation of the propagation of noise in the GIS tool.



Applying the simple sound propagation model (Equation 1) and recommended practical spreading loss model (Equation 7) to a noise source of 185dB re 1µPa m would result in the received level at the centre of the four adjacent neighbouring cells of 135dB re 1µPa m and a received level at the centre of the four diagonal neighbouring cells of 133dB re 1µPa m. The calculation steps followed in this example are provided below.

Equation 8: Simple sound propagation model.

$$RL = SL - TL$$

Equation 9: Practical spreading model.

$$TL = 15\ log_{10}(R)$$

Equation 10 and 11 combined:

$$RL = SL - 15log_{10}(R)$$

$$RL\ (adjacent\ neighbouring\ cell) = 185dB\ re\ 1\mu Pa\ m - \ 15log_{10}(2000m)$$
$$RL\ (adjacent\ neighbouring\ cell) = 135dB\ re\ 1\mu Pa\ m$$

$$RL\ (diagonal\ neighbouring\ cell) = 185dB\ re\ 1\mu Pa\ m - \ 15log_{10}(2{,}828m)$$
$$RL\ (diagonal\ neighbouring\ cell) = 133dB\ re\ 1\mu Pa\ m$$

4.4.2 Temporal aspects of pressure

Spatial data on the location and intensity of relevant anthropogenic activities that have been sourced relate to different time periods. EMS aggregate data and VMS fishing data are available as annual layers and provide information on effort in hours. Commercial shipping data are available as a count (number of vessels per week per grid cell) and transect data (which have been used to identify length of transect through a grid cell and also provide an estimate of time to travel through the grid cell based on assumptions about vessel speed). The final model outputs have therefore been primarily based on representing annual shipping density data. It was not considered practical to use the transit line information given computational constraints and time limitations of the study.

4.4.3 Representation of sound frequencies

Based on the findings of the literature review, all the noise sources that have been included in the GIS tool are broadband, spanning a wide range of frequencies (1-120,000Hz), with the majority of the energy occurring at low frequencies (<5,000Hz). The evidence that was collated as part of the literature review rarely provided detailed information on sound pressure levels across the entire frequency spectrum (including the 1/3 octave bands 63 and 125Hz (centre frequency)). It was therefore not possible to clearly represent the varying sound pressure levels at different frequencies in the generalised GIS tool. For the purposes of the model it has been assumed that peak noise levels occur in the 1/3 octave bands 63 and 125Hz (centre frequency). This assumption is considered to be slightly conservative and is likely to overestimate the noise levels generated by the GIS tool.

4.4.4 Cumulative impacts of underwater noise

It is not possible to calculate the combined impact of two or more noise sources in the GIS tool as the spatial data layers do not provide the precise timing of the various anthropogenic noise sources and this information is critical to being able to estimate the impact of combined noise sources. For the purposes of the GIS tool, therefore, it has been assumed that all noise sources within each model cell occur independently of one another. The GIS tool has been used to generate, for each model grid cell, histograms of the time (in hours) on the y-axis of all the different noise sources (e.g. number of passenger vessels, mobile gear fishing activity, etc.) occurring over a year in 3dB bands on the x-axis. In this way, cumulative noise sources will be crudely represented in the GIS tool.

5. Outputs from the GIS Tool

The GIS tool developed for this study has enabled a range of data layers of continuous underwater noise generated by anthropogenic activities to be produced for the purposes of this study. Figures 4 to 6 present some example map outputs of the GIS tool.

Figure 4 shows the time (in hours) that typical (mean) noise levels in each grid cell exceed 100dB re 1µPa m over a year. Based on the literature review of published field measurements, this threshold level was considered to be representative of relatively low levels of background ambient noise in the south marine plan areas. It is clear from the figure that most of the area exceeds this low threshold for relatively long periods of time (more than around 700 hours per year which equates to approximately 29 days per year or 8% of the year). The main shipping channels in the English Channel, Southampton Water and the central and eastern Solent exceed this threshold for very long periods (more than 5,000 hours per year which equates to approximately 208 days per year or 57% of the year).

Figure 4: Hours that mean noise levels exceed 100dB re 1µPa m in the south marine plan areas.

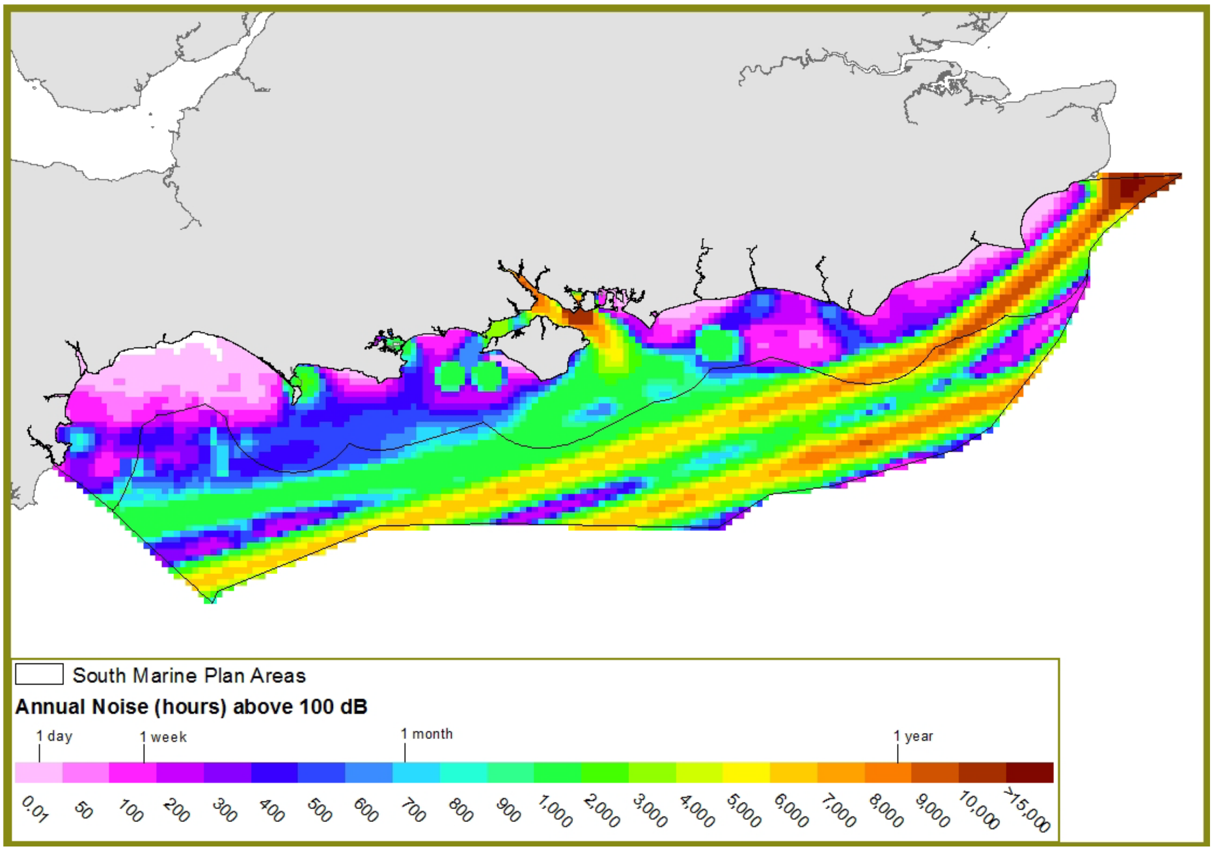


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Figure 5: Hours that mean noise levels exceed 130dB re 1µPa m in the south marine plan areas.

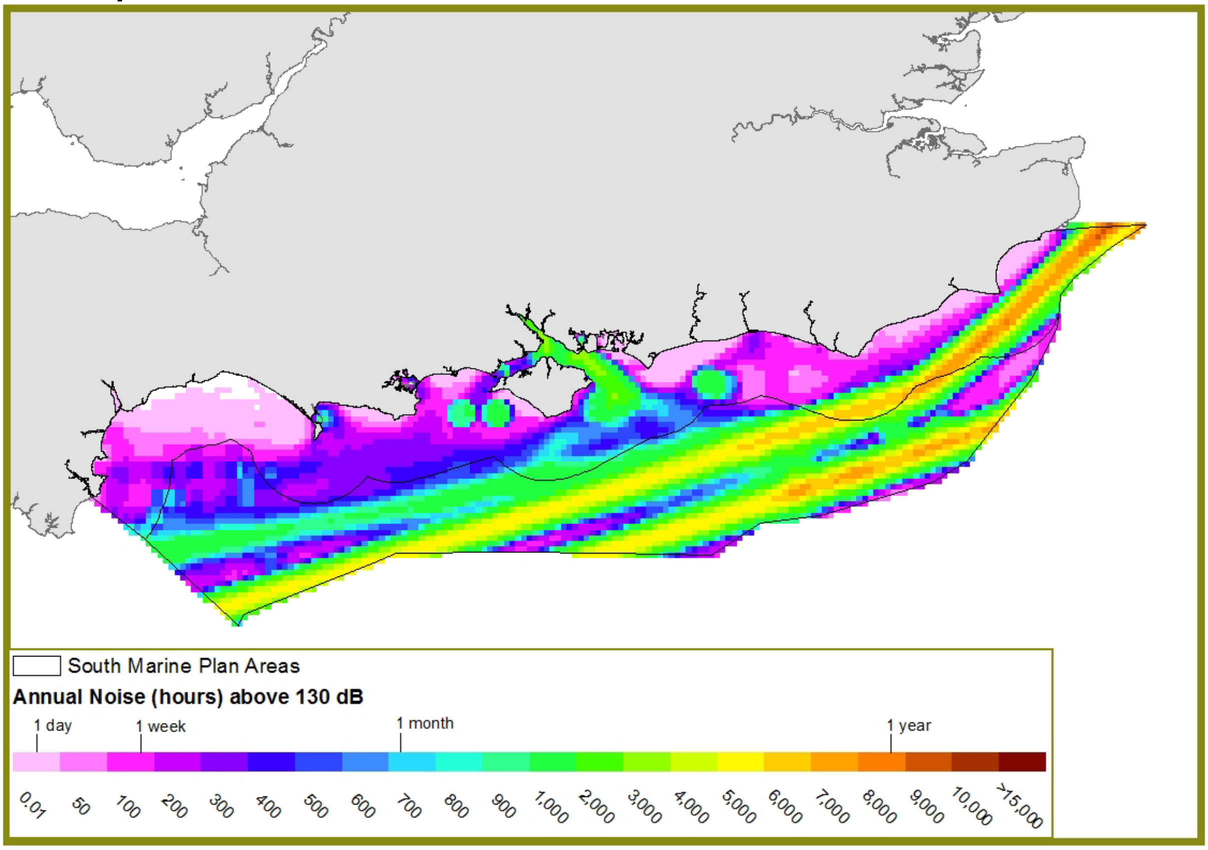

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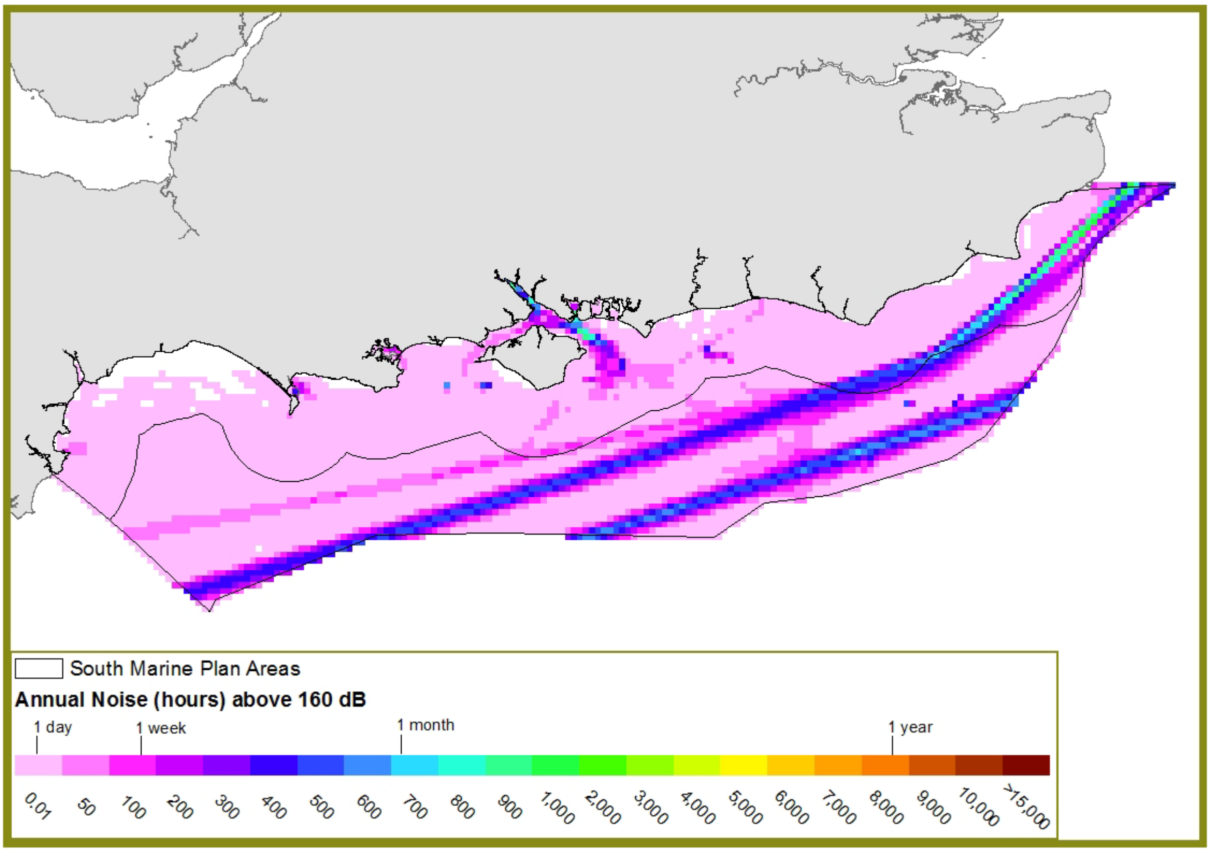
Figure 5 shows the time (in hours) that typical (mean) noise levels in each grid cell exceed 130dB re 1µPa m over a year. This threshold was chosen to approximately represent the level at which a mild behavioural reaction could potentially occur in fish with sensitive hearing (i.e. Atlantic cod and herring). This ecological threshold is exceeded for relatively long periods of time (i.e. more than 900 hours per year which is equivalent to around 10% of the year) within and close to main shipping routes, as well as a few isolated spots where aggregate dredging occurs (e.g. East and West of the Isle of Wight). Outside of these areas, the ecological threshold is only exceeded for relatively short periods of time (i.e. less than 300 hours per year which is equivalent to around 3% of the year).

Figure 6 shows the time (in hours) that typical (mean) noise levels in each grid cell exceed 160dB re 1µPa m over a year. This threshold was chosen to characterise high levels of noise which are limited to the main shipping routes in the English Channel, Southampton Water and the central and eastern Solent, as well as a few small isolated spots related to aggregate dredging in the south marine plan areas.

Figure 6: Hours that mean noise levels exceed 160dB re 1µPa m in south marine plan areas.



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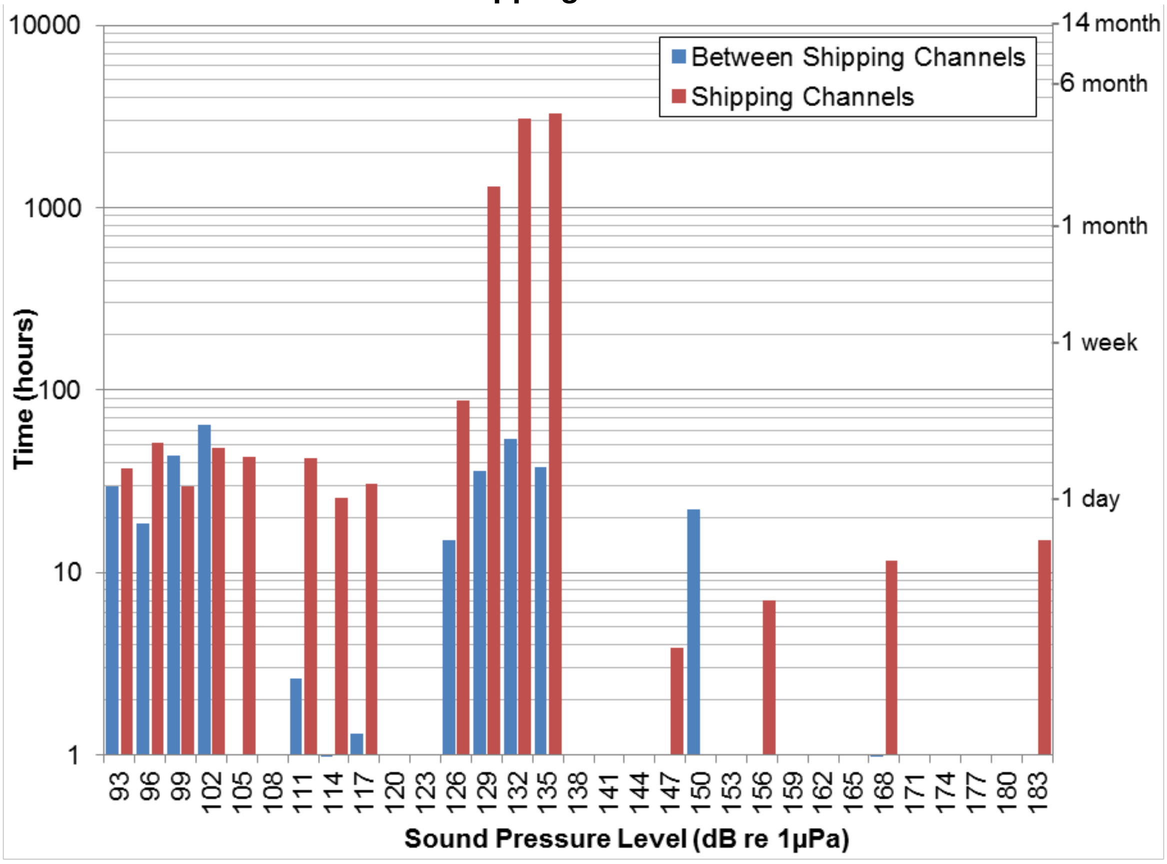
The GIS tool has also been used to generate histograms of the time (in hours) that all noise sources occur in a year in 3dB bands in a grid cell within and another grid cell between the main shipping channels (Figure 7). This figure shows that there are higher levels of noise inside the shipping channel comprising various vessels and also propagated noise from adjacent cells compared to between the shipping channel.

Figure 7: Time (in hours) that noise levels occur in a year at a given grid cell within and between the main shipping channels.

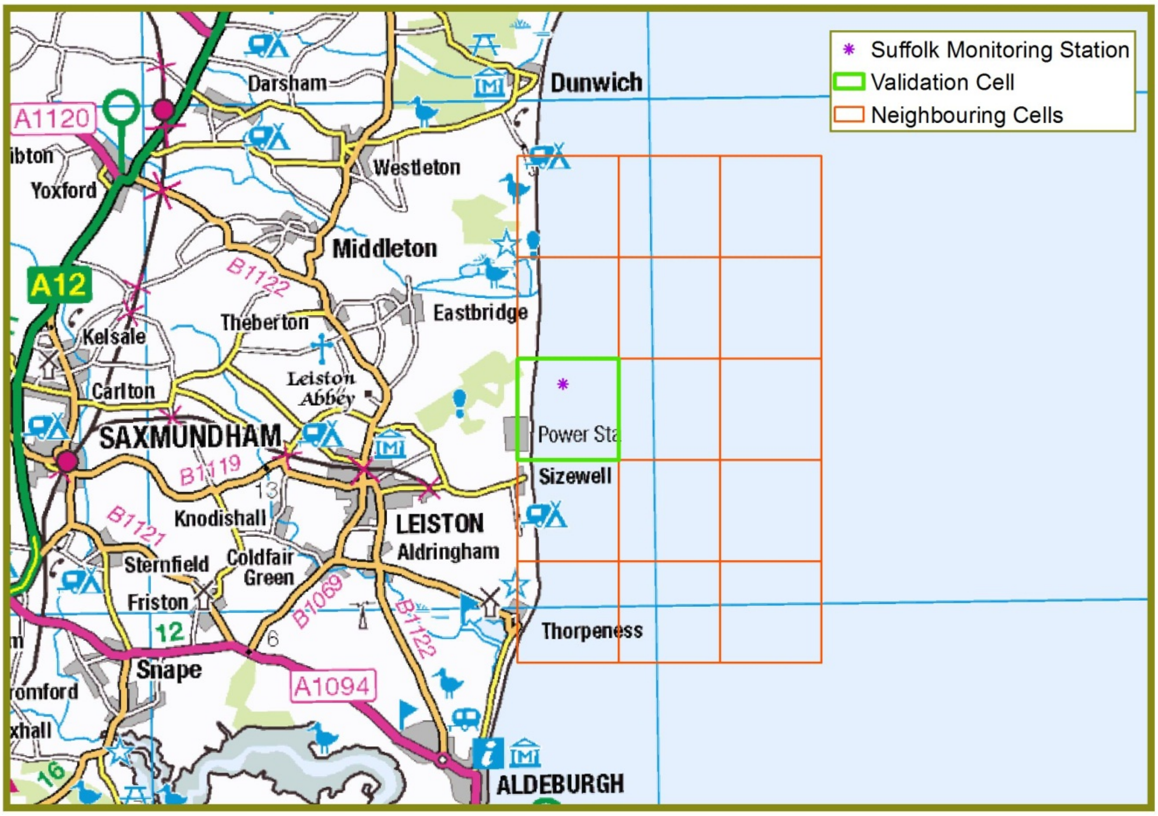


5.1 Validation

In order to develop an accurate and credible model, it is important to validate modelled outputs against actual data where possible. Models are approximate simulations of real-world systems and they never exactly imitate the real-world system. Due to that, a model should be verified and validated to the degree needed for the models intended purpose or application (Sargent, 2011).

Continuous ambient underwater noise data from one location sited 550m offshore of the Suffolk coast were provided by Cefas with kind permission of EDF Energy (Figure 8). The monitoring data have been used to validate the outputs of the GIS tool. There are two weeks available in which the monitoring data coincide with the period available for the AIS data (3 to 9 January 2012 and 1 to 7 November 2012). Continuous ambient noise data recorded at the monitoring station have been processed and analysed in 1/3-octave bands. The frequency bands (63 and 125Hz) recorded during these two weeks at the monitoring station were extracted from the monitoring dataset. Frequency histograms in 3dB bands were then plotted to compare the noise monitoring data with the GIS tool output data at the relevant grid cell comprising the monitoring station (Figure 9 and Figure 10).

Figure 8: Location of underwater noise monitoring station in Suffolk.



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The monitoring data indicate that the variability in noise levels at the Suffolk site was relatively low, particularly at 63Hz. There were a number of noise sources contributing to ambient noise at this location, including shipping and the Sizewell Nuclear Power Station. The 1 to 7 November 2012 dataset suggests that the power station was elevating noise levels, particularly in the 63Hz band.

By comparing the measured noise levels of the monitoring data to those predicted by the GIS tool it appears that the GIS tool is overestimating the magnitude of noise levels at that location (Figure 9 and Figure 10). There are a number of possible reasons for this. Typical source levels that have been used to represent anthropogenic activities in the GIS model cover such a wide variability that they may not always represent reality. It is also possible that the propagation of noise in the GIS tool is under-representing attenuation and thus overestimating received levels.

Figure 9: Frequency histograms of measured and modelled noise levels at monitoring station in Suffolk, 3 to 9 January 2012.

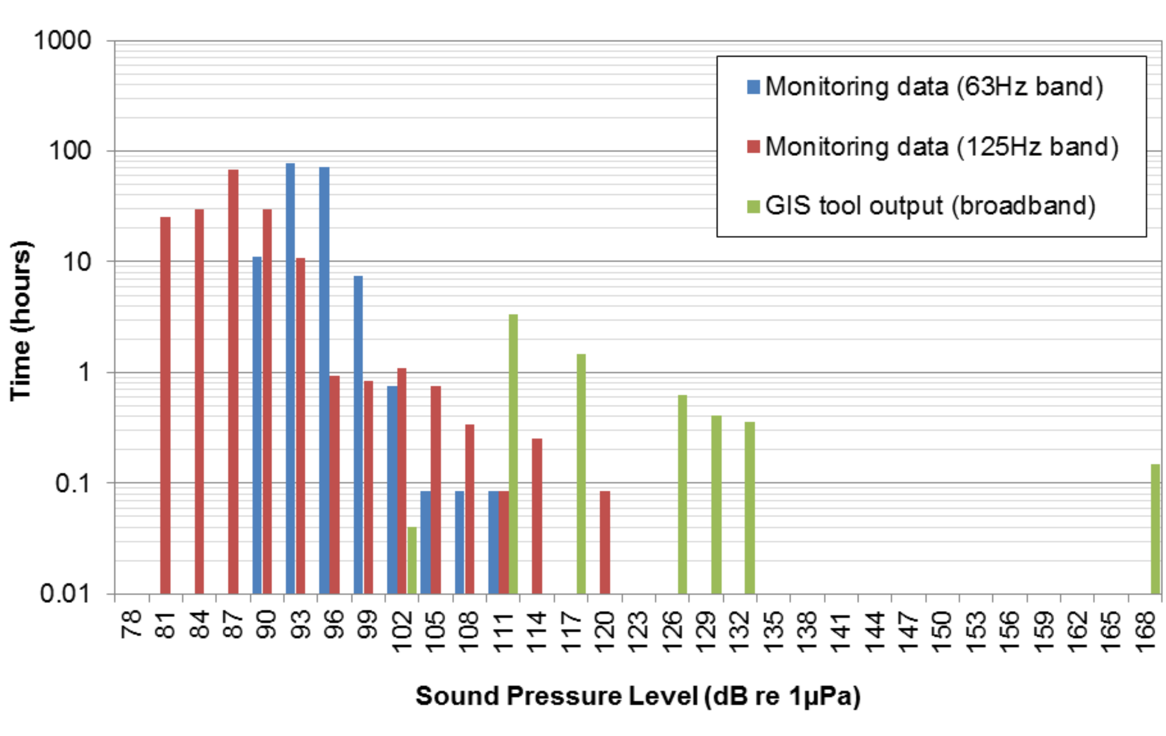
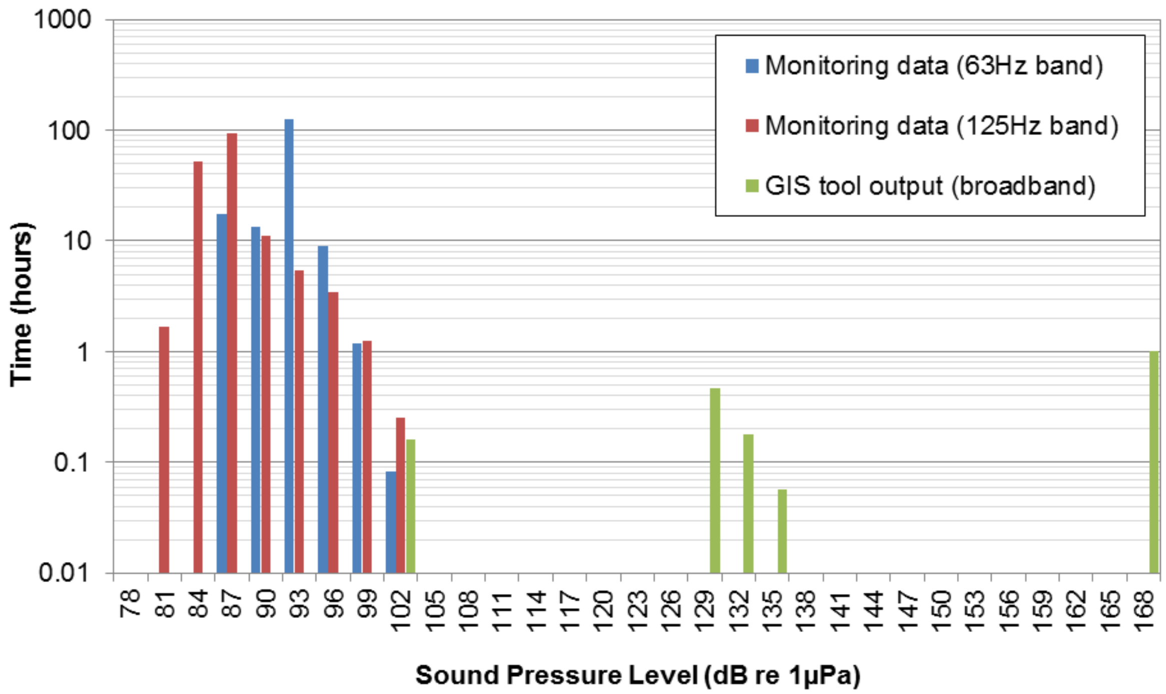
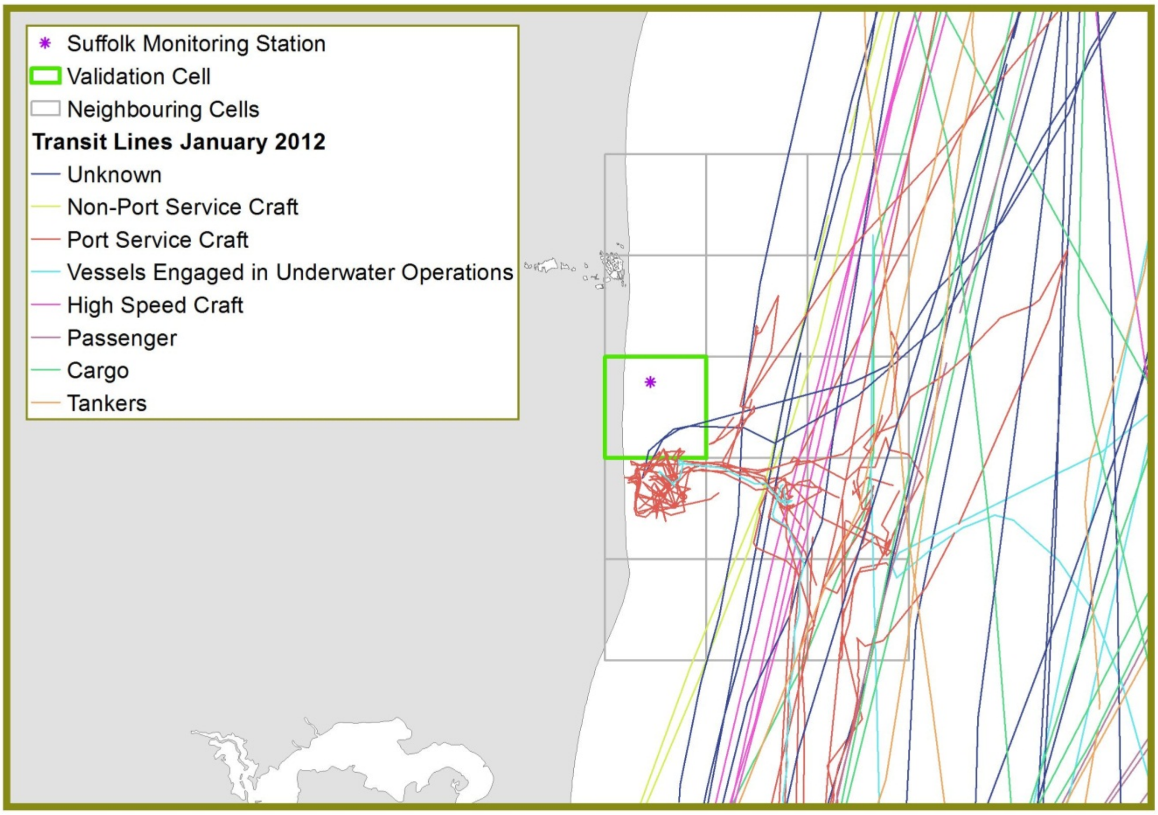


Figure 10: Frequency histograms of measured and modelled noise levels at monitoring station in Suffolk, 1 to 7 November 2012.



The duration of noise in each 3dB band appears to be poorly represented in the GIS tool. The actual AIS transit lines during the two week periods have been plotted to help clarify why the GIS tool might be misrepresenting the magnitude and/or the duration of noise (Figure 11 and Figure 12).

Figure 11: AIS transit lines at the monitoring station in Suffolk, 3 to 9 January 2012.



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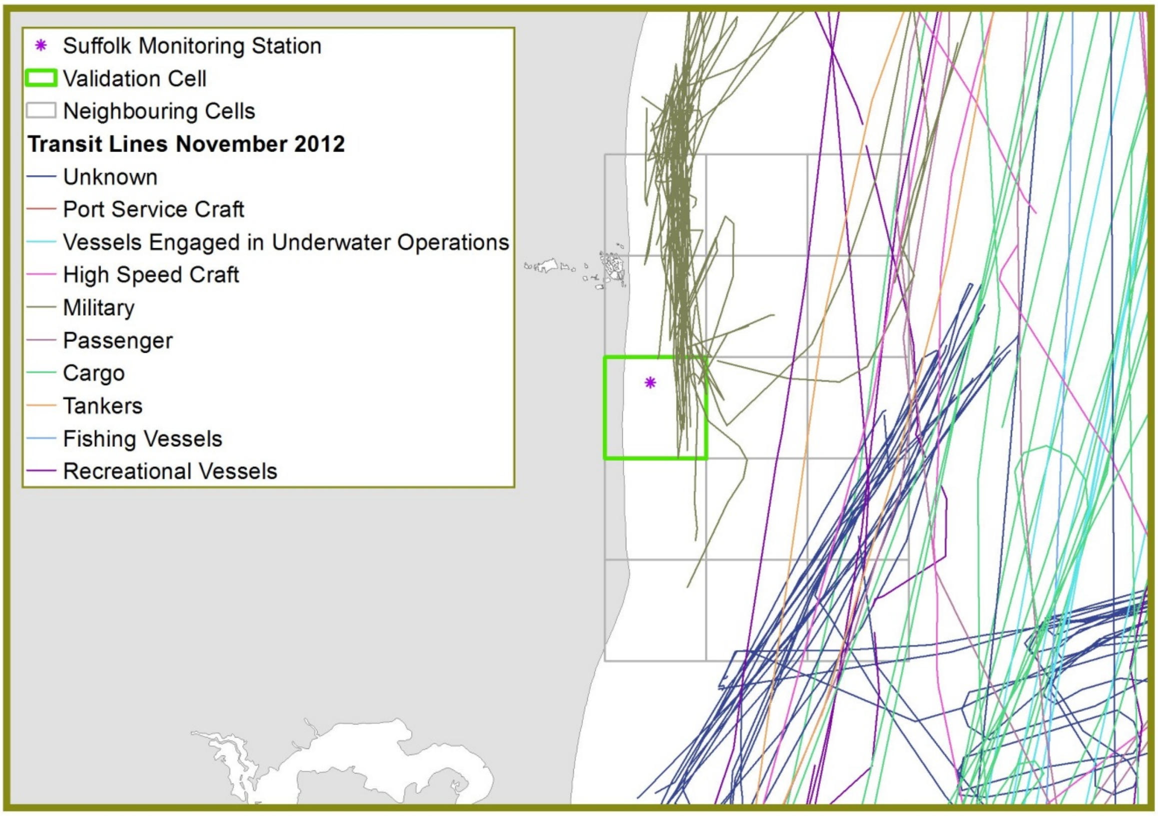
During 3 to 9 January 2012, there were vessels within close proximity to the monitoring station from the Ship Type Groups: Port service craft; Unknown; and Vessels engaged in dredging or underwater operations. The GIS tool includes port service craft vessels and dredgers but not unknown vessels. Unknown vessels are those that have not had a ship type entered into the AIS metadata. This could be any type of vessel although it is most likely to be smaller vessels that are not legally required to carry an AIS receiver but do so on a voluntary basis, and are usually not set up properly to record information (e.g. ship type). These smaller vessels are likely to generate relatively low levels of noise in the low frequency bands of interest compared to larger vessels.

The general pattern recorded at the monitoring station and predicted by the GIS tool are broadly similar. The main spread in noise levels comprise around two orders of magnitude (81 to 114dB bands in the monitoring data and 102 to 132dB bands in the GIS tool). The choice of source levels used in the GIS tool may be the main reason for the approximately 20dB difference in the magnitude of actual and modelled noise levels. There is an outlier in the GIS tool data at the 168dB band (Figure 10). This outlier corresponds to the source level of the port service craft vessel. The AIS transit lines indicate that this vessel was located on the edge of the 2km grid and therefore actually approximately 1.5km from the monitoring station. The levels that would have been recorded at the monitoring station would have been significantly lower than the actual source level. The use of a 2km grid resolution in the GIS tool has therefore also contributed to the overestimation of noise levels.

Figure 12: AIS transit lines at the monitoring station in Suffolk, 1 to 7 November 2012.



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During 1 to 7 November 2012, vessels from the Ship Type Group: Military or law enforcement were recorded close to the monitoring station. The GIS tool, however, does not include military vessels given the lack of source level data available in the literature for these vessels and this may in part explain the difference in actual and predicted noise levels. The elevated noise levels recorded at the monitoring station in 1 to 7 November 2012 dataset are also considered to be due to the power station. Noise sources from activities taking place on land (e.g. nuclear power stations, landside port operations) are not included in the GIS tool and therefore the outputs of the GIS tool may be underrepresenting these additional contributions to underwater ambient noise.

It is also important to note that the VMS fishing spatial data layer does not overlap with the grid cell in the GIS tool that corresponds to the monitoring station or the adjacent neighbouring cells that propagate noise into that validation cell. In any case, the VMS fishing data that have been made available for this project is from 2011 which does not coincide with the two weeks in 2012 of monitoring and AIS data. No aggregate dredging occurs in the vicinity of the monitoring station and for this reason the EMS spatial data layer was not required to be included in the validation exercise.

The monitoring station that was used to validate the outputs of the GIS tool was in hindsight not the most suitable site given that it was not located close to a shipping lane and did not overlap with VMS fishing and EMS aggregate spatial data layers. Further validation of the GIS tool using available monitoring data from a range of locations is, therefore, an important recommendation for further work (Section 6).

5.2 Confidence

The sources levels that have been used to characterise different activities in the GIS tool are considered to be the greatest uncertainty in the model input data. This is due to the very large (usually several orders of magnitude) variation in source levels of different noise activity categories in the literature. This variation may be due to a number of reasons, including the different transit conditions of individual vessels (McKenna *et al*., 2013). A discussion on the potential limitations associated with all the data sources which may contribute to some of this variability is provided in Section 2.4. A confidence level (high, medium or low) was assigned to the source level data based on any limitations and/or constraints associated with the data (Table 1).

There are uncertainties associated with the AIS data that have been used to underpin the GIS tool. Whilst AIS information provides an accurate representation of the received data, it is what ‘is not’ received that provides the greatest limitation (MMO, 2014). AIS-A provides characterisation of commercial shipping (AIS-A) but misses the bulk of non-AIS vessels, including commercial vessels below 300 GT, recreational vessels and fishing vessels. Further limitations of AIS data relate to the quality of the received records, where potential sources of error exist within the data. For example, AIS transponders may be switched on or off during a ship’s passage or be defective, thereby not capturing the full transit. In addition, errors with the vessel associated AIS positioning system can provide inaccurate locations. Voyage data are largely user entered, and therefore has inherent limitations due to operator error or misrepresentation of information. AIS-B is a non-mandatory form of AIS typically used by small commercial craft, fishing vessels and recreational vessels. To prevent overloading of the available bandwidth, transmission power is restricted, giving a smaller range of up to 10 nautical miles. Information regarding use patterns by these types of craft from AIS sources alone will therefore significantly underplay the true frequency and use patterns (MMO, 2014).

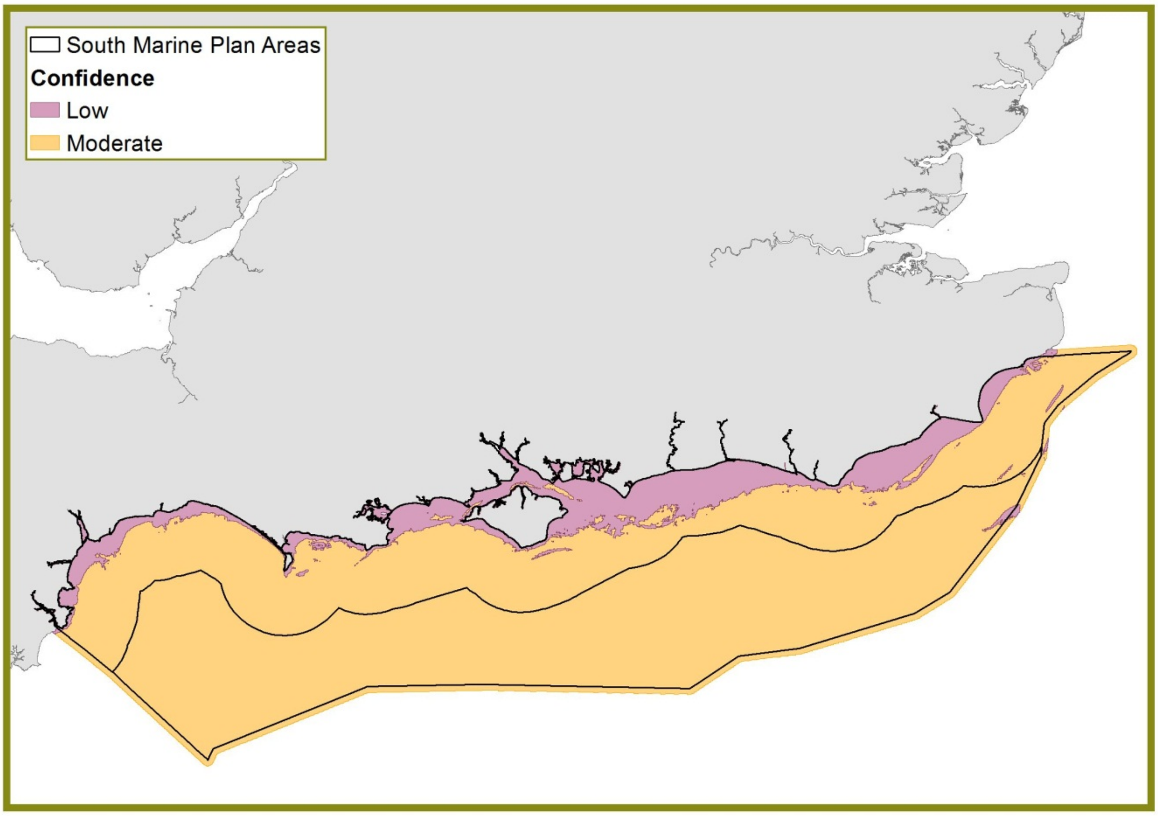
The manner in which the source level has been represented in the grid cell could be overestimating the spatiotemporal distribution of actual noise levels given that a core assumption of the model is that all noise sources within each model cell occur independently of one another. However, this was considered a reasonable way of representing the spatial data layers given the lack of information on the precise timing of the various anthropogenic noise sources.

Assumptions have been made on the time that a vessel spends within a cell in order for the GIS tool to represent the temporal distribution of vessel noise categories. The calculation is based on the average speed of vessels and average transit distance

(1.5km) within one cell of the south marine plan areas. This approach is considered to provide a reasonable estimate of the duration of noise sources within an individual cell associated with these vessels.

The limitations associated with the recommended practical spreading model (Equation 7) that has been used to represent transmission loss in the GIS tool are discussed in Section 3.4. Figure 13presents a visual representation of the level of confidence (medium and low) associated with this propagation model as a physical data layer. A high confidence level has not been assigned given the limitations associated with this simple model. This visual representation of confidence is based on bathymetry given that the propagation model does not take account of reflection and refraction (which are more predominant in shallow water). Areas that show a low confidence in the propagation model therefore correspond to greater uncertainty in received levels in shallow water (less than 20m) compared to deeper water (more than 20m). Areas of low confidence (where water depth is less than 20m) comprise all constrained areas of the coast, including shallow inlets and bay.

Figure 13: Level of confidence in the noise propagation model applied to the GIS tool.



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6. Recommendations for Further Work

Where it has not been possible to incorporate specific elements in to the GIS tool due to the limitations of time and resources, recommendations on priorities for further development of the model and how this might be achieved are considered in this section. There are a number of simple improvements that could be made to the GIS tool. These are as presented in Table 4.

Table 4: Simple improvements that can be made to GIS tool.

Improvement	Requirements
Further validation of the GIS tool using available monitoring data from a range of locations.	• Access to existing monitoring data that are suitable for validation of GIS tool • Processing of AIS data.
Updating the catalogue of noise source levels for the different noise categories and refining the typical source levels that are used to underpin the GIS tool.	• Collating new source level data
Applying different source levels to represent low vessel speeds in areas where there are speed restrictions and high vessel speeds outside of these areas. This could initially be crudely represented by applying the lower speed to all harbour areas and further refining the model once more site specific spatial information is available.	• New spatial data layers on vessel speed restrictions • Build a new step into the GIS tool to apply multiple noise levels to one spatial data layer.
Using common years for all the spatial data layers used in the GIS, as well as averaging across multiple years where data are available.	• New spatial data layers on VMS fishing • Obtaining spatial data layers on EMS aggregate dredging • Processing AIS spatial data.
Including the noise generated by structures (e.g. offshore wind turbines, oil and gas installations) that are not currently present in the south marine plan areas but may be relevant to other plan areas.	• Adding new noise categories in the GIS tool.
Including recreational craft once improved spatial data layers become available.	• New and improved spatial data layers on recreational vessels • Adding a new noise category in the GIS tool.

Improvement	Requirements
Including non VMS fishing data once spatial data layers become available.	• New spatial data layers on non VMS fishing • Adding a new noise category in the GIS tool.
Including low frequency sonar should this information become publicly available, although it is arguably a source of impulsive rather than continuous noise.	• New spatial data layers on low frequency sonar • Adding a new noise category in the GIS tool.

The final recommendation is considered to be particularly valuable. The Suffolk monitoring station that was used to validate the GIS tool in this study was in hindsight not the most suitable given that it was not located close to a shipping lane and did not overlap with VMS fishing and EMS aggregate spatial data layers. It may be possible to access data from projects such as an offshore wind farm development where underwater noise monitoring has been conducted. Alternatively, it would also be possible to identify a range of locations with good underwater noise monitoring data from Cefas and acquiring the AIS data for the corresponding time period. It would be relatively low cost to process a small amount of AIS data in the relevant grid cells.

With significant further investment it would also be possible to produce a more sophisticated GIS tool that incorporates the following elements:

- A more refined propagation model that takes account of environmental parameters (e.g. bathymetry, absorption in water and seabed, temperature).
- A GIS tool based on the original AIS transit line information rather than the density grid. This would provide the precise timing of vessel noise sources and allow consideration of the combined impact of two or more noise sources rather than assuming that noise sources within a cell occur independently of one another.
- A more highly resolved grid resolution that is greater than 2km x 2km.

However, as has been evident from running the current simple tool that has been developed for this study, there would be significant computational constraints in the required processing power that would need to be overcome in any future tool development. Furthermore, the large variability in reported source levels for different noise categories already places a very large uncertainty in the outputs of the GIS tool. A further limitation is the paucity of noise source level data for a number of the noise categories.

Until it is possible to accurately model and predict the variation in source levels, it is not considered reasonably practical to expend the necessary significant time and effort to refine these other aspects of the GIS tool. These improvements are likely to be well within the boundary of the variation in source levels and therefore inconsequential to the actual outputs.

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