

Article

Underwater Noise Mapping of Small Vessels Without Automatic Identification System Transmitters

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Abstract

Anthropogenic underwater noise impacts marine life across many taxa and life stages. Underwater noise mapping is an important tool in estimation and mitigation of this impact. The present study develops a framework for noise mapping of continuous underwater noise from vessels without Automatic Identification System (AIS) transmitters. The framework is applied to a study area in the Kosterhavet Marine National Park on the Swedish west coast. A geographical density of small vessels, estimated from satellite observations, is used to predict underwater noise levels. Source levels are estimated by refining a recently published source model for small vessels. Extensive propagation loss measurements support development of a semi-empirical propagation loss model. Predicted noise levels display good agreement with measured levels at two sites, while at two other sites, levels are underestimated, likely due to failure to resolve local boat density variations and insufficient consideration of local bathymetry. Our results show that underwater noise mapping of small vessels without AIS transmitters is feasible, and that levels of underwater noise due to small vessels significantly exceed the natural background noise in our study area. Furthermore, the framework is used to demonstrate the effectiveness of enforcing local speed regulations in reducing underwater noise levels.

Keywords: underwater noise; small vessels; noise mapping

1. Introduction

Anthropogenic underwater noise is widely recognised as a pervasive stressor in marine environments. Over recent decades, increasing contributions from maritime activities have altered coastal and offshore soundscapes at regional and global scales [1–4]. These changes have the potential to affect the behaviour and physiology of aquatic life across a wide variety of taxa and life stages [4].

Underwater noise mapping has emerged as a structured methodology for quantifying spatial distributions of anthropogenic sound. Similar to terrestrial environmental noise mapping, underwater noise mapping integrates (i) spatially resolved source information, (ii) source level characterisation, and (iii) acoustic propagation modelling to estimate received sound levels across defined spatial grids [5–7]. Commercial shipping is widely recognised as the dominant source of continuous anthropogenic underwater noise on a global scale. Ship underwater noise mapping is a mature technology, using vessel



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position and characteristics from the Automatic Identification System (AIS) with empirical or semi-empirical source models for estimating ship source levels as functions of vessel parameters [8,9]. Combined with numerical or semi-empirical propagation models, this has enabled large-scale shipping noise maps [5,10,11].

While commercial shipping has received substantial attention, recreational boating activity has rarely been incorporated into spatial noise mapping frameworks. In this study, the terms “boat”, “small vessel”, and “recreational vessel” are used interchangeably. In many sheltered coastal and archipelagic environments, however, recreational vessels dominate vessel density during peak seasons. Hermannsen et al. [12] showed that vessels without AIS transponders—primarily recreational boats—were responsible for the majority of measured anthropogenic noise in a shallow Danish marine area. Similarly, Wilson et al. [13] quantified sound levels generated by small recreational boats in shallow coastal habitats and demonstrated that even relatively low-powered vessels can produce received levels sufficient to mask biologically relevant signals. Several studies have shown that motorboat underwater noise can have a negative impact on different taxa, including several fish species [14–16] and harbour porpoises [17,18].

Underwater noise mapping for small vessels is associated with several challenges. First, recreational vessels are not required to have AIS transmitters, and many choose not to carry them, likely due to the additional cost and licence requirements. Dedicated positioning is necessary for accurate underwater noise mapping and can be accomplished in several different ways, e.g., using satellite observations [19], a theodolite [12] or cameras [20]. Second, the established mapping framework requires a model that can predict source levels. There are several well-established source models for large commercial vessels, e.g., the Wittekind model [8] and the Echo-Jomopans model [9]. These models predict source levels as functions of vessel parameters such as length, speed, and vessel category. While source levels of recreational boats have been reported [21–23], the development of empirical source models has not progressed as far. Recently, the first source level modelling framework for small vessels was published [24]. Third, recreational boating activity is concentrated in shallow and coastal environments where sound propagation is strongly influenced by bathymetry, shoreline geometry, and bottom properties [25]. In addition to depth-related effects, coastal geometries with islands and curved shorelines may introduce diffraction and shadowing effects.

This study develops methodology for spatial noise mapping in a coastal case study area on the Swedish west coast, where the soundscape is dominated by small vessel traffic. The method and results can be used to estimate small vessel noise contributions critical for environmental assessments and management decisions in coastal areas, and to enable comparisons to other noise sources.

2. Material and Methods

This section first describes the method developed to perform noise mapping for small vessels, in Sections 2.1–2.3. These more general sections are followed by a description of the case study (Section 2.4), and two sections on more site-specific semi-empirical models (Sections 2.5 and 2.6). Section 2.7 details how the model results were compared to in situ measurements, and finally, Section 2.8 describes the modelled noise management scenarios.

2.1. Noise Mapping Based on Vessel Density

This study represents the spatial distribution of small vessels statistically using a vessel density field. Noise mapping based on spatial density estimation is not commonly used, but was recently employed to make large vessel underwater noise maps [10]. Inherent in this methodology is that it only estimates average sound pressure levels. This section

describes the vessel density-based mapping framework, which is based on a vessel density map that is estimated from observed snapshots of vessel locations (see Section 2.2).

Let $\rho(\mathbf{x})$ denote the expected number of vessels per unit area at location $\mathbf{x}$. This quantity represents a temporal average over the observation period. Using $\rho(\mathbf{x})$ and making simplifying assumptions on homogeneity, expected underwater noise levels can be predicted as follows.

Consider a spatial grid $\mathbf{x}_{i,j}$ in which each cell has area A . Assuming that A is small enough that the vessel density is approximately constant within each cell, the expected number of vessels $N_{i,j}$ in cell (i, j) is

$$N_{i,j} = \rho(\mathbf{x}_{i,j})A, \quad (1)$$

where $\rho(\mathbf{x}_{i,j})$ is the vessel density within the cell.

With the assumption that the vessels within a cell act as multiple independent (and uncorrelated) sources, we can represent them by an average source level $L_{s,(i,j)}(f)$, where f is the frequency. This source level, expressed as a power spectral density [dB re $1\mu\text{Pa}^2\text{m}^2\text{Hz}^{-1}$], is location-dependent when seen over the entire map but assumed to be sufficiently constant within each grid cell (see Section 2.3). Each grid cell is then treated as an equivalent acoustic source representing the expected contribution from all vessels within that cell, $L'_{s,(i,j)}(f)$:

$$L'_{s,(i,j)}(f) = L_{s,(i,j)}(f) + 10\log_{10}(N_{i,j}). \quad (2)$$

Note that the equivalent source level of a grid cell depends on the area of the cell, since the expected number of vessels in a cell is proportional to the cell area. If the cell area is halved, the expected number of vessels in the cell is halved, and the equivalent source level is reduced by 3 dB. This is compensated by the fact that in a given study area, the number of cells is doubled, so the total radiated power from all cells is unchanged. Variations in vessel density and source level at finer scales than the grid resolution are not resolved. The acoustic power transmitted from source cells different from the receiving cell is considered to radiate from the centre of the source cell. For source cells far from a receiver, this simplification has negligible effects.

When computing radiation from a cell to itself, considering all the source power in the cell to be located at the centre of the cell would greatly decrease the propagation distances for a large portion of the source power within that cell. This would artificially increase the received levels considerably. To alleviate this issue, a subdivision process is applied when computing the radiation from a cell to itself. The cell is split into a smaller 8×8 grid, and each of those subcells is allocated $1/64$ of the source power of the original cell. An 8×8 grid was selected following an evaluation of increasingly fine grid subdivisions for a range of test cases. Relative to simulations using very fine subdivisions, the 8×8 grid typically resulted in errors below 0.5 dB.

The propagation from each of the subcells to the centre of the cell is computed as for any other cell, but using the centres of the subcells as the source positions. All the power radiated from the 64 subcells and received in the centre of the original cell is added to form the contribution from a cell to itself.

The sound pressure power spectral density $L'_{p,(i,j,k,l)}(f)$ at receiver position $\mathbf{x}_{k,l}$ due to noise radiation from small vessels at position $\mathbf{x}_{i,j}$ can be computed as

$$L'_{p,(i,j,k,l)}(f) = L'_{s,(i,j)}(f) - PL_{i,j,k,l}(f), \quad (3)$$

where $PL_{i,j,k,l}(f)$ is the propagation loss from the centre of cell (i,j) to the centre of cell (k,l) at frequency f .

The total sound pressure power spectral density $L_{p,(i,j,k,l)}(f)$ at the receiver position $\mathbf{x}_{k,l}$ is then obtained by adding the contributions from all grid cells and the natural background noise $L_{bg}(f)$:

$$L_{p,(k,l)}(f) = 10 \log_{10} \left(\sum_{i,j} 10^{L'_{p,(i,j,k,l)}(f)/10} + 10^{L_{bg}(f)/10} \right). \quad (4)$$

Here, the background noise $L_{bg}(f)$ is assumed to be constant across the study area and is predicted according to Equation (22).

2.2. Satellite-Based Vessel Density Estimation

This study uses satellite images to estimate vessel density due to their excellent area coverage and low costs. The approach is based on detecting individual boats using classical image processing techniques. For a recent review of satellite-based monitoring of small boats; see [19].

Copernicus Sentinel-2 optical images with ground resolution of approximately 6.5 to 12.7 m per pixel and a revisit frequency of 2–3 days in Northern Europe were used in this study. These images come with associated land and cloud masks, which were used to immediately discard images with more than 20% cloud coverage. This means that the density map (and the resulting noise map) represents similar situations, e.g., fair weather. The land masks were dilated to properly exclude detections of objects on land or at the immediate waterline.

Each satellite image was processed in 250×250 pixel segments, applying Canny edge detection [26] to a greyscale version of the image. This produced an outline of objects that differ from the image background. These outlines were filled using a morphological closing approach, then dilated to merge adjacent detections. Objects that did not overlap the land or cloud masks were stored individually for each image.

Objects consistently detected in the same location across different images were removed, leaving only moving objects and removing stationary detections such as rocks and small islets. Finally, large objects with an area above 500 pixels (roughly 20,000 m²) were removed, since they are unlikely to be marine vessels in this region.

If a vessel moves around the study area and is detected in multiple images, each detection is counted separately. This is consistent with the definition of vessel density, which is the expected number of vessels per unit area. The vessel density map represents the average number of vessels in the area at any given time, rather than the number of unique vessels.

To produce a proper boat density, the individual detections from all the images were used as the input to a kernel density estimation. Kernel density estimation is a non-parametric method for estimating the probability density function of a random variable from a finite set of independent and identically distributed observations, without assuming a specific parametric form for the underlying distribution [27].

Defining the locations of M detected vessels in the I images as $\hat{\mathbf{x}}_m = (\hat{x}_m, \hat{y}_m)$, $m = 1, \dots, M$, the vessel density estimator $\rho(\mathbf{x})$, $\mathbf{x} = (x, y)$, is computed as

$$\rho(\mathbf{x}) = \frac{1}{2\pi Ih^2} \sum_{m=1}^M \exp \left[-\frac{(x - \hat{x}_m)^2 + (y - \hat{y}_m)^2}{2h^2} \right]. \quad (5)$$

A Gaussian kernel function is used, and $h > 0$ is a smoothing parameter known as the bandwidth. Here, a bandwidth of 1000 m was selected based on visual inspection of the resulting density map.

2.3. Small Vessel Underwater Noise Source Level Modelling

In a recent study, separate source models for small vessels of different hull types were developed [24]. These measurements were made in different locations across southern Sweden and are considered relevant and representative for the current study area. It is not possible to estimate the hull type from the relatively low-resolution satellite images employed here, so these models cannot be used as is. Instead, a source model for all small vessels regardless of hull type is developed using the same framework. This study uses the simple parametric model developed in [24] for a compact formulation. The averaged source level spectra per vessel speed reported in [24] are fitted to an equation of the form

$$L_s(f, v) = K - 10 \log_{10} \left[\left(1 - \frac{f}{f_c(v)} \right)^2 + D^2 \right] \quad (6)$$

where

$$f_c = av_1^b \quad (7)$$

and

$$v_1 = v_0 - \log(1 + e^{v_0 - v}). \quad (8)$$

In the above equations, f is the frequency and f_c is a speed-dependent corner frequency. $D = 3$ is a parameter that controls spectral shape around the corner frequency. v is the vessel speed (knots), and v_1 is a softmax function of speed, which allows the model to capture a weak speed dependence over a transition speed v_0 as reported for planing vessels [21]. The original source model developed in [24] used the vessel speed v in (7). K , a , b , and v_0 are parameters to be fitted. Here, K is the low-frequency source level, while a and b control the speed dependence of the corner frequency. These parameters were determined by least-squares fitting using the method `least_squares` from the Python SciPy library [28], which uses the Trust Region Reflective algorithm to solve nonlinear least-squares problems with bounds [29]. The employed bounds for the parameters were

$$\begin{aligned} 120 &\leq K \leq 180 \\ 0.1 &\leq a \leq 5 \\ 0.1 &\leq b \leq 5 \\ 0 &\leq v_0 \leq 30 \end{aligned} \quad (9)$$

and the initial values $[K, a, b, v_0] = [150, 2, 2, 15]$. The ranges of K , a and b were selected to cover the range of values reported in [24], while the range of v_0 was selected to cover the range of vessel speeds in that study, but was extended to 0 knots.

One important component in the source model is vessel speed. As stated, it is difficult to estimate vessel speed from the low-resolution satellite images employed in this study. Instead, a speed map is proposed. Vessels in a grid square were assumed to move at the same speed, which was modelled as a function of the distance to shore R as

$$v_{i,j}(R) = v_{\text{close}} + \frac{1}{2}(v_{\text{open}} - v_{\text{close}}) \left[1 + \tanh\left(\frac{R - R_0}{w}\right) \right], \quad (10)$$

where R is the distance to the nearest shore, v_{close} is the speed close to land, v_{open} is the speed in open water, R_0 is the distance at which the transition occurs, and w controls the width of the transition. The parameters were set to $v_{\text{close}} = 10$ kn, $v_{\text{open}} = 15$ kn, $R_0 = 500$ m, and $w = 200$ m. These parameters were chosen based on local knowledge of the study area, and should likely be chosen differently in other regions.

2.4. Case Study

The study was performed in a study area within Kosterhavet Marine National Park (NP) on the Swedish west coast; see Figure 1. Kosterhavet is Sweden's first marine NP, covering an area of 389 km², and is home to a varied landscape with a rich biodiversity. The park is also a popular spot for recreation and tourism, situated close to the border between Sweden and Norway. Much of the area is quite shallow, at depths below 20 m, with many small islets. This prevents commercial shipping traffic in the area, making recreational boating a dominant anthropogenic noise source. To the east of the main islands, there is a deeper trench, with depths reaching 200 m. The study area is approximately 13 km by 16 km, covering the main Koster Islands and the area surrounding them, including the main archipelago to the southwest of the main islands.

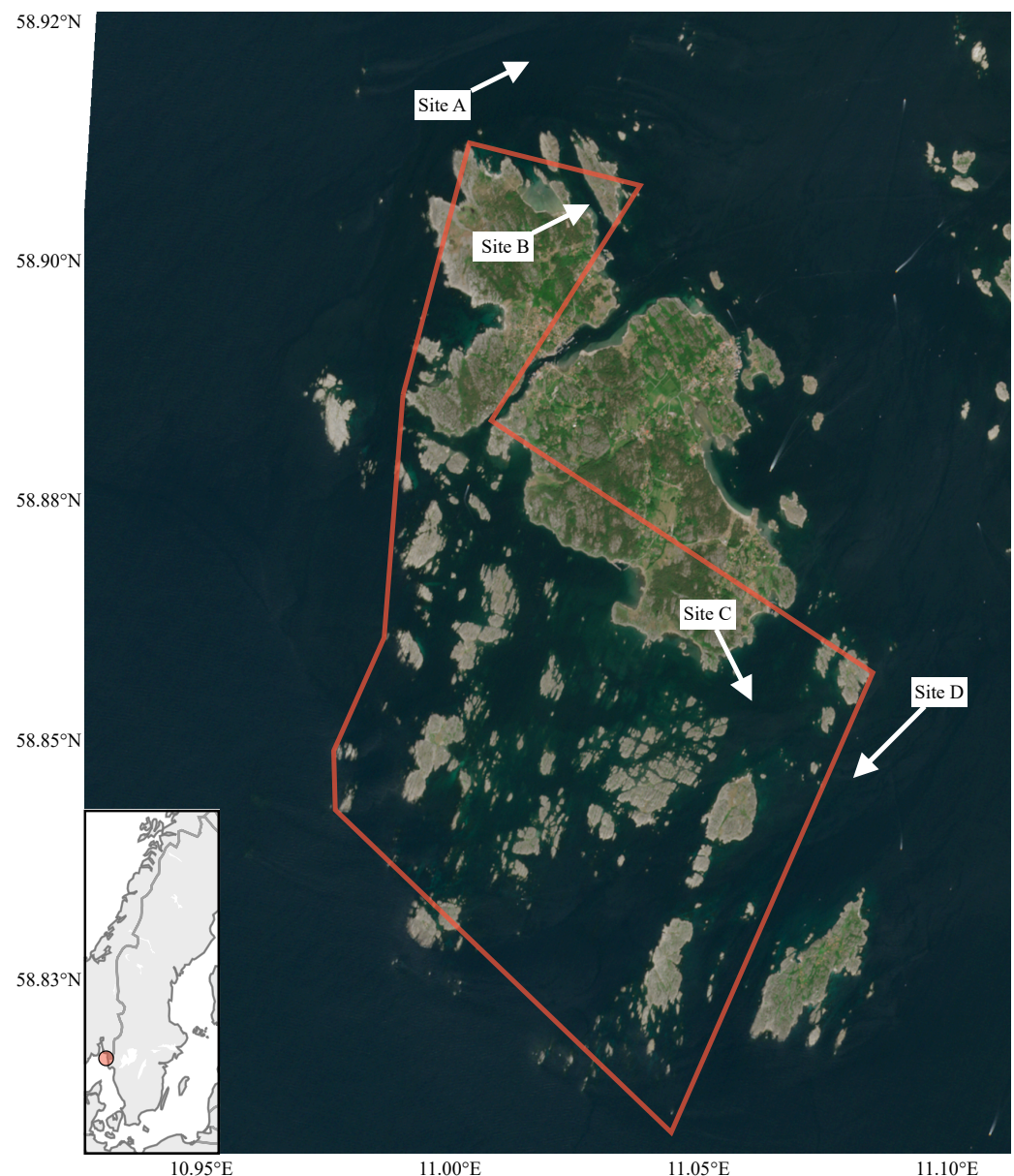


Figure 1. The Kosterhavet Marine NP study area and the 5 kn speed restriction zone (red). Locations of noise measurement sites are shown; see Section 2.7. The insert shows a map of Sweden, with the study area marked in red. Source: Copernicus Sentinel-2 data, 2023.

The study area also includes a speed restriction zone, where a maximum speed of 5 kn applies. In this restriction zone, the vessel speeds are capped at a maximum speed instead

of applying (10). Note that different scenarios (see Section 2.8) have different speed caps used in this zone.

The noise mapping is performed on a 250 m square grid, in the decidecade frequency bands from 10 Hz to 10 kHz.

The satellite images were captured between the 1st of June and the 31st of August, which is the peak boating season in the study area. Due to the schedule of the satellite, all the images were taken around noon. A total of 8 images of the study area, with less than 20% cloud coverage, was available during the selected time period. All images were from the year 2023. The vessel density map and the underwater noise map therefore apply to 2023.

2.5. Propagation Loss Measurements and Modelling

The Koster Islands study area has an archipelagic environment with many islands of different sizes, large depth variations and an underwater canyon reaching over 200 m deep. Understanding and describing the sound propagation in the study area is a challenging task. Many numerical models for underwater acoustic propagation introduce assumptions that may not be appropriate in this kind of environment, e.g., constant bathymetry or no backscattering of the acoustic energy [25]. Those that do not make assumptions are computationally demanding and will require detailed knowledge of boundary conditions. Further, while noise mapping for commercial shipping typically uses propagation loss models that work on straight lines between source and receiver, it is expected that the many small islands in the study area cause diffracted paths to be of relevance.

This study used a semi-empirical approach calibrated using in situ measurements, as suggested by [25]. The modelling approach is described first, and the later parts of the section describe the measurements and parameter estimation.

The propagation loss model used here has three parts: a spherical spreading component, a cylindrical spreading component, and a diffraction model using curved arc propagation paths. For propagation through open waters, the model is inspired by recent developments in propagation loss models for shallow water measurements of source levels [30,31]. By describing the propagation loss with a propagation factor $F = 10^{-PL/10}$, it can be written as a spherical spreading term F_{sph} and a cylindrical spreading term F_{cyl} :

$$F = F_{\text{sph}} + F_{\text{cyl}}. \quad (11)$$

The spherical spreading term includes the propagation paths that travel directly from the source to the receiver together with its reflection from the surface, i.e., the Lloyd mirror effect. If this effect is averaged in frequency, the spherical part can be written as

$$F_{\text{sph}} = \frac{1}{r^2} \left(F_{\text{sph, LF}}^{-1} + F_{\text{sph, HF}}^{-1} \right)^{-1} \quad (12)$$

where the low-frequency approximation $F_{\text{sph, LF}} = (2kd \sin \theta)^2$ and the high-frequency approximation $F_{\text{sph, HF}} = 2$ are mixed, with r being the source-receiver distance, k the wavenumber, d the source depth, and θ the observation angle below the sea surface. The cylindrical term can similarly be described as

$$F_{\text{cyl}} = \frac{1}{Hr} \left(F_{\text{cyl, LF}}^{-1} + F_{\text{cyl, HF}}^{-1} \right)^{-1} \quad (13)$$

where the low-frequency and high-frequency approximations are

$$\begin{aligned} F_{\text{cyl, LF}} &= (kd)^2 (2\psi_c - \sin(2\psi_c) - (2\theta_{\min} - \sin(2\theta_{\min}))) \\ F_{\text{cyl, HF}} &= 2(\psi_c - \theta_{\min}). \end{aligned} \quad (14)$$

Here, $\psi_c = \arccos(c_{\text{water}}/c_{\text{seabed}})$ is the seabed critical angle, $\theta_{\min} = \min(\psi_c, \arcsin(2H/r))$, and H is the water depth. Up to this point, the equations match those presented in [31], and we refer the reader there for further details. (Note that the form of $F_{\text{cyl,LF}}$ used here is the more accurate one found in the supplementary materials of [31].)

The above equations were originally intended for simple propagation loss modelling at relatively short ranges and flat seafloors. Propagation at longer ranges causes a number of acoustic effects not included in this set of equations. To handle this, additional parameters m and n for the range dependencies were added, following simple empirical models of the $M \log R$ -form that have been used in many studies [32,33]. This changes the spherical and cylindrical parts to

$$\begin{aligned}\tilde{F}_{\text{sph}} &= \frac{1}{r^{m/10}} \left(F_{\text{sph,LF}}^{-1} + F_{\text{sph,HF}}^{-1} \right)^{-1} \\ \tilde{F}_{\text{cyl}} &= \frac{1}{\tilde{H} r^{n/10}} \left(F_{\text{cyl,LF}}^{-1} + F_{\text{cyl,HF}}^{-1} \right)^{-1}\end{aligned}\quad (15)$$

where the *effective depth* $\tilde{H}$ has been introduced. Several equations for $\tilde{H}$ were tested, with separate parameter fits for each. The one which gave the best agreement between measurements and the model was

$$\tilde{H} = \frac{H_s H_r}{H_{\min}} \quad (16)$$

with H_s and H_r being the maximum water depth within 50 m of the source and receiver, respectively. $H_{\min}$ is computed by first finding the maximum water depth within 50 m at each point along the propagation path, then taking the minimum of those values. This is similar to earlier attempts at handling depth variations in a simple manner [34–36].

The propagation model is extended with propagation along curved arcs to account for diffraction around islands. For source-receiver paths that do not have a straight line path through open water, the conceptual idea is to

1. Find a curved path that avoids land.
2. Calculate the propagation loss along this path as if it were straight.
3. Add additional loss due to the curvature of the path.

The first step, finding a curved path, was done using a parameterised arc that was placed from the source to the receiver. These arcs were first constructed in a normalised coordinate system, so that every arc goes from $(\xi, \eta) = (0, 0)$ to $(\xi, \eta) = (1, 0)$. The arcs were parameterised using two parameters: the height γ and location α of the arc apex, i.e., the arc has its highest point at (α, γ) . The shape for these arcs was defined as

$$\begin{aligned}\phi(\xi) &= (1 - \alpha)\xi / ((1 - 2\alpha)\xi + \alpha) \\ \eta(\xi) &= 4\gamma\phi(1 - \phi)\end{aligned}\quad (17)$$

These normalised coordinates (ξ, η) were then transformed to the actual coordinates of the source and receiver. A search was performed over a range of values for γ and α . The geometry of the candidate arcs was successively adjusted with increasing curvature until one that did not cross land was found, considering both positive and negative γ and a range of values for α . The propagation loss was computed only along the first valid arc found, with the assumption that this straightest arc provided the dominant propagation path.

The propagation along the curved arc was first computed using the “flattened” geometry, e.g., ranges were computed from the arc length instead of the straight-line distance. In addition to these increased losses due to the geometrical changes, the sound will also be attenuated due to diffraction-like effects. In other words, it is expected that the propagation loss along these curved arcs is higher than the propagation loss along an actual straight

line with the otherwise same geometry. This was described by a loss factor F_{diff} , combined with the spherical and cylindrical factors as

$$\tilde{F} = (\tilde{F}_{\text{sph}} + \tilde{F}_{\text{cyl}}) F_{\text{diff}}. \quad (18)$$

The following compact form for F_{diff} was found to provide a reasonable fit to the measured data:

$$F_{\text{diff}} = (1 + \Gamma/\lambda)^{-C/10} \quad (19)$$

where λ is the wavelength, and Γ is the actual maximum distance between the arc and the straight line between source and receiver, i.e., γ scaled by the distance between source and receiver. This formulation has the key property that it approaches 1 when Γ is small, i.e., for straight lines.

The propagation model described by $\tilde{F}$ in (18), computed from (15) and (19), was tuned to local measurements of propagation loss at the measurement sites in Figure 2. In the propagation loss measurements, five receivers per site were placed 1 m above the seabed. The receivers were Sylence LP (RTSYS Underwater Tech., Lanester, France) and SoundTrap ST300 (Ocean Instruments Inc., Auckland, New Zealand), see Table 1. Transmissions were made from a small boat using a source at 2 m depth, which was the minimum operational depth of the employed Lubell LL-1424 (Lubell Labs, Whitehall, OH, USA) underwater speaker. The measurements were done using exponentially swept sine signals, correlating the received signal with the sent signal to improve signal-to-noise ratio [37]. Measurements were performed separately for the decade bands at 125 Hz, 250 Hz, 500 Hz, 1 kHz, and 2 kHz, and also with a long sweep from 100 Hz to 5000 Hz. The speaker was not able to produce enough output power below 100 Hz for propagation loss measurement. Counting all pairs of source locations, receiver locations, and repetitions at each frequency band, a total of 12,310 measurements were performed of which 9131 had at least 6 dB signal-to-noise ratio after correlation. Of these remaining 9131 measurements, 7611 were for propagation along straight lines, and 1520 were for curved arc propagation.

The fitting was done based on the logarithmic propagation loss, i.e., $PL = -10 \log_{10}(\tilde{F})$, using the `curve_fit` function from the Python SciPy library [28]. The four model parameters are m and n from (15), C from (19), and the sound speed in the seabed c_{seabed} in (14). These were fitted using bounds

$$\begin{aligned} 15 \leq m \leq 35 & & m_0 = 20 \\ 5 \leq n \leq 20 & & n_0 = 10 \\ 0 \leq C \leq 50 & & C_0 = 10 \\ 1500 \leq c_{\text{seabed}} \leq 1600 & & c_{\text{seabed},0} = 1510 \end{aligned} \quad (20)$$

assuming $c_{\text{water}} = 1500$ m/s.

The source model used here is based on measurement data compensated only for distance, but not for interactions with the water surface, i.e., the Lloyd mirror effect. To match this, the Lloyd mirror compensation in the propagation model is dropped when used to compute the propagation loss for the noise map. This changes the spherical and cylindrical parts to

$$\begin{aligned} \tilde{F}_{\text{sph}} &= \frac{1}{r^{m/10}} \\ \tilde{F}_{\text{cyl}} &= \frac{1}{\tilde{H} r^{n/10}} (\psi_c - \theta_{\min}) \end{aligned} \quad (21)$$

meaning that the only frequency-dependent part of the propagation model lies in the diffraction factor in (19).

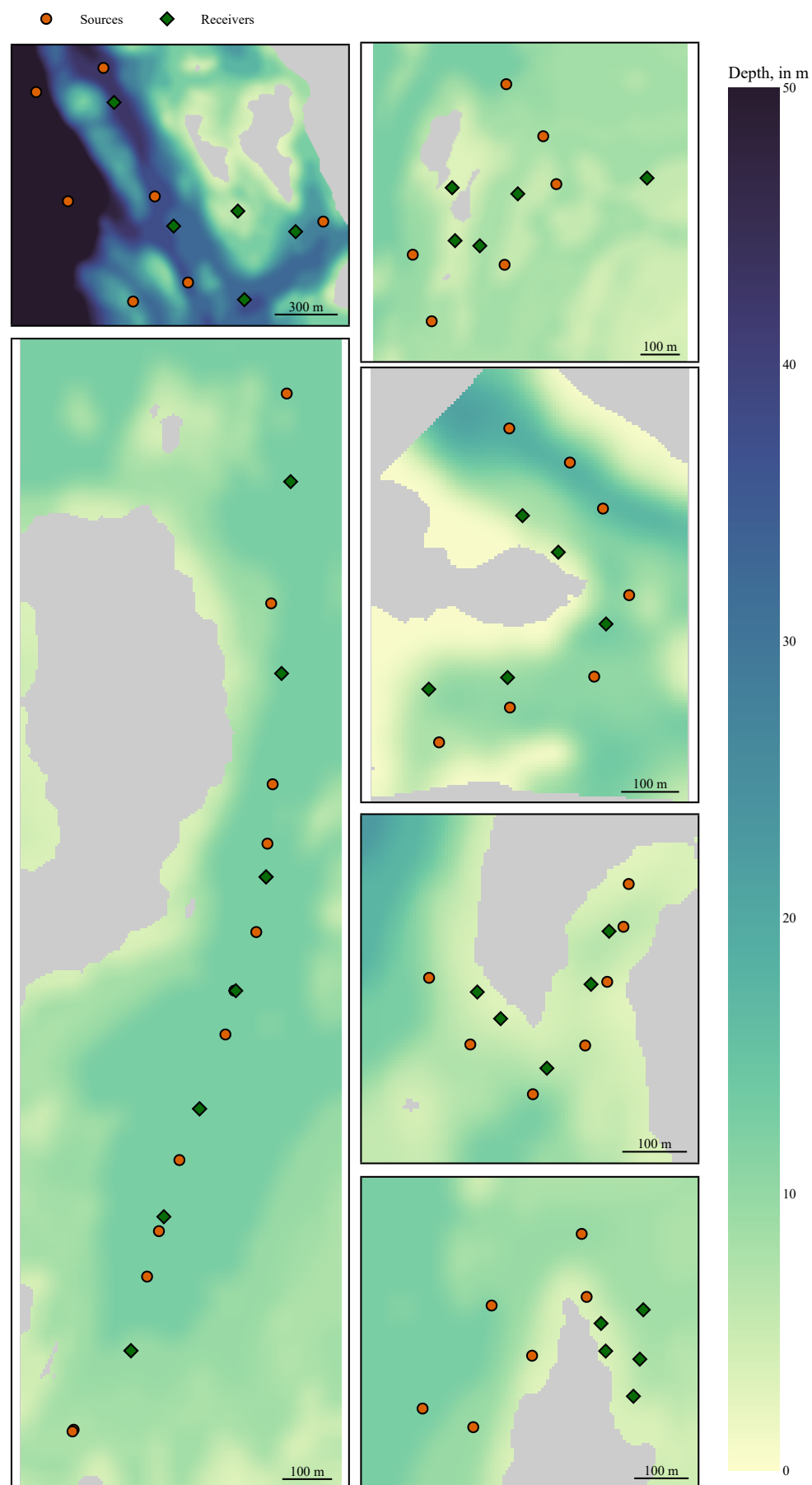


Figure 2. Propagation loss measurement sites. The lower-left figure shows a combination of two sites, where some receivers were moved between transmissions.

Table 1. Recording site information and recorder settings.

Site	Coordinates (WGS 84)	Depth (m)	Recorder Type	Sampling Frequency (kHz)	Sensitivity (Incl. Gain) (dB re 1 V/μPa)
Site A	58°55.414' N, 11°0.154' E	22	Sylence LP	128	−163.7
Site B	58°54.546' N, 11°0.985' E	6	SoundTrap 300ST	96	−175.1
Site C	58°51.459' N, 11°3.131' E	11	SoundTrap 300ST	96	−177.3
Site D	58°51.065' N, 11°4.569' E	30	Sylence LP	128	−164.2

2.6. Background Noise Modelling

Since the study area is mainly shallow, natural background noise models developed for the shallow Finnish archipelago sea were used [38]. These models predict the power spectral density $L_{bg}(f, u)$ of the wind-driven ambient noise as

$$L_{bg}(f, u) = L_0(u) + 10 \log_{10} \left[\frac{1 + \left(\frac{f_0(u)}{f} \right)^{m_0(u)}}{\left(1 + \left(\frac{f}{f_1(u)} \right)^{m_1(u)} \right) \left(1 + \left(\frac{f_2(u)}{f} \right)^{m_2(u)} \right)} \right], \quad (22)$$

where u is wind speed (m/s), L_0 is a reference level, f_0, f_1, f_2 are corner frequencies, and m_0, m_1 , and m_2 are parameters that control the spectral shape around the corner frequencies. By fitting the model to measured night-time noise levels, assumed to represent the background noise (see Section 2.7), a good fit was found for a wind speed of 7 m/s. The parameters at $u = 7$ m/s are given by

$$(L_0, f_0, m_0, f_1, m_1, f_2, m_2) = (66, 130, 6.6, 1200, 1.6, 260, 4.5). \quad (23)$$

2.7. Comparative Noise Measurements

Long-term underwater noise measurements were performed at four sites in the study area, with the aim of providing data for evaluating the uncertainty of the noise mapping framework. Receivers were deployed so that hydrophones were 1 m above the seabed. Each receiver was attached to a rope between a lifting buoy and a weight, with a surface buoy or an acoustic releaser for retrieval, depending on the location. Two receivers were SoundTrap 300ST (Ocean Instruments Inc., Auckland, New Zealand) and two were Sylence LP (RTSYS Underwater Tech., Lanester, France). The SoundTraps were calibrated at the FOI tank laboratory, Stockholm, Sweden, prior to deployment. All recorders were post-calibrated at TNO, The Hague, Netherlands, after deployment. The SoundTraps used the standard built-in hydrophones, while the Sylence LPs used HTI-92WB hydrophones (High Tech Inc., Long Beach, MS, USA) mounted on 3 m cables. The receivers were deployed on 9 July 2024 and retrieved on 27 August 2024, resulting in a measurement period covering much of the peak season for recreational boating in the area. Recordings were made continuously. Location information and other recorder settings are given in Table 1. Analysis of noise recordings was performed using the Python library Uwacan (available at <https://pypi.org/project/uwacan/> (accessed on 10 September 2026)). Moreover, 1 s spectrograms were computed using a Hanning window and 50% overlap and averaged to produce power spectral density estimates for the selected time intervals.

For a fair comparison to the noise map predictions, it is necessary to consider that the satellite images underlying the vessel density estimation were captured at noon on days with good weather conditions. The noise map therefore represents expected noise levels around noon on good weather days, and the comparison should be performed against measurements from similar conditions. To this end, the noise map predictions were compared to measurements from 10 am to 2 pm on days with good weather conditions

in that time interval. Good weather conditions were defined as at most 30% cloud cover and no precipitation, according to the Swedish Meteorological and Hydrological Institute (SMHI) weather station on the northern main island in the study area.

The background noise model was compared to measurements at night-time (1 am to 4 am), when vessel noise is expected to be minimal. The same calendar days as for the daytime data set were used.

The daytime results were further processed to compute the total sound pressure levels in four frequency bands: 20 Hz to 160 Hz, 200 Hz to 1600 Hz, 2 kHz to 10 kHz, and 20 Hz to 10 kHz. The frequencies given correspond to the centre frequencies of the decade bands included in each broader frequency band. The actual frequency ranges are therefore somewhat wider than indicated. The difference between the measured and modelled results within these four bands is used as a more compact quantification of the error in the model. This evaluation methodology was chosen to align with earlier work on producing noise maps for commercial shipping [39].

2.8. Noise Mitigation Scenarios

A noise mitigation scenario was developed in collaboration with the County Administrative Board (CAB) of Västra Götaland, which manages the Kosterhavet Marine National Park. The Swedish Agency for Marine and Water Management and the Swedish Transport Agency were also consulted. The noise mapping framework is used to predict noise levels under the scenario, allowing for an assessment of the potential noise reductions associated with it.

The CAB considered that many vessels in the speed restriction zone exceed the speed limit, and advised that a typical speed of 7 kn should be used in the speed restriction zone for the baseline scenario. For the mitigation scenario, it was assumed that the speed limit is fully enforced and that all vessels comply with the 5 kn limit.

A second scenario did not consider mitigation measures, but instead evaluated how underwater noise levels would change if the number of small vessels changed. Within the Interreg North Sea project DEMASK, which this study is part of, a number of scenarios for underwater noise levels in 2035 were developed. Here, we attempt to predict small vessel numbers in 2035 based on the historical trend in vessel numbers. It was then assumed that the predicted trends can be applied to the current study area, and that the vessel density distribution there remains unchanged. Conceptually, the small vessel density is scaled with this percentage, and the rest of the computations are performed again. However, this percentage will transfer unchanged through all the computation steps, increasing the resulting sound power at the receivers by the same factor. This means that the change in the noise levels can be computed as $10 \log_{10}(P)$, where P is the percentage change in overall vessel count.

Small vessel statistics were obtained from the regular boating surveys conducted by the Swedish Transport Agency, e.g., [40]. From the survey data, vessel numbers in Sweden were estimated for the years 2004, 2010, 2015, 2020, and 2025. The count included only seaworthy boats. Kayaks, canoes, sailboats and other small boats that are not expected to produce significant underwater noise were excluded. The resulting small vessel numbers are shown in Table 2.

The numbers in 2004, 2015 and 2020 are lower than the numbers in 2010 and 2025, making it difficult to predict future vessel numbers based on the historical trend. Nevertheless, it is relevant to illustrate how changes in vessel numbers could affect underwater noise levels, and to compare those changes to the changes expected due to the speed regulation scenario. A linear fit to the data in Table 2 was employed to predict vessel numbers in 2035, using two different base intervals: 2004–2025 and 2020–2025. The historical data do

not appear to follow a linear trend, but a more detailed modelling approach would not be justified due to the small number of data points. The first interval was used to illustrate the long-term trend, while the second interval was used to illustrate the short-term trend. Admittedly, the second interval is short and the resulting prediction is highly uncertain. This prediction is included mainly to illustrate that even large changes in vessel numbers are not expected to have a large effect on underwater noise levels.

Table 2. Small motorised vessel counts in Sweden.

Year	Number of Vessels
2025	701,700
2020	481,300
2015	461,500
2010	626,500
2004	499,000

3. Results

3.1. Small Vessel Density Map

Figure 3 shows vessel detections and the resulting density map of the study area. The highest densities are found in the eastern parts of the study area, with a peak vessel density of 1.4 vessels/km². This concentration of vessels is caused by a major fairway for recreational boating—one of the main fairways along the western coast of Sweden.

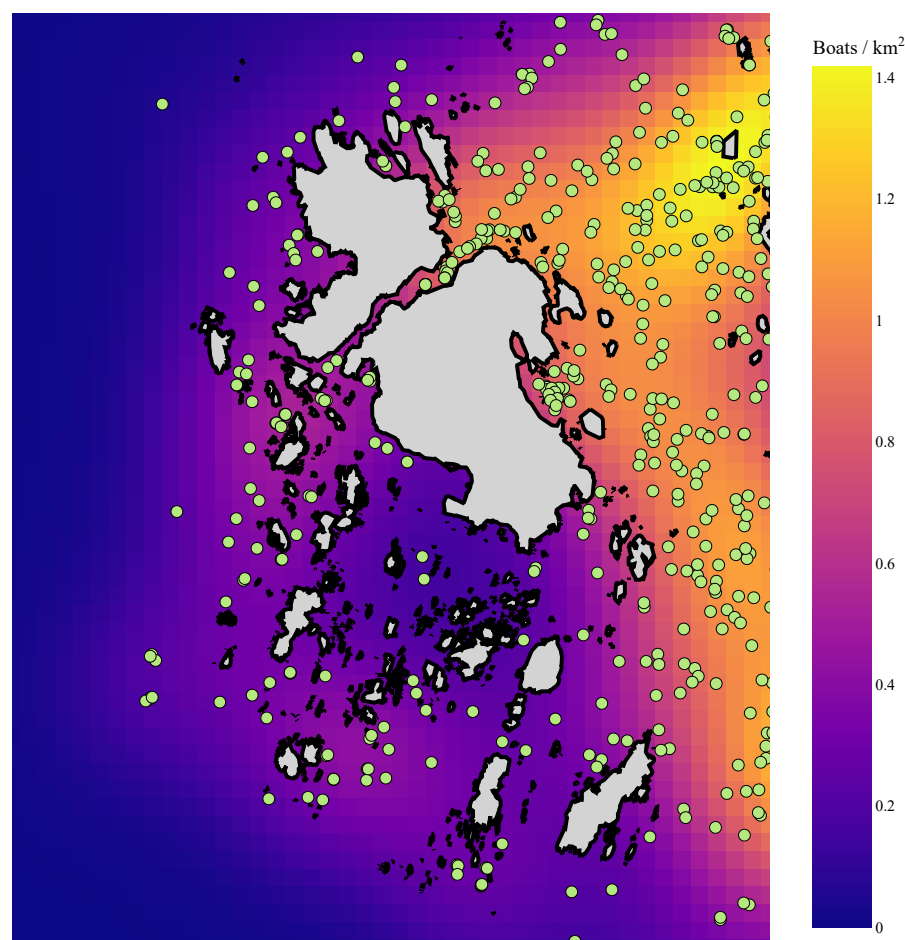


Figure 3. Small vessel detections (lime dots) and density map (colour map) of the study area. Note that the detections are from 8 images, i.e., they correspond to a density that is 8 times higher than the density shown by the colour scale.

The lowest densities are found in the interior of the archipelago and in the westmost part of the study area, towards the open sea. There is an increase in vessel density amongst the smaller islands on the south-western side of the archipelago.

3.2. Small Vessel Underwater Noise Source Level Model

The final parameters of the simple parametric model developed for small vessel underwater noise source level modelling are $[K, a, b, v_0] = [142, 0.24, 2.70, 10.8]$. Figure 4 shows predicted source level spectra and the total broadband noise level at different speeds. We see that the source levels at frequencies below 100 Hz do not change much with speeds above 7 kn. For higher speeds, this almost constant low-frequency level extends to higher frequencies. At approximately 12 kn, the source model has reached its asymptotic limit, and higher speeds do not further increase the broadband source level nor modify the spectral distribution.

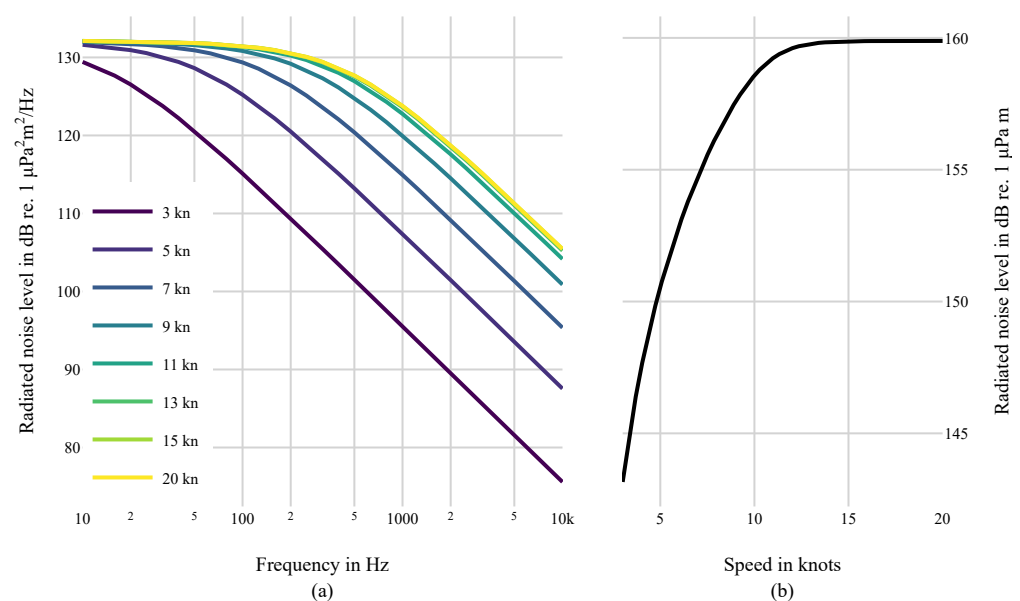


Figure 4. Small vessel source level spectra (a) and broadband level (b) at different speeds as predicted by the model.

3.3. Propagation Loss Model

The parameter fit using the 9131 propagation loss measurements with sufficient quality resulted in model parameters

$$\begin{aligned} m &= 19.7 \\ n &= 12.8 \\ C &= 9.2 \\ c_{\text{seabed}} &= 1503 \text{ m/s} \end{aligned} \quad (24)$$

and gave an overall root-mean-square error (RMSE) of 6.53 dB. The model estimates were nearly unbiased, with a mean error of 0.43 dB. The standard deviation of the residuals was similar to the RMSE, at 6.52 dB. Considering only straight-line propagation, the RMSE was 6.57 dB, while the curved parts had an RMSE of 6.08 dB. Figure 5 shows a comparison between measured and modelled propagation loss for all the 9131 measurements used in the parameter tuning. Overall, the model captures the trend of the measured propagation losses over a wide range. There is a slight tendency for the model to underestimate propagation loss at high losses, as indicated by the downward shift of the data points at the higher losses.

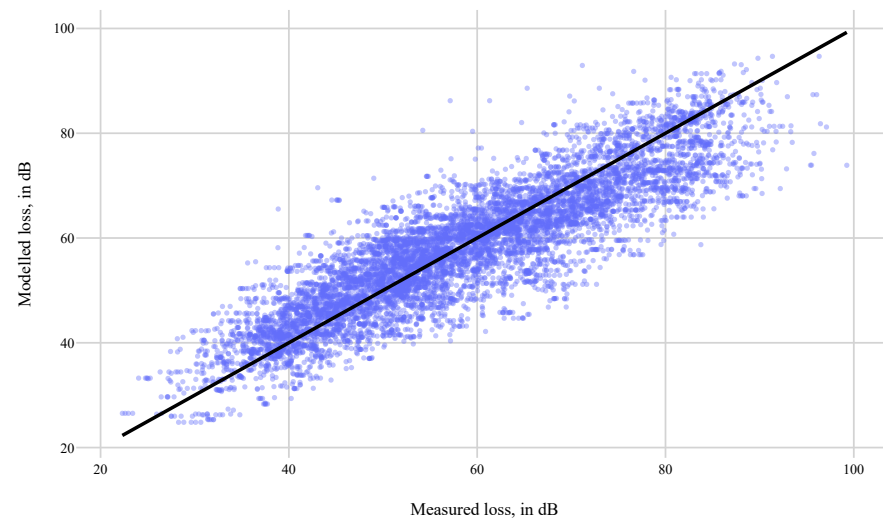


Figure 5. Measured vs. modelled propagation loss for all individual frequency bands and propagation measurement sites.

3.4. Noise Map

Figure 6 shows the computed noise map at three frequency bands, highlighting typical effects, and the total broadband level. Spatially, the levels are higher to the east of the islands, where the recreational boat fairway is located. The levels at the 315 Hz and 1 kHz bands are clearly lower in the speed restriction zone (see Figure 1). In the 100 Hz band, the speed restriction zone is not apparent in the result, but the levels are still lower in the interior of the archipelago due to the lower vessel density there. Overall, broadband levels reach nearly 120 dB re 1 μPa to the east of the islands, while in the interior of the archipelago we see lower levels around 105 dB re 1 μPa .

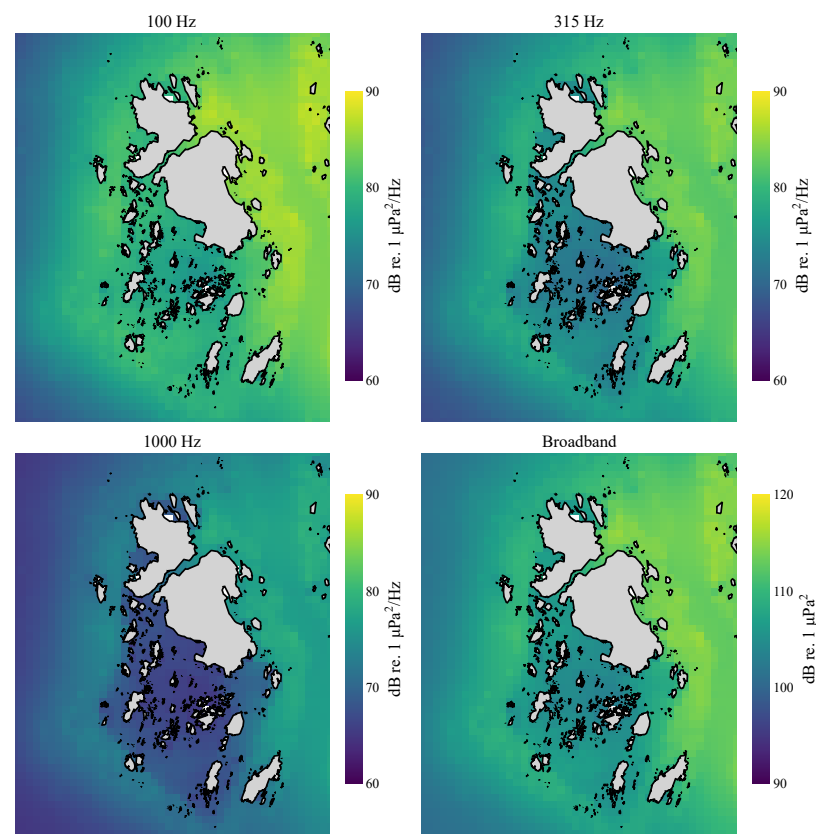


Figure 6. Noise map at different frequencies and for the broadband signal.

3.5. Uncertainty Assessment

A comparison between the modelled and measured levels is shown in Figure 7. Table 3 gives the difference in sound pressure levels in wider frequency bands. For the daytime comparison, the model matches the measured levels very well at two of the sites: Site A and Site D. At Site C, the model captures the general trend, but the measured levels are typically 8 dB higher than the model predicts. At Site B, the measured levels are typically 10 dB to 15 dB higher than the model prediction and also contain a strong peak around 40 Hz to 160 Hz. These errors are in a similar range to those earlier work on shipping [39].

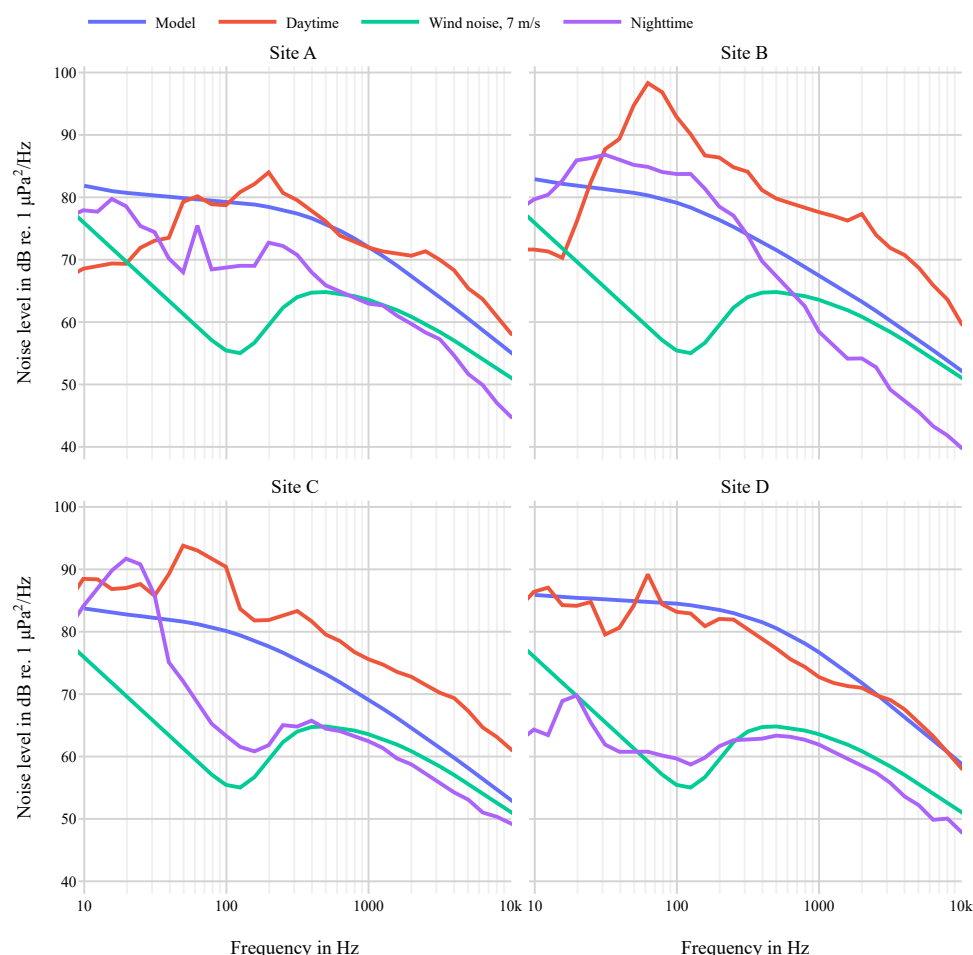


Figure 7. Spectra at four measurement sites and their corresponding model results.

Table 3. Difference between modelled and measured daytime sound pressure levels across different frequency bands, at the four noise measurement sites. Positive values indicate that the measured results are higher than the model, and vice versa.

Site	20–160 Hz	200–1600 Hz	2–10 kHz	20 Hz–10 kHz
A	0.3 dB	1.6 dB	4.5 dB	2.2 dB
B	13.6 dB	9.7 dB	11.9 dB	12.0 dB
C	8.8 dB	6.6 dB	8.4 dB	7.9 dB
D	−0.6 dB	−2.6 dB	−0.2 dB	−1.5 dB

The levels at night-time compared to the wind-driven noise show a reasonable agreement above 500 Hz for Sites A, C, and D. At lower frequencies, there is less agreement between the model and the measurements, with measured levels typically higher than the modelled levels. At Site B, the night-time levels do not resemble the spectral shape of the modelled wind-driven noise, with much higher levels below 300 Hz but lower levels above 1 kHz.

3.6. Scenarios

Figure 8 shows the effects of the modelled scenario—changing the speed restriction from 7 kn to 5 kn. As expected, the levels are reduced within the speed restriction zone, but not outside of it. The effect is less at the edges of the zone where noise radiates into the zone from the surrounding area. In certain spots, e.g., at the eastern edge of the zone just below the southern tip of the main island, the open water allows the noise from the outside to radiate much farther into the zone.

The effects of the slow-down scenario are further demonstrated by Figure 9, which shows the average and maximum effect within the speed reduction zone, evaluated per frequency band. It is clear that the effect is strongest in the middle frequencies, centred at 200 Hz, where the effect can reach a reduction of up to 6 dB. At frequencies below 30 Hz or above 2 kHz, the average effect is less than 1 dB.

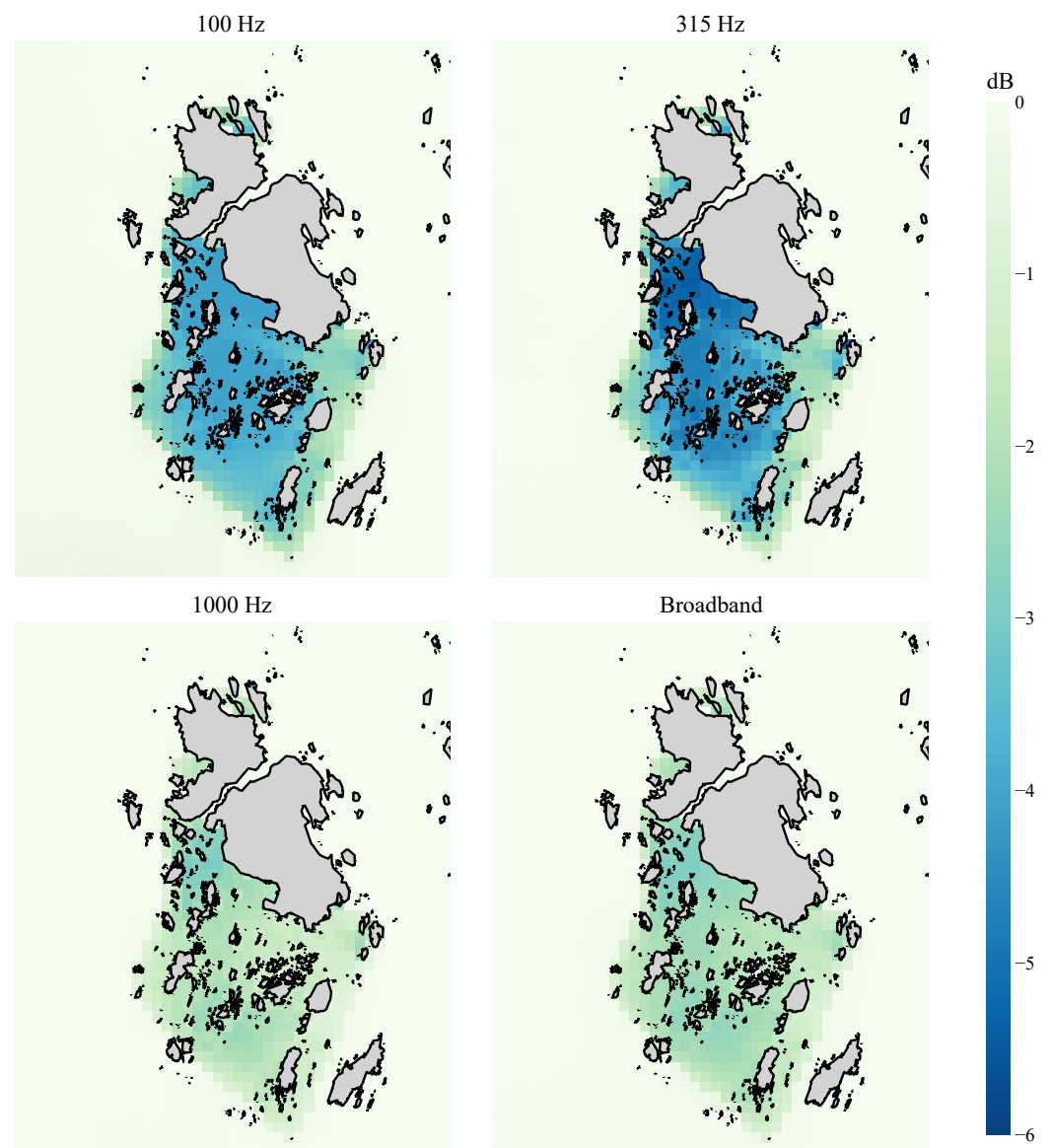


Figure 8. Level difference between the 5-knot and 7-knot scenarios.

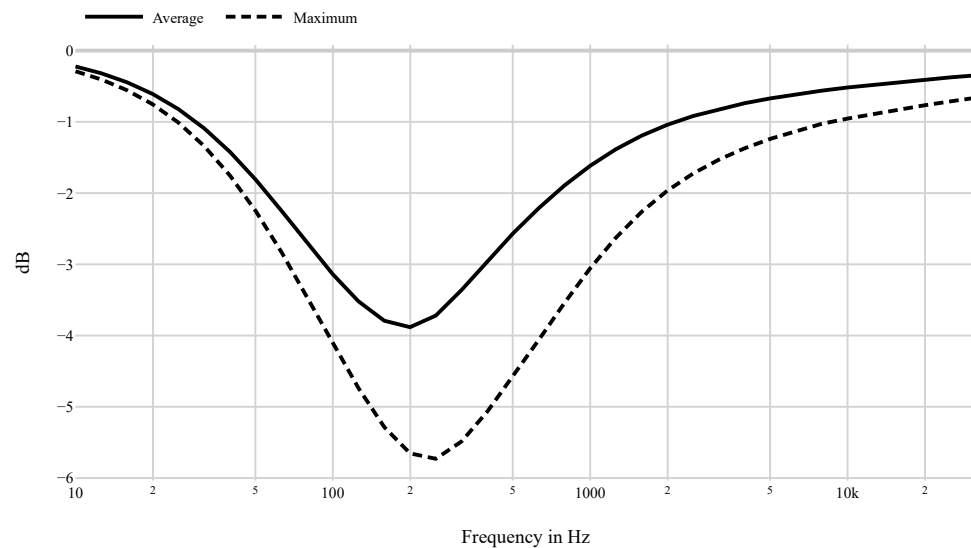


Figure 9. Average and maximum effect of the scenario, considering only receiver locations within the speed reduction zone.

For the scenario on changing vessel numbers, Table 4 shows the estimated vessel numbers in 2023 and 2035, the percentage change in vessel numbers, and the resulting expected change in underwater noise levels. Considering the base interval 2004–2025, the expected change in underwater noise levels due to the predicted 10.1% change in vessel numbers is +0.42 dB. This is a very minor effect, far smaller than the effect of enforcing speed reduction. Considering the base interval 2020–2025, the expected change in underwater noise levels due to the predicted 64.7% change in vessel numbers is +2.2 dB. Even at this larger change in vessel numbers, the effect on underwater noise levels is, at frequencies between 63 Hz and 630 Hz, still smaller than the effect of enforcing speed reduction.

Table 4. Boat count scenario results.

Base Interval	Estimated Count in 2023	Predicted Count in 2035	Percentage Change	Expected Noise Level Change
2004–2025	595,060	655,150	+10.1%	+0.42 dB
2020–2025	613,540	1,010,260	+64.7%	+2.2 dB

4. Discussion

The results of Section 3.5 showed good agreement with measurements at Sites A and D, confirming that the method can predict average noise levels due to small vessels and natural background noise in a coastal area. At Sites B and C, the proposed method underestimated the noise levels. Site B is situated close to shore in a narrow passage between two islands. This passage is a known thoroughfare for small vessel traffic, yet the boat density map does not show elevated densities there. The resolution of the boat density map is probably too low to capture this feature. Waves breaking and hitting the nearby shore also inflate the background noise, as evidenced by elevated levels at night (Figure 7). Site C is shallower and more sheltered by nearby islands than Sites A and D. While the propagation model was developed to model such conditions, it may not fully capture the acoustic behaviour in this area. The site is also in the speed restriction zone but near its edge. The noise map assumes that vessels in this area travel at 7 kn, which may not be the case. It is also possible that the source model needs refinement at low speeds.

It should also be noted that the satellite images are all from 2023, while the noise measurements are from 2024. The satellite images are the underlying data for the vessel density map, which forms the basis for the noise mapping. This mismatch likely explains some of the differences between the measured and modelled results. However, as the vessel count scenario shows, a change in the vessel count only gives rise to a small change in the model results. For example, a uniform doubling (or halving) of the vessel count will increase (or decrease) the noise levels by 3 dB. To match the 8 dB error at Site C, the vessel density would have to increase by 530 %.

Observed differences between night-time noise levels and predicted wind-driven noise may be caused by breaking waves at the nearby shore (Site B) and by differing conditions in the study area and in the Finnish archipelago sea, where measurements underlying the wind-driven noise model were made. The study area has a varying depth profile with depths exceeding 200 m and large shallow areas at depths below 20 m, while the background noise model was made from measurements at 16 m depth. This model may not be appropriate at greater depths, but the depths of the measurement sites here are similar. Moreover, the study area is a salt water environment, while the salinity is much lower in the brackish Finnish archipelago sea. Salinity affects bubble size and thus may affect wind-driven underwater noise [38].

The background noise was assumed to be the same during the daytime and the night-time. In reality, there are several factors that might influence the background noise so that the average daytime noise and the average night-time noise differ. In this region, the wind speeds are often higher during the day than during the night, which would increase the wind-driven background noise. To properly characterise this would require selecting segments from recordings where there are no anthropogenic noise sources nearby, which was deemed out of scope for the current work and left for the future.

The model developed here predicts that speed reductions for small vessels already operating at slow speeds are an effective underwater noise mitigation measure. In a wide frequency range (63 Hz to 630 Hz), the achieved reduction is greater than the predicted noise increase due to a 65% increase in vessel numbers. This is an example of how the framework developed in this study can be used to evaluate noise management policies and support decision-making, with the end goal of supporting healthy coastal marine ecosystems.

Because the satellite-based vessel detection was performed using optical imagery, the resulting density map and noise estimates are only valid for conditions when the satellite images were acquired, which in this case was during midday under clear weather conditions. This means that the noise maps shown here represent conditions near midday on clear weather days. This may be expected to represent peak boating activity, and average levels over a full boating season are likely lower. The use of expected vessel densities means it is not possible to capture the temporal variability in the underwater soundscape. Capturing this variability would enable detailed estimates of the environmental impact of an underwater soundscape, but this is left for future work.

The low resolution of the satellite images used to make the small vessel density map means that some small vessels may not have been detected and that moving objects that are in fact not motorised, e.g., sailboats, may be detected and included in the density map. Further, this study used a relatively large 1000 m bandwidth in the KDE estimation of small vessel density from observations due to the relatively low number of observations. It is likely that there are variations in the actual boat density on finer scales, e.g., near marinas, but this is not resolved.

Small vessel densities can also be estimated from coastal radar, passive acoustic monitoring or camera surveys [13,20,41]. Coastal radar has long range and can generate time-stamped detections continuously both day and night, but islands can create shadow

zones. Moreover, coastal radar systems do not operate in all areas, and not all of them are accessible for research purposes. Passive acoustic monitoring can be effective at short ranges, but there is little information on detection ranges of small vessels. Further, single-hydrophone PAM does not give precise locations for the detections. Camera monitoring can localise small vessels but is weather-sensitive, and maximum detection ranges are not known. Satellite monitoring provides the large area coverage that is needed to make a noise map of the full 200 km² area studied here. Future work could explore the use of additional satellite images acquired at different times and using different sensing modalities, e.g., radar, for improved robustness to bad weather.

The source level model employed here is based on a limited dataset of small vessel noise measurements, and while it captures the general relationship between speed and source level, there is uncertainty in the model parameters and predictions. The measurements underlying the source model were made in Sweden on a set of vessels that are typical of the Swedish fleet of small vessels. In other regions, the fleet may be different, and the source model may need to be adjusted accordingly. Note, however, that neither [24] nor [22] found strong correlations between small vessel parameters, such as length and engine power, and source level. The model is valid for small vessels of all hull types, while [24] develops models for different hull types. The model developed here is similar to the planing vessel model of [24]. This is expected because most of the vessels in the dataset underlying the development here are planing vessels. The results of [24] show that the source level of small vessels varies depending on hull type, but here it was not possible to incorporate hull type into the model because hull type could not be determined from the satellite images. A higher spatial resolution would enable extraction of more detailed information about the detected vessels. However, high-resolution satellite data can be costly, limiting their utility for large-scale noise mapping. The study reported here employed freely available Sentinel-2 data, which can be accessed and processed at no cost.

The propagation model is based on a large number of measurements from the current study area, representing the local sound propagation conditions. Nevertheless, the model uses simplified single-value descriptions of seabed properties and the depth profile between source and receiver, which may both have an effect on the propagation. It also attempts to model diffraction in a simplified manner. A three-dimensional numerical solution of the wave equation with appropriate simplifications could be more accurate than the present model, but was not considered here. Such a full numerical solution would be far more computationally expensive, likely making it intractable for noise mapping purposes, and would require detailed information on depth and seabed properties [42]. Such information was only available at a coarse level.

The present framework does not consider other sources of underwater noise, such as shipping, wind farms, port operations and construction. The current study area was chosen because it is relatively free of these other sources. In other coastal areas, they may be significant contributors to the underwater soundscape and should be included in future noise mapping efforts.

5. Conclusions

This study developed and demonstrated a methodological framework for spatial mapping of underwater noise in a coastal area where the soundscape is dominated by recreational traffic. The framework integrated satellite-based vessel detection, spatial density estimation, empirical source modelling incorporating vessel speed, and semi-empirical shallow-water propagation modelling. The resulting noise map provides a spatially resolved estimate of small vessel noise contributions across the study area, which can be used to inform environmental assessments and management decisions.

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