Noise and its propagation in the observation area of the Makassar Strait Waters

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Abstract. Underwater noise has become a critical issue in oceanographic and marine ecological research because of increasing anthropogenic activities such as commercial shipping, offshore operations, and coastal infrastructure development. The Makassar Strait, a major international shipping corridor connecting the Pacific and Indian Oceans, is subject to intense vessel traffic that significantly contributes to acoustic pressure in the marine environment. This study quantifies and characterizes underwater noise levels in the Makassar Strait using in situ hydrophone measurements and acoustic spectral and statistical analyses conducted at 19 observation stations. The results indicate elevated sound pressure levels in proximity to the primary shipping lanes, with dominant acoustic energy concentrated below 1 kHz, consistent with large-vessel noise signatures. While propagation analysis suggests that the recorded noise levels do not exceed the temporary or permanent threshold shift criteria for marine mammals based on the NMFS (2024) guidelines, several locations exhibit high sound exposure levels that may increase the potential for behavioral disturbance and acoustic masking. These findings highlight the ecological significance of underwater noise in the Makassar Strait, and underscore the importance of incorporating acoustic considerations into marine spatial planning and environmental management strategies in Indonesian waters.

Keywords: Makassar strait, SEL, Sound propagation, SPL, Underwater noise

1 Introduction

Marine noise originates from both natural sources, such as waves, rainfall, and biological activity (e.g., whale and fish vocalizations), and anthropogenic sources, including vessel traffic, oil and gas exploration, seismic surveys, military sonar, and underwater construction [1-3]. Among these, vessel noise is particularly significant because of its continuous nature and widespread spatial footprint, with documented impacts on marine mammals ranging from behavioural alterations and acoustic masking to auditory impairment and physiological

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stress [4]. Source levels from small vessels typically range between 130 and 160 dB re 1 μPa·m, while large commercial ships may exceed 200 dB re 1 μPa·m. Prolonged exposure to elevated sound levels has been associated with temporary or permanent threshold shifts, especially in low-frequency cetaceans [4-6].

Passive Acoustic Monitoring (PAM) is widely recognized as a cost-effective and non-invasive method for characterizing underwater soundscapes and assessing anthropogenic acoustic pressures [7]. The ecological impact of underwater noise depends not only on sound intensity, but also on the frequency composition, exposure duration, and spatial proximity to sensitive species. Furthermore, sound propagation in the marine environment is strongly modulated by environmental factors, such as temperature, salinity, and depth, which govern acoustic transmission loss and spatial variability in the reflected sound level [3, 8].

Although underwater noise has been extensively studied in industrialized and temperate regions, including the North Atlantic, North Sea, and Arctic waters, significant scientific gaps remain in tropical, high-traffic archipelagic regions. In particular, Makassar Strait, a major international shipping corridor connecting the Pacific and Indian Oceans [9], experiences intense vessel traffic while simultaneously supporting ecologically productive tropical marine ecosystems. However, region-specific baseline acoustic data and noise propagation characteristics remain poorly documented, including robust assessments of ecological risks and evidence-based marine spatial management.

Therefore, this study aims to quantify and characterize the spatial distribution of underwater noise in the Makassar Strait by analyzing the Sound Pressure Level (SPL) across 19 observation stations and evaluating the acoustic propagation patterns under local environmental conditions. By providing baseline exposure matrices relevant to biological threshold considerations, this study contributes to improving assessments of potential acoustic disturbances and supports the integration of underwater noise in marine spatial planning and environmental management frameworks in Indonesian waters.

2 Materials and methods

2.1 Study area and instrumentation

Observations were conducted in the Makassar Strait from January 19 to 22, 2025 (**Fig. 1**), a major international shipping corridor for commercial vessels transiting Java, Sulawesi, and Kalimantan. The underwater noise was recorded using an SQ26-H1B omnidirectional hydrophone with an operational frequency range of 0.020–45 kHz. The hydrophone sensitivity was -193 dB re 1 V/μPa (factory calibration), as specified by the manufacturer, and was used to convert the recorder voltage signals into absolute sound pressure levels. Factory calibration was assumed to be valid for this study because no significant sensor drift was expected during the short deployment period.

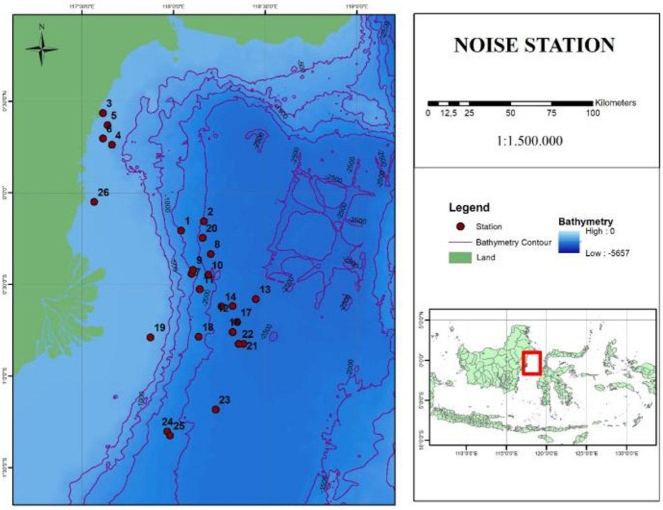

Fig. 1. Study site.

2.2 Data collection and processing

Underwater noise measurements followed the ISO 17208-1:2016 guidelines for marine acoustic measurements in marine environments [10], with adjustments to accommodate local field conditions. Passive acoustic recordings were collected at 19 observation stations using a stationary hydrophone deployed approximately 3 m below the sea surface to minimize surface wave interference while maintaining safe deployment conditions.

The recording duration ranged from 5 to 20 min per station. This duration range was selected to balance the adequate temporal representation of ambient noise conditions with operational constraints, including vessel traffic variability, sea state, and safety considerations. Shorter recordings (~ 5 min) were applied during periods of unstable weather or high surface disturbance, whereas longer recordings (up to 20 min) were obtained under relatively calm conditions to improve the statistical robustness of the spectral and exposure matrices.

The sampling rate was set to cover frequencies between 0.2 kHz and 45 kHz, and all acoustic data were stored in the *. wav format. Measurements under fully undisturbed sea states are not always achievable, as wind and surface wave activity occasionally contribute to elevated low-frequency noise levels, particularly below 500 Hz [11]. Periods strongly affected by transient surface noise were identified through spectral inspection and were accounted for during the analysis.

2.3 Acoustic analysis

Acoustic data were analyzed using Python with several scientific libraries. The *soundfile* module was used to read the *. wav files, while *scipy.signal* was supported digital filtering (low-pass, band-pass), Fast Fourier Transform (FFT), Welch's Power Spectral Density (PSD), Short-Time Fourier Transform (STFT), and Hilbert transform analysis. *NumPy* and *Matplotlib* were applied for numerical computation and visualization of the SPL time series, frequency spectra, and propagation patterns. *Librosa* was used for spectrogram analysis, *Pandas* for tabulation and statistical handling of acoustic matrices, and *Noisereduce* for background noise attenuation.

The Absolute Sound Pressure Levels (SPL) were calculated following ISO 17208-1:2016 [5, 8], using hydrophone sensitivity calibration to convert the recorded voltage to pressure units. The Sound Exposure Level (SEL, dB re 1 µPa²·s) was computed as the time-integrated squared sound pressure for each recording interval. The derived SEL values were evaluated against regulatory-based thresholds for high-frequency cetaceans (Delphinidae) [2, 3, 7], including:

- 181 dB re 1 µPa²·s → Temporary Threshold Shift (TTS, temporary hearing impairment).
- 201 dB re 1 µPa²·s → Permanent Threshold Shift (PTS, permanent hearing impairment).

3 Results and discussion

3.1 SPL and SEL observations

The Root Mean Square Sound Pressure Level (SPL) represented the average acoustic pressure recorded during each measurement period. Across all stations, the SPL RMS values ranged from approximately 100 to 150 dB re 1 µPa (**Table 1**; **Fig. 2**). The highest SPL RMS values were obtained at Stations St1, St5, St7, and St24 (≈ 145–150 dB re 1 µPa), while Stations St11 and St16 exhibited the lowest values (~ 100 dB re 1 µPa). These results indicate substantial spatial variability in the underwater noise conditions across The Makassar Strait.

Table 1. Setting Word's margins.

Station	SPL_RMS (dB_re_1uPa)	SEL (dB re 1 µPa²·s)	Duration_s
St1	150.6	181.5	1,221.0
St4	141.0	255.3	426.9
St5	135.8	223.8	445.5
St7	147.3	164.8	721.2
St9	141.0	252.2	776.1
St10	132.6	223.8	445.5
St11	100.9	258.8	434.1
St12	136.2	262.6	416.9
St14	126.9	269.8	601.9
St16	100.9	265.3	300.9
St17	136.0	166.6	480.8
St18	139.9	164.8	416.7
St19	145.6	176.8	624.8
St21	144.1	169.3	443.4
St22	139.8	263.6	426.1
St23	138.6	265.0	588.3
St24	148.8	257.9	375.3
St25	142.8	271.8	647.8
St26	140.9	263.6	422.3

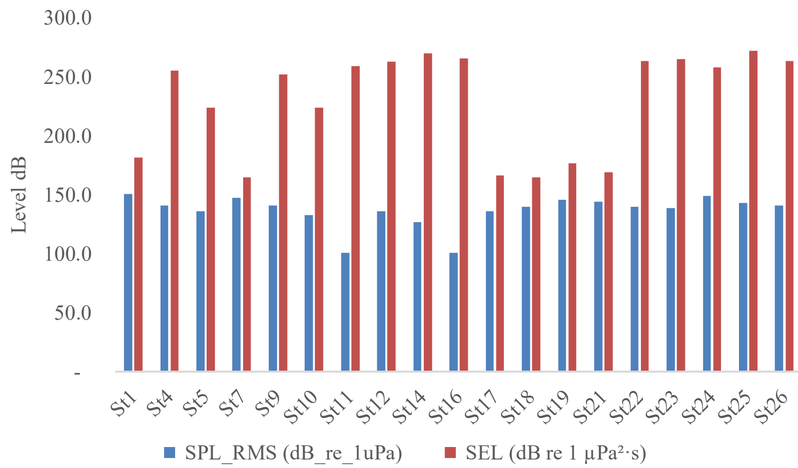

Fig. 2. SPL RMS and SEL values recorded at each observation station.

Sound Exposure Level (SEL), which integrates acoustic energy over the recording duration, also varied considerable among stations, SEL values ranged from 164.7 to 271.8 dB re 1 µPa²·s, reflecting defferences in both sound intensity and recording duration. Stations with longer continuous noise recordings exhibited the highest SEL values even when the SPL RMS levels were moderate. Conversely, some stations with elevated SPL RMS values displayed relatively lower SEL, indicating shorter durations of high-intensity events.

Overall, the observed SPL and SEL distributions demonstrate that the underwater noise conditions in the study area are spatially heterogeneous and influenced by both instantaneous sound level and exposure duration.

3.2 Acoustics exposure implication

The divergence between the SPL RMS and SEL patterns across stations highlights the importance of considering both metrics when evaluating the underwater noise exposure. High SPL RMS values indicate a strong instantaneous sound level, typically associated with vessel engines or propeller cavitation, where high SEL values reflect prolonged or repeated exposure to moderate-intensity noise. Stations exhibiting moderate SPL but elevated SEL likely represent areas of continuous vessel traffic rather than short impulsive events.

It is important to note that the highest SEL values reported here result from time-integrated ambient recordings, and therefore represent cumulative exposure over the measurement period, rather than single impulsive events. As such, these values should not be interpreted as instantaneous source levels but as indicators of prolonged acoustic presence within the soundscape [13].

3.3 SEL propagation model and threshold evaluation

To illustrate the potential attenuation of underwater noise with distance, a simplified logarithmic propagation model was applied using a representative SEL value derived from observed near-source conditions (≈140 dB re 1 µPa²·s) rather than the maximum cumulative SEL obtained from long-duration recordings. This approach avoids the overestimation associated with time-integrated ambient measurements.

The propagation model incorporates environmental parameters representative of the study area, including temperature (30.0°C), salinity (32.0 ppt), pH (8.0), and a dominant frequency of 1 kHz, assuming spherical spreading loss (N = 20). The modelled SEL decreased rapidly with distance, reaching approximately 120–125 dB at 10 m and 95–105 dB beyond 50–100 m (**Fig. 3**).

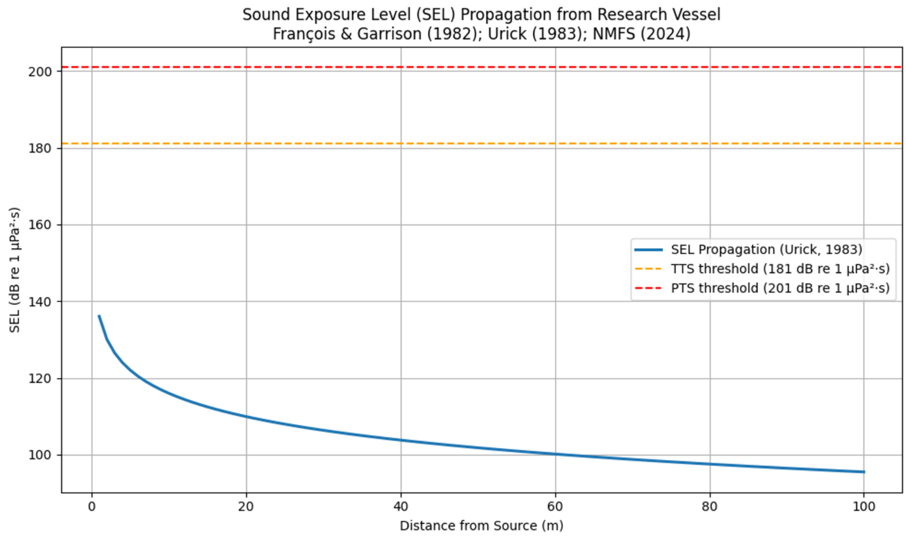

Fig. 3. Propagation of Sound Exposure Level (SEL) as a function of distance from the acoustic source.

When compared with the established marine mammal exposure thresholds (181 dB SEL for TTS and 201 dB SEL for PTS), the modeled SEL values remained well below the injury criteria at all distances considered. This suggests that underwater noise levels in the study area are unlikely to induce auditory injury under the observed conditions, although potential behavioral disturbances and acoustic masking cannot be excluded [12, 14].

4. Conclusion

This study demonstrates that underwater noise in the Makassar Strait is spatially heterogeneous and predominantly influenced by continuous vessel activity associated with major shipping lanes. Rather than being driven by short impulsive events, the combined SPL and SEL analyses indicated that prolonged, moderate-intensity noise represents the dominant acoustic exposure mechanism in the region.

Propagation modelling shows that noise from vessel sources attenuates rapidly with distance and remains below the NMFS (2024) injury threshold for temporary and permanent threshold shifts in marine mammals. While the risk of direct auditory injury appears low, the persistence of vessel-related noise suggests that acoustic masking is the primary ecological concern, with potential implications for the communication, navigation, and foraging behaviour of marine fauna.

This study had several limitations. The analysis was based on short-duration recordings at a single shallow deployment depth and relied on factory hydrophone calibration, which may be influenced by surface noise conditions and temporal variability in vessel traffic. In addition, the absence of vessel-tracking data limits the direct attribution of noise levels to specific sources.

Despite these limitations, this study provides a valuable baseline characterization of underwater noise conditions in the Makassar Strait, and highlights the importance of integrating acoustic metrics into marine spatial planning and environmental management in Indonesian waters. Future studies employing long-term passive acoustic monitoring and vessel traffic data would further strengthen the assessments of cumulative noise exposure and ecological risk.

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