Regression methods for evaluation of the underwater noise levels in the Slovenian Sea

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Abstract in English

Anthropogenic underwater noise pollution of seas and oceans caused by shipping can have negative effects on marine animals. The aim of this study was to evaluate quantitatively how much the underwater noise levels in the Slovenian Sea were influenced by anthropogenic pressures and meteorological parameters in the period from 2015 until 2018. For this purpose, correlation method and least squares multiple linear regression analysis were used. The results of this study show that the correlation of underwater noise levels with the dredging activity is significant but low, while correlation with the ship densities is insignificant, which could be due to reduced sound wave propagation in the shallow sea levels. Correlation of the underwater noise levels with the wind speed was significant but low to medium, which could be explained by the breaking waves generated by the wind that produced sound.

Keywords: Underwater noise, correlation, multiple linear regression, anthropogenic pressures, meteorological parameters

Abstract in Slovene

Antropogeno onesnaževanje morij in oceanov s podvodnim hrupom zaradi ladijskega prometa ima lahko negativen vpliv na morske živali. Cilj te študije je bil kvantitativno oceniti, koliko so bile vrednosti ravni podvodnega hrupa v slovenskem morju odvisne od antropogenih pritiskov in meteoroloških parametrov v obdobju od 2015 do 2018. V ta namen sta bili uporabljeni korelacijska metoda in multipla linearna regresijska analiza z metodo najmanjših kvadratov. Rezultati te študije so pokazali, da je bila korelacija ravni podvodnega hrupa z aktivnostjo poglabljanja morskega dna signifikantna, toda nizka, medtem ko je bila korelacija z gostoto ladij zanemarljiva, kar je lahko posledica zmanjšanega širjenja zvočnega valovanja v plitvem morju. Korelacija ravni podvodnega hrupa s hitrostjo vetra je bila signifikantna, vendar nizka do srednja, kar je mogoče razložiti z zvokom nastalim zaradi lomljenja valov, ki jih je generiral veter.

Ključne besede: Podvodni hrup, korelacija, multipla linearna regresija, antropogeni pritiski, meteorološki parametri

Introduction

Anthropogenic noise pollution is present in a number of world's the seas and oceans, caused, in particular, by marine traffic. Continuous underwater noise from ships disturbs communication of marine mammals, such as dolphins and whales, which causes problems in their orientation, mating, and feeding that are critical to their survival [1, 2].

To study the correlations of underwater noise with ship traffic that is representative for shallow waters worldwide, examples were chosen in the Celtic and North Seas of the UK, the Scotian Shelf of Canada, the Guanabara Bay in Southeast Brazil and in the shallow waters of the Indian Ocean. An example of the underwater noise of biological origin was chosen in the lagoon of a coral atoll in the Indian Ocean. For correlations of underwater noise with the

ship traffic representative of deep waters examples were chosen in the Northeast Pacific Ocean in the USA; the Ramsey Sound, Pembrokeshire, West Wales in the UK; and the Gulf of Mexico (Table 1).

An analysis of shallow-water ambient noise levels collected during 14 cruises was reported for the Scotian Shelf on the eastern Canadian coast over the period from 1972 to 1985 [3]. The frequency range covered was 30 Hz to 900 Hz. It was found that the average ambient noise levels (Table 1) were characteristic of shallow water areas with high shipping densities.

The results of an analysis of temporal fluctuations in the noise power spectrum level of shallow water ambient noise in the bandwidth of 100 Hz to 4 kHz were presented in India [4]. The results showed that variation in the average noise spectrum level was higher in the lower frequency level (100 Hz to 1 kHz) (Table 1) and assumed a constant level from there onwards. It was concluded that the temporal fluctuations of the noise levels were due mostly to ship traffic and changes in the weather conditions [4].

Frequency spectra of the underwater ambient noise were measured in the lagoon of a coral atoll, outside the reef and on shallow-water banks in the tropical zone of the Indian Ocean [5]. The measurements were performed in the frequency range of 0.003–9 kHz. In all the regions studied, continuous underwater noise (Table 1) of biological origin was observed, attributed to croaker fish [5].

Continuous measurements of underwater noise levels in the Northeast Pacific Ocean west of San Nicolas Island, California, USA over 138 days, spanning 2003–2004 were compared with measurements made during the 1960s at the same site (Table 1) [6]. Ambient noise levels at 30–50 Hz were 10–12 dB higher in 2003–2004 than in 1964–1966 (Table 1), suggesting an average noise increase rate of 2.5–3 dB per decade. Low frequency (10–50 Hz) ocean ambient noise levels were closely related to the shipping vessel traffic. Increases in commercial shipping were believed to account for the observed low-frequency ambient noise increase. Above 50 Hz the noise level differences between recording periods gradually diminished to only 1–3 dB at 100–300 Hz [6].

Higher underwater noise levels were measured in the area of Ramsey Sound, Pembrokeshire, West Wales, UK, in the summer of 2009 during the season with increased boat traffic (Table 1) compared with the underwater noise levels measured in the spring of 2009 during the season with decreased boat traffic [7]. Below 2 kHz, the noise was thought to come from boat traffic. The peak in sound pressure level around 10 Hz in both seasons was thought to originate from a variety of shipping-related sources, including propeller-excited hull resonance, hull pressure, or propeller blades which could appear from 4 to 70 Hz. These lower frequencies could originate from surface noise due to waves associated with shipping or from breaking on the rocks. The survey taken in the summer, during periods of increased tourist boat activity, showed a distinct peak around 100 Hz that was not apparent during the low season survey. The origin of this noise was likely to be diesel engines, propeller cavitation, engine harmonics and gearboxes [7].

The first study in Brazil to characterise noise levels in the coastal zone was carried out in Guanabara Bay (Southeast Brazil). It showed underwater noise pollution related to the ship traffic and small vessel traffic (Table 1) [8]. Locations with ship traffic had the highest noise levels, while locations with small vessel traffic had the lowest noise levels.

Elevated noise conditions were observed across the Gulf of Mexico, where anthropogenic marine activities were prominent [9]. The LF (low frequency) band was selected to include the environmental, meteorological, biological, and anthropogenic sounds that occur primarily between 10 Hz and 500 Hz. At recording sites positioned nearest to high-density shipping lanes that lead to the Port of South Louisiana (H-3) and the Port of Houston (H-1) the highest L_{01} values ($T = 1$ h) were recorded (Table 1) [9].

Nationally coordinated efforts to quantify underwater noise levels in the UK were presented, in support of UK policy objectives under the EU Marine Strategy Framework Directive (MSFD) [10]. Field measurements were made during 2013 and 2014 at twelve sites around the UK (Table 1). Noise exposure varied considerably, with little anthropogenic influence

Table 1: *Examples of underwater noise levels related mainly to the ship traffic in the global seas and oceans.*

Location, depth of the hydrophone and depth of the sea water	Year of study	Underwater noise levels at different frequencies	Location, depth of the hydrophone and depth of the sea water	Year of study	Underwater noise levels at different frequencies
Scotian Shelf, Canada, hydrophone depth of 31 m and water depth of 79 m [3]	1972–1985	Winter average noise levels at zero wind speed [3]: 30 Hz: 90.8 dB re µPa²/Hz 45 Hz: 90.5 dB re µPa²/Hz 80 Hz: 87.9 dB re µPa²/Hz 150 Hz: 81.9 dB re µPa²/Hz 300 Hz: 74.1 dB re µPa²/Hz 600 Hz: 64.4 dB re µPa²/Hz 900 Hz: 64.3 dB re µPa²/Hz	Ramsey Sound, Pembrokeshire, West Wales, UK, hydrophone depth of 20 m and a water depth of 460 m [7]	2009	Sound pressure levels [7]: Between 5 Hz and 10 Hz: - 92.6 dB re 1 µPa ± 3.9 dB re 1 µPa during spring - 104.7 dB re 1 µPa ± 2.2 dB re 1 µPa during summer Around 100 Hz: - 85.9 dB re 1 µPa ± 2.4 dB re 1 µPa during spring - 104.6 dB re 1 µPa ± 2.4dB re 1 µPa during summer
India, shallow water, hydrophone depth of 5 m and water depth of 25 m [4]	2006	Average noise levels [4]: 98 Hz: 130.3 dB re µPa/√Hz 195 Hz: 128.6 dB re µPa/√Hz 293 Hz: 127.3 dB re µPa/√Hz 586 Hz: 127.6 dB re µPa/√Hz 977 Hz: 127.4 dB re µPa/√Hz 3027 Hz: 127.1 dB re µPa/√Hz 4023 Hz: 127.1 dB re µPa/√Hz	Guanabara Bay, SE Brazil, hydrophone depth of 2 m and a water depth of 4 m [8]	2011–2012	The highest mean sound pressure level [8]: At 187 Hz: 111.6 ± 9.0 dB re 1 µPa At 15.89 kHz: 76.2 ± 8.3 dB re 1 µPa
Indian Ocean, the lagoon of a coral atoll, hydrophone depth of 2–15 m and water depth of 50 m [5]	2005	Spectral maxima observed at 1 kHz and 7.5 kHz [5]: 1,000 Hz: 72 dB re µPa²/Hz 2,000 Hz: 65 dB re µPa²/Hz 7,500 Hz: 80 dB re µPa²/Hz	Port of South Louisiana (H-3), Port of Houston (H-1), NE Gulf of Mexico, hydrophone depth from 250–1,370 m [9]	2010–2012	The highest values L_{01} (T = 1 h) at two sites (H-3 and H-1) nearest to high-shipping lanes [9] in LF band (10–500 Hz) were: 130 dB re 1 µPa and 128 dB re 1 µPa, respectively (L_{01} = sound levels that were exceeded 1% of the time)
Northeast Pacific Ocean, SW of the San Nicolas Island, California, USA, hydrophone depth of 1,090–1,106 m [6]	1966 – 2006	Mean ambient noise levels: -30–50 Hz in 1964–1966: 73–75 dB re 1 Pa²/Hz -30–50 Hz in 2003–2004: 85 dB re 1 Pa²/Hz [6]	Celtic Sea, northern and southern North Sea in UK, hydrophone depth of 100 m and a water depth of 200 m [10]	2013– 2014	Median noise levels for 1/3 octave bands from 63 Hz to 500 Hz [10]: 81.5–95.5 dB re 1µPa

at the Celtic Sea site to several North Sea sites with persistent vessel noise [10].

The above studies showed that man-made noise pollution is present in a number of world seas and oceans caused, in particular, by the maritime traffic (Table 1).

In January 2019, a group of NGOs specialising in the protection of marine life warned that most EU member states were probably not going to honour their commitment to reduce marine noise pollution by 2020 [11]. In this regard, methodological guidance on the underwater noise mitigation measures were prepared by ACCOBAMS in 2019 [12]. These are very useful to be taken into consideration in order to successfully mitigate underwater noise sources in the worlds' seas and oceans.

The aim of this study was to prepare a methodology for quantitative determination of the relationship of the measured underwater noise levels in the Slovenian Sea with anthropogenic pressures and meteorological parameters.

The content of the study is important primarily from the point of view of properly recognising the correlation between the pressures and the status of the marine environment and of determining the optimal mitigating measures for achieving the objective of the Marine Directive (2008/56/EC) [13].

Materials and methods

Underwater noise is monitored near the lighthouse foundation 300 m off the coast at Debeli rtič, Slovenia (lat.: 45°35' 28.2'' N, lon.: 13°41' 59.1'' E), beginning in February 2015. Hydrophone of type Bruel and Kjaer 8,105 was installed 1 m away from the lighthouse foundation at a depth of 4 m (sea depth is 5 m) and connected to a sound analyser of type Bruel and Kjaer 2,250, with a sound level meter and an octave-based frequency analyser that operates in the frequency range of 6.3 Hz to 20 kHz [14]. A sound analyser is closed inside the lighthouse. Measuring unit of the underwater noise levels is dB re μPa.

Dependent variables were continuous underwater noise levels (in dB) in 1/3 octave bands with center frequencies of 63 Hz and 125 Hz, $L_{eq,63Hz}$ and $L_{eq,125Hz}$ (dB). Independent variables were ship densities in the four different areas of 2 NM and 5 NM from the measuring station, in the Gulf of Trieste and in the Gulf of Venice ($\rho_{L,2\,NM}$, $\rho_{L,\,5NM}$, $\rho_{L,Trieste}$, $\rho_{L,Venice}$), dredging activities, cleaning of the sea floor, wind speed at v_v (m/s) and precipitation at h_p (mm). Wind speed data from the Piran buoy and precipitation data from the meteorological station in the Port of Koper were obtained from the Environmental Agency of the Republic of Slovenia. Ship densities were provided from Automatic Information System data [15].

Measuring periods were the following: from 13 February 2015 to 5 May 2015; from 26 September 2015 to 31 December 2015; from 18 August 2016 to 1 November 2016; from 6 July 2017 to 27 August 2017; and from 18 August 2018 to 31 December 2018, in which measured underwater noise levels were available.

For the analysis of the correlation between the dependent variables and the independent variables, the Pearson correlation coefficient r was used [16], which is a measure of the linear correlation between the two variables that gives information about the degree, or magnitude, of the association or correlation, as well as of the direction (+/-) of the relationship between the variables. It is most suitable for use if the distribution of variables is normal (or at least symmetric and unimodal). With r we can examine whether two variables tend to move together. If the large values of one variable are related to the large values of the other variable, the correlation is positive. If the small values of one variable are related to the large values of the other variable, the correlation is negative. If the values of the two variables are not related, the correlation is close to or equal to 0.

The results of the analysis of the correlation between dependent and independent variables are presented in tables, the results being interpreted and the weights of the influence of the anthropogenic and meteorological noise sources on the measured underwater noise levels estimated.

With this correlation analysis, the interdependence of dependent and independent variables was investigated, while multiple linear regression analysis was used to study how strongly the values of the dependent variables were affected by the values of independent variables.

To predict the dependent variables from independent variables, a linear regression model was used, including the least squares method, in which the sum of the squares of deviations is minimal.

The multiple correlation coefficient r between the dependent variables and the independent variables was analysed, and the results are presented in the next section.

The quality of the regression model was evaluated based on the coefficient of determination R^2, which tells how much of the variance of the dependent variables is explained by the variability of the independent variable – ie explained variance. In the case of the linear regression, it is equal to the square of the Pearson correlation coefficient, R^2. However, $1 - R^2$ is an unexplained variance and its root is a standard prediction error.

The test of statistical significance of the correlation was performed based on p-values (significance level). In the regression equation, those variables that have a p-value of less than 0.05 are significant, which means that there is less than a 5 % probability that the correlation is due to an error, which means that there is a 95 % probability that the variables are related to each other.

If the p-value is less than or equal to 0.05 ($p \leq 0.05$), then the results can be generalised with high certainty (95%) from the sample to the population, ie that there are differences between the two variables or that the two variables are interrelated. If the p-value is greater than 0.05 ($p > 0.05$), then the results cannot be generalised from the sample to the population, and we must interpret the results only at the sample level.

From the regression analysis, we estimated the weights of the influence of the anthropogenic and meteorological noise sources on the levels of underwater noise measured.

Results and discussion

The average $L_{eq,63Hz}$ and $L_{eq,125Hz}$ levels measured in the Slovenian Sea in the period between 2015 and 2018 were 82.8–101.1 dB re 1 µPa and 83.9–98.1 dB re 1 µPa, respectively. The average ship densities were 2–252. The average wind speed was 1.8–4.6 m/s and the average precipitation was 0.02–0.07 mm [14].

Results of the correlation analysis
Interdependence between the dependent ($L_{eq,63Hz}$ and $L_{eq,125Hz}$) and independent ($\rho_{L,2NM}$, $\rho_{L,5NM}$, $\rho_{L,Trieste}$, $\rho_{L,Venice}$, dreadg. act., clean. act., v_v and h_p) variables using the Pearson correlation coefficients is presented in Table 2 (for $L_{eq,63Hz}$) and Table 3 (for $L_{eq,125Hz}$).

The highest correlation between the underwater noise and the anthropogenic noise sources was obtained between the $L_{eq,63Hz}$ and the dredging activities ($r = 0.31$) (Table 2). The highest correlation between the underwater noise ($L_{eq,63Hz}$ and $L_{eq,125Hz}$) and the ship density ($\rho_{L,2NM}$, $\rho_{L,5NM}$, $\rho_{L,Trieste}$, $\rho_{L,Venice}$) was 0.18. Correlation between the underwater noise

Table 2. *The Pearson correlation coefficients between the dependent variable ($L_{eq,63Hz}$) and the independent variables ($\rho_{L,2NM}$, $\rho_{L,5NM}$, $\rho_{L,Trieste}$, $\rho_{L,Venice,}$ dreadg. act., clean. act., v_v and h_p) in all measuring periods.*

Pearson's correlation coefficient	From 13.02.2015 to 05.05.2015	From 26.09.2015 to 31.12.2015	From 18.08.2016 to 01.11.2016	From 06.07.2017 to 07.08.2017	From 18.08.2018 to 31.12.2018
$r(v_v)$	0.58	0.51	0.54	0.39	0.35
$r(h_p)$	-0.02	0.06	0.08	0.08	0.07
$r(\rho_{L,2NM})$	0.13	-0.06	0.05	-0.04	0.05
$r(\rho_{L,5NM})$	0.06	-0.06	0.02	0.09	0.08
$r(\rho_{L,Trieste})$	-0.02	-0.03	0.08	0.12	0.12
$r(\rho_{L,Venice})$	-0.10	-0.05	-0.05	0.01	-0.11
r (dredg. act.)	n.a.	0.31	n.a.	n.a.	n.a.
r (clean. act.)	n.a.	n.a.	-0.10	n.a.	n.a.

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Table 3: *The Pearson correlation coefficients between the dependent variable ($L_{eq,125Hz}$) and the independent variables ($\rho_{L,2NM}$, $\rho_{L,5NM}$, $\rho_{L,Trieste}$, $\rho_{L,Venice}$, dreadg. act., clean. act., v_v and h_p) in all measuring periods.*

Pearsons correlation coefficients	From 13.02.2015 to 05.05.2015	From 26.09.2015 to 31.12.2015	From 18.08.2016 to 01.11.2016	From 06.07.2017 to 07.08.2017	From 18.08.2018 to 31.12.2018
r (v_v)	0.39	0.18	0.55	0.24	0.15
r (h_p)	-0.02	0.01	0.09	0.04	0.02
r $(\rho_{L,2NM})$	0.11	0.06	0.07	0.02	0.12
r $(\rho_{L,5NM})$	0.05	0.05	-0.04	0.17	0.02
r $(\rho_{L,Trieste})$	-0.02	0.02	0.01	0.18	0.04
r $(\rho_{L,Venice})$	-0.08	-0.01	-0.09	-0.01	-0.10
r (dredg. act.)	n.a.	0.10	n.a.	n.a.	n.a.
r (clean. act.)	n.a.	n.a.	-0.10	n.a.	n.a.

($L_{eq,63Hz}$ and $L_{eq,125Hz}$) and the cleaning of the sea floor was -0.10.

Correlation analyses showed that the relationship between the $L_{eq,63Hz}$ and the v_v was between 0.35 and 0.58, while that between $L_{eq,125Hz}$ and the v_v, was between 0.15 and 0.55. The relation between the underwater noise ($L_{eq,63Hz}$ and $L_{eq,125Hz}$) and the meteorological parameter – precipitation, h_p – was between -0.02 and 0.09 (Tables 2 and 3). These results of the correlation analyses are interpreted in the subsection discussion.

Results of the multiple linear regression analysis

Furthermore, the least squares multiple linear regression analysis in Table 4 shows how much the values of the dependent variables were affected by the values of the independent variables. The multiple correlation coefficients between the dependent variable $L_{eq,63Hz}$ and the independent variables in all measuring periods were moderate (r = 0.40 – 0.59), while those between the dependent variable $L_{eq,125Hz}$ and the independent variables were low to moderate (r = 0.21 – 0.59) (Table 4).

In the regression analysis, 16%–35% of the variance of the dependent variable $L_{eq,63Hz}$ and 5%–34% of the variance of the dependent variable $L_{eq,125Hz}$ can be explained by the variability of the independent variables ($\rho_{L,2NM}$, $\rho_{L,5NM}$, $\rho_{L,Trieste}$, $\rho_{L,Venice}$, *dreadg. act., clean. act., vv and hp*),

with which the predictive power of the multiple regression model is shown (Table 5).

The statistical significance test of the correlation based on the *p*-value indicated that there was only one independent variable, wind speed vv, that had a significant correlation with both dependent variables ($L_{eq,63Hz}$ and $L_{eq,125Hz}$) in all the measuring periods (Tables 6 and 7). Dredging and cleaning activities also had a significant correlation with $L_{eq,63Hz}$ and $L_{eq,125Hz}$. Precipitation, hp, was mostly insignificant. Ship densities ($\rho_{L,2NM}$, $\rho_{L,5NM}$, ρ_L, Trieste, ρ_L, Venice) were in some cases significant and in some insignificant.

Subsequently, the multiple regression analysis was repeated without the insignificant independent variables in each measuring period. Regression equations in which the dependent variables ($L_{eq,63Hz}$ and $L_{eq,125Hz}$) were predicted by the significant independent variables are presented in Tables 8 and 9.

Discussion of the results

The average continuous underwater noise levels ($L_{eq,63Hz}$ and $L_{eq,125Hz}$) measured in the Slovenian Sea [13] were similar to those reported in the literature, which were related to the shipping noise (Table 1).

Multiple correlation coefficients between the dependent variables ($L_{eq,63Hz}$ and $L_{eq,125Hz}$) and independent variables (anthropogenic

Table 4: *Multiple correlation coefficients (r) between dependent variables ($L_{eq,63Hz}$ and $L_{eq,125Hz}$) and independent variables ($\rho_{L,2NM}$, $\rho_{L,5NM}$, $\rho_{L,Trieste}$, $\rho_{L,Venice}$, dreadg. act., clean. act., v_v and h_p) in all measuring periods.*

Multiple correlation coefficients	From 13.02.2015 to 05.05.2015	From 26.09.2015 to 31.12.2015	From 18.08.2016 to 01.11.2016	From 06.07.2017 to 07.08.2017	From 18.08.2018 to 31.12.2018
$r\,(L_{eq,63Hz})$	0.59	0.55	0.57	0.40	0.40
$r\,(L_{eq,125Hz})$	0.41	0.21	0.59	0.29	0.23

Table 5: *Coefficients of determination (R^2) between the dependent variables ($L_{eq,63Hz}$ and $L_{eq,125Hz}$) and the independent variables ($\rho_{L,2NM}$, $\rho_{L,5NM}$, $\rho_{L,Trieste}$, $\rho_{L,Venice}$, dreadg. act., clean. act., v_v and h_p) in all measuring periods.*

Coefficients of determination	From 13.02.2015 to 05.05.2015	From 26.09.2015 to 31.12.2015	From 18.08.2016 to 01.11.2016	From 06.07.2017 to 07.08.2017	From 18.08.2018 to 31.12.2018
$R^2\,(L_{eq,63Hz})$	0.35	0.30	0.33	0.16	0.16
$R^2\,(L_{eq,125Hz})$	0.17	0.05	0.34	0.09	0.05

Table 6: *Significant independent variables with p-values lower than 0.05, meaning that there was a more than 95 % probability that these variables were related to the dependent variable $L_{eq,63Hz}$. The grey fields indicate insignificant independent variables, with p-values greater than 0.05. The abbreviation n.a. means not applicable.*

p-values	From 13.02.2015 to 05.05.2015	From 26.09.2015 to 31.12.2015	From 18.08.2016 to 01.11.2016	From 06.07.2017 to 07.08.2017	From 18.08.2018 to 31.12.2018
$p\,(v_v)$	0.000	0.000	0.000	0.000	0.000
$p\,(h_p)$	0.001	0.061	0.240	0.923	0.010
$p\,(\rho_{L,2NM})$	0.005	0.691	0.048	0.003	0.036
$p\,(\rho_{L,5NM})$	0.007	0.015	0.000	0.556	0.000
$p\,(\rho_{L,Trieste})$	0.327	0.794	0.000	0.119	0.000
$p\,(\rho_{L,Venice})$	0.037	0.087	0.023	0.342	0.000
p (dredg. act.)	n.a.	0.000	n.a.	n.a.	n.a.
p (clean. act.)	n.a.	n.a.	0.002	n.a.	n.a.

Table 7: *Significant independent variables with p-values less than 0.05, meaning that there was a more than 95 % probability that these variables were related to the dependent variable $L_{eq,125Hz}$. The grey fields indicate insignificant independent variables with p-values greater than 0.05. The abbreviation n.a. means not applicable.*

p-values	From 13.02.2015 to 05.05.2015	From 26.09.2015 to 31.12.2015	From 18.08.2016 to 01.11.2016	From 06.07.2017 to 07.08.2017	From 18.08.2018 to 31.12.2018
$p\,(v_v)$	0.000	0.000	0.000	0.000	0.000
$p\,(h_p)$	0.019	0.509	0.111	0.867	0.599
$p\,(\rho_{L,2NM})$	0.097	0.022	0.000	0.033	0.000
$p\,(\rho_{L,5NM})$	0.000	0.000	0.000	0.215	0.002
$p\,(\rho_{L,Tireste})$	0.001	0.000	0.000	0.033	0.000
$p\,(\rho_{L,Venice})$	0.256	0.110	0.036	0.000	0.000
p (dredg. act.)	n.a.	0.000	n.a.	n.a.	n.a.
p (clean. act.)	n.a.	n.a.	0.021	n.a.	n.a.

Table 8: *Regression equations in which the dependent variable $L_{eq,63Hz}$ was predicted by the significant independent variables ($\rho_{L,2NM}$, $\rho_{L,5NM}$, $\rho_{L,Trieste}$, $\rho_{L,Venice}$, dreadg. act., clean. act., v_v and h_p).*

Measuring periods	Regression equations
13.02.2015–05.05.2015	$L_{eq,63Hz} = 1.378*v_v - 3.898*h_p + 0.357*\rho_{L,2NM} + 0.103*\rho_{L,5NM} - 0.014*\rho_{L,Venice} + 63.450$
26.09.2015–31.12.2015	$L_{eq,63Hz} = 1.117*v_v - 0.093*\rho_{L,5NM} + 4.304*$dred.act. $+ 67.800$
18.08.2016–01.11.2016	$L_{eq,63Hz} = 2.227*v_v + 0.165*\rho_{L,2NM} - 0.627*\rho_{L,5NM} + 0.528*\rho_{L,Trieste} - 0.012*\rho_{L,Venice} - 3.1*$clean.a. $+ 81.77$
06.07.2017–07.08.2017	$L_{eq,63Hz} = 2.762*v_v - 0.196*\rho_{L,2NM} + 70.065$
18.08.2018–31.12.2018	$L_{eq,63Hz} = 1.555*v_v + 1.116*h_p + 0.112*\rho_{L,2NM} - 0.216*\rho_{L,5NM} + 0.268*\rho_{L,Trieste} - 0.022*\rho_{L,Venice} + 73.576$

Table 9: *Regression equations in which the dependent variable $L_{eq,125Hz}$ was predicted by the significant independent variables ($\rho_{L,2NM}$, $\rho_{L,5NM}$, $\rho_{L,Trieste}$, $\rho_{L,Venice}$, dreadg. act., clean. act., v_v and h_p).*

Measuring periods	Regression equations
13.02.2015–05.05.2015	$L_{eq,125Hz} = 0.752*v_v - 2.659*h_p + 0.263*\rho_{L,5NM} - 0.153*\rho_{L,Trieste} + 77.786$
26.09.2015–31.12.2015	$L_{eq,125Hz} = 0.248*v_v + 0.192*\rho_{L,2NM} + 0.167*\rho_{L,5NM} - 0.117*\rho_{L,Trieste} + 1.181*$dred. $+ 77.375$
18.08.2016–01.11.2016	$L_{eq,125Hz} = 1.869*v_v + 0.265*\rho_{L,2NM} - 0.551*\rho_{L,5NM} + 0.368*\rho_{L,Trieste} - 0.009*\rho_{L,Venice} - 1.87*$ clean.a. $+ 84.6$
06.07.2017–07.08.2017	$L_{eq,125Hz} = 1.063*v_v - 0.122*\rho_{L,2NM} + 0.151*\rho_{L,Triestre} - 0.017*\rho_{L,Venice} + 71.912$
18.08.2018–31.12.2018	$L_{eq,125Hz} = 0.562*v_v + 0.364*\rho_{L,2NM} - 0.126*\rho_{L,5NM} + 0.121*\rho_{L,Trieste} - 0.017*\rho_{L,Venice} + 91.705$

pressures and meteorological parameters) were low to moderate ($r = 0.21 - 0.59$) (Table 4). In the regression analysis up to 35 % of the variance of the dependent variable can be explained by the independent variables (Table 5).

The correlation coefficient between the measured underwater noise levels ($L_{eq,63Hz}$) and dredging activity as an anthropogenic noise source was significant but low ($r = 0.31$) (Table 2). The highest correlation between the underwater noise levels ($L_{eq,63Hz}$ and $L_{eq,125Hz}$) and the ship densities was up to 0.13 and 0.18, respectively (Tables 2 and 3), which could be explained by reduced sound wave propagation in the shallow sea [10,17–19]. Low frequency sound waves below the cut-off frequency do not propagate, because the sound propagates into the sea bed [20, 21]. The correlation between underwater noise and the cleaning of the sea floor was negligible (Tables 2 and 3), which was expected, because cleaning was performed with an excavator from the mainland.

The relation between underwater noise and the meteorological parameter – precipitation – was insignificant. Correlation between the $L_{eq,63Hz}$ and the wind speed was low to medium and correlation between the $L_{eq,125Hz}$ and the wind speed was negligible to medium (Tables 2 and 3), which could be explained by the wind-generated waves that break when they are large enough and produce sound [22–28]. That is, underwater ambient sound measurements were, in some cases, used to estimate wind speed over the seas and oceans. The results of these cases showed a very strong correlation between estimated wind speed, provided by a passive acoustic recorder algorithm and in situ measurements of the wind speed [29, 30].

Relevant to our study is the problem of selection of frequencies in the 1/3 octave band as indicators of shipping noise. We based our measurements on the European Marine Strategy Framework Directive which focuses on low frequency vessel noise, in 1/3 octave bands with centre frequencies of 63 Hz and 125 Hz,

as pressure indicators for ship noise [31]. The two bands were selected based on recordings of ship noise in deep-water areas where, in general, these bands are most powerful [22]. A Danish study of ship noise in shallow water has shown that the aforementioned MSFD indicators of shipping noise turned out to be poor proxies for the impact of noise on small cetaceans at higher frequencies. Thus, higher frequencies were proposed to be included in the assessment of good environmental status, ie in the 1/3 octave band with a centre frequency of 10 kHz, which was chosen as a compromise between the range of hearing of small cetaceans and frequency dependent absorption [32]. For this reason, higher frequencies should also be included in further studies of underwater noise in the northern, shallow part of the Adriatic Sea.

Conclusions

Given the multiple linear regression analysis we conclude that dependent variables were affected by the values of independent variables to a low to moderate degree. The correlation of the underwater noise levels with the dredging activity was significant but low, and the one with the ship densities was insignificant, which could be explained by reduced sound wave propagation in the shallow sea. The correlation between underwater noise and the cleaning of the sea floor was negligible, which could be explained by the fact that cleaning was performed with an excavator from the mainland. The relation between the underwater noise and the meteorological parameter – precipitation was insignificant, while correlation between underwater noise and the wind speed was significant but low to medium, which could be explained by the breaking waves generated by the wind that produced sound.

In the near future, the methodology presented will be used to evaluate underwater noise data measured in the years 2019 and 2020. In addition to MSFD pressure indicators for ship noise in 1/3 octave bands with center frequencies of 63 Hz and 125 Hz higher frequencies will be included.

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