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Research Article

Exploring spatial patterns of environmental noise and perceived sound source dominance in urban areas. Case study: the city of Athens, Greece

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Keywords

Noise mapping,
Perceived sound source
dominance,
Acoustic environment,
Urban areas,
Athens

Abstract

The aim of the present study is to map spatial patterns related to noise pollution and the acoustic environment -in a broader context- in the urban area of Athens, Greece. The primary goal of this thesis is to present a comprehensive approach that combines elements of two basic methodologies related to acoustic environment studies: a) noise mapping and b) the soundscape approach. The main inputs are environmental noise measurements and perceptual sound source-related observations. The results feature three noise pollution maps (LAeq,30 sec, L10, and L90 indices) and three sound source maps which reflect the way in which the human ear perceives the presence of sounds. Additionally, the question of whether the spatial distribution of sound source dominance can be explained by the dispersion of environmental noise levels was examined using geographically weighted regressions (GWR). The GWR models showed that sound source-related observations are explained to a significant extent by all three indicators. Four important findings emerge from the analysis. Firstly, areas with high levels of noise pollution are characterized by high to moderate presence of technological and absence of anthropic and natural sounds. Secondly, regions, where there is a simultaneous presence of all sound sources, are characterized by moderate to low noise levels. Thirdly, the absence of technological sounds is observed in quiet areas. Finally, areas featuring a moderate presence of technological and natural sounds are mostly urban green spaces built-in proximity to the main road network.

Highlights:

- Comprehensive methodology combining elements of noise mapping and soundscape approach
- Using Kriging Spatial Interpolation and Geographically Weighted Regression techniques
- Sound source dominance is explained to a significant extent by noise levels
- Absence of anthropic and natural sounds in high noise-affected areas
- Absence of technological sounds in quiet areas



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1. INTRODUCTION

Dense transportation systems, including roads, railways, and air traffic, characterize the modern urban environment. These systems have caused environmental noise (also known as community noise) pollution. According to WHO (WHO, 1999), community noise is defined as noise emitted from all sources except noise at the industrial workplace. Main sources of community noise include road, rail and air traffic; industries; construction and public work; and the neighbourhood. In recent years, road traffic has played a dominant role in causing environmental noise, which can have ill effects on communities (Mehdi et al., 2011).

As the population grows and as sources of noise become more numerous and more powerful, there is increasing exposure to noise pollution, which has profound public health implications (Goines & Hagler, 2007). According to the review report from the Environmental Burden of Disease (EBD) (Hänninen et al., 2014), noise was ranked second among the selected environmental stressors evaluated in terms of their public health impact in six European countries (Margaritis et al., 2018). Noise pollution may cause negative effects on human health (Stansfeld & Matheson, 2003; Halperin, 2014; Swinburn et al., 2015) and on the environment (Francis et al., 2012; Filiciotto et al., 2014). In this context, Directive 2002/49/EC of the European Parliament and of the Council on the assessment and management of environmental noise (END - European Noise Directive) was adopted. The main objective of the above directive is to prevent and reduce environmental noise where necessary and particularly where exposure levels can induce harmful effects on human health and to preserve environmental noise quality where it is good. This directive also aims at providing a basis for developing Community measures to reduce noise emitted by the major sources, in particular road and rail vehicles and infrastructure, aircraft, outdoor and industrial equipment and mobile machinery (EC, 2002).

For environmental noise research, mapping is an extremely important part of the process of quantifying and visualizing noise pollution levels. Indeed, environmental noise pollution is an inherently spatial phenomenon. It varies across geographic space depending on the location of the noise source, the receiver and the intervening obstacles (e.g., the terrain, buildings, barriers). Understanding how it varies across space, how many people it affects and how it can be mitigated is all part of the process of strategic noise mapping (Murphy & King, 2014).

Strategic noise maps have been calculated in many European countries as obliged by the Environmental Noise Directive issued in 2002 (Wei et al., 2016). According to the 2002/49/EC (EC, 2002), a *strategic noise map* shall mean a map designed for the global assessment of noise exposure in a given area due to different noise sources or for overall predictions for such an area. Strategic Noise Maps (S.N.M.) and the associated Noise Action Plans (N.A.P.) are tools which have the advantage of using mapping and represent the quantitative criteria (e.g., L_{den} and L_{night}) on a territory thus ensuring the reproducibility of the studies. It should be noted that the S.N.Ms and N.A.Ps foreseen in the Directive take into account the topography of the site, three-dimensional urban forms, floor coverings, and road, rail, airport and industrial noises. Although, these tools simulated a set of limited sources; all the sound sources related to human activity (e.g., leisure, works, neighbourhoods), as well as those coming from natural sources, also need to be taken into account (Vogiatzis & Remy, 2017).

Various methods have been developed to address the problem of noise pollution such as on-site measurements, population surveys and noise mapping. Environmental noise is however a component of the acoustic environment, consequently environmental noise is only a part of this whole: it is only a way to appreciate the sound environment of a place. Another approach that emerged from the late 60s is known as soundscape, which focuses on recognising all acoustic fields of study, including environmental noise; however, the central focal point of this movement is to consider both sound environment and environmental noise from a "positive" point of view through the concept of soundscape, taking out the usually "negative" connotation of the term *noise* (Rodríguez-Manzo et al., 2015).

According to R.M. Schafer (1993), a soundscape is “the sonic environment with emphasis on the way it is perceived and understood by the individual, or by a society”. While, the International Organization for Standardization (ISO, 2014), defines soundscape as “the acoustic environment as perceived or experienced and/or understood by a person or people, in context”. An understanding of the soundscape offers the ability to unlock a community’s complex response to noise besides the data from technical measurements (Schulte-Fortkamp & Jordan 2016).

Assessment tools for soundscape are as follows: soundwalk and/or questionnaire and/or guided interview in addition to the binaural measurements (ISO, 2017). A soundscape map is the visualisation of soundscape pattern information (Liu et al., 2013). Soundscape map studies can be summarized into three main themes/categories: the sound source map, psychoacoustic map, and perceptual quality map of the sound environment. Sound source maps provide information on various source types including both noise and positive sources. Psychoacoustic maps can provide more information on sound quality perceptions than noise maps. Genuit et al. (2008) drew maps for psychoacoustic parameters including *loudness*, *sharpness*, and *roughness* values in public spaces in Berlin using measured acoustic data. Soundscape quality mapping describing people’s subjective perceptions is a useful tool for soundscape planning (Hong & Jeon, 2017).

Various methodologies have been proposed for the assessment and evaluation of the urban acoustic environment. Several studies are based on the spatial distribution of noise levels (Yagoub & Alkaabi, 2019; Vogiatzis, 2012), various papers introduce the time variable into their measurements (Mehdi et al., 2011), others rely on crowdsourcing and noise pollution tracking applications found on smartphones (D’Hondt et al., 2013; Guillaume et al., 2016), while there are studies implementing the soundscape approach (Rodríguez-Manzo et al., 2015; Liu, et al., 2013). In the present work, we attempt to implement a comprehensive methodology by combining measurements of noise levels (and their spatial distribution) with specified elements of the soundscape approach (Schulte-Fortkamp & Jordan, 2016; Vogiatzis & Remy, 2017; Aletta & Kang, 2015) aiming at an outcome that provides a wide aspect of the study area’s acoustic environment. The current research does not rely completely on the above approach because it does not assess either soundscape attributes (e.g. pleasant, unpleasant, calm, chaotic, eventful, monotonous), (Margaritis & Kang (2017) or psychoacoustic parameters, or soundscape quality (Hong & Jeon, 2017), therefore it is limited to the perceived sound source dominance evaluation.

The main object of this study is to map spatial patterns related to noise pollution and the acoustic environment -in a broader context- in the urban area of Athens, Greece. The basic motive behind this research was the occurrence of high noise pollution levels in the study area (National Center for the Environment and Sustainable Development, 2018). The European Union also considers environmental noise to be a significant environmental issue and has thus introduced Directive 2002/49/EC. Finally, it is important to mention that modern scientific circles (Margaritis & Kang, 2017; Liu et al., 2013; Schulte-Fortkamp & Jordan, 2017;) consider that results obtained from urban soundscape research provide useful information for urban planning and design.

2. METHODOLOGY

2.1. Planning framework

The methodology adopted by the present study was partially influenced by the work of Margaritis & Kang (2017). Besides, it is important to underline that this experimental approach is the first (in the field of environmental noise) to be conducted in the broader area of downtown Athens. The main inputs are environmental noise measurements and sound source-related observations at selected sampling points. The unsampled locations are assigned spatially interpolated values using the Ordinary Kriging method. The results feature three noise

pollution maps ($L_{Aeq,30\text{ sec}}$, L_{10} and L_{90} indices) and three sound source maps that reflect the way the human ear perceives the presence of sounds. Depending on their source, these sounds are categorized into anthropic, natural and technological. Additionally, the question of whether the spatial distribution of sound source dominance can be explained by the dispersion of environmental noise levels was examined using geographically weighted regressions (GWR). Furthermore, a visualization of the perceived sound source dominance of the area was attempted through the process of the cartographic overlay.

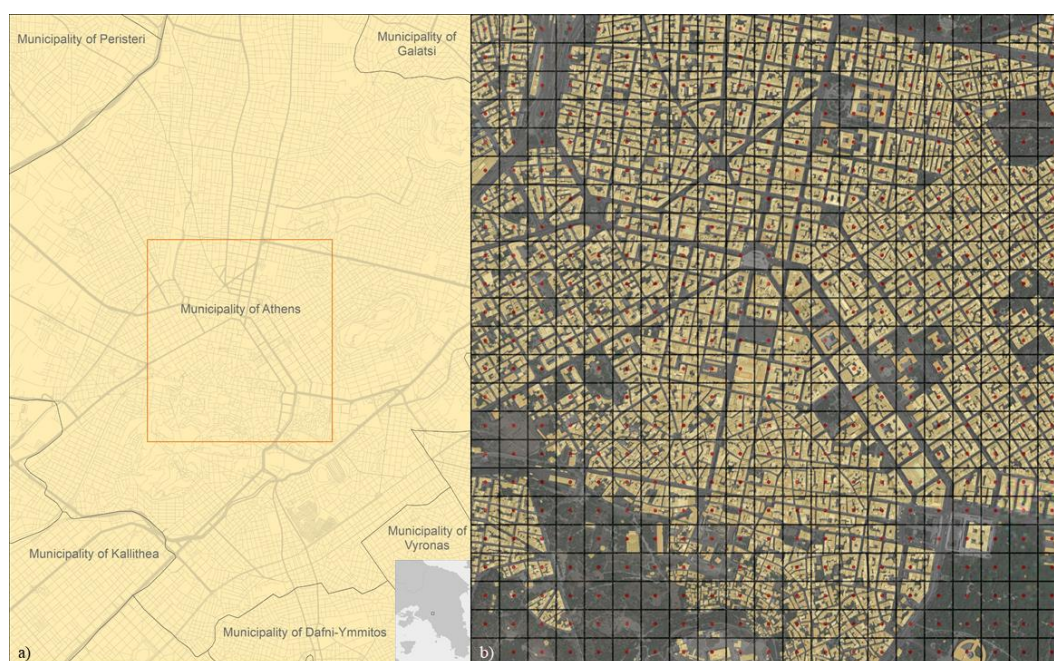
In the first phase, the study area boundaries were determined. The next step was to specify the (physical and perceptual) data collection method. Afterward, the spatial scale and the time period during which the measurements and observations will take place were defined. Then, the selection of the spatial interpolation method was accomplished, and the last step was to visualize and interpret the results.

2.2. Study area

The area that was examined in the context of the present study concerns an important part of downtown Athens. This territory is of scientific interest since it qualifies as the essential and symbolic core of Greece. Additionally, it combines a variety of land use characteristics and is marked by a dense and diverse road network (from local streets to central avenues) as well as highly developed transport infrastructures (e.g., buses, railways, tram, subway).

The total area extends to 4.83 km². A grid of 100 × 100m was implemented, segregating the region into 483 tiles (fig. 1b). Each centroid of the aforementioned tiles was assigned as the sampling point. The measurement points were defined using a systematic sampling method with a fixed distance interval of 100 meters from one measurement point to the other. In this way, a smooth and accurate prediction surface was created as opposed to a random sampling method (Margaritis & Kang, 2017). In case a centroid turned out to be non-accessible due to legal or physical obstacles (e.g., buildings), the closest publicly accessible point was selected.

Figure 1. (a) location of the study area in Athens, (b) depiction of the 483 measurement points and the applied grid (100×100) meters



Source: <https://geodata.gov.gr/>, <https://www.geofabrik.de/>, own processing

2.3. Data collection

2.3.1. Environmental noise levels recording

Data collection was performed between 26/2/2020 and 11/3/2020 (working days only). The measurements were carried out in a specific time slot (16:00 - 19:00), representing the usual rush hour in Athens, using the NoiseCapture application (see Picaut et al., 2019) which was installed on a smartphone and is based on participatory sensing. This approach rests upon the assessment of noise levels by volunteers thanks to the microphone embedded in their smartphone. These complex devices are able to both capture the ambient sound levels and geolocalize the data (Guillaume et al., 2016). The aforementioned application was used to record sound pressure levels at each of the selected locations. It is crucial to mention that during the measurement period there were no COVID-19 related restrictions. Furthermore, the authors decided to conduct fieldwork based on noise measurements via NoiseCapture since the official noise map (see fig. 3) was outdated (10/2014) and provided in a non-editable form. Besides, to address the issue of reduced accuracy of the NoiseCapture application, the measurement points were by far increased (483 compared to 11 on the official map).

To measure the environmental noise levels, recordings of 30 seconds were made at each sampling point, and through "NoiseCapture" the following indices were automatically calculated: a) $L_{Aeq, 30sec}$, b) L_{10} , c), L_{90} d) L_{50} in dB(A). The application takes instantaneous measurements of noise levels every second (hence in 30 seconds, 30 measurements are taken). The indicators used to create the noise maps are $L_{Aeq, 30sec}$, and the percentile L_{10} and L_{90} . The equivalent sound pressure level L_{Aeq} includes the total sound energy received at a measurement location and refers to the mean noise level. L_{10} indicates the noise level exceeded 10% of the measurement time and is, therefore, indicative of peak levels. L_{90} indicates the noise level exceeded 90% of the measurement time and can be considered as the background noise level. Both L_{10} and L_{90} are widely used in studies of noise disturbance and background noise quality (Wei et al., 2016).

2.3.2. Sound source dominance assessment

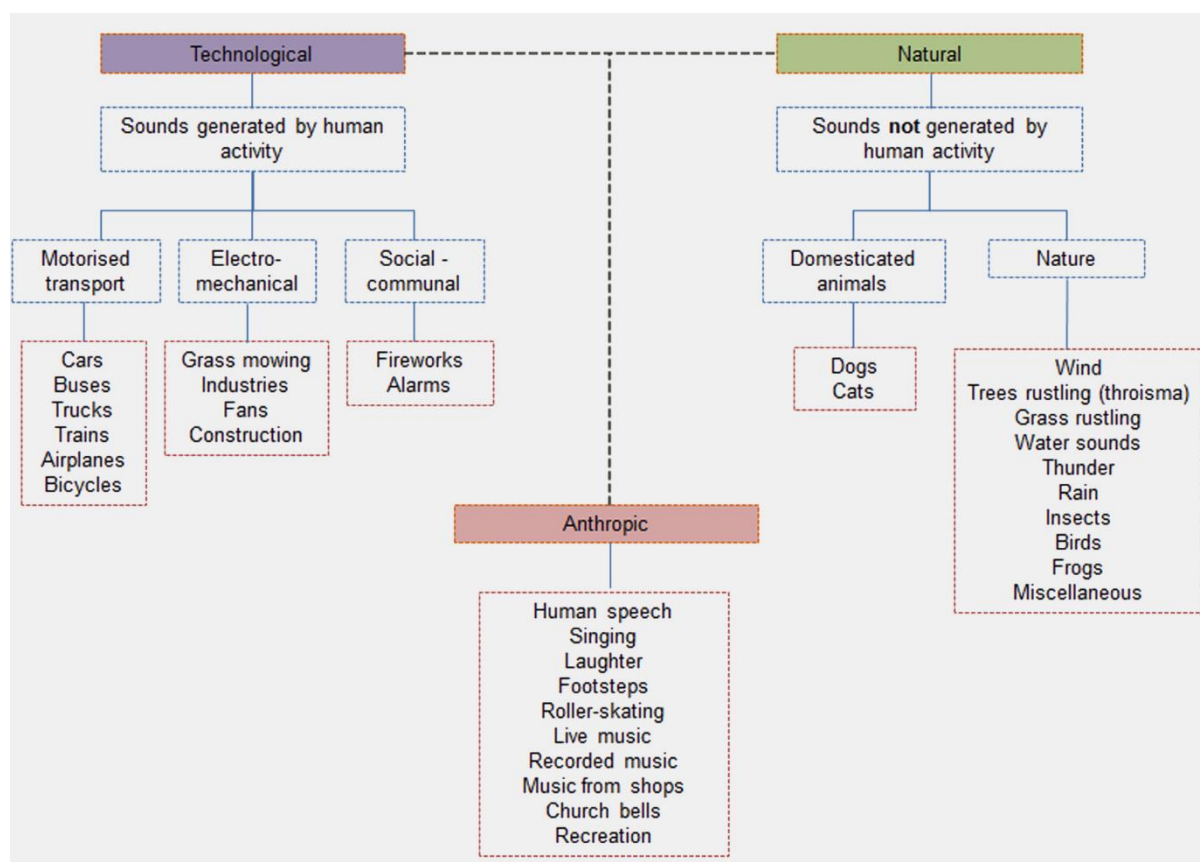
Throughout the measurement period, using the *individual soundwalk* approach, Dimitris Markou noted the perceptual contributions of the sound sources to the acoustic environment of each sampling point. The author walked along the route and evaluated the urban soundscape to focus on careful listening practice emphasizing his own viewpoints (Yong Jeon et al., 2013). Then, his perceptual responses to the acoustical, visual, aesthetic, geographic, social and cultural differences (ISO, 2017) of every sample point were observed and measured.

The soundwalk is a very common method for collecting individual responses about the sonic environment in soundscape studies (Aletta and Kang, 2015). A systematic soundwalk has advantages for quantitatively and qualitatively evaluating soundscapes as multimodal experiences, which can compensate for a lack of laboratory experiments. It can allow for both subjective responses and objective measurement of soundscapes (Yong Jeon et al., 2013). Soundwalk methods can be divided in two clusters. The first one diversifies them according to the time of selecting the measurement points, which varies either before (a priori) or during the measurement period. The second cluster distinguishes soundwalks based on the data collection process followed by the participants, which can take place either in groups or individually (Margaritis & Kang, 2017). The sources were divided into three main categories (technological, anthropic, natural) according to the classification (fig. 2) proposed by Brown et al. (2011) and used by Margaritis & Kang (2017).

Human perception is a notion that cannot be easily quantified; thus, a qualitative measurement scale was used. The perceptual intensities of each type of sound source were recorded on a scale that begins with 0 (complete absence) and ends at 5 (maximum intensity).

Afterward, the contribution of each category was calculated by dividing the intensity of each group by the intensity aggregate (all three types of sources).

Figure 2. Three main types of sound sources with subcategories



Source: Margaritis & Kang, 2017

2.4. Mapping content

After the data collection, the acquired information was transferred for further processing into ArcGIS (version 10.4), while the map visualisation procedure took part in QGIS (version 3.4.8.) software. It should be noted that the geodetic reference system EGSA '87 was used. To create three noise maps and three maps showing the dispersion of sound sources, the spatial interpolation method "Ordinary Kriging" with a spherical semi-variogram was chosen. The map which represents the visualization of the perceived sound source dominance of the area was created using the process of the cartographic overlay.

2.5. Assessment of mapping effectiveness

The evaluation of the interpolation results is a necessary step in the process of spatial interpolation since it determines the level of efficiency of the selected method. This process is performed using the "Geostatistical Wizard" tool. The lag size was set, in accordance with the grid size, at 100 meters. The final results of the cross-validation process are shown in table 1.

In terms of bias assessment, the lowest values were found in anthropic, natural and technological sources, as Mean Prediction Error (MPE) and Mean Standardized Error (MSE) are approximately zero, while the Root Mean Squared Prediction Error (RMSPE) is at its

minimum values. On the contrary, the model is more biased towards noise levels since RMSPE is much higher than the corresponding values observed in sound sources.

Table 1: Error diagnostics using the cross-validation process

Conditions	Errors	L _{Aeq}	L ₉₀	L ₁₀	Tech.	Anth.	Nat.
MPE→ 0	MPE	0,043	-0,010	-0,064	-0,002	0,000	0,001
MSE→ 0	MSE	-0,007	-0,001	-0,009	-0,008	0,000	0,004
RMSPE→ min	RMSPE	5,832	5,131	6,474	0,192	0,163	0,130
ASE=RMSPE	ASE	5,910	5,225	6,526	0,194	0,164	0,133
RMSSE≈ 1	RMSSE	0,984	0,979	0,989	0,988	0,993	0,976

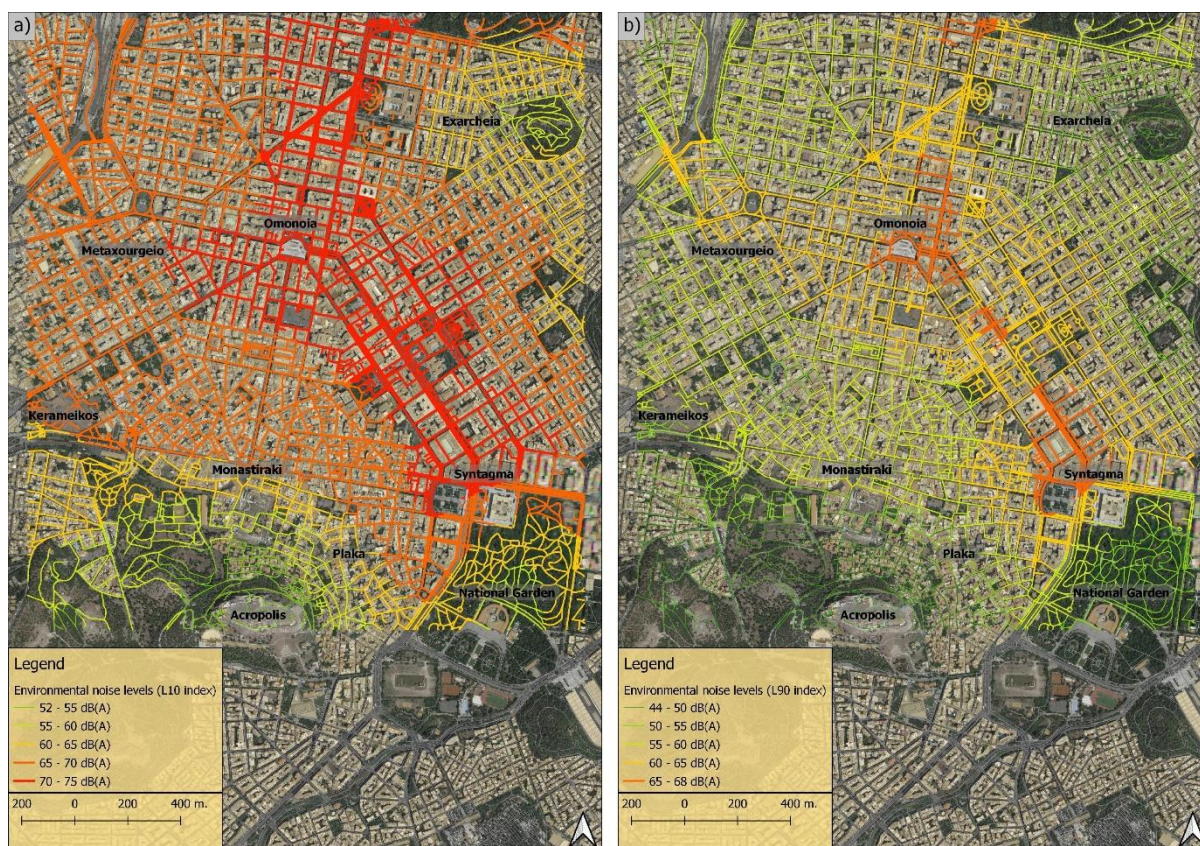
The uncertainty assessment, which measures the prediction standard errors to estimate correct variability (Margaritis & Kang, 2017), showed that the variability has been calculated with accuracy in all the examined variables. More specifically, the Average Standard Error (ASE) displays values almost similar to those of the RMSPE, while the values of the Root Mean Squared Standardized Error (RMSSE) approach the optimal value, which is equal to one. Anthropogenic sources are the variable with the highest accuracy since its RMSSE is equal to 0.993, while natural sources are characterized by the lowest accuracy as they possess the lowest RMSSE (the value of which is 0.976).

2.6. Statistical analysis

At this stage, the degree of spatial dependence between perceived sound source dominance and environmental noise levels is examined. This procedure was performed using geographically weighted regressions (GWR). For the above research, a sound source dominance index was created, which results from the combination of the three sound source-related variables and acquires separate values for each point. The sound source dominance index is derived from the weighted sum of sound source perceptual intensities: technological were multiplied by 100, anthropic by 10 and natural sources by 1. The above index aims to capture the composition of the acoustic environment in each sampling point. Therefore, the sound source-related variables are included in the 3 digits of this experimental index (technological sounds are represented by the first digit, anthropic ones by the middle and natural ones by the last one). The GWR were carried out using the sound source dominance index as a dependent variable, while the environmental noise indicators (L_{Aeq,30s}, L₉₀ and L₁₀) were defined (individually and in pairs) as independent variables.

To strengthen the model, the correlation (using the Spearman index) between the technological sounds and the typical traffic data (working days only) for the 483 sampling points was tested. The traffic data were extracted from Google Maps. The Spearman coefficient revealed a positive correlation (coefficient (Rs) = 0.723) between the aforementioned variables.

Finally, a spatial autocorrelation test was performed for each GWR. The tool used for the above procedure is the spatial autocorrelation coefficient Moran's I. The vector file resulting from the geographically weighted regression was assigned as input. The examined field was the residual which results from the subtraction of the measured environmental noise value (e.g. L_{Aeq} Index, 30s) from the corresponding estimated value resulting from the regression.

Figure 4. Spatial distribution of environmental noise levels: a) L_{10} , b) L_{90} indices

3.2. Spatial distribution of perceived sound source dominance

As shown in figure 5(b) and table 2, technological sound sources are the main component of the study area's soundscape. The perceived dominance of technological (along with anthropic and natural) sounds, as mentioned in a previous chapter, is based on a scale that begins with 0 (complete absence) and ends at 5 (maximum intensity), while its contribution is calculated by dividing the intensity of each group by the intensity aggregate (all three types of sources). More precisely, the acoustic environment of the areas located near Omonia Square consists mainly of technological sounds. Regions that are characterized by a moderate to strong presence are those located in the northern (except the Exarcheia district) and the central part. A moderate presence can be found in the southern part of the commercial triangle, in a significant part of the Plaka district, in the National Garden, and in the residential areas of the Kerameikos district. It becomes obvious that when the distance from the major avenues (which are characterized by a strong presence of cars, buses, trolleys, etc.) increases, the occurrence of technological sources decreases. More specifically, a low presence is observed in the south where urban green areas prevail (e.g. the National Garden, Alsos Petralonon) and areas with strong tourist activity such as Anafiotika, Plaka and the Acropolis.

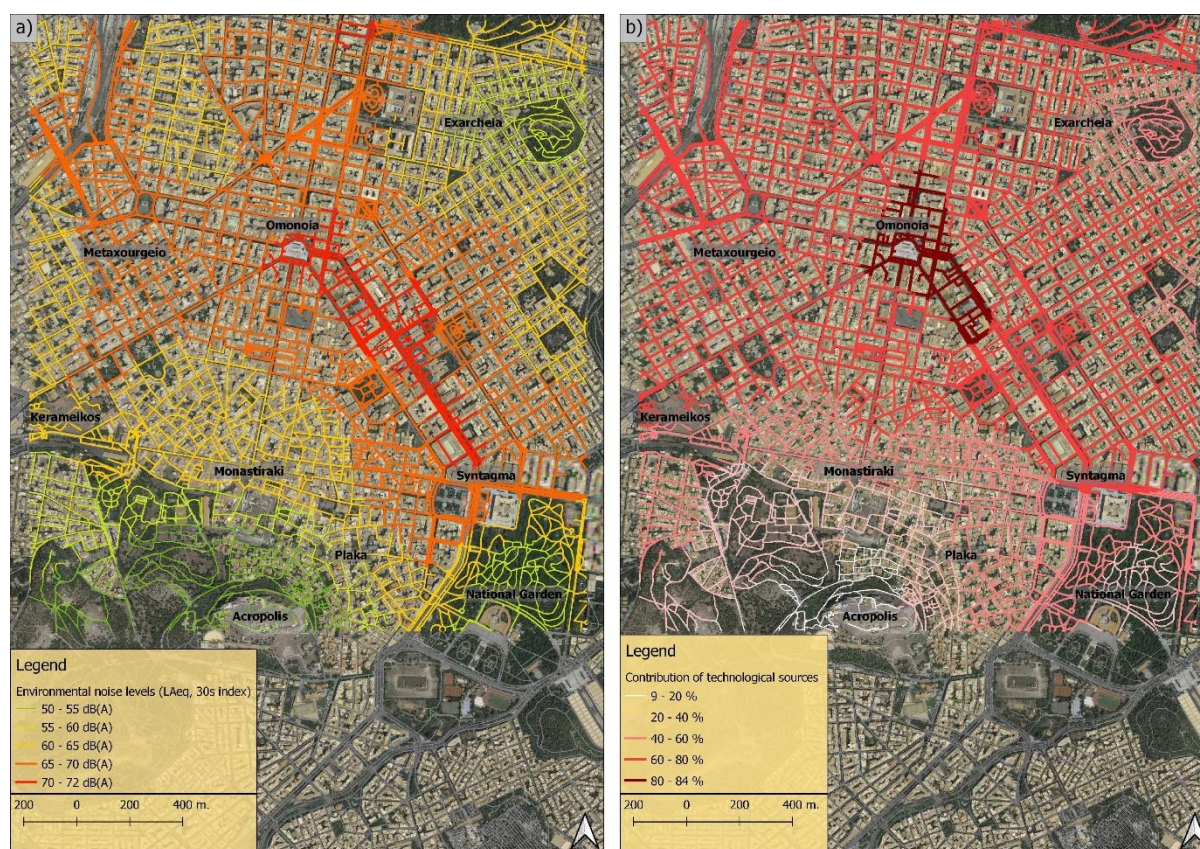
In contrast to technological sources, anthropic ones are not characterized at any point by high presence. Their maximum contribution reaches the medium levels which are observed in the central and the southern areas (fig. 6a). Areas located in the southern part of the commercial triangle, in the western part of the Plaka district, east of Kerameikos and the wider area of the Acropolis form the sites where the prevailing sounds indicate a moderate anthropic presence. The above areas refer to places that have commercial (cafes, restaurants, shops, etc.), tourist and recreational uses, or are historic sites of international importance such as the Acropolis. The remaining part consists of places that are marked by either medium to low or

low presence. It has been observed, generally, that high noise levels are accompanied by a low presence of anthropic sources, as technological sounds overlap with anthropic ones (masking effect of traffic sounds). However, areas that are identified as quiet do not necessarily have to be represented by anthropic sounds (e.g. National Garden, Exarchia - Strefi Hill, the southern part of the Kerameikos district -Alsos Petralonon).

Table 2: Contribution per category of sound sources

Sound source	Contribution to the acoustic environment	Area (km ²)	Area (%)
Technological	High	3,11	64,3%
	Medium	1,33	27,5%
	Low	0,40	8,2%
Anthropic	High	-	-
	Medium	1,17	24,2%
	Low	3,66	75,8%
Natural	High	-	-
	Medium	0,63	13,1%
	Low	4,20	86,9%
Total		4,83	100,0%

Figure 5. Spatial distribution of (a) environmental noise levels ($L_{Aeq, 30s}$ index), (b) technological sound sources



The contribution of natural, similarly to anthropic sources, is average to low. The areas which feature a moderate presence of natural sounds, as shown in figure 6(b), are the wider area around the Acropolis and the inner part of the National Garden. It was noticed that the Archaeological Site of the Acropolis (which is located at a considerable distance from the busy centre) consists of technological sounds which acquire low intensity. Therefore, the natural sounds (which originate mainly from various birds that take shelter there) find a breeding ground. The National Garden, on the other hand, despite being closer to the main avenues, has more members (mostly birds) of the animal kingdom which can mask the noise that comes from the adjacent roads. Areas that demonstrate medium to low presence of natural sounds are Anafiotika, a part of the Plaka district, and the Exarcheia district. The latter is primarily affected by the existence of Strefi Hill, as well as some domestic birds which manage to be "heard" since the traffic is, relatively to other urbanized sections, significantly reduced.

Figure 6. Spatial distribution of (a) anthropic, (b) natural sound sources



3.3. Spatial regression models

At this stage, an attempt is made to assess whether the dispersion of sound source-related observations (contribution of technological, anthropic and natural sound sources) could be explained by the spatial distribution of environmental noise levels ($L_{Aeq,30s}$, L_{90} and L_{10} indicators). The process of geographically weighted regression (GWR) was performed using the sound source dominance index as dependent variable, while the environmental noise indicators were defined individually and in pairs as independent variables. The results of the regressions are shown in the table below.

In light of the above results, it is observed that the statistical value R-squared, which acquires the highest value (92%) when $L_{Aeq,30s}$ and L_{90} indices are defined as dependent variables, and the lowest (77%) when the respective position is assigned to L_{90} and L_{10} ,

denotes that all three environmental noise indicators interpret to a very satisfactory degree the variability of sound source dominance index. As can be seen from the table below, the use of two independent variables in the performance of the regressions differentiated to some extent the adaptability of the model: on the one hand it was improved by 12% when the background noise level L_{90} was added to the equivalent sound pressure $L_{Aeq,30s}$, and on the other hand it was decreased by 6% when the L_{90} index was added to the L_{10} index. It is worth mentioning that it was not possible to perform a geographically weighted regression either by defining the $L_{Aeq,30s}$ and L_{10} indices as the two independent ones or by introducing a third variable (i.e., all the noise indicators). The above-stated examinations could not be completed since the measured values of the indicators $L_{Aeq,30s}$ and L_{10} showed a particularly strong spatial correlation between them ($R^2 = 98\%$).

Table 3: Results of the GWR process

Dependent variable	Independent variable 1	Independent variable 2	R^2
Sound source dominance index	$L_{Aeq,30s}$	-	0.826
	L_{90}	-	0.799
	L_{10}	-	0.811
	$L_{Aeq,30s}$	L_{90}	0.924
	$L_{Aeq,30s}$	L_{10}	-
	L_{90}	L_{10}	0.766

The next step in the process was to examine the spatial autocorrelation of the residuals resulting from the subtraction of the measured environmental noise value from the estimated value resulting from the GWR. As mentioned above, this test was performed based on the spatial autocorrelation coefficient Moran's I. The purpose of this process is to determine whether the regression assumptions are satisfied. The above-stated becomes possible when the residuals: a) are independent of each other and their values do not associate with the values of neighbouring locations, b) are characterized by constant variation and c) are distributed evenly. Moran's I index values may vary from -1 to +1. Values close to +1 indicate significant positive autocorrelation, values close to -1 denote strong negative autocorrelation, while there is no spatial autocorrelation when Moran's I index displays values close to 0. At the same time, two more indicators were calculated:

- the Z-score which demonstrates the standard deviation of the model. The closer it lies to 0, the more the examined amount (in our case the residuals) is characterized by a constant spatial variation
- and the P-value which measures the possibility that the observed spatial pattern was created by a random process. When the p-value obtains high values (close to 1), the pattern is more likely to have arisen because of stochastic procedures.

The spatial autocorrelation test was performed for all five geographically weighted regressions, and the results derived from it are shown in table 4.

In light of the above, it can be concluded that there is no spatial autocorrelation in the residuals in any of the regressions performed since the Moran's I index demonstrates values very close to 0 in all three cases. Additionally, the performance of the Z-score shows that the

residuals of the regression using L_{90} as an independent variable are characterized by the most stable spatial fluctuation. Respectively, the above-mentioned index displays a particularly high rating in P-value which indicates that the observed spatial pattern is the most likely to have arisen because of random processes. Thus, it can be safely reported that in all five cases, the errors are independent from each other, are characterized by constant variation, are equally spatially distributed, and arise through arbitrary procedures. In this way, the adaptability of the model is further increased.

Table 4. Aggregate results of Moran's I spatial autocorrelation test

Dependent variable	Independent variable 1	Independent variable 2	Moran's I index	Z-score	P-value	Spatial pattern
Sound source dominance index	$L_{Aeq,30s}$	-	-0.014	-0.354	0.723	Random
	L_{90}	-	-0.011	-0.268	0.789	Random
	L_{10}	-	-0.014	-0.374	0.708	Random
	$L_{Aeq,30s}$	L_{90}	-0.021	-0.564	0.573	Random
	$L_{Aeq,30s}$	L_{10}	-	-	-	-
	L_{90}	L_{10}	-0.032	-0.908	0.364	Random

3.4. Sound source dominance profiles

The categorization of the sound sources (based on their contribution) led to the determination of three groups which are differentiated based on the simultaneous absence or presence of a specific group of sounds.

Low presence of anthropic sources

As shown in figure 7, technological sounds prevail over most of the area. More precisely, in almost the entire northern part of the region, the presence of technological sources is high while the respective presence of anthropic and natural are both at low levels. These areas display high environmental noise levels. In parts of the Plaka and Exarcheia districts, the wider area of Syntagma and the National Garden there is a decrease in the contribution of technological sources without any increase in other sound sources. In Plaka, Syntagma and the outer section of the National Garden, the masking phenomenon of the natural and anthropic sounds by the technological ones, which come from the adjacent highways, is observed. In the Exarcheia district (mainly on the Strefi Hill) and in the inner part of the National Garden the human presence (in the form of sounds) is absent while the natural and the technological are both at moderate levels. Exarcheia is a degraded district whose pure residential character prevents anthropic sounds from being prevalent. This sound source dominance profile covers an area that amounts to 3.61 sq.km and corresponds to 75% of the total (table 5).

Low presence of technological sources

As far as the southern part is concerned, there are several differences. Firstly, there is a significant reduction of the technological sources in the quiet southern/southwestern areas

(Acropolis, Anafiotika, Alsos Petralonon and a small part of the Plaka district). The above locations are mainly recreational areas that are significantly away from the noisy central avenues and show low environmental levels. The wider area around the Acropolis is characterized by an equally significant anthropic and natural sound presence while as one moves westward the anthropic contribution decreases, while if one moves northwards the natural one decreases. These specific locations occupy an area equal to 0.4 sq.km and their percentage barely reaches 8%.

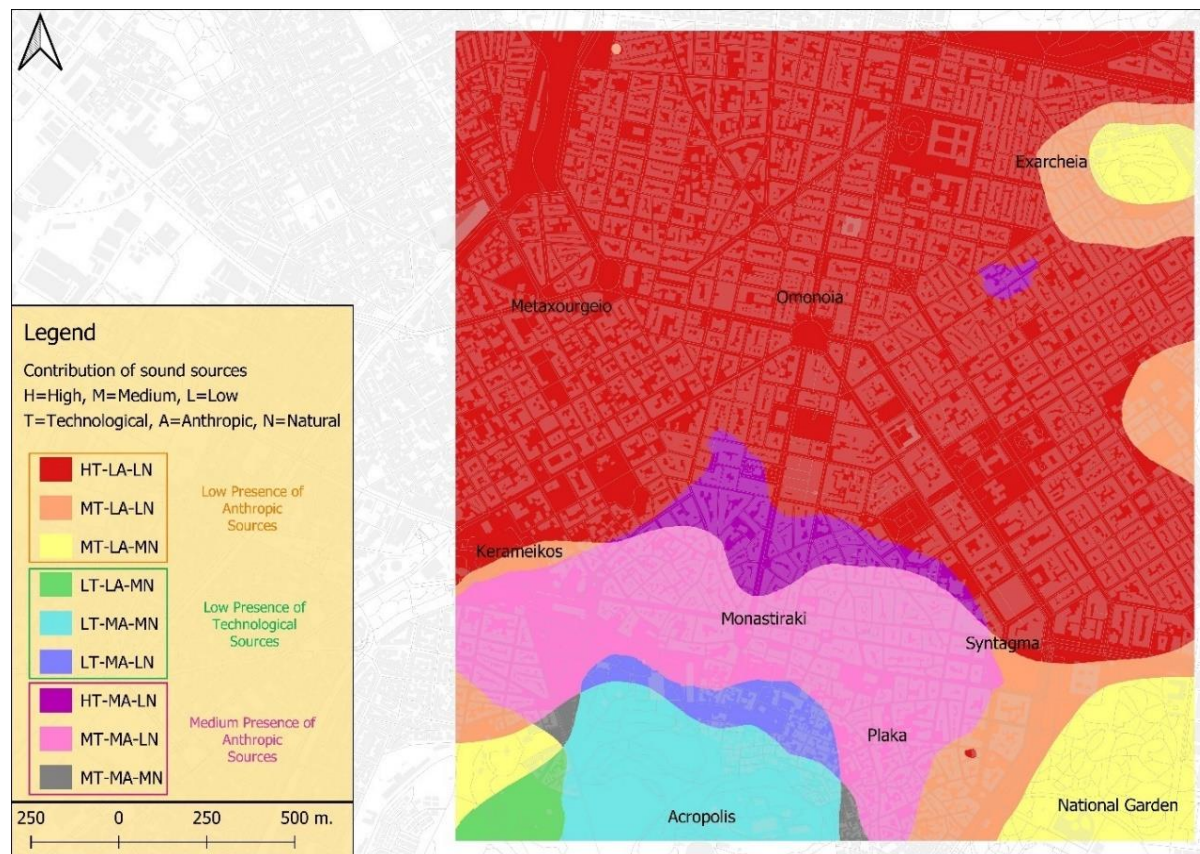
Moderate presence of anthropic sources

It is worthwhile to mention the increased presence of anthropic sources (while the technological ones remain either at high or moderate levels) in a considerable part of the region (17% of the total). The locations that are associated with this profile are the central and southern part of the commercial triangle, in Kerameikos and Plaka. The aforementioned areas are associated with medium-high environmental noise levels and represent the most vibrant and multifaceted section of the Athens Centre.

Table 4. Sound source dominance profile (area covered)

Profile	Low presence of anthropic sources	Low presence of technological sources	Moderate presence of anthropic sources
Area(km ²)	3.61	0.40	0.82
Area (%)	74.8%	8.2%	17.0%

Figure 7. Spatial Representation of the nine “High” (H), “Medium” (M) and “Low” (L) profiles of the sound sources and classification thereof in three larger groups



4. DISCUSSION

4.1. Conclusions

The aim of this study was primarily to assess the environmental noise levels and sound source-related variables in downtown Athens during the period between 26/2/2020 and 11/3/2020. Secondly, the question of whether spatial distribution of sound source dominance can be explained by the dispersion of environmental noise levels as well as the estimation of the accuracy of the model were examined.

Regarding the correlation between the environmental noise levels and the perceived sound source dominance, it is reported that the GWR models showed that sound source dominance is explained to a significant extent by all three noise indicators ($R^2=80\%$ for L_{90} , $R^2=81\%$ for L_{10} and $R^2=83\%$ for $L_{Aeq, 30s}$), which implies good adaptability of the proposed methodology. Furthermore, it is worth mentioning that the use of two independent variables when performing the GWR, differentiated to some extent the flexibility of the model: on the one hand when the sound pressure equivalent $L_{Aeq, 30s}$ was added to the L_{90} background noise indicator, the statistical value R-squared increased to 92% and on the other hand when the traffic nuisance indicator L_{10} was added to L_{90} index, the corresponding percentage decreased to 77%.

Concerning the spatial distribution of the examined quantities (environmental noise indicators and sound sources), the main conclusions drawn are as follows:

- areas with high levels of noise pollution (northern and northern-to-central except the Exarcheia district) are characterized by high to moderate presence of technological and absence of anthropic and natural sounds
- in the central-to-southern regions (significant part of the commercial triangle, Monastiraki, Plaka and Kerameikos districts) there is a simultaneous presence of all sound sources; moderate-high technological, moderate anthropic and low natural. This region is characterized by moderate to low environmental noise levels and is marked by several commercial activities
- areas with absence of technological sounds in which combinations of anthropic and natural sounds prevail are in the south and southwest where low levels of environmental noise are detected. These recreational districts (e.g. Vrahakia Acropolis, Alsos Petralonon) are reasonably distanced from the noisy centre
- areas featuring a moderate presence of technological and natural sound sources where anthropic ones are absent are mostly urban green spaces (e.g. the National Garden, Strefi Hill in Exarcheia) built in proximity to the main road network as the noise produced by the latter does not leave the adjacent acoustic environment unaffected

As far as the sound source dominance profiles are concerned, it is noted that most of the area (75%) belongs to the profile which is characterized by the absence of anthropic sounds. The second place belongs to the locations where anthropic sound sources maximize their contribution by reaching medium levels (17% of the total area). Finally, the smallest area (8%) is occupied by areas where the technological presence is minimized.

4.2. Obstacles – Limitations

In all stages of the composition of the present study, there were some limitations and various issues arose which should be mentioned at this point. First of all, it should be noted that it was practically impossible to conduct noise pollution measurements and sound source-related

observations at the 483 selected sampling sites simultaneously. Therefore, a time "window" was selected (16:00 to 19:00 on working days) during which the prevailing environmental conditions (e.g. flow of vehicles and people) were characterized, in general, by slight fluctuations. Moreover, the fact that it was not feasible to measure environmental noise levels using a professional device (e.g., sound level meter, decibel meter, etc.), affected, to some extent, the accuracy of the results. This obstacle was attempted to be overcome by reducing the (horizontal and vertical) distance (100 m) between sampling points. The corresponding value used by Margaritis & Kang (2017) was 200 meters. Last, the fact that the sound source dominance assessment was made by only one person, introduces to a significant degree a subjective aspect in the results.

4.3. Future research

At this point, it is considered necessary to mention possible ways in which the present results can be enriched, confirmed and even overturned. Firstly, it would be beneficial to use the adopted methodology to investigate spatio-temporal patterns (e.g. measurements at different times of the day, sampling on non-working days, etc.) that may occur in the area. Secondly, it would be particularly useful from a scientific aspect to examine how noise affects people's lives (e.g. residents, workers, tourists, etc.) and how they perceive the soundscape of the area. The above can be accomplished by conducting research based on questionnaires or guided interviews. Last, similar research could be carried out using professional devices (e.g. sound level meters, decibel meters) which are characterized by a high degree of accuracy.

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REFERENCES

- Aletta, F., & Kang, J. (2015). Soundscape approach integrating noise mapping techniques: A case study in Brighton, UK. *Noise Mapping*, 2(1).
<https://www.degruyter.com/document/doi/10.1515/noise-2015-0001/html>
- Brown, A. L., Kang, J., & Gjestland, T. (2011). Towards standardization in soundscape preference assessment. *Applied acoustics*, 72(6), 387-392.
<https://www.sciencedirect.com/science/article/abs/pii/S0003682X11000028?via%3Dihub>
- D'Hondt, E., Stevens, M., & Jacobs, A. (2013). Participatory noise mapping works! An evaluation of participatory sensing as an alternative to standard techniques for environmental monitoring. *Pervasive and Mobile Computing*, 9(5), 681-694.
<https://www.sciencedirect.com/science/article/abs/pii/S1574119212001137?via%3Dihub>
- European Directive (EC), (2002). *2002/49 of the European Parliament and the Council of 25 June 2002 relating to the assessment and management of environmental noise*. Brussels: Publications Office of the European Union. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002L0049&from=EN>

- Filiciotto, F., Vazzana, M., Celi, M., Maccarrone, V., Ceraulo, M., Buffa, G., ... & Buscaino, G. (2014). Behavioural and biochemical stress responses of *Palinurus elephas* after exposure to boat noise pollution in tank. *Marine pollution bulletin*, 84(1-2), 104-114. <https://www.sciencedirect.com/science/article/abs/pii/S0025326X14003075?via%3Dihub>
- Francis, C. D., Kleist, N. J., Ortega, C. P., & Cruz, A. (2012). Noise pollution alters ecological services: enhanced pollination and disrupted seed dispersal. *Proceedings of the Royal Society B: Biological Sciences*, 279(1739), 2727-2735. <https://royalsocietypublishing.org/doi/10.1098/rspb.2012.0230>
- Genuit, K., & Fiebig, A. (2006). Psychoacoustics and its benefit for the soundscape approach. *Acta acustica united with acustica*, 92(6), 952-958. https://global.head-acoustics.com/downloads/publications/environmental_noise/Acta06_Psychoacoustics.pdf
- Geodata.gov.gr (2015). *Municipality boundaries (Kallikratis)*. Retrieved from <https://geodata.gov.gr/en/dataset/oria-demon-kallikrates>
- Geofabrik.de (2018). *Download OpenStreetMap data for this region: Greece*. Retrieved from <https://download.geofabrik.de/europe/greece.html>
- Goines, L., & Hagler, L. (2007). Noise pollution: a modern plague. *South Med J*, 100(3), 287-94. <https://sma.org/southern-medical-journal/article/noise-pollution-a-modern-plague/>
- Google (2020). *Google Maps*. Retrieved from <https://www.google.com/maps>
- Guillaume, G., Can, A., Petit, G., Fortin, N., Palominos, S., Gauvreau, B., ... & Picaut, J. (2016). Noise mapping based on participative measurements. *Noise Mapping*, 3(1). <https://www.degruyter.com/document/doi/10.1515/noise-2016-0011/html>
- Halperin, D. (2014). Environmental noise and sleep disturbances: A threat to health?. *Sleep science*, 7(4), 209-212. <https://www.sciencedirect.com/science/article/pii/S1984006314000601?via%3Dihub>
- Hänninen, O., Knol, A. B., Jantunen, M., Lim, T. A., Conrad, A., Rappolder, M., ... & EBoDE Working Group. (2014). Environmental burden of disease in Europe: assessing nine risk factors in six countries. *Environmental health perspectives*, 122(5), 439-446. <https://ehp.niehs.nih.gov/doi/pdf/10.1289/ehp.1206154>
- Hellenic Ministry of Environment and Energy (2020). *Chartografisi Thoryvou Poleodomikon Sygkrotimaton (Noise Mapping of Urban Complexes)*. Retrieved from: <https://ypen.gov.gr/perivallon/thoryvos-aktinovolies/chartografisi-thoryvou-poleodomikon-sygkrotimaton/>
- Hong, J. Y., & Jeon, J. Y. (2017). Exploring spatial relationships among soundscape variables in urban areas: A spatial statistical modelling approach. *Landscape and Urban Planning*, 157, 352-364. <https://www.sciencedirect.com/science/article/abs/pii/S016920461630158X?via%3Dihub>

- International Organization for Standardization (2014). ISO 12913-1:2014 *Acoustics - Soundscape - Part 1: Definition and conceptual framework*, Geneva, Switzerland: ISO. Retrieved from <https://www.iso.org/standard/52161.html>
- International Organization for Standardization (2017). ISO 12913-2:2017 *Acoustics - Soundscape - Part 2: Data collection and reporting requirements*, Geneva, Switzerland: ISO. Retrieved from <https://www.iso.org/standard/75267.html>
- Liu, J., Kang, J., Luo, T., Behm, H., & Coppack, T. (2013). Spatiotemporal variability of soundscapes in a multiple functional urban area. *Landscape and urban planning*, 115, 1-9.
<https://www.sciencedirect.com/science/article/abs/pii/S0169204613000571?via%3Dihub>
- Margaritis, E., & Kang, J. (2017). Soundscape mapping in environmental noise management and urban planning: case studies in two UK cities. *Noise mapping*, 4(1), 87-103.
<https://www.degruyter.com/document/doi/10.1515/noise-2017-0007/html>
- Margaritis, E., Kang, J., Filipan, K., & Botteldooren, D. (2018). The influence of vegetation and surrounding traffic noise parameters on the sound environment of urban parks. *Applied geography*, 94, 199-212.
<https://www.sciencedirect.com/science/article/abs/pii/S0143622817309694?via%3Dihub>
- Mehdi, M. R., Kim, M., Seong, J. C., & Arsalan, M. H. (2011). Spatio-temporal patterns of road traffic noise pollution in Karachi, Pakistan. *Environment international*, 37(1), 97-104.
<https://www.sciencedirect.com/science/article/pii/S0160412010001534?via%3Dihub>
- Murphy, E., & King, E. (2014). *Environmental noise pollution: Noise mapping, public health, and policy*. Newnes.
- National Center for the Environment and Sustainable Development (2018). *Greece State of the Environment Report-Summary 2018*. Retrieved from https://necca.gov.gr/wp-content/uploads/2019/10/Greece-State-of-the-Environment-Report-Summary-2018-English-Version_WEB.pdf
- Picaut, J., Fortin, N., Bocher, E., Petit, G., Aumond, P., & Guillaume, G. (2019). An open-science crowdsourcing approach for producing community noise maps using smartphones. *Building and Environment*, 148, 20-33.
<https://www.sciencedirect.com/science/article/pii/S0360132318306747?via%3Dihub>
- Rodríguez-Manzo, F. E., Garay-Vargas, E., García-Martínez, S., Lancón-Rivera, L., & Ponce-Patrón, D. (2015). Moving towards the visualisation of the urban sonic space through soundscape mapping. *Proceedings of the ICSV*, 12-16.
https://www.researchgate.net/publication/315663931_MOVING_TOWARDS_THE_VISUALISATION_OF_THE_URBAN_SONIC_SPACE_THROUGH_SOUNDSCAPE_MAPPING
- Schafer, R. M. (1993). *The soundscape: Our sonic environment and the tuning of the world*. Simon and Schuster.
- Schulte-Fortkamp, B., & Jordan, P. (2016). When soundscape meets architecture. *Noise mapping*, 3(1).
<https://www.degruyter.com/document/doi/10.1515/noise-2016-0015/html>

- Stansfeld, S. A., & Matheson, M. P. (2003). Noise pollution: non-auditory effects on health. *British medical bulletin*, 68(1), 243-257.
<https://academic.oup.com/bmb/article/68/1/243/421340>
- Swinburn, T. K., Hammer, M. S., & Neitzel, R. L. (2015). Valuing quiet: an economic assessment of US environmental noise as a cardiovascular health hazard. *American journal of preventive medicine*, 49(3), 345-353.
[https://www.ajpmonline.org/article/S0749-3797\(15\)00080-X/fulltext](https://www.ajpmonline.org/article/S0749-3797(15)00080-X/fulltext)
- Vogiatzis, K. (2012). Airport environmental noise mapping and land use management as an environmental protection action policy tool. The case of the Larnaka International Airport (Cyprus). *Science of the Total Environment*, 424, 162-173.
<https://www.sciencedirect.com/science/article/abs/pii/S004896971200246X?via%3Dihub>
- Vogiatzis, K., & Remy, N. (2017). Soundscape design guidelines through noise mapping methodologies: An application to medium urban agglomerations. *Noise Mapping*, 4(1), 1-19. <https://www.degruyter.com/document/doi/10.1515/noise-2017-0001/html>
- Wei, W., Van Renterghem, T., De Coensel, B., & Botteldooren, D. (2016). Dynamic noise mapping: A map-based interpolation between noise measurements with high temporal resolution. *Applied Acoustics*, 101, 127-140.
<https://www.sciencedirect.com/science/article/abs/pii/S0003682X15002194?via%3Dihub>
- WHO (1999). *Guidelines for Community Noise*, World Health Organization, Geneva. Retrieved from <https://www.who.int/docstore/peh/noise/Comnoise-1.pdf>
- Yagoub, M., & Alkaabi K., (2019). Variation in land use/land cover and aircraft sound levels around Abu Dhabi International Airport. *European Journal of Geography*, 10(1), 68-84.
<https://eurogeojournal.eu/showPaper.php?id=1486>
- Yong Jeon, J., Young Hong, J., & Jik Lee, P. (2013). Soundwalk approach to identify urban soundscapes individually. *The Journal of the Acoustical Society of America*, 134(1), 803-812. <https://asa.scitation.org/doi/10.1121/1.4807801>