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Research Article

Citizens as Environmental Sensors: Noise Mapping and Assessment on Lemnos Island, Greece, Using VGI and Web Technologies

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Abstract: Noise caused by industrial activities, urban life and traffic has a negative impact on people's health and quality of life. Environmental noise mapping is an important tool to study and address this problem. Through specialized measurement and analysis techniques, it is possible to identify areas at high risk of noise and understand the extent of the problem. This information can be used to develop strategies to protect the population exposed to high noise levels. In this paper, a method for collecting, processing, managing and mapping spatial noise data based on Volunteered Geographic Information (VGI) and web mapping technologies is presented. The proposed method uses noise pollution data collected from citizens using mobile devices. This includes both on-site measurements and information on users' subjective perceptions, providing a comprehensive picture of the problem. This enables authorities to take into account the individual perceptions and needs of citizens when planning noise mitigation measures, which has not been the case in the inter-national literature to date. To achieve this goal, a prototype of a free and opensource tool called "Noise Pollution" was developed. The proposed methodology and the resulting system are intended to help improve the quality of life in noisy environments and protect the health of citizens. They provide a practical tool for collecting and analyzing noise data and enable the development of noise mitigation strategies for the benefit of the population exposed to high noise levels.

Keywords: noise pollution; VGI; perception; smartphones; calibration; system

Highlights:

- Introduction of a novel method to collect, process, manage, and visualize noise pollution data using Volunteered Geographic Information (VGI) and web mapping technologies.
- Highlighting the unique approach of combining objective noise measurements with citizens' subjective perceptions to gain a comprehensive understanding of noise exposure.
- Presentation of the practical application of the developed mobile application on the island of Lemnos, Greece, to demonstrate its potential to improve environmental noise management and enhance citizens' quality of life.

1. Introduction

Environmental noise refers to unwanted sounds generated by human activities that can be considered as harmful to human health and quality of life (Murphy & King, 2014). It can be distinguished into noise originating from all types of mechanical installations, as well as noise from transportation and urban noise (Mesene, Meskele, & Mengistu, 2022). Several studies have been conducted on the measurement (Maisonneuve, Stevens, Niessen, & Steels, 2009; Picaut, Can, Fortin, Ardouin, & Lagrange, 2020), assessment (Yang, He, He, & Cai, 2020), prediction (Awan, Minerva, & Crespi, 2021), and management (Chauhan, Shrestha, & Khanal, 2021) of noise from transportation and mechanical installations (Owoyemi, Falemara, & Owoyemi, 2016; Biały, Bołoz, & Sitko, 2021) and urban noise from social events, citizen assemblies, and leisure centers (Paiva, Cardoso, & Rodrigues, 2015).

Environmental noise is one of the main factors affecting the quality of life in Europe (European Environment Agency, 2020). According to a report by the World Health Organization (World Health Organization, 2019), excessive noise seriously harms human health and can interfere with daily activities at school, at work, and at home, including during leisure time. It can also disrupt sleep, cause cardiovascular and psychological problems, reduce performance and lead to annoyance and changes in social behavior (Münzel et al., 2018; Hoffmann et al., 2006). The European Commission has implemented the 'Towards Zero Pollution for Air, Water and Soil', action Plan, which aims to reduce the number of people suffering from chronic noise pollution by 30% by 2030, in comparison to 2017 levels. Planned measures include, amongst others, lowering speed limits on urban roads, electrifying the road vehicle fleet by 50%, maintaining and creating smoother rail transport, using quieter aircraft and banning night flights (European Commission, 2021).

The first comprehensive attempt to address environmental noise at European level was made on June 25, 2002, when Directive 2002/49/EC of the European Parliament and of the Council (European Parliament, Council of the European Union, 2002) on the assessment and management

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of environmental noise was adopted. The Directive introduced rules for the assessment and management of noise. At the same time, the member states were obliged to produce strategic noise maps for all major cities, roads, railroads, airports and industrial areas, as well as to update these every five years.

Mapping is an extremely important part of the noise exposure assessment process, in the context of studying environmental noise. Noise exposure maps are a useful tool for assessing the state of noise at the local level and evaluating its impact. Two main approaches have been used to create noise maps (Kurakula, Stoter, & Kluijver, 2007;MARKOU, 2022). The first involves measuring noise levels in the field (Lee, Garg, & Lim, 2020; Marques & Pitarma, 2019), and the second involves developing methods to predict noise (Ranpise, Tandel, & Singh, 2021).

In recent years, several applications have been developed for smartphones for the purpose of measuring noise pollution on site. Several of such application are available for free for Android or iOS devices and differ in the way they collect information. The main differences between the apps are, inter alia: how the noise is recorded, how the noise is measured, whether photos or videos are taken at the same time, how feedback is provided to users, and how the information collected is made available. Characteristic examples of such applications are: Noise Tube, Noisemap, CITI-SENSE, NoiseDroid, NoiseWatch and Hush City (Radicchi, Henckel, & Memmel, 2018). Further, it is also worth mentioning the "Noise Planet" system, an advanced project that started in 2008 and aims to record, model and evaluate environmental noise (Bocher et al., 2016; Picaut et al., 2019; Bescond, 2022).

In addition to applications which are based on measurements of noise exposure, several others have been developed that aim to develop models for the prediction of environmental noise. Modelling the natural mechanisms of traffic noise with analytical correlations and numerical simulations is quite complex, due to the complicated nature of the phenomenon and the nonlinear processes involved. Models for traffic noise can be mainly divided into three types: empirical models, semi-dynamic models, and machine learning models (Zhang, Kuehnelt, & De Roeck, 2021). Empirical models, or statistical models, describe traffic noise as a function of traffic volume, vehicle type, and sometimes average traffic speed over a long period of time (Rey Gozalo, Aumond, & Can, 2020). Some common empirical models for traffic noise are FHWA (Barry, Reagan, & null, 1978), CoRTN (Givargis & Mahmoud, 2008), amongst others. Dynamic models predict the level of traffic noise at each instant based on the instantaneous speeds and accelerations of vehicles. Moreover, the use of CNOSSOS has been mandatory since December 31, 2018 (European Commission, 2015). It is worth noting that machine learning models have emerged in recent years. Machine learning models attempt to establish a relationship between traffic noise and traffic flow characteristics through the application of machine learning technologies.

Furthermore, the use of the Internet as a means of map dissemination can be seen as a pivotal point in the development of noise mapping applications. Web-based mapping is the process of designing, creating and delivering maps via the World Wide Web (Neumann, 2008). Web maps can easily provide up-to-date information, due to the fact that, when they are automatically generated from databases, they can display information in near real-time (Veenendaal, Brovelli, & Li, 2017).

The low cost of creating them is another important advantage, as the materials and tools for producing web mapping servers are either cheap or free, so the products can be distributed and reproduced many times at little or no cost. Web maps enable collaborative mapping as users work together to create and improve the web mapping. They also offer the opportunity to incorporate other forms of data presentation such as video, audio and animations (Neumann, 2008). Despite the benefits of web mapping, it remains a complex process, due to the fact that issues can arise when creating web maps, such as the high cost of geospatial data, limited screen space, quality and accuracy issues, pre-development complexity, privacy and intellectual property issues (Nivala et al., 2008).

What is more, the use of portable device technology, the development of WEB 2.0 (Aghaei, 2012) and Open Source Software (OSS), in conjunction with user perception and participation in cartographic representation, costitute the dominant trends of our time. Environmental perception is usually defined as the awareness or feeling of the environment and the act of understanding the environment through the senses. Information about people's perceptions of the environment can inform policy makers, designers and managers about the public's values and concerns about the environment and about people's potential responses to environmental conditions.

Studies on noise pollution usually focus on the noise associated with airport traffic (Yang, He, He, & Cai, 2020), highways and urban traffic (Okokon et al., 2015; Paiva, Cardoso, & Zannin, 2019). Factors that can affect the perception of noise include gender, age, education, occupation and neighborhood/building characteristics (Koprowska, Łaszkiewicz, Kronenberg, & Marcińczak, 2018).

The use of Volunteer Geographic Information (VGI) is a promising modern method for mapping noise. The term was first introduced by geographer Michael Goodchild (Goodchild & Glennon, 2010) to describe the way in which citizens can use GPS devices (often integrated into mobile devices) to act as "volunteer sensors" and produce collective geospatial knowledge. VGI is regularly referred to as a subset of crowdsourcing, although the terms do not completely overlap (Cooper, Coetzee, & Kourie, 2017; Aumond, Can, Mallet, Gauvreau, & Guillaume, 2021). VGI has many advantages as a mechanism for capturing and collecting geospatial data that could reveal the spatio-temporal dynamics of social and natural phenomena. It has the ability to collect geospatial data over large areas and provide rich local information that can extend over a large temporal range, as citizens have accumulated knowledge of their surroundings over long periods of time as local experts.

In light of the above, the aim of this paper is to present a method based on Volunteered Geographic Information (VGI) and web mapping technologies for the collection, processing, management, and mapping of geographic noise data. The method uses noise pollution data collected from citizens via mobile devices to create a comprehensive picture of the problem, including field measurements and information on users' subjective perceptions. In this way, the relevant authorities can take citizens' individual perceptions and needs into account when planning noise mitigation measures. This forms an innovative approach which has not yet been studied in depth in international literature. To achieve this goal, the "Noise Pollution" system, which is a free and open-source tool, was developed. The proposed methodology and the implemented system should assist in improving the quality of life in noisy environments and protect the health of citizens. They provide a practical tool for collecting and analyzing noise data and enable the development of noise mitigation strategies for the benefit of the population exposed to high noise levels. The "Noise Pollution" system was tested on the island of Lemnos, but can be applied to any study area.

2. Methods & Materials

This section delves into an overview of the basic methodology for addressing noise pollution and provides a comprehensive understanding of the main tools and their practical implementation. The methodology applied places the greatest emphasis on the subjective perception of noise by users and thus differs from conventional research and scientific efforts in this field. The main focus of this work is to capture the user's perception, to enable comprehensive recordings and continuous monitoring of noise levels, which differs from conventional noise measurement methods. Given the inherent subjectivity that arises from the diverse backgrounds of users, it is crucial to collect data that provides a comprehensive



understanding of different perceptions and allows for the creation of an unbiased data set. At the heart of this methodology lies the use of crowdsourcing as a powerful means of collecting large amounts of data. In addition, the integration of the Internet of Things (IoT) and state-ofthe-art tools plays an important role in collecting information directly from users. The goal of this method is to visualize the collected data in interactive maps and thus make the hotspots of noise pollution tangible. By using interactive maps, the relevant authorities can easily identify and assess high noise levels in specific areas. This visualization tool will help to identify critical noise pollution zones and enable authorities to take appropriate action and implement effective strategies to address excessive noise levels. The combination of user perception data, crowdsourcing, IoT and interactive maps is thus a comprehensive approach to tackling noise pollution and promoting informed noise mitigation decisions. The proposed method is based on a comprehensive framework that addresses the problem of noise pollution. It is designed to utilize Volunteered Geographic Information (VGI) and free and open-source software to provide a multi-layered approach to noise pollution. This framework comprises four key layers, each of which contributes to the overall effectiveness of the methodology. The first level is about data collection, with a focus on capturing subjective perceptions of noise levels. Users are encouraged to share their individual acoustic observations and experiences of noise pollution to create a diverse data set. The second level focuses on the processing and transformation of the data. The geospatial data collected from various sources is carefully curated and standardized to ensure consistency and reliability for subsequent analyzes. The third level involves the establishment of a robust system for data management and dissemination. Within this proposed structure, great attention will be paid to the efficient storage, organization and sharing of geospatial data. The system should ensure seamless access and collaboration between stakeholders and authorities, enabling effective use of the information collected for noise impact analysis and decision-making processes. Finally, the fourth level is concerned with the visualization and analysis of data. Interactive mapping techniques are used to visualize noise pollution patterns and hotspots. This visual representation assists in identifying areas of high noise exposure and facilitates informed decision-making. Through following this structured set of rules, the proposed method provides a flexible and adaptable approach to understanding and addressing noise pollution. Finally, by leveraging data provided by users, processing and managing geospatial data, and using visualization techniques, this method enables authorities to gain insights and implement appropriate strategies to effectively mitigate noise pollution.

2.1. Materials

The "Noise Pollution" system was developed using a range of materials and software tools. The system is based on the concept of Volunteered Geographic Information (VGI) and uses free and open source software. The materials used include Android devices for the implementation of the "NoisePollutionApp" application and a mobile calibration subsystem. Software tools such as QGIS and Postgis are used to collect, clean, and transform geospatial data. GeoServer is used to manage and disseminate the geospatial data, while Leaflet is used to create an interactive map and visualize the results. These materials and software enable the system to effectively capture sound intensity, process the collected data, manage the database, and provide users with interactive and informative noise maps.

2.2. System Architecture

The system developed is based on the idea of Volunteered Geographic Information (VGI) and uses free and open-source software such as Android, QGIS, Postgis, GeoServer and Leaflet. The "Noise Pollution" system consists of four levels. The first level includes the "NoisePollutionApp" application implemented for Android devices and a mobile calibration subsystem. The second level involves collecting, cleaning and transforming the geospatial data obtained in the previous level using the QGIS and Postgis software. The third stage involves the management and dissemination of geodata using GeoServer. Finally, the last stage involves the creation of an interactive map and the visualization of the results using Leaflet (Figure 1).

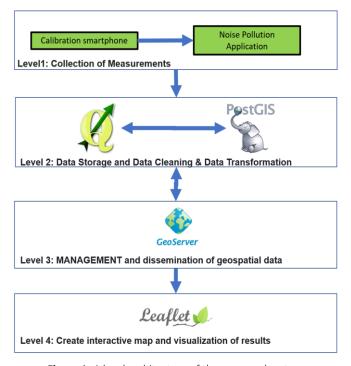


Figure 1. 4-level architecture of the proposed system.



2.3. Smartphone and Calibration

The application allows users to record the sound intensity at a specific place and time and provide information based on their subjective perception of the measurement, as well as certain characteristics such as age and gender, while always maintaining anonymity. Sound intensity is measured in decibels (dB) with Z-weighting using the Leq formula, and the time-weighted average of the exposure is used to calculate the value. Given the wide variety of mobile devices and the lack of technical specifications for their microphones, it is difficult to obtain comparable noise measurements, even for identical devices. Usually, frequency weightings such as the A-weighting (recommended by the World Health Organization (WHO)), the C-weighting and others are used in noise measurement with sound meters (sound level meters) or equivalent applications. In this paper, the Z(ero) weighting was chosen, i.e. no weighting at all. It relies on the user's personal understanding of the subjective intensity, rather than considering only mobile devices. As can be appreciated, this ensures a higher degree of objectivity in the data we collect from the user and aims to approximate Fletcher & Munson's (Fletcher & Munson, 1933) contours of equal loudness, which represent the difference in intensity perceived by the human ear as a function of sound frequency. For this reason, a calibration system was implemented that uses the ESP32 to calibrate mobile devices before measurement. To calibrate a mobile device, the user must open the calibration page of the NoisePollutionApp application and connect to the ESP32 via Bluetooth. Due to the fact that there is no frequency weighting, the focus of the calibration is not on the frequencies, but on the different intensities (measured in decibels). The calibration station essentially constitutes both a sound generation and a sound intensity recording system using the same algorithm to calculate the Leq intensity in Decibels, selecting the same sampling frequency of 44.100Hz with 16-bit encoding and the same sampling time (10 seconds). The use of four calibration groups was selected based on noise intensity to ensure comparability between different mobile phone measurements. To calibrate the mobile device in each group, we use sirens of different intensities matching each group to measure the intensity picked up by the station's microphone and the intensity recorded by the mobile phone's microphone and compare them. The calculated difference is then kept for the calibration of future recordings of the mobile device of the same

Given the logarithmic nature of sound, the ideal calibrated microphone would require an unlimited number of calibrations at all noise levels to achieve accuracy. However, since it is not possible to have an unlimited number of calibration groups, we have chosen the number based on practical considerations and constraints. The research conducted by the Technical Chamber of Greece (TEE, 2008) proposes a series of noise levels categorized as "Comfortable" (up to 68 dB), "Smooth" (69 dB to 71 dB), "Almost tolerable" (72 dB to 74 dB), "Barely bearable - Noisy" (75 dB to 77 dB), "Marginally tolerable - Very noisy" (78 dB to 80 dB), and "Intolerable" (81 dB and above) (Table 1 / Column 1). To compare the final mapping results from user acoustic observations and mobile device measurements, we consolidated and categorized these levels as follows: "Comfortable" (up to 68 dB), "Almost tolerable" (69 dB to 74 dB), "Barely bearable - Very noisy" (75 dB to 80 dB), and "Intolerable" (81 dB and above), as presented in Table 1 and Column 4. Based on this categorization, the calibration of microphones emerged, as described in Section 3.1, taking into account the levels presented in Table 1 and Column 3. The assignment of the values resulting from the acoustic observations of the users in the field to the suggested levels in column 3 is shown in column 5 of Table 1.

Permissible noise levels according to TEE (TEE,2008) Adjustment of the permitted noise levels for the implementation of the system Condition (1) Noise thresholds (db) (2) Calibration levels (3) Condition (4) Categorization by user acoustic observations (5) Intolerable ≥81 Calibration Group 4 Intolerable 4 Marginally tolerable (Very noisy) 78-80 Calibration Group 3 Marginally tolerable 3 (Very noisy) Barely bearable (Noisy) 75-77 Almost tolerable Almost tolerable 72-74 Calibration Group 2 2 Smooth 69-71 Calibration Group 1 Comfortable ≤68 Comfortable 1

Table 1. Matching the proposed calibration levels for the microphones with those set by the TEE (TEE,2008)

The main objective of the system is to map noise according to the user's acoustic observation. The application records information about the characteristics and the user's perception of the recorded sound (Figure 4). The additional information helps to use the measurements obtained with the device more effectively in order to achieve optimal and more objective noise mapping. Specifically, the user enters:

- Gender (Male, Female, Other)
- Age
- Perception of sound intensity on a qualitative scale of four categories according to Table 1. It should be noted that the classes proposed in ISO/TS 12913-3:2019 (ISO/TS 12913-3:2019, 2019) were not followed, as we chose to have a correspondence with the classes defined between mobile phone measurements and the data resulting from user acoustic observations (Table 1).
- The source of the noise (Figure 4), following ISO/ PRF TS 12913-2, 2018 Acoustics Soundscape Part 2: Data collection and reporting requirements (ISO/TC 43/SC 1, 2018). In particular:



- 1. The urban/rural distinction is not always readily defined but remains useful.
- 2. The wilderness category includes national parks, undeveloped natural and coastal zones and large recreation areas for example, though the wilderness/rural divide is not always clear-cut.
- 3. While 'nature' and 'domesticated animals' sources are shown as being 'not generated by human activity' there are many areas of overlap, e.g., the sounds of running water in constructed water features or the sound of wind on buildings. Domesticated animal sounds are generally from animals associated with a human activity/facility.
- 4. Recording, replay and amplification can occur for any type of sound, e.g., in installations playing nature/wildlife sounds.
- 5. Due to the different acoustic impedances in air and water, many of the terrestrial sound sources would not normally be observed under water, but overall the same classification system is still applicable.
- 6. Coughing, by way of example.

Guide for using the application:

1. Options upon Opening the Application:

a. Upon opening the application, users are presented with two options: to start recording or to calibrate the mobile device.

2. Recording (Figure 2):

- a. To initiate a recording session, users press the "Record" button.
- b. The recording session lasts for 10 seconds and can be stopped by pressing the "Stop" button.
- c. After recording, users have the option to upload the sample. By pressing on the "Advanced" switch.
- d. To upload the sample, users are prompted to provide personal information and details about the environmental noise recording, including gender, age, and perception of the noise.
- e. Additionally, users must describe the noise source by indicating the weight of each source namely Urban, Rural, Wilderness and Underwater. The total sum of these weights must be exactly 10.
- f. Once all required information is provided, users can press the "Upload" button to upload the measurement.

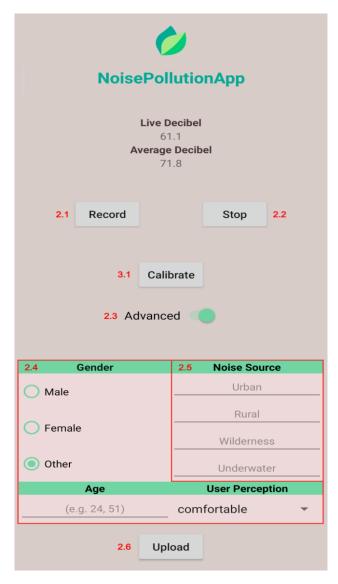


Figure 2. Excerpt from the initial application screen that describes the steps for collecting data regarding noise levels.



3. Calibration (Figure 3):

- a. Pressing the "Calibrate" button directs users to a different screen dedicated to calibrating the mobile device (Figure 3).
- b. Users are presented with a button to connect to a calibration device and four buttons to calibrate based on a calibration group.
- c. Users must first connect to the calibration device (ESP32) via Bluetooth before proceeding with any other action.
- d. Upon successful connection, users can start calibrating their mobile device with the calibration device as a reference.
- e. Pressing a "Calibrate" button triggers 10 seconds of noise generated by a siren matching the intensity of the calibration group.

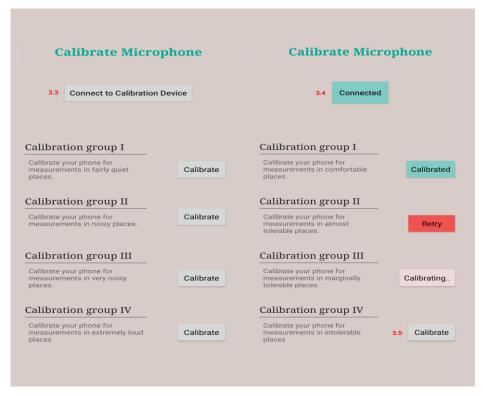


Figure 3. Excerpt from the application screen that describes the steps of calibration.

It is important to mention that internet access is required to send data to the Postgis spatial database. The user can upload only one recording at a time to prevent the unwanted submission of identical sound recordings.

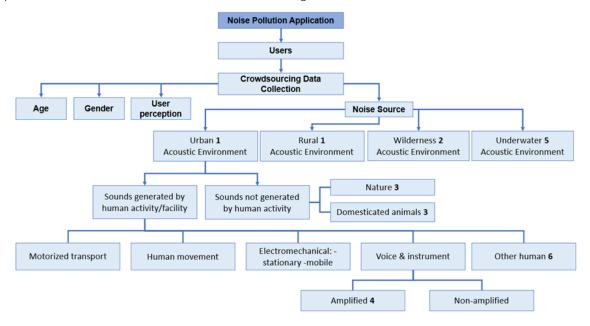


Figure 4. Data collection according to users' perception (ACOUSTICS BULLETIN, 2018).



Once the calibration of the mobile devices is complete, users can record the sound intensity in real time for a period of 10 seconds. The average value of the measurements, the coordinates of the point at which the measurement was taken, as well as the date and time of the measurement, are recorded (Figure 5). We opted for a 10-second time frame to create a user-friendly application and allow users to take multiple samples quickly. Unlike other applications such as Noise Capture, we aim for a concise decibel sample with minimal outliers, allowing users to focus better within a shorter time frame. The measurements we obtain from the mobile devices serve as a useful tool to check the validity of the data obtained from the users' acoustic observations.

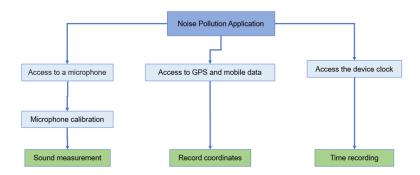


Figure 5. Stages of collecting noise pollution data from smartphones.

It is important to note that internet access is required to send data to the Postgis spatial database. Users can only upload one recording at a time to prevent the unwanted transmission of identical recordings.

2.4. Data Storage

The transfer and storage of data from the device to the spatial database "PostGIS" are highlighted as key aspects of the system. At the second level, the collected data is temporarily stored in the device's memory and transferred to the "PostGIS" spatial database "when the device is connected to the Internet, either via mobile telephony or Wi-Fi services. Further, the data is stored in the fields of the created table and contains information such as the average noise exposure, date, time, geographical location, age, gender, subjective perception of the user and the type of noise. In addition, a grid of hexagons relating to the study area was added to the spatial database. Each hexagon was selected in a pilot test to cover an area of 1875 square meters in order to obtain equally sized areas. For each hexagon, a unique value is determined that represents the average of the measurements within that hexagon. Finally, the hexagons are color coded according to their categorization based on the defined noise levels

Furthermore, a critical phase of the proposed system is data cleaning. The process of data cleaning is an important step in data analysis as it helps to correct errors, remove unwanted or unusual values and extract useful information from the data. Unwanted semantic or numerical errors can be caused by various factors, such as inadequacies in data recording, loss of information during transmission, technical problems or even human error.

On a final note, for geospatial data processing and cleaning, we use the QGIS software, which allows us to connect directly to the "PostGIS" spatial database in real time to clean both semantic and numerical data. Various techniques were used to correct semantic errors, including consistency checking, inconsistency detection and data validation. This can include searching for and replacing unwanted values, correcting inconsistencies, and harmonizing data from different sources.

2.5. Management and Dissemination of Geospatial Data

Geospatial data is managed and disseminated using Geoserver software, which uses three types of services: WMS (Web Map Service), WFS (Web Feature Service), and WCS (Web Coverage Service). Upon connecting Geoserver to the geodatabase, we added the necessary layers using the "Create new SQL view" option (Figure 6).



Figure 6. Snippet of SQL code to map the noise for the whole day in Geoserver



According to Directive 2002/49/ EC (European Parliament, 2002), the 24-hour division is divided into 07:00 - 19:00 during the day, 19:00 - 23:00 during the evening and 23:00 - 07:00 during the night and early morning hours. The cartographic background that was implemented concerned noise maps for the measurements collected by smartphones for specific time periods, as well as a noise map for the entire 24-hour period. Corresponding maps were created for the data collected by users according to their subjective perception. In addition, the time period for which the user would like to map the noise was specified as a parameter.

2.6. Creation of the interactive map and the geographic background data

For the purpose of creating the interactive noise map in our system, we used the open-source Leaflet library. This choice was made due to its simplicity, flexibility, and ease of use. The Leaflet library allows us to create high-quality maps with minimal code and offers numerous additional features and plugins that improve the user experience. To present a comprehensive representation of the noise in our study area, we integrated geographic background data from OpenStreetMap (OSM) maps. OSM maps contain detailed information about infrastructure, roads, buildings and other geographical elements that add realism and completeness to our map. This background data allows us to visualize the noise levels in different areas and create a realistic user experience (Figure 7).

By way of using Leaflet and OSM map data, users can explore the area, interact with noise-related information, and gain valuable insights into the environmental health of their surroundings. With this interactive map, we provide an up-to-date tool to help users understand and address noise in their environment. The choice of Leaflet and OSM maps has proven effective and successful in creating a dynamic, comprehensive, and useful noise mapping tool for our system. Additionally, users have the option to compare the results of the mobile measurements with the data provided by volunteers, based on their subjective perception. The implemented maps are based on the division of a 24-hour period according to Directive 2002/49/ EC, which includes the hours 07:00 - 19:00 for the day, 19:00 - 23:00 for the evening and 23:00 - 07:00 for the night. In this way, users can choose the period they need to study the noise in their area.

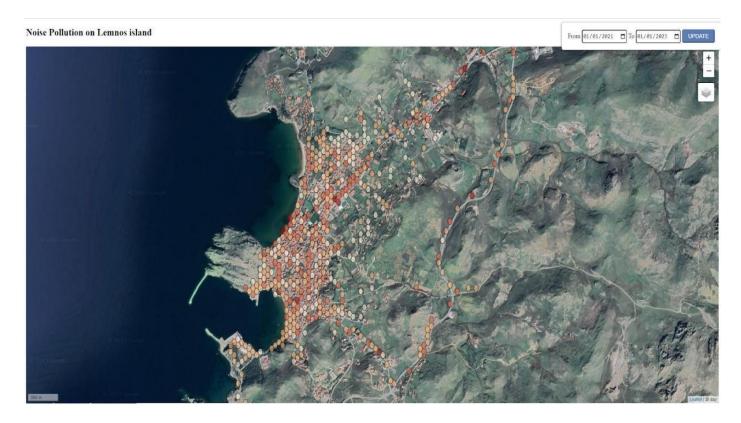


Figure 7. Interactive noise map for the area of the Municipal Community of Myrina of the Municipality of Lemnos

3. Results

3.1. Mobile calibration system

The "NoisePollution" system was tested in the municipal community of Myrina, on the island of Lemnos, Greece. The "NoisePollutionApp" was made available to citizens free of charge and provides a simple and user-friendly platform for monitoring and recording noise pollution. In order to obtain reliable measurements from different models of mobile devices, a calibration station was set up at a central point in the area of the Municipal Community of Myrina, where users had to calibrate their devices at different sound intensities before they could take measurements (Figure 8).

In order for a user to calibrate their mobile device, they must be in a specially configured space where the calibration station is located, connect to it via Bluetooth, and place their device near to the calibration station. This space is configured so that external noise sources are minimized as much as possible and the required noise level can be generated for each intensity group. Specifically, the first calibration group measures the noise intensity without a siren, as the room has been measured to never exceed 68 dB, which is the upper limit of calibration group I. For calibration group II, the total noise generated with the corresponding siren was measured to match the limits of the second group (69 dB-



74 dB), and so on. Once the connection to the station is established, the user can select one of the calibration groups displayed in the application and initiate the calibration process.

At the start of calibration, the station emits a constant intensity sound that is recorded by the station's microphone and transmitted to the mobile device via Bluetooth. The mobile device then calculates and compares the average value of each microphone and applies a weighting for the respective group (decibel range). This process is repeated for each calibration group, as a mobile device and therefore its microphone is considered calibrated once it has been calibrated in all calibration groups. In this way, we ensure that the microphones of the mobile devices measure the intensity in relation to the calibration station despite any differences (after all, decibels are by definition a relative measure that expresses the relationship between two different quantities)

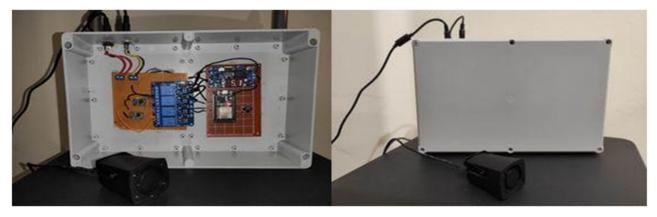


Figure 8. Mobile calibration system.

3.2. Measurements Results

Due to the increased activity in the wider area caused by tourism, a total of 437 measurements were taken. The measurements were taken at different times of day, which were then divided into three categories: daytime from 07:00 to 19:00, evening from 19:00 to 12:00 and nighttime from 12:00 to 07:00. For each time period, the average values of the measurements in each 2056 square meter hexagon were calculated. The values calculated for each hexagon were divided into four classes, with the first-class comprising values from 0 to 68 decibels, the second class from 69 to 74, the third from 75 to 80 and the fourth from 81 and above.

Comparing the frequency histograms (Figure 9) obtained from the data collected from the noise measurements of mobile devices and from the users' statements on the intensity of the noise for each point, it is concluded that the highest frequency of values is found in the second class between the values of 69 to 74 decibels, where the situation in the study area is described as "tolerable". A differentiation can be observed in the frequency histogram for the night-time noise values from midnight to 7 am. Here, 48 measurements were carried out, with the highest frequency of noise values being found in the range from 0 to 68 decibels, which characterizes the situation as "good", in contrast to the histogram resulting from the subjective perception of the users, where the highest frequency of values is found in the range from 69 to 74 decibels, which characterizes the situation as "tolerable".

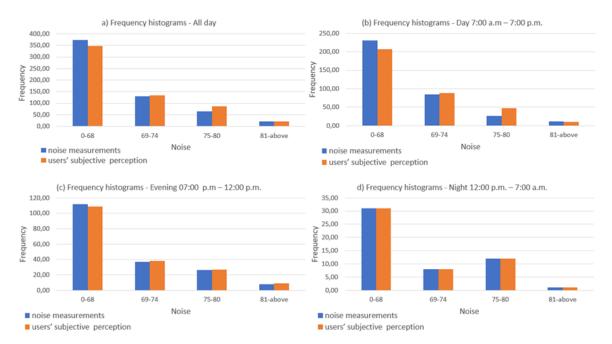


Figure 9. Frequency Histograms of Noise Measurements and Users' Subjective Perception: (a) All Day. (b) Day 7:00 a.m – 7:00 p.m.(c) Evening 07:00 p.m – 12:00 p.m.. (d) Night 12:00 p.m. – 7:00 a.m.



3.3. Cartographic Results

The main goal of the system is to map noise based on the user's acoustic observations. Users have the option to choose from a four-level scale, starting with "Comfortable" (0-68 dB), "Almost tolerable" (69-74 dB), "Marginally tolerable - Very noisy" (75-80 dB) and "Intolerable" (81 dB and above), which the system maps on a numerical scale from 1 to 4, as shown in Table 1. The measurement data from mobile devices is not the primary tool for noise mapping, but it is used to verify the objectivity of users' acoustic observations.

The cartographic results presented in Figures 10 and 11 show that there are no significant differences between the results obtained from user acoustic observations compared to those obtained from mobile device measurements. The comparison of these results indicates that the proposed system can provide reliable information about the noise level in our study area based primarily on users' acoustic observations.

The results of the noise mapping evidence that noise pollution is particularly high along the central road arteries and in the port area. In addition, noise pollution is relatively high in urban areas, while no noise is observed in areas outside the built-up environment.

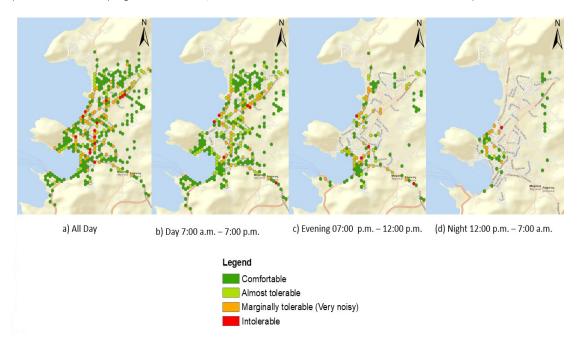


Figure 10. Cartographic background according to the measurements we received from the mobile devices: (a) All Day. (b) Day 7:00 a.m – 7:00 p.m. (c) Evening 07:00 p.m – 12:00 p.m. (d) Night 12:00 p.m. – 7:00 a.m.

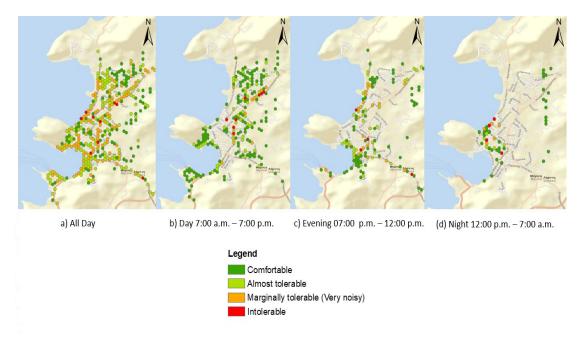


Figure 11. Map background according to the classification of noise values by users' subjective perception of noise intensity for each measurement: (a) All Day. (b) Day 7:00 a.m – 7:00 p.m. (c) Evening 07:00 p.m – 12:00 p.m. (d) Night 12:00 p.m. – 7:00 a.m.



4. Discussion

The proposed method represents an innovative approach that emphasizes the importance of comprehensively understanding and addressing the problem of noise pollution. While similar methods have been proposed in the international literature (Murphy & King, 2016; Boumchich et al., 2022; Radicchi, 2017), this approach stands out in that it focuses on users' subjective perceptions in noise mapping and complements them with objective measurements.

In recent years, several applications have been developed for smartphones that can be used to assess local noise pollution. Examples of these applications are Noise Tube, Noisemap, CITI-SENSE, NoiseDroid, NoiseWatch and Hush City (Radicchi, Henckel, & Memmel, 2018). The main differences between these applications lie in the method of noise recording and measurement, as well as whether photo or video recordings are made simultaneously, the provision of input to users and the method of data dissemination. However, these applications do not take into account the user's acoustic observations like the proposed system developed in this research context. The main difference of this mobile application compared to others is a more accurate representation of the noise intensity rather than the soundscape. The proposed system primarily aims to map data from users' acoustic observations, using measurements from mobile devices as a means of verifying this data. It is noteworthy that the final mapping result obtained by the user with the proposed system is limited solely to information derived from user acoustic observations. The mapping of results to data collected through user observation is similar to the results of applications that use mobile devices to collect measurement data indicating higher noise levels on main roads and shopping streets. Conversely, most applications do not indicate high noise levels in areas away from commercial centers or in areas that are predominantly residential (Lee et al, 2020; Murphy & King, 2016; Dubey et al, 2020; Dubey, Bharadwaj, & Biswas, 2020). In addition, some studies have shown that noise annoyance is not only limited to noise intensity, but also to other characteristics such as duration, repetition (Sternad, 2018), etc.

The integrated approach of the proposed application emphasizes that the noise problem should not only be considered from the perspective of simple measurements, but also from the perspective of the perceptions, sensations and emotions of the people experiencing the noise. The methodology therefore takes into account the diversity of perceptions and experiences and takes into account the subjective dimension of the problem.

Furthermore, the active participation of citizens is an important part of the process. By contributing to data collection via mobile devices, the community becomes an active partner in identifying and solving noise problems. Citizen participation increases enthusiasm and engagement in problem solving while contributing to an expanded awareness of the importance of environmental quality (Alashaikh & Alhazemi, 2022). Using and analyzing both quantitative data, such as noise measurements, and qualitative data, such as users' subjective perceptions and emotions, leads to an enriched and comprehensive analysis of the problem. Through this analysis, clear trends, noise sources and impacts on the community can be uncovered. In the specific application, users were asked to categorize all forms of environmental noise based on their acoustic observations and select the intensity of the noise generated. We note that urban soundscapes predominate as the study area is an urban area. This method can be applied in various areas where the analysis of noise data can be useful and contribute to improving people's quality of life. It can help architects and urban planners to take noise into account when designing cities and buildings. By incorporating data on noise levels and patterns, informed decisions can be made about the placement of buildings, the design of urban space and the implementation of noise mitigation measures. This approach promotes the creation of quieter and more adaptable urban environments and improves the quality of life of residents. It can be used to assess the impact of noise on the environment and the protection of natural and biological diversity. It can help monitor noise in sensitive areas and implement noise mitigation measures in environmentally significant areas. It can also assess the impact of noise on health and well-being. It can help to monitor noise in residential areas and identify areas of high noise pollution where measures are needed to improve the quality of life of local residents. Finally, it can be used to assess noise caused by traffic and transportation infrastructure. It can help to identify areas of high noise pollution near roads, airports, rail networks, etc. and provide data on noise reduction in the transport sector. Future enhancements to the methodology and tool presented in this article include improving citizen participation through awareness campaigns and integrating more social networking features. In addition, expanding the geographical coverage would enable the collection of data from different regions and cities to gain a more comprehensive understanding of noise pollution on a global scale. The integration of machine learning and pattern recognition would automate data processing and analysis and enable the identification of sources and patterns. Furthermore, further development of the "Noise Pollution" tool could include additional features such as real-time visualization, parameter selection for noise assessment and reporting for authorities and policy makers. The proposed system has been developed in an English version to appeal to a wider audience and to achieve our goal of expanding the use of the system to other countries. A future extension of the system would include a Greek version that only takes into account the translation of the noise level classification system. These improvements would contribute to the further improvement and development of the methodology and the tool, leading to a more effective approach to addressing noise pollution and improving the quality of life of

We note that the proposed methodology has certain advantages and limitations. The advantages include citizen participation in the collection and reporting of noise data, a comprehensive understanding of the problem through the combined analysis of objective measurements and subjective perspectives, and flexibility in the development of noise mitigation strategies through the "Noise Pollution" tool. However, limitations must also be considered, such as possible inaccuracies due to different sensitivities and perceptions of citizens, limited representation of certain areas or population groups, and biases and misinformation that may influence subjective perspectives. It is also worth noting that while the 10-second recording duration is effective for standard measurements, it does not guarantee that outliers are excluded. This limitation emphasizes the need for a robust data cleaning process to ensure the accuracy and reliability of the recorded noise levels. Therefore, careful handling of these limitations is necessary to obtain a reliable analysis of the noise problem and to make balanced decisions based on scientific and social data.

On a final note, the integration of artificial intelligence (AI) and machine learning (ML) into the "noise pollution" system is expected to play a crucial role in improving the detection and categorization of noise data. All can be trained to recognize different types of noise and categorize them accurately (Green & Murphy, 2020, Alvares-Sanches et al., 2021). In this way, important information can be collected to better understand and address noise. The development of advanced data analytics tools will enable the detection of patterns and understanding of the source of noise, providing further insights into our environment. An interesting perspective would be the integration of sensors that can collect additional environmental information. These sensors can measure factors such as temperature, humidity, air quality and other parameters that can influence noise (Aram et al., 2012). Collecting this information contributes to a comprehensive understanding of the environmental context and allows for a more accurate analysis and management of noise. Furthermore, the integration of the social dimension is an important addition to the system. Involving citizens in the reporting and sharing of information on noise levels can raise awareness of the problem of noise pollution and promote



the active participation of citizens in environmental protection. As for using the ESP32 device to calibrate portable devices, it provides a reliable and cost-effective solution that ensures consistency of data collection from different phone models. By using the ESP32 measurements in each calibration group as a source of truth for all mobile devices, we achieve a form of objectivity between all calibrated phone recordings, which is crucial for the accuracy of noise measurements and the presentation of results. Future research can focus on improving the calibration method. Facilitate calibration compatibility between a calibrated mobile device and non-calibrated mobile devices, simplifying the calibration process for users. Enabling exclusive access to the database for calibrated users to ensure that only those with a calibrated badge can upload samples. including the technical specifications of the microphones used in the manufacture of mobile devices. These improvements can increase the overall accuracy and reliability of the system and enable the further use of noise data for decision making and environmental policy support.

5. Conclusions

This study proposes an alternative method for the development of a noise pollution detection system at the local level, using alternative recording and perception techniques based on crowdsourcing. The implemented system is innovative in its approach to measuring and capturing noise pollution, as it focuses on the subjective perception of users and uses mobile measurements as additional data for validation, providing more reliable results. It should be noted that although these applications are standardized, they can never fully replace the use of an official sound level meter. Whereas, they provide a fairly good estimate of the actual noise level, but with the limitations associated with their use. The application of the proposed system is aimed at users all over the world, and this was the main reason why it was written in English. In the future, it could also be translated into other languages. In addition, the dynamic noise maps produced with alternative technologies and citizen participation will not necessarily be linked to the strategic framework for noise mapping and the corresponding noise action plans under the EU Directive. However, they can serve as useful alternative tools to help make informed decisions at local level, even in areas that fall below the population threshold of the EU Directive. The implemented system is based on a four-layer architecture that uses free and open-source software on each layer and offers an affordable option for creating a noise mapping system. "Noise Pollution" is based on the idea of Volunteer Geographic Information (VGI), uses web mapping technologies and proposes a hybrid approach, both in the architecture of the system and in the way the data is collected, processed and visualized through interactive online maps.

The "Noise Pollution" system is able to utilize both the measurements made by the users on site and the information obtained from the users' subjective perception of the measured noise, which has not yet been extensively addressed in the international literature. In the context of this article, the system was applied in a pilot project on the island of Lemnos, although it can be applied in any study area. It offers the possibility to compare and evaluate results by producing real-time maps and maps for different time periods. The creation of interactive noise maps at local level should contribute to optimal decision-making by the relevant authorities in order to reduce high noise emissions. The main reasons for interactive noise mapping are outlined below:

- To determine the extent to which noise exceeds legally permissible levels, to define noise zones in relation to permissible noise levels and to identify areas of high noise exposure.
- Identify the population affected by noise, study noise sources and activities that cause permanent, periodic or temporary noise;
- And finally, providing data for the development of strategic action plans and information for citizens.

Forming a part of additional research and with the aim of further improving the system, it is proposed to carry out a comprehensive analysis of the characteristics that influence users' perception, with the aim of involving them in the mapping process. In addition, the continuous updating of the application to meet constantly evolving technologies and user requirements is an important part of its functionality and usability. Finally, cooperation with the municipalities and the pilot implementation of the system contribute significantly to its further development.

Conflicts of Interest: The authors declare no conflict of interest.

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