SPACE-TIME MAPPING OF ENVIRONMENTAL NOISE IN THE URBAN AREA OF RIOBAMBA (ECUADOR)

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Abstract
The objective of this research was to generate a spatio-temporal mapping of environmental noise in the urban area of the city of Riobamba (Ecuador), through the use of geographic information technologies focused on spatial analysis and geostatistical methods, as well as acoustic evaluation methods with compatibility based on the ISO 12913-2:2018 Acoustics-Soundscape Part 2 standard. generating indicators that allow the management of the territory considering territorial environmental criteria and especially with the factor called noise pollution, constituting a contribution to the development of policies aimed at environmental sustainability in urbanization processes. The analytical results revealed that the study area suffers from noise pollution, where a high percentage of the population is exposed to unacceptable noise environments, indicating that strategies to improve noise control are urgent.

Keywords: Noise, territory, geostatistics, environment, acoustics.

Introduction

A considerable proportion of the global population is exposed to elevated levels of noise, which has been associated with various physical and mental health concerns for urban residents (GILES-CORTI et al., 2016). These challenges encompass a spectrum of issues, ranging from hearing impairment to adverse effects on productivity and social interaction (ARANA, 2010). Consequently, noise pollution is recognized as a significant public health issue (TORRES JARA et al., 2018).

The acoustic environment exerts a significant influence on the comfort experienced in open urban public spaces (OZCEVIK; YUKSEL, 2021). The identity of a space is not solely defined by its urbanism and visual quality, but also by its soundscape (YANG; KANG, 2004). In urban environments, environmental noise constitutes a physically perceptible stressor that is widely regarded negatively (Campbell, 1983). It is a low-cost form of stress generation (Correa-Restrepo et al., 2011), and it has been demonstrated to modify social behavior (Stanfeld et al., 2000), disturb sleep (Jones et al., 2012), interfere with the performance of complex tasks (Jones et al., 2012), and cause discomfort (Jones et al., 2012). The perception of noise as a nuisance is influenced by various factors, including the characteristics of the noise itself, as well as the physiological, psychological, and social characteristics of the exposed population (JAKOVLJEVIC et al., 2009). Therefore, it is essential to study the perception of sounds by the inhabitants (YANG; KANG, 2004).

Cities have been identified as pivotal agents of sustainable development, serving as nexuses for connectivity and providing a range of services to neighboring regions (SHAHPARI et al., 2021). The reduction of noise has been identified as a pivotal factor in enhancing the quality of life for residents (OROZCO; GONZÁLEZ, 2015). As indicated by Gozalo et al. (2020), noise constitutes an element that must be taken into account in the pursuit of sustainable urban development. The urban design of numerous cities is influenced by road traffic, as substantiated by Rey et al. (2016). As demonstrated in the research by Fielder and Zannin (2015), an association has been identified between noise pollution and the urban mobility model. Urban planners face the formidable task of developing land-use models that enhance the sustainability and resilience of cities (YAMAGATA et al., 2016).

Urban planning is imperative for mitigating acoustic impact, as it organizes land uses, relocating those with the highest noise generation away from sensitive receptors (LUQUE et al., 2020). Adequate land use planning has been demonstrated to influence the reduction of the effect of noise pollution (GOZALO et al., 2013; REY et al., 2016; MORILLAS et al., 2018). Noise management has evolved from a marginal consideration to a cornerstone of strategic planning. It is intertwined with various aspects of urban planning, including quality of life, economic development, municipal connectivity, and mobility (Hernández et al., 2019).

Territorial planning is responsible for developing a methodology for characterizing the soundscape as a fundamental instrument for the management of urban and rural territories (LÓPEZ, 2012). In order to develop effective strategies for noise pollution management, it is essential to assess and measure noise levels in urban areas (BRAVO et al., 2022). As demonstrated in the extant literature, noise possesses a variable spatial nature (YEPES et al., 2009), and noise maps have been successfully employed to understand noise level distributions in urban areas (YEPES et al., 2009; WANG et al., 2018; CAMPELLO-VICENTE et al., 2017; FIEDLER; ZANNIN, 2021; TSAI et al., 2018). A noise map can assist regulatory bodies in implementing appropriate measures to ensure a healthy living environment in urban areas (MASUM et al., 2021).

Noise pollution is considered the second most significant environmental stressor due to its profound impact on public health (Ruggiero, 2017). To achieve sustainable urban development, it is imperative to address noise pollution, as current levels of noise exposure pose a substantial threat to the health and quality of life of citizens (Gozalo et al., 2020).

Road traffic noise has been identified as the most significant source of environmental noise exposure on a global scale (GILES et al., 2016). A study by the European Environment Agency (EEA, 2019) found that approximately 40% of European Union cities experience road traffic noise levels exceeding 55 dB, which is considered the maximum acceptable outdoor limit by the World Health Organization (PLATZER et al., 2007). In Latin America, partial reductions at a rate of -5 dB every 5 years were

anticipated, yet these were not attained (FUCHS, 2007). This was due to the demand for mobility and, in general, the increase in traffic and/or vehicle speeds (PRANGE; TORRES, 2017). Noise monitoring is lacking in most cities (BRAVO et al., 2022), and most acoustic impact studies have been conducted with uneven mapping (ARANA, 2010) and without considering the perception of the population (PALACIOS et al., 2021).
The objective of this study was to obtain environmental noise indicators and generate noise maps using the perception of the population, spatial analysis, and geostatistics in the urban area of the city of Riobamba (Ecuador). In addition, the study sought to identify critical points of noise pollution in the territory. Therefore, the objective is twofold: first, to ascertain the presence of noise, and second, to determine the location of activities that are incompatible with land use and the population's approach, in order to implement noise management measures.

Methodology

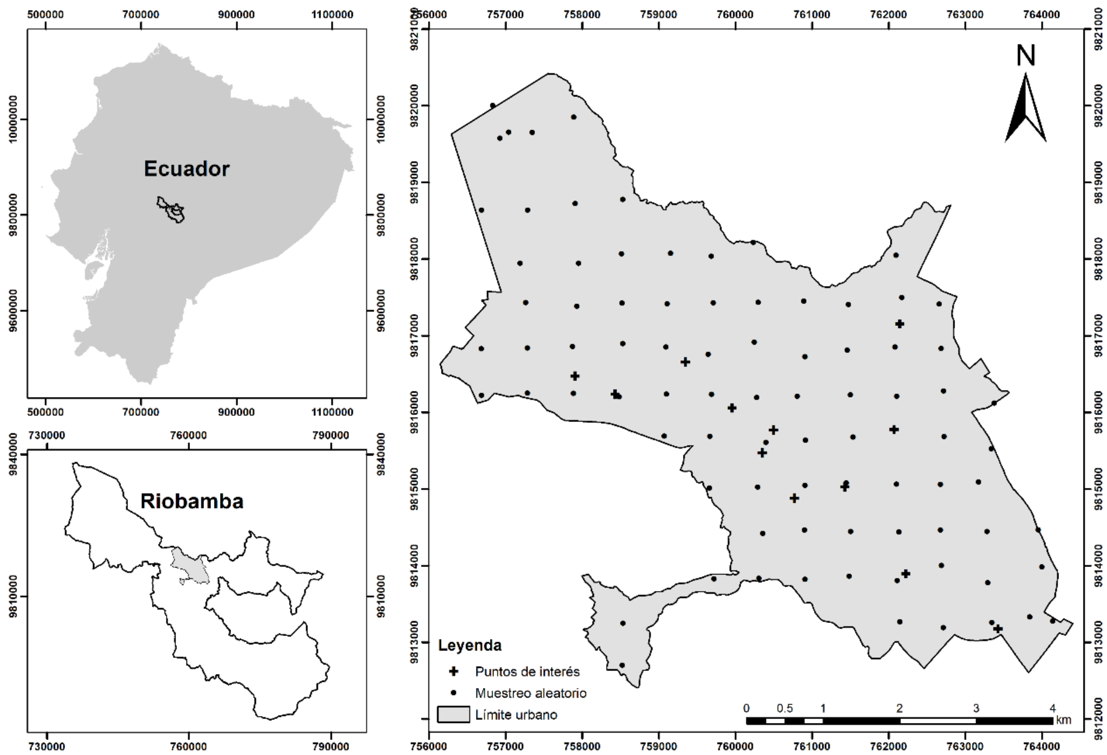
The research was developed under a quantitative approach, which enabled the measurement of noise pollution in decibels as a unit of measurement. This approach involved the application of statistics to quantify the perceptual criterion of the population. It is characterized by its ability to describe, explain, and predict phenomena, basing its conclusions on the rigorous use of the metric (Sánchez Flores, 2019).
A variety of methodologies exist for the assessment of urban noise. One such methodology is Noise Pollution Mapping, which utilizes Geographic Information System (GIS) technology. Noise Pollution Mapping employs spatial analysis and geostatistical methods to integrate noise calculation models with spatial data, thereby facilitating the construction of noise maps (AKILADEVI et al., 2015).
In addition, acoustic evaluation methods compatible with ISO 12913 have been utilized. The objective of ISO 12913 is to evaluate, conserve, and acoustic rehabilitate urban areas. The conceptual framework of these studies is based on ISO 12913-2:2018 Acoustics—Soundscape Part 2: Reporting and Data Collection Requirements.
Correlative research was also carried out to determine the degree of relationship between concepts, categories, or variables (ZÁRATE et al., 2019). This research indicates that noise levels in the city of Riobamba have an impact on territorial planning.

Study Site

The urban structure of Riobamba encompasses an area of 2,812 hectares, developed from the orthogonal grid of the historic central core (GAD RIOBAMBA, 2020). The origin of the orthogonal layout of the cities of the New World is a subject of debate. Some theories posit that it is the reference in the ancient cities, while others suggest that the use of the reticular layout arose from the need for colonization of the conquered territories (DE TOMÁS MEDINA, 2017). From the historic central core until the 1980s of the last century, Riobamba was developed in a radial fashion. However, the implementation of the airport led to a significant alteration in the urban layout (GAD RIOBAMBA, 2020).
In recent years, the city of Riobamba has undergone significant expansion, primarily in the northwestern and southeastern directions. This expansion has resulted in conurbation processes with the Guano canton and the rural parishes of Licán and San Luis, as well as notable spontaneous peripheral developments in the northern part of the city (GAD RIOBAMBA, 2020).

The city of Riobamba is located in central Ecuador (see Figure 1), has a population of 174,988 inhabitants, of which 65% is concentrated in the urban area and is developed from the orthogonal grid of the historic central core (GAD RIOBAMBA, 2020). The study site is the urban area of Riobamba, which encompasses an area of 31 square kilometers, a perimeter of 40,156 meters, and a total of 13,937 vertices. To date, the city of Riobamba has not yet published a final report or conducted a comprehensive noise map. Consequently, it has not been possible to make decisions aimed at either reducing noise exposure for the city's inhabitants or improving land use policies.

Figure 1. Study Site Location



Source: authors, 2021.

Noise Monitoring

Soundscape mapping is contingent upon the utilization of interpolation tools, which are capable of predicting cell values at locations that are not known a priori based on cells with known values in the study area (Margaritis & Kang, 2017). The interpolation tool employed was ArcGIS software, given the absence of stringent guidelines for soundscape mapping (Margaritis & Kang, 2017). Previous studies have utilized various interpolation algorithms, including:

Kriging's ordinary method is a well-known interpolation technique that has been utilized in a variety of environmental applications. It shares notable similarities with classical data assimilation methods that have facilitated environmental prediction, particularly at the urban scale for noise pollution (AUMOND et al., 2018).

The grid method is the most widely used technique for noise assessment. It consists of superimposing a certain grid over a city. This method is included in the ISO 1996-2:2017 standard, which recommends a distance of 200 meters between the grid and the subject (Fiannacca et al., 2017). However, the density of points required can become impractical at an acceptable cost (Morillas et al., 2018). In accordance with the findings

of preceding studies (Zambrano & Ruano, 2019; Yepes et al., 2009), a random sampling method was implemented using ArcGIS software, encompassing a 600-meter grid that delineated a set of 87 points, uniformly dispersed throughout the designated area. This sampling approach exceeded the minimum requirement of 50 points necessary to attain geostatistical representativeness (Yepes et al., 2009). Furthermore, given that the representativeness of a sample is contingent on the area under study and its variations, a total of 12 points of interest were surveyed in the primary centralities of the city of Riobamba. This resulted in a total sampling of 99 points, as illustrated in Figure 1.
The Ministry of Environment, Water and Ecological Transition of Ecuador's methodology for measuring noise was applied in Annex 5 of Ministerial Agreement 097-A, entitled "Maximum noise emission levels and measurement methodology for fixed and mobile sources." In this study, the sound pressure levels (NPS) were compared with the maximum permissible thresholds for land use, as established by the same Ecuadorian legal body.

Board 1NPS eq dB (A) maximum allowable.

Land Use	Diurnal From 07H01 to 21H00	Nocturnal From 9:01 p.m. to 7:00 a.m.
Residential	55	45
Equipment	55	45
Industrial	65	55
Multiple use	55	45
Protection	37	31

Source: authors, 2021.

Noise measurement technology
The methodology proposed by the Ministry of Environment, Water and Ecological Transition of Ecuador in Annex 5 Maximum noise emission levels and measurement methodology for fixed and mobile sources, of Ministerial Agreement 097-A of this state portfolio, was applied.
For the evaluation of noise levels, the values recommended by the Municipal Code of Riobamba – Second Codification (Book IV Part 3) and the permissible limits established in Ministerial Agreement 097-A (MINISTRY OF THE ENVIRONMENT, 2015) were used.
Noise Maps
A noise map makes it easier to monitor environmental noise pollution in urban areas. It can raise awareness among citizens about noise pollution levels and assist in the development of mitigation strategies to deal with adverse effects (ARANA *et al*., 2010).
Ascigil (2021) defines that an efficient way to assess the quality of life regarding noise pollution could be the creation of local models that use all the information collected for noise mapping as well as be used by local authorities for territorial planning.
Day and night noise maps were generated using ArcGIS software, with the Kriging technique, which is a recommended interpolation method for urban noise studies (YEPES *et al*., 2009; OLIVER; WEBSTER, 2014; AUMOND *et al*., 2018; GONÇALVES *et al*., 2019). The general interpolation formula is formed as a weighted sum of the data:

$\hat{Z}(S_0) = \sum_{i=1}^{N} \lambda_i Z(S_i)$ *Equation 1.*

Where: Z(Si) is the measured value at location i, λ_i is an unknown weighting for the measured value at location i, S0 is the prediction location, and N is the number of measured values (AUMOND *et al*., 2018).

This technique includes the existence of a spatial dependence on the noise produced that was analyzed by means of a classic and robust semivariogram adjustment (OLIVER; WEBSTER, 2014).

$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{\substack{\forall(x_i,x_j) \\ |x_i,x_j|-h}} \left[Z(x_i) - Z(x_j)\right]^2$ *Equation 2.*

Where N (h) – number of experimental pairs of observations separated by the distance h; y, Z (xi) and Z (x_j) – random variables at locations xi and x_j.

The semivariogram is represented by the graph γ(h) versus h. With the adjustment of a mathematical model to the calculated values of γ(h), the coefficients of the theoretical model for the semivariogram were estimated. They are: nugget effect (C0); threshold (C0 C1) and range (AUMOND *et al*., 2018). The robust estimator of semivariogram values is less susceptible to the influence of mass data values than the classical estimator (CRESSIE; HAWKINS, 1980). Therefore, the robust estimator is described by the equation.

$\hat{\gamma}(h) = \frac{1}{2} \frac{\left[N(h)^{-1} \sum_{N(h)} \sqrt{|Z(x+h) - Z(x)|}\right]^4}{0.457 + \frac{0.494}{N(h)}}$ *Equation 3.*

Where: N (h) – number of experimental pairs of observations; y, Z (x), Z (x h) – separated by a distance h. This estimator assumes that the differences Z (x h) – Z (x) are normally distributed for all pairs (x h, x). The adjustment of the semivariogram methods was chosen based on Ordinary Least Squares (OLS) and Weighted Least Squares (WLS), estimated by classic and robust mode (WEBSTER; OLIVER, 2007). The wave model was tested for all methods, totaling four semivariograms for the variable under study.

$$\hat{\gamma}(h) = C_0^2 + \frac{a}{h} sen\left(\frac{h}{a}\right)^4 \quad Ecuación\ 4$$

Where: C0 – nugget effect; a – range; and h – distance between samples.

A third-degree polynomial was used to eliminate the trend that could interfere with the spatial dependence of the data and thus fit the semivariograms to the residues and then aggregate the residues with the tendency to obtain the final map. For the choice of semivariogram adjustment methods, cross-validation of the data was considered (GONÇALVES *et al*., 2019).

Cross-validation is the error estimation technique that allows the predicted values to be compared with those sampled. The value of the sample, at a given location Z (if), is temporarily discarded from the dataset, and then a kriging prediction is made at location Z (s (i)), using the remaining samples. In this way, it is possible to extract some very useful values for the choice of method, such as the mean error (ME), the standard deviation of the mean errors (SDME), the reduced mean error (RE) and the standard deviation of the reduced mean. Errors (SDRE). Selection criteria based on cross-validation should find the closest ME and RE value to zero, the SDME value should be the lowest, and the SDRE value should be the closest to one (HARMAN, 2015).

In the noise dataset, the Stable Model indicated a lower bias between values according to the average diagnosis, it also provided better predictions compared to the other two models evaluated according to the mean square diagnosis, the standardized average indicator is not better than the Gaussian Model, however, it has a value close to 0, and the standardized mean square value is also close to 1.

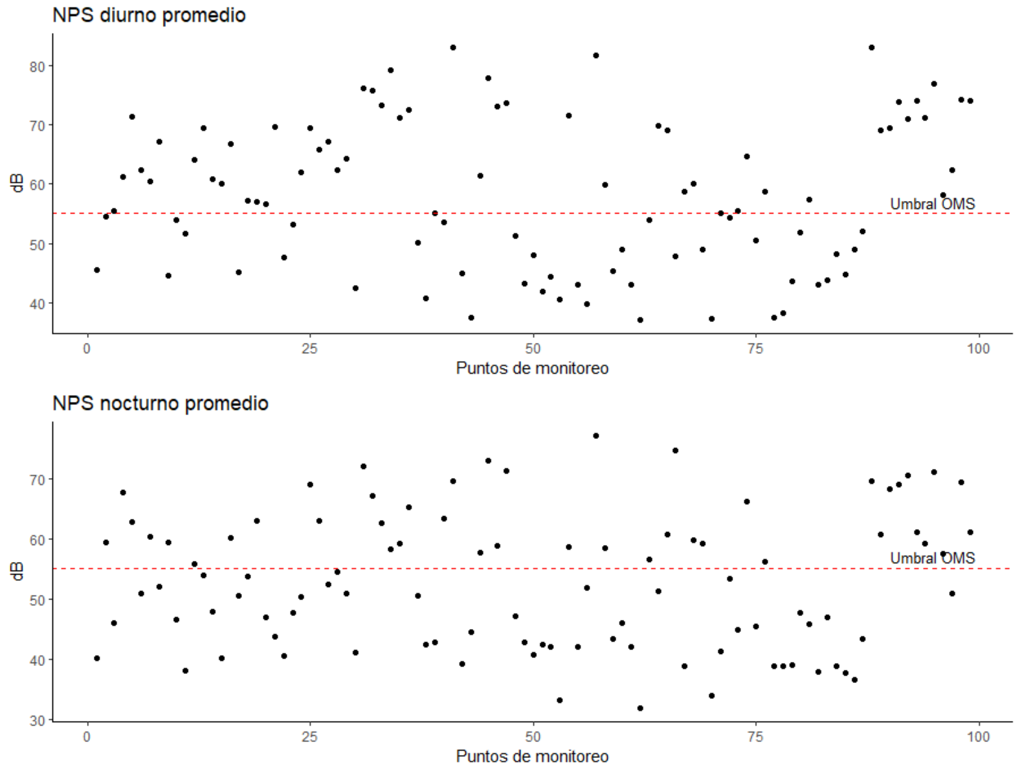
Results and discussion

The correlation between adequate land use planning and the reduction of the effect of noise pollution has been demonstrated in several studies (GOZALO *et al*., 2020; MORILLAS *et al*., 2018; REY *et al*., 2016), since the urban design of several cities is conditioned by road traffic, which has led to an increase in noise pollution; it has also been shown that the functionality of streets as communication routes between different parts of a city is strongly associated with noise pollution (REY *et al*., 2016) and some aspects of land use such as land use and road traffic have very significant correlations with noise levels (MORILLAS *et al*., 2018).

Noise Monitoring

Average sound pressure (SPL) levels were obtained at each of the monitoring points, 62.2% of points during the day and 43.3% at night, are exposed to road traffic noise at levels above 55 dB, the maximum desirable threshold outdoors set by the World Health Organization (WHO) as shown in Figure 2.

Figure 2. Day and night NPS.



Source: authors, 2021.

In order to analyze noise in different areas, a five-category system for land use was employed. The majority of the territory studied is defined as residential land. The maximum permissible thresholds according to current Ecuadorian regulations were illustrated. A comparison of the mean noise levels at the observed points reveals that the established permissible levels were not adhered to in 46.48% of the daytime points and 63.38% of the nighttime points. The highest levels of noncompliance were observed in areas designated for protection, while the lowest levels were observed in areas intended for industrial use. This discrepancy can be attributed to the less stringent restrictions imposed on the maximum thresholds in these areas.

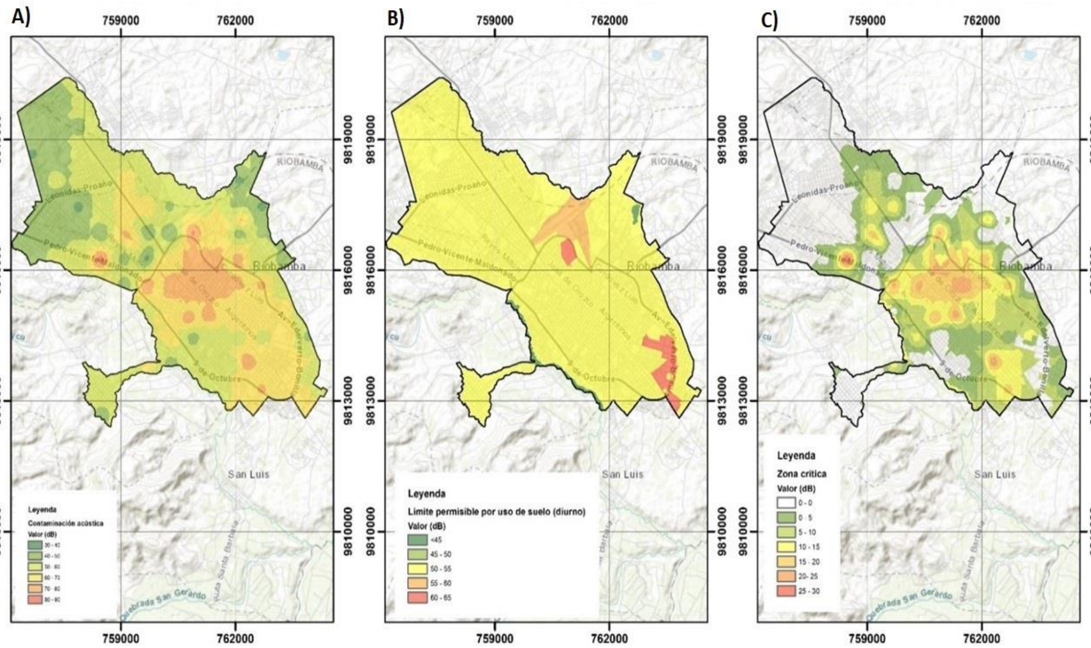
Urban noise is a complex and variable phenomenon. Conducting a comprehensive analysis of the territory would necessitate an immense volume of information, which would be impractical to manage and compare (BONELLO et al., 2002). Kriging interpolation has been demonstrated to facilitate the forecasting of noise values across urban territories. Previous studies have validated the efficacy of mapping in depicting the prevailing state of pollution (MASUM et al., 2021).

The thresholds were represented according to the current Ecuadorian regulations, and a map algebra was carried out to identify the focal points that exceed the permissible limit with a high degree of accuracy. The findings of the study indicated that daytime noise pollution manifested to a greater extent in the city center. Conversely, at night, the dispersion of noise and a greater number of critical points were identified. Therefore, it is imperative to manage noise by prioritizing these points. Urban noise pollution has been identified as a significant factor that can contribute to the degradation of quality of life in urban environments (RAIMBAULT; DUBOIS, 2005).

The lowest sound pressure level (SPL) range detected during the day corresponds to [37–40] dB according to the applied model. This range constitutes 0.26% of the urban territory. The range corresponding to [>40–50] dB constitutes 34.05% of the territory, primarily in the border area. The range of [>50–60] dB constitutes 45.27% of the territory. These places correspond to a low noise environment according to the World Health Organization (WHO).

The range of 60–70 dB, encompassing 16.46% of the examined territory, is predominantly situated in areas adjacent to the historic center. The range of 70–80 dB, constituting 3.94% of the territory, is primarily concentrated within the historic center of Riobamba. The range exceeding 80 dB, representing 0.03% of the territory, is found in areas experiencing high vehicular traffic. These locations are characterized by a noisy environment, as classified by the WHO (Figure 3-A).

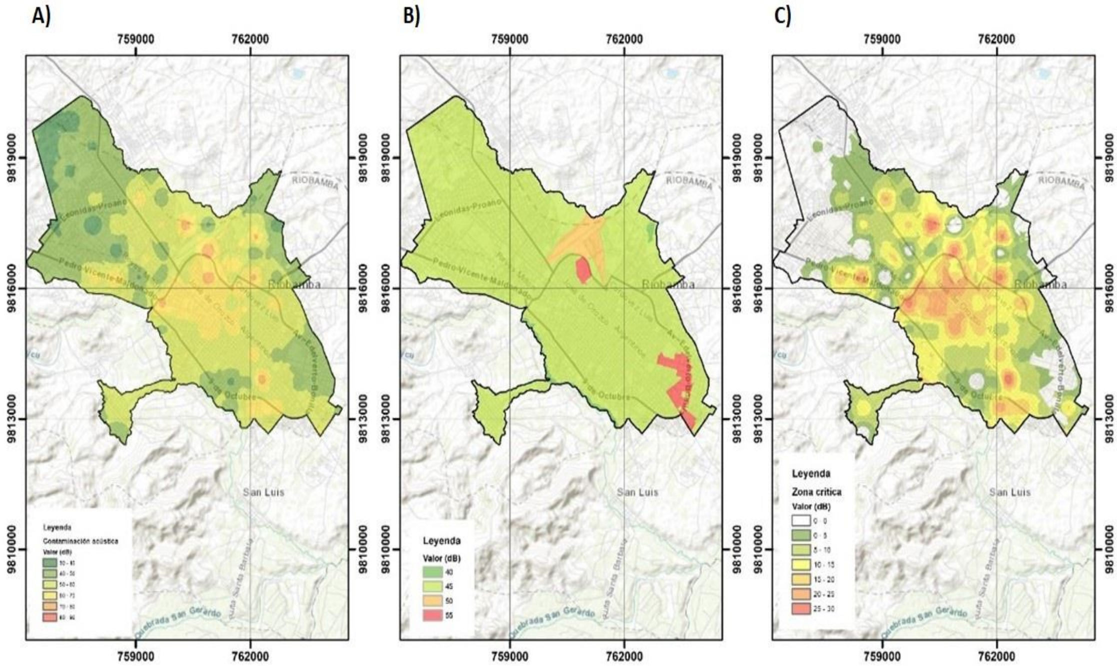
Figure 3. A) Daytime noise map **B)** Map of maximum permissible thresholds for land use according to Ecuadorian regulations **C)** Critical noise points**.**



Source: authors, 2021.

At night it can be observed that the noise decreases considerably in this way, the lowest range identified ranges between [31 - 40] dB and is located in 3.56% of the urban area, the range of [>40 – 50] dB corresponds to 48.95% of the territory, between [>50 – 60] dB is 10.06%, in the range of [>60 – 70] dB it is observed in 7.26% of the study area and the NPS of [>70 at 80] dB is 0.16% of the territory (Figure 4-A).

Figure 4. A) Night-time noise map **B)** Map of maximum permissible thresholds for land use according to Ecuadorian regulations **C)** Critical noise points**.**



Source: authors, 2021.

Citizens' perception of noise pollution

A comprehensive understanding of citizens' exposure to environmental noise is imperative for the development of a strategic approach to mitigate this issue. Such an understanding is instrumental in fostering inclusive, safe, resilient, and sustainable cities. It enables planners to effectively support the elimination of undesirable sounds or the incorporation of desired sounds within the urban landscape. Furthermore, it is crucial to acknowledge that certain sound sources are inherently part of citizens' daily lives. Poor decisions regarding noise management can potentially engender a sense of alienation among citizens (GILES et al., 2016).

The survey of citizen perception regarding noise pollution was carried out on 384 people, identifying that most of their households (61.98%) are made up of three and four members, coinciding with the value of the average population per household in the country according to INEC (2010).

A negative correlation has been demonstrated between noise levels and the quality of life experienced by the general population (DRATVA et al., 2010). In the event that noise pollution is evidenced, it is imperative to ascertain the public's perception. The following findings were derived from a survey:

A significant proportion of the population, constituting 80.47%, reports that noise has a detrimental impact on their quality of life. In contrast, the remaining 19.53% of the population does not perceive noise to have a negative effect on their quality of life.

The degree of annoyance experienced by individuals within their residences due to noise exposure exhibits significant variation. The majority of respondents (35.16%) reported minimal disturbance, indicating that the perception of noise disturbance is contingent on the residential context. The predominant source of noise perceived within residential environments is attributed to vehicular traffic, accounting for 46.61% of the responses. In outdoor environments, buses, trucks, and heavy transport were identified as the most significant source of noise.

The objective of the present study was to categorize the perception of noise according to the time of day. The findings indicated that nocturnal noise is more likely to cause annoyance among citizens. This phenomenon can be attributed to the reduced sound levels during nocturnal hours, which allows for more distinct perception of sounds. Additionally, the sound waves that generate these sounds do not intersect with those produced by other sources, thereby creating a more isolated auditory environment. Another contributing factor is the heightened sensitivity of the ear during nocturnal hours (Cohen & Castillo, 2017).

Noise has been shown to have a detrimental effect on the normal performance of certain daily activities. Therefore, the objective of this study was to identify the activity in which noise makes it more difficult to execute. The study found that studying was the activity that obtained the most value compared to the other activities.

It is imperative to acknowledge the existence of scientific evidence substantiating the impact of noise on the population. To this end, an effort was made to ascertain the most salient effect on the population. It was ascertained that stress is the most pertinent effect, superseding other potential outcomes. Noise has been identified as a prevalent, non-specific physical stressor. Acute stress can be induced by unanticipated noise, while chronic stress has been demonstrated to precipitate various diseases (Palacíos et al., 2021).

In the urban area of Riobamba, approximately 78% of the territory is dedicated exclusively to residential land use. The following discussion will address noise pollution affecting urban areas, with particular regard to its impact on family life and indoor environments, as well as the factors that influence noise levels outside the home.

An investigation was conducted into the effect of different sound sources on people's perception in outdoor environments. The degree of perceived noise level was determined by assigning each criterion a weighting as follows: very high (5), high (4), medium (3), low (2), and very low (1). The total score for each noise source was then calculated, and the source that presented the greatest problem for citizens was identified. The results of the investigation revealed that buses, trucks, and heavy transport were the most significant source of perceived noise, followed by car noise.

Noise by land use

Most of the territory of the city of Riobamba is defined as residential land, which according to the monitoring does not comply with the permissible levels in 46.48% of places during the day and in 63.38% of sites at night, in this work each monitored point was compared with national and local regulations.

In cities, it has been observed that current noise pollution comes from old urban planning errors (FERNÁNDEZ, 2020), it was necessary to know if the population of the urban area of the city of Riobamba considers whether territorial planning influences the presence of noise pollution, determining that for most of the population (81%) it does have an influence.

Conclusions

A comprehensive understanding of citizens' exposure to environmental noise is imperative for the development of a strategic approach to mitigate this issue. Such an understanding is instrumental in fostering inclusive, safe, resilient, and sustainable cities. It enables planners to effectively support the elimination of undesirable sounds or the incorporation of desired sounds within the urban landscape. Furthermore, it is crucial to acknowledge that certain sound sources are inherently part of citizens' daily lives. Poor decisions regarding noise management can potentially engender a sense of alienation among citizens (GILES et al., 2016).

The population perceives noise as a detrimental factor that adversely impacts their quality of life. On-site monitoring revealed that noise levels exceed the recommended thresholds established by the World Health Organization (WHO) and Ecuadorian regulations in a substantial portion of the territory. A notable incompatibility between noise levels and the intended use of the land for residential purposes was identified. Furthermore, elevated noise levels were observed on roads, indicating the potential for the population to promote the adoption of a more effective urban planning model.

The present study constructed noise maps for the urban area of the city of Riobamba, thereby demonstrating the efficacy of noise maps in understanding noise level distributions. The analytical results indicated that the study area is experiencing significant noise pollution, with a considerable proportion of the population being exposed to unacceptable noise levels. This suggests the need for the implementation of effective noise control strategies. The development of noise exposure maps has facilitated the identification of critical points, thereby generating windows of opportunity for noise mitigation. These maps serve as qualitative tools for evaluating the most sensitive areas of a city and provide a foundation for the permanent control and monitoring by the competent authority.

Environmental noise is a significant indicator of the quality of urban life. It has prompted the development of strategies to achieve acceptable acoustic quality. These strategies have led to the improvement of innovative and sustainable approaches through integrated policies, such as urban planning and monitoring policies.

The design of a strategic plan will represent a project with intersectoral objectives. This project will be capable of mobilizing different actors and the population of Rio de Janeiro. It will do so with the aim of achieving goals and improving the quality of life of the population.

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