Mapping and Mitigating Urban Noise: A Case Study of Loja, Ecuador's Soundscape

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Résumé

La pollution sonore dans les pays d'Amérique latine, comme l'Équateur, est un problème environnemental qui a été scientifiquement évalué mais ignoré dans les actions réglementaires. Jusqu'en 2022, Loja occupait la neuvième position en termes de population parmi les villes du pays et a connu une croissance substantielle du secteur automobile, atteignant la dixième position au cours de la dernière décennie. Bien qu'une ordonnance municipale visant à atténuer la pollution sonore soit en vigueur depuis 2006, les évaluations approfondies ont été limitées et la mise en œuvre des politiques internes s'est révélée inefficace. Cette étude évalue les niveaux de pression acoustique dans la zone urbaine de Loja en Équateur pour évaluer la pollution sonore actuelle et développer la première carte du bruit pour en dériver des politiques internes. Soixante-seize points de prélèvement ont été répartis autour des zones résidentielles, commerciales, industrielles et tertiaires qui ont été surveillées à l'aide de sonomètres intégrés de type 1. Les mesures prises se situaient entre 55 et 72,9 dBA, soit une moyenne de 67 dBA. Ces résultats ont révélé que 94% des points dépassaient les limites maximales autorisées selon les différentes utilisations du sol. Les endroits les plus bruyants sont associés aux grands axes de circulation, principalement les avenues avec un flux constant de véhicules. Pour atténuer la pollution sonore, une gestion de la circulation aux heures de pointe, des campagnes de sensibilisation promouvant des modes de transport plus silencieux et des contrôles semestriels sont suggérés.

Mots clefs : Pollution sonore, carte de bruit, politiques internes, zones urbaines, bruit de la circulation

Abstract

Noise pollution in Latin American countries, such as Ecuador, is an environmental problem that has been scientifically assessed but ignored in regulatory action. Up to 2022, Loja held the ninth position in population among cities in the country and experienced substantial automotive sector growth, attaining the tenth position over the last decade. Although a municipal ordinance to mitigate noise pollution has been in effect since 2006, thorough assessments have been limited, and internal policy implementation has proven ineffective. This study evaluates the levels of sound pressure in the urban area of Loja in Ecuador to assess the current noise pollution and develop the first noise map to derive internal policies. Seventy-six sampling points were distributed around residential, commercial, industrial, and service areas and monitored using type 1 integrating sound level meters. Results revealed that 94% of the points exceeded the maximum allowed limits, with an average of 67 dBA between 55 and 72.9 dBA. The noisiest places are associated with major traffic routes, primarily avenues with a constant flow of vehicles. To mitigate noise pollution, traffic flow management during peak hours, awareness campaigns promoting quieter transportation modes, and biannual controls are suggested.

Keywords: Noise pollution, noise map, internal policies, urban areas, traffic noise

1 Introduction

Over the years, noise has emerged as one of the primary pollutants of urban environments, causing substantial impacts on the quality of life of inhabitants, yet awareness levels vary widely depending on factors such as education, location, and exposure to information [1, 2]. The increasing population and the growth of transportation, construction, commercial, and industrial activities have led to a significant rise in sound pressure levels (SPL) in urban areas [3].

The Organization for Economic Cooperation and Development (OECD) has evidenced that millions of people are exposed to noise levels exceeding 65 dBA daily [4], values above those recommended by the World Health Organization (WHO) of 55 dBA for daytime and 50 dBA for nighttime [5].

A study by Hernández-Ocampo et al. [6] in Loja – Ecuador, carried out at the most frequented neighborhoods of the urban parishes of the city of Loja, including different land uses such as commercial, residential, industrial, social, and public services, revealed that, over 12 years, sound pressure levels reached, on average, 70.6 dB. There was estimated to be an increase of 1.5 dB per year. Relatively higher, the evaluation of noise levels in the city of Cuenca - Ecuador recorded SPL between 62 and 76 dBA [1, 7].

The importance of evaluating noise levels relies on the negative repercussions on people's quality of life, health, and well-being, as it influences rest, hearing capacity, com-

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munication and cognitive development, and physical and emotional health. In other words, noise produces psychological and physiological effects on humans [8–10].

Noise maps serve as valuable tools for performing spatiotemporal analyses, allowing for a comprehensive examination of the distribution and intensity of sound levels in specific areas. In urban settings, these maps prove instrumental in pinpointing sources of noise pollution and assessing the diverse levels of sound pressure impacting the population. This comprehensive understanding of the issue empowers informed decision-making aimed at effective noise-reduction strategies [3, 11].

According to Annex 5 of Ministerial Agreement No. 097-A, exposing the Ecuadorian environmental norms, the development of noise maps is one of the responsibilities of decentralized autonomous governments (GAD) whose inhabitants exceed or are equal to 250,000. Furthermore, the National Environmental Authority may request the development of noise maps in populations smaller than 250,000 if the environmental issue warrants it [12]. Loja reached the limit with 250,028 inhabitants by 2023 [13].

So far, few cities have spared resources to combat the impacts generated by noise [3]. In Loja, the municipal ordinance for protection against acoustic pollution was issued in 2006, and despite a series of action plans being suggested, inhabitants are unaware of them. Considering this context and practices in the noise field, such as the study presented by Hernández-Ocampo et al. [6], no other studies have been published that could serve as a reference for updating municipal ordinances or implementing mitigation measures. Therefore, this article highlights the importance of evaluating the impact on the care and well-being of the citizens of Loja, recognizing the critical scarcity of studies in this area. To obtain this, the present study aims to comprehensively assess noise levels across different land use categories in Loja while identifying major sources and spatial patterns of noise pollution in the city. The findings will establish the city's first noise map, intended to serve as a fundamental resource for policymakers, researchers, and the local community. Feasible mitigation measures will also be proposed as part of this comprehensive effort.

2 Method

2.1 Study Area

The study area encompasses the urban region of Loja, situated in southern Ecuador at an elevation of 2,065 m above sea level, and an urban area extending over 57.3 km² [14].

2.2 Data Collection

The sampling points were determined using the grid method established in Standard UNE ISO 1996-2:2009. For this, the city map was divided into 100 m x 100 m quadrants, resulting in 2974 quadrants covering an area of 29.74 km². Subsequently, land use was assigned to each quadrant according to the predominant activities. For this assignment, the five land use categories established by Ministerial Agreement No. 097-A were used as a reference [12]. The study area was divided into the following number of quadrants: 1257 quadrants in the Residential zone, 582 quadrants in the Industrial zone, 81 quadrants in the Commercial zone, 20 quadrants in the Public Service Equipment zone, 138 quadrants in the Social Service Equipment zone, and 896 quadrants in unclassified zones. A stratified sampling was chosen using the five previously mentioned land use categories. To define a representative number of sampling points under the budget of this project, Equation 1 was used. N is the size of the classified quadrants (2078 quadrants), e of 0.20 is the margin of error, z of 1.96 is the confidence level at 95% confidence, and p and q correspond to the 5% probability of success and failure, respectively.

$$n = \frac{N}{1 + \frac{(e^2)(N-1)}{z^2\,(p.q)}} \tag{1}$$

Of 24 points for each of the five strata or 120 monitoring points, only 76 were selected, as this was the only way to ensure the study was completed within the assigned time and budget. Considering those commercial activities and a higher concentration of vehicles occur in the city's central area, the 24 points suggested by Equation 1 were maintained in this stratum (Commercial Zone). Overall, the selection and distribution of the 76 monitoring points were established, considering the diverse land uses, along with vehicular mobility flows, such as private and urban transportation, highways, and stops of urban transportation. Thus, the points were strategically distributed throughout the entire urban core of the city. As a reference, the number of selected points in each stratum were: i) Commercial (CM): 24 points, among which are considered neighborhood, sectoral, zonal, and city commercial services; ii) Social Services Equipment (EQ1): 16 points, which include facilities that generate goods and services related to health, education, culture, social welfare, recreation and sports; iii) Public Services Equipment (EQ2): 6 points including public administration services, funeral services, transportation infrastructure facilities; iv) Industrial establishments (ID3/ID4): 15 points which their environmental impact can be considered as medium and high impact, v) Residential (R1): 15 points.

Figure 1 shows the monitoring points in the urban area of Loja city.

Two type 1 integrating sound level meters, Delta OHM model HD2010UC/A and Cesva model SC310, were placed at a height of 1.5 m and a minimum of 1 m away from any obstacle to minimize rebound effects. The microphone was positioned towards the noise source at a 45-degree angle. Recorded acoustic parameters included equivalent continuous sound level (LAeq,20min), maximum (Lamax), and minimum (Lamin) noise levels. Acoustic calibration using a 1kHz sound level generator, HD2020, preceded the sampling. Data collection was programmed at 10 s intervals for 20 continuous minutes per point, utilizing A-weighting in slow mode. Sampling occurred weekly during daytime hours (6:00 am to 8:00 pm, Monday to Friday). To avoid data bias due to vehicle congestion flows at different times and days of the week, the schedule was divided into two-time slots: peak hours (6:00 a.m. – 9:00 a.m., 12:00 p.m. – 3:00 p.m., 6:00 p.m. – 8:00 p.m.) and non-peak hours (9:20 a.m. – 11:40 a.m.,

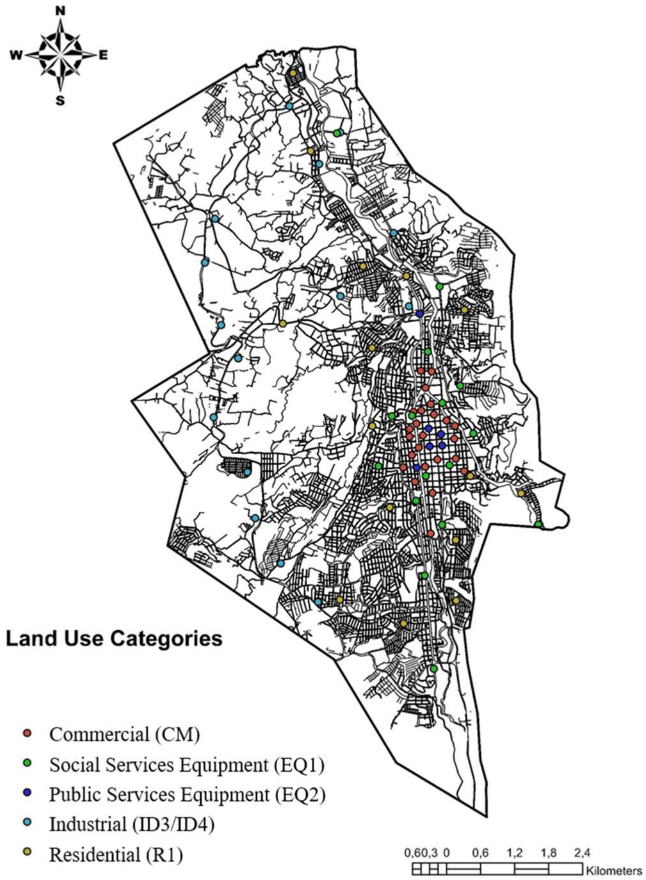


Figure 1: Monitoring points in the urban area of Loja city considering the five-monitoring land use

3:20 p.m. – 6:00 p.m.). In this way, five measurements were obtained during peak hours and five during non-peak hours for each day of the week, giving 10 replicas for each sampling point. The measurement points were defined using a systematic sampling method with a fixed distance interval of 0.5 km to 1 km between one measurement point and another. Data from noise measurements were retrieved using manufacturer-specific software, NoiseStudio for Delta OHM and CaptureStudio for Cesva.

2.3 Data analyses

Subsequently, databases were compiled in Excel, calculating LAeq,20 min for each point using Equation 2, where T represents the total measurement duration, Leq1, Leq2, Leqn denotes equivalent continuous sound pressure levels for each 10-second integration interval, and t represents fractions of the total measurement time. The sum of these fractions equals T. Finally, the total noise value was computed by averaging LAeq,20 min values from the ten recorded replicas for each monitoring point, resulting in 76 values for subsequent analysis and interpretation.

$$L_{eq} = 10\log\left(\frac{1}{T}\left(10^{\frac{Leq1}{10}}t1 + 10^{\frac{Leq2}{10}}t\,2 + \ldots + 10^{\frac{Leqn}{10}}tn\right)\right) \quad (2)$$

A noise map was generated using the ordinary Kriging geostatistical interpolation method to represent equivalent continuous sound pressure levels in the urban area of Loja. This technique predicts noise values at unmonitored locations based on existing data. Subsequently, points exceeding the permissible limits outlined in Table 1 were identified.

Table 1: Maximum permissible limits of the Ministerial Agreement 097-A. Annex 5.

Land use	L_{eq} (dBA) Daytime period 07:01 to 21:00 hours
Residential (R1)	55
Social Services Equipment (EQ1)	55
Public Services Equipment (EQ2)	60
Commercial (CM)	60
Industrial (ID3/ID4)	65

Traffic data were then extracted using the Google Traffic tool via RStudio to establish a correlation between noise levels and vehicular traffic at the study points. Shapefile layers were downloaded every 30 minutes over three weeks from 6:00 am to 8:00 pm, Monday to Friday, to obtain three replicates per point for enhanced representativity. Traffic criteria were defined based on the four initial categories provided by Google Traffic (low, moderate, intense, and severe). They were re-categorized into two traffic levels, high (intense and severe) and low (low and moderate), to facilitate the interpretation and integration of the data for subsequent analysis. Although Google Traffic considers certain criteria to establish its classifications, such as i) Vehicle speed, ii) Traffic density, and iii) Historical data and predictions, it does not allow obtaining data on these metrics, so only the traffic categories were considered for correlation.

3 Results

3.1 Noise Monitoring

The noise monitoring extended for three months from March to May 2023, encompassing 760 measurements and yielding 91,200 data points corresponding to the duration and integration mode configured in the sound level meters.

Upon analyzing the averaged LAeq,20min values across the 76 monitoring points, it was evidenced that 94% of these points surpassed the maximum noise limits for their corresponding land use. The calculated average LAeq,20min value for Loja resulted in 67 dBA, with a Leqmin,20 min of 55 dBA and a Leqmax,20 min of 72.9 dBA. These values exceed the WHO recommendations of 55 dBA for the daytime period, established to prevent adverse health effects.

According to the results, the loudest points are mainly concentrated in areas where vehicular flow is excessive and constant, such as avenues and streets like Universitaria Avenue, Manuel Agustín Aguirre, Pío Jaramillo, 8 de Diciembre, Lauro Guerrero, and Juan José Peña—main routes for both urban public and private transportation.

Maximum LAeq,20 min values are observed in the Belén neighborhood at 72.9 dBA, followed by the roundabout at the bus terminal, Universitaria Avenue, and Imbabura, each with 72.7 dBA. Conversely, the minimum LAeq,20min value was recorded on Vía de Integración Barrial Avenue, specifically in the Ángel Felisismo Rojas and Cuzco intersections with 55 dBA, these being 2 of the 4 points that are within the permissible noise limits for industrial land.

Analyzing values by land use, residential areas (R1) ranged between 59.7 and 72.9 dBA, social services equipment (EQ1) between 61.5 and 71 dBA, public services equipment (EQ2) between 65.9 and 72.7 dBA, commercial areas (CM) between 64.3 and 72.7 dBA, and industrial land use (ID3/ID4) between 55 and 70.2 dBA.

A box plot in Figure 2 shows the differences among the monitored land uses. It can be observed that all land uses have a median ranging between 65 and 70 dBA, surpassing the maximum limits indicated by a red line. It is important to emphasize that land uses corresponding to Social Services Equipment (EQ1), which includes hospitals and educational centers, and Residential (R1), designated for rest and the satisfaction of social needs such as health and education, record average values that exceed the permissible maximum limit of 55 dBA by 12 and 11 dBA, respectively.

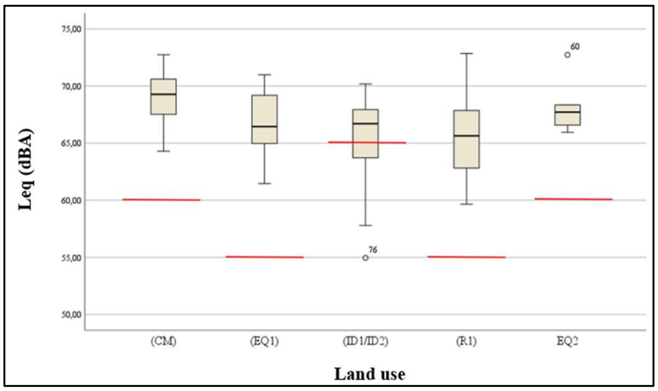


Figure 2: Blox plots according to the land use. The red line shows the maximum allowable limits the Ministerial Agreement 097-A set.

To determine whether there are significant differences in the time slots where noise measurements were taken, a normality test was conducted on the 76 average LAeq,20 min data points for both peak and off-peak hours. The Kolmogorov-Smirnov test confirmed that the data for peak and off-peak hours did not follow a normal distribution with a significance level below 5%, thus rejecting the null hypothesis of normal distribution.

Consequently, a non-parametric Wilcoxon test for related samples assessed the mean differences. The results indicated no significant differences between the average LAeq,20 min values for peak and off-peak hours. The significance value above 5% retained the null hypothesis.

Ultimately, a noise map illustrated the averaged Leq,20 min values, and a series of steps were followed to validate the map's prediction. An exploratory analysis of the 76 LAeq,20 min data points was conducted using a Kolmogorov-Smirnov normality test, demonstrating a normal distribution with a significance value above 5%. While the significance level may not be high, it indicates normality in the assessed data. Complementary frequency histograms and QQ plots supported the analyses and conclusion. The frequency histogram in Figure 3 confirmed the data's normal distribution, as evidenced by the similarity between the mean (67.01) and the median (67.35). The histogram exhibits a bell-shaped curve, revealing a pronounced leftward skew where lower LAeq,20min values are concentrated. The negative skewness of -0.8974, shown in Table 2, represents unnecessary data transformation.

Table 2: Descriptive Statistics table and quartile statistics resulting from the frequency histogram analysis.

Descriptive Statistics	
Count: 76	**Asymmetry:** -0.8974
Min: 55	**Kurtosis:** 4.3058
Max: 72.9	**1 Quartile:** 65.2
Mean: 67.01	**Median:** 67.35
Standard deviation: 3.3867	**3 Quartile:** 69.5

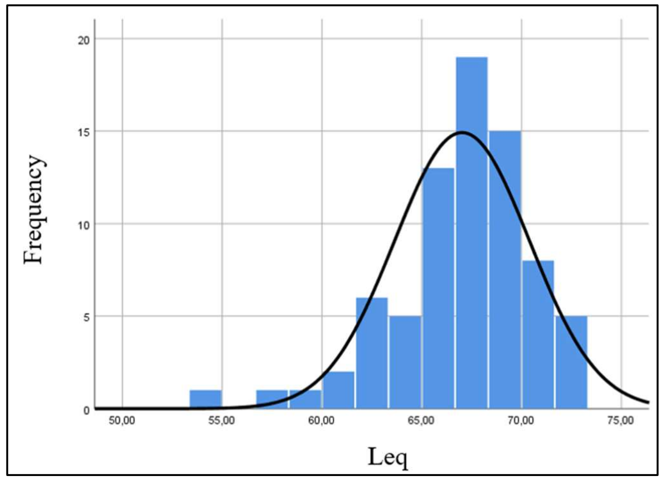


Figure 3: Frequency histogram to evaluate the normality of the data for the 76 average LAeq,20min values.

In the Q-Q plot presented in Figure 4, most values exhibit a normal distribution, with the tails of the data points deviating slightly from the theoretical line. The minimal spread of points in the tails suggests that extreme values occur less frequently, and the data points tend to cluster more closely around the expected values. The Q-Q plot also shows a symmetrical pattern, with the points on either side of the line exhibiting a similar deviation.

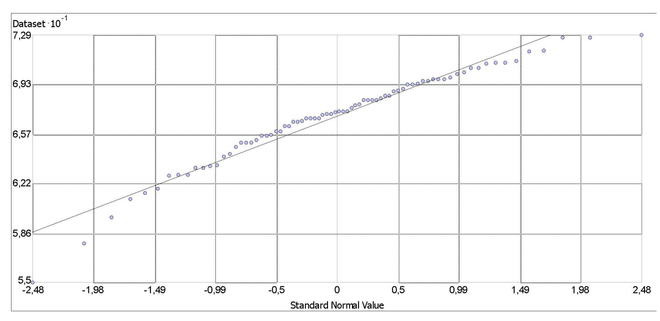


Figure 4: Normal QQ Plot. Data set: LAeq,20min 76. Total Attribute: Leq

The trend analysis in Figure 5 reveals that our data forms an inverted U shape from east to west (x-axis) and from north to south (y-axis). This pattern illustrates that higher values are concentrated in the center and decrease towards the extremes, indicating the presence of a visible trend in the collected noise measurements.

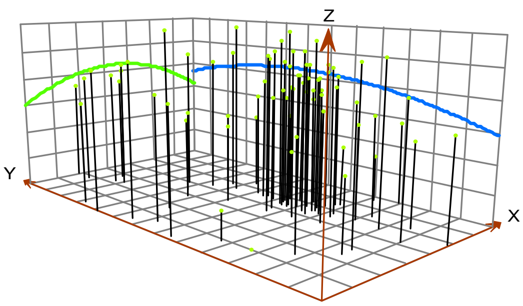


Figure 5: Trend Analysis. Data set: LAeq,20min 76. Total Attribute: Leq

The semivariogram cloud in Figure 6 confirmed the presence of spatial autocorrelation among the data due to the significant clustering of similar values among closely located points. Tobler's principle or the principle of spatial autocorrelation implies that data points near exhibit more remarkable similarity in contrast to those situated at a greater distance. This principle holds true even in spatial objects like buildings and roads, which are integral when creating noise maps [15].

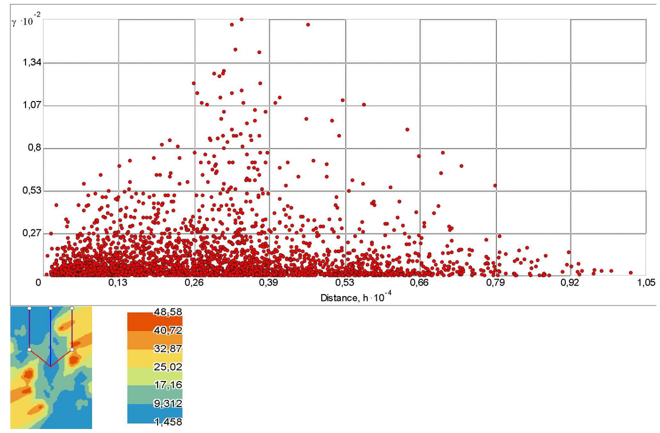
Figure 7 verifies through the calculation of Moran's Index that the data has a spatial autocorrelation, revealing a clustered trend, as evidenced by a z-value of 3.947125.

As a second step, a sampling process was conducted by randomly dividing the collected data into two groups, allocating 70% of the data for model training and 30% for validation. Subsequently, using ArcGIS tools, an Ordinary Kriging interpolation was implemented following a Gaussian prediction model. This model was chosen for its ability to capture the smooth and continuous variations characteristic of noise. It is supported by several studies, as presented by Mishra et al. [16] who mentions a list of countries around Europe, Asia, and North and South America where integration of GIS and noise models helped to attain continuous spatial models of noise levels and to perform spatial analysis.

Through cross-validation, it was possible to confirm that the established adjustments for the training model's predictions are acceptable, as shown in Table 3. These resulting values align with the criteria proposed by Garnier-Villarreal [17] and Melo Martinez [18], indicating that the training model provides valid predictions. For a reliable model, mean standardized prediction error (MSPE) values should be close to 0, and root mean square standardized prediction error (RMSSPE) values close to 1 [17].

Table 3: Statistical results of cross-validation of the training model with 70% of the LAeq,20min data.

Prediction errors	
Samples:	53 of 53
Mean:	0.0804
Root mean square:	3.1237
Mean standardized:	0.0056
Root mean square standardized prediction error:	1.2887
Average standard error:	2.3203



Dataset : Leq_76_Total Attribute: Leq

Figure 6: Semivariogram / Covariance Cloud

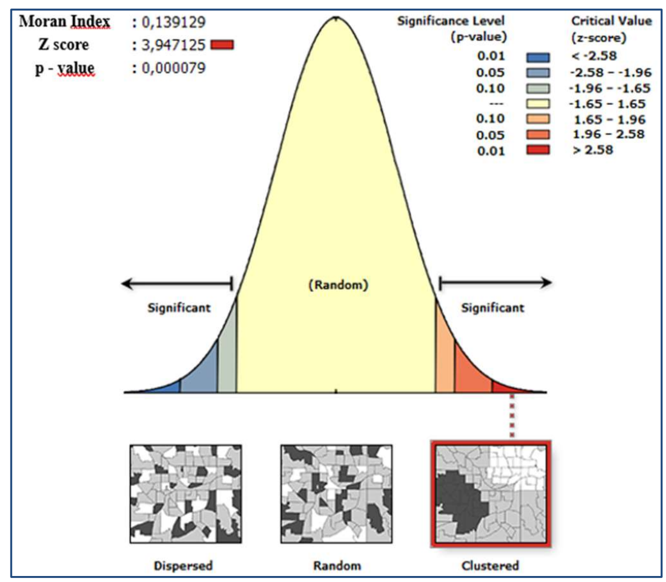


Figure 7: Moran index used to determine the spatial autocorrelation of collected data.

As the third step, the predictive model using the remaining 30% of the collected data was validated and presented in Table 4. The mean error, with a value of -0.4241, is deemed acceptable, given that these values should be close to 0. Therefore, it is confirmed that the employed model demonstrates predictive capability.

Table 4: Descriptive statistical results of the predictive model validation using 30% of the LAeq,20min data.

Descriptive statistics	
Count	23
Minimum:	-6.5501
Maximum:	6.8035
Sum:	-9.7550
Mean:	-0.4241
Standard deviation:	3.4281

Finally, considering the validated interpolation model settings, the LAeq,20min values were systematically represented on a noise map for the urban area of the city of Loja.

The values obtained from cross-validation, shown in Table 5, revealed that the generated map is deemed suitable.

Table 5: Statistical cross-validation results using 100% of the LAeq,20min data.

Samples:	76 of 76
Mean:	-0.0330
Root mean square:	3.1718
Mean standardized:	-0.0189
Root mean square standardized prediction error:	1.2763
Average standard error:	2.4422

The noise map in Figure 8 depicts predominant noise zones ranging from 66.7 dBA to 72.9 dBA, distributed across two sectors: the northwestern area and the commercial zone located in the city center. Additionally, maximum values are concentrated along the main traffic routes. In the city's northwestern area, the noise levels are notably elevated near the bypass of the Integración Barrial Road and Isidro Ayora Avenue, which leads to the roundabout of the bus terminal. High noise levels characterize this zone due to the convergence of vehicular traffic across the city.

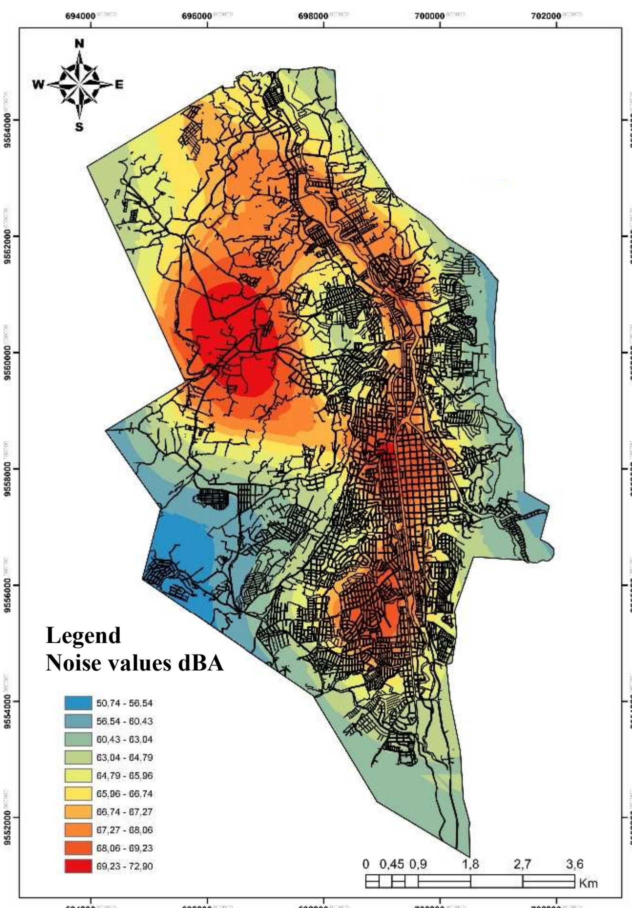


Figure 8: Noise map of the urban area of Loja City – Ecuador

Conversely, in the northern region, streets or avenues with the highest noise levels include 8 de Diciembre Street, Cuxibamba Avenue, and Salvador Bustamante Celi Avenue. In the central part, noise-intensive areas encompass 18 de Noviembre Street, Universitaria Avenue, Lauro Guerrero, Manuel Agustín Aguirre, Ramón Pinto, Juan José Peña streets, and in the southern part, along Pío Jaramillo Avenue. Regarding lower noise levels, distinct clusters are noticeable, predominantly situated in the peripheral zones of the city with values ranging between 55 dBA and 65.5 dBA. These areas correspond to residential zones, while in the southwestern part, they correspond to the industrial zone.

4 Discussion

The noise levels in the urban area of the city of Loja during the daytime period exceed the noise levels established in Annex 5 of Ministerial Agreement 097-A for the various land uses considered at the monitoring points in this study. The maximum value in the study was found in the northwestern part of the city, where values ranged from LAeq,20 min 67.3 dBA to 72.9 dBA. In the areas with these values, there is both incoming and outgoing traffic to the city, and it also includes one of the routes for the city's public transportation. Additionally, there is a connecting road that crosses from north to south through the western part of the city, where, due to its functionality, various types of vehicles circulate, with heavy vehicles primarily contributing to increased noise levels in this area. In the city center, where most monitoring points are situated, diverse, predominantly commercial activities occur, resulting in increased flow and vehicular traffic.

Yang et al. [19], in their study, evidenced that the noise-receiving points along the main roads receive a high sound pressure level at the rush hour because most of the vehicles are concentrated in these zones; in that way, alternative routes evidence less traffic load, thus a decrease in the noise level. During non-peak periods, vehicular movement was not predominantly influenced by commuting needs, yet maximum noise emission limits were exceeded due to increased car speed. Similarly, our study showed that noise levels during peak and non-peak hours recorded at CM, EQ1, EQ2, and R1 areas exceeded Ecuadorian noise emission limits and others fixed in Latin American countries [20]–[22]. Loja, the ninth most populated city in Ecuador, has 64.7% of its population working in the informal sector [23]. It comprises the street trade and central markets of agricultural products, fast food, clothing, handicrafts, fruits, and vegetables. Thus, noise affectation occurs even during non-peak hours, as people promote their products and bus stops experience higher passenger traffic. Like other parts of the world, buses are the most used mass transportation mode for urban mobility, particularly in Latin America. Consequently, there is a significant demand for buses to meet this need. Unfortunately, most of these buses are in poor condition, leading to high noise levels due to engine sounds and frequent horn usage [24]–[26].

Furthermore, the excessive noise levels concentrated in the northwestern part, as well as in the north-to-south extension of the city, are influenced by the circulation of all types of vehicles on the streets and avenues throughout the city, as there are no delimited areas for the exclusive flow of light transportation. This results in heavy vehicles traversing the central part of the city, except for buses from urban transportation. The lower noise values in the study are primarily observed in residential areas and, in some cases, such as the southwestern part as industrial zones, which share the characteristic of being in the city's peripheral areas. Consequently, they experience lower vehicular movement and exhibit lower noise levels. Soni et al. [27] predicted the annual growth rate of the automobile sector in their study, categorizing vehicles into light and heavy groups according to their weights. Their findings showed a significant difference between the two groups, with light vehicles contributing the highest noise levels. These findings suggest the importance of evaluating ambient noise levels within mixed-category zones in metropolitan areas to reassess ambient noise levels grounded in a city's land use patterns. Soni et al. [27] and Stepova et al. [28] agreed that this approach allows the establishment of policies and strategies to mitigate the impacts of noise pollution by optimizing traffic flows.

The lack of territorial planning in the city can lead to various problems, including traffic congestion and noise [24]. As a result, areas of heightened sensitivity, such as healthcare and educational facilities, are exposed to noise levels exceeding the established limit of 55 dBA. Their proximity to high-traffic roadways, and in the case of the latter two, bus stops in front of these establishments increase noise levels. Patella et al. [29] showed that the optimization of traffic flows could lead to higher traffic volumes on extra-urban high-capacity roads, reaching a reduction of noise levels on intra-urban roads [29]. Increasing traffic volumes, mainly of the noisiest cars, to the high-capacity roads connecting intra-urban or highways rather than the city center roads would decrease noise levels in EQ1 and R1 areas. With the support of the acquisition of autonomous vehicles, hybrid electric vehicles, and battery electric vehicles, a reduction of 10 dBA has been predicted, as they produce less noise due to the elimination of propulsion noise in urban environments [29].

In connection with these urban zones, the maximum limits taken as reference from Annex 5 of Ministerial Agreement No. 097-A, ranging between 50 dBA and 55 dBA for daytime periods, align with the maximum values established by other countries for each zone according to their sensitivity, including residential and hospital areas [30], [31]. These areas require increased attention, and in the case of this study, noise levels range from 59.7 dBA to 72.9 dBA. Similarly, the values recorded based on the different land uses in the city of Loja exceed the recommended WHO and Latin American regulated limits of 55 dBA for the daytime period [5], [12], [21], [22].

When comparing the noise values recorded in the city of Loja with other studies conducted in cities of neighboring countries such as Colombia and Peru with a similar population size, similarities can be identified, and in some instances, even cases with higher noise levels [32]–[34]. In their study, Varón & Garcia-Delgadillo [34], evaluated the effectiveness of restrictive measures, such as the case of 'pico y placa,' in the city of Ibagué, where vehicle circulation is restricted during two time slots: from 7:30 to 9:00 and from 17:30 to 19:00, Monday to Friday. The measure is applied based on the last digit of the vehicle's license plate, excluding two numbers per day, thereby reducing the number of vehicles in circulation and, consequently, the ambient noise level by approximately 10 dBA. However, the recorded noise values with and without restrictive measures still exceed permissible limits, emphasizing the importance of refining the study by considering the types of vehicles circulating under these restrictions. In the case of the city of Loja, this restrictive measure is not currently implemented. Nevertheless, if implemented with a rigorous education campaign, it could achieve the required impact of reducing noise levels to values close to the regulations. Quito, the capital of Ecuador, implemented this measure in 2010, with no significant success in reducing pollution and noise levels due to middle and high-income families acquiring one or more vehicles [35]. Based on the above, the importance of education on noise pollution for the population and stringent control over the necessity of acquiring additional vehicles becomes evident.

Implementing comprehensive measures is crucial for effective noise control in urban environments. This article underscores the significance of creating regulatory frameworks to address noise pollution in cities such as Loja, which aims for a sustainable management of the territory by 2030 based on the United Nations Sustainable Development Goals. Key initiatives include relocating commercial bus terminals away from the city center, imposing parking restrictions, ensuring regular road maintenance, developing low-noise road surfaces, and establishing a specialized traffic control unit to enforce adherence to traffic regulations. Additionally, measures encompass car maintenance standards, emission controls, legislation governing the use of horns and sirens, and speed limiting. The distribution of traffic plays a pivotal role in controlling vehicular noise and air quality and enhancing safety. Strategies for reducing traffic volumes involve encouraging public transport, promoting cycling and walking for short distances, efficient parking management, and restricting access to specific areas for heavy trucks. Furthermore, route designation and bypassing traffic around protected areas are identified as effective means to mitigate the impact of noise pollution on urban settings, which have been tested and effectively shown a decrease in noise reduction in other parts of the world [36]–[38]. Novel building materials can become soundproofing solutions to mitigate noise at its source. The implementation of technologies such as double-glazed windows, sound-absorbing panels, and insulated walls can reduce external noise infiltration into homes and workplaces, fostering quieter interiors [39]–[41].

In this study, the ordinary Kriging interpolation method was used to create a noise map with the LAeq,20min values from the 76 monitoring points in the urban area of Loja. Despite being a useful tool for evaluating noise, it is necessary to incorporate independent variables that were not considered in this study, such as the speed and flow of vehicles, the characteristics of the road (type, width, slope, and composition material), the number of light and heavy vehicles, as well as the distances from the noise source to the receivers. These factors directly influence traffic noise levels and their propagation. Including these variables can enhance the accuracy and robustness of the generated noise map [42]–[44]. Although our current model may not fully capture the spatial variability of noise, acquiring and integrating additional data, particularly in regions with pronounced noise pollution, could significantly enhance its predictive accuracy. This would benefit urban planning and environmental health assessments, ensuring more effective noise mitigation strategies.

Nevertheless, it is crucial to underscore the economic constraints encountered by small urban cities in developing nations. The latest findings affirm that noise pollution remains a persistent issue impacting the Loja population, notwithstanding a municipal ordinance. Our current study features a more robust data analysis than Hernandez-Ocampo et al.[6], considering that the LAeq,20 min data was obtained at 76 locations alongside the Google traffic tool. This approach not only reduced costs but also minimized data-intensive processes. As a result, the study offers a comprehensive overview of noise levels across different types of land use.

5 Conclusion

This study reveals that noise levels in Loja exceed the maximum limits established in the environmental measurements of Ecuador, the WHO, and other Latin American partner countries. In some areas, noise values are particularly elevated, closely associated with land use activities, mainly CM, EQ1, EQ2, and R1, and the types of vehicles circulating in the city center and peripheric areas. The study also reveals a need for vehicular regulations or controls, considering that vehicles are the primary contributors to urban noise, especially in the city center, where most activities occur. Citizens in this central area are exposed to average noise levels of 67 dBA, potentially posing long-term health effects. The WHO highlights that excessive noise pollution significantly harms human health, disrupts daily activities and sleep, causes cardiovascular and psychophysiological issues, reduces productivity, and provokes annoyance and changes in social behavior. In Loja, the impact on noise levels and population annoyance is influenced by the number of vehicles and their speed, traffic regulations, poor street conditions, and the lack of noise warning signage placement. Factors such as urban regeneration processes, the city's terrain, the centralization of services in Loja, and inadequate parking exacerbate traffic chaos and acoustic pollution. Furthermore, inadequate territorial planning is evident, particularly in the central part of the city, exposing sensitive areas such as healthcare and educational establishments to noise levels exceeding 55 dBA by a significant margin. Loja is a city that aims to achieve sustainable territory management by 2030 based on the SDGs; thus, implementing mitigation measures is urgent to address the prevailing noise issues, enabling control and reduction of excessive noise levels and ultimately enhancing the daily environment for the local population.

The distribution of environmental noise is complex, displaying significant spatial variability and heterogeneity in the data. Though predicting noise maps using road composition and characteristics data maps gives more accurate values, the process is expensive and time-consuming.

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