WHERE ARE WE OUT? SPATIAL ANALYSIS OF NOISE POLLUTION IN BOGOTA

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ABSTRACT

Nowadays, as urban populations grow, noise pollution is significantly affecting residents' quality of life. Studies for Bogota, Colombia suggest that the main source of noise is road traffic. Bogota's situation is likely to worsen as the total volume of vehicles increases at around 10% per annum. Although strong legislation has been approved to address noise pollution, limited understanding exists of where these limits are exceeded.
Using Geographic Information Systems a noise map for Bogota was developed. It presents theoretical noise levels based on experimental calculations of sound pressure and traffic flows across the road network calculated by a four-step transport model.
Results showed that legal limits are extensively exceeded in Bogota.
This analysis highlights areas that are most likely to exceed noise pollution standards, indicating areas where noise monitoring should be implemented. Field-based measurements are needed to confirm and refine the results of the modeling.

KEYWORDS: Noise, GIS, FHWA-TNM

1. INTRODUCTION

Today, reaching a good quality of life in cities constitutes a great challenge for authorities. Quality of life implies good services, transport systems, safety and effective pollution control. The increasing number of people moving to cities generates higher pollution. As a consequence, urban inhabitants feel strongly concerned by their environment. Air, Noise, Soil and Water pollution have become topical issues.
Noise pollution can cause hearing diseases, disturbance and discomfort. It has been widely reported that high sound pressure levels can affect health in general (C. Martimportugués et al.; T. Kujala, 2009). Noise pollution is obviously a compelling issue in urban areas where densities of population, traffic and industries are higher.
Besides, traffic has been recognized as the main noise source in cities, with cities in developing countries strongly affected. Generally, authorities focus first on making improvements to air quality. Norms and laws exist in many countries to limit noise. However, in most cases, the noise level is rarely controlled and nothing is done to set up real and effective limits.

Bogotá, the capital of Colombia is a rapidly developing city with 8 million inhabitants. To satisfy the demand, the city uses several different public transport systems. Bogotá is served in most principal roads by old buses that produce a disproportional level of noise pollution.

This study presents a methodology, using Geographic Information Systems (GIS), to estimate how much area of a city is exceeding its legal limits in terms of noise levels. A case study in the city of Bogotá was conducted.
This paper is divided in four parts. The first part presents a review of current research in the area of noise pollution estimation and legislation. The case study of Bogotá is introduced. The second part describes the methodology used. Then results from applying the methodology to the case study are discussed. Finally, conclusions for the research and opportunities for further work are presented.

2. BACKGROUND

Noise pollution Issue

In most of the world's cities, populations are increasing. The phenomenon is particularly visible in developing countries where urban areas are expanding constantly. This situation leads to an increase of the vehicular fleet increasing congestion. Noise pollution becomes a topical issue and legal limits have been defined all over the world (B.Berglund et al., 1999; P. Martinez Suarez).

Several studies point out traffic as the main cause of noise pollution (W.Q. Gan et al., 2012; M. El-Fadel et al., 2002; A. Ramírez González et al., 2011). Among the different emitting vehicles, the major noise generator is the bus (A. Ramírez González et al., 2011; J.A. Pacheco et al., 2012).

Noise not only generates discomfort; it can lead to serious diseases. Hearing problems and deafness (Miyara, Estimación del riesgo auditivo por exposición a ruido según la Norma ISO 1999:1990) are obviously directly linked with the noise level in the patient’s environment (Miyara, Ruido, juventud y derechos humanos, 2007). Noise can also disturb the ear development of babies (Miyara, Ruido, juventud y derechos humanos, 2007) and affect the brain with respect to concentration and speech skills (T. Kujala et al., 2009). Other consequences include: negative emotions, stress and lack of visual concentration (Z. Santalla Peñaloza et al., 1999; C. Martimportugués et al.). Studies also accuse noise of generating more dangerous health problems such as cardiovascular disease (E. Murphy, 2010).
Noise is recognized by everyone as a disturbance but many people ignore the consequences of chronic exposure to high level sound pollution (G. Maya V. et al., 2010). In many cases, cities lack the equipment and expertise required for the measurement and control of noise.

Studies also stress that each country and city has to be analyzed separately as noise levels should be linked to specific criteria that are relevant to the local economic development and transport system (J.M. Barrigón Morillas et al., 2002).

Noise pollution modeling

In order to obtain the sound pressure level in a whole city, the first step is to get the sound pressure level emitted by particular cars and buses.

US Federal Highway Administration (FHWA) -TNM Traffic Noise Model algorithm was chosen to get the coefficients needed to obtain the sound pressure level for two vehicle categories: cars and buses (J.A. Pacheco et al., 2012).
FHWA-TNM is a recent methodology that has been proven to be efficient and reliable (M. El-Fadel, 2002). Other methods are used to model noise propagation using field measurements and then interpolating these values to the whole city with GIS tools (K.T. Tsai, 2009; B. & M., 2005). These methods require field measures for the entire city.

In a previous paper (J.A. Pacheco et al., 2012), a methodology based on the FHWA-TNM algorithm was developed to obtain the noise emitted by different vehicle types. Field samplings were used to get local Reference Energy Mean Emission Levels (REMEL) for different vehicle categories.
Emissions were measured during static and dynamic tests with different speeds following the

conditions required by this algorithm.
A regression method enabled the determination of the A, B and C coefficients using the following equation:

$$L_E(s) = 10\log_{10}(\ 10^C + S^{A/10}10^{B/10}\ )$$

Equation (1)

Thus, the coefficients A, B and C are known for each type of vehicle:
-Passenger Cars (PC)
-Light Trucks: Goods vehicles, 4 wheels (LT)
-Heavy Trucks: Goods vehicles, 6 wheels (HT)
-Small Bus: Public transportation vehicle, maximum capacity of 20 passengers (MB)
-Bus: Public transportation vehicle, capacity over 20 passengers (B)
-Motorcycle (M)

Results are summed up in the following table:

Vehicle Category	FHWA [6]				This Study			
	A	B	C	ΔE	A	B	C	ΔE
PC	41.7	0.22	47.86	0.92	24.39	23.11	50.9	0.45
LT	33.9	19.49	66.9	1.09	5.69	59.94	61.92	1.36
HT	35.87	20.3	73.58	0.71	3.75	65.11	62.64	2.99
B	23.5	38	66.9	n/a	3.01	70.73	62.35	0.7
M	41.02	7.33	56	n/a	18.3	35	51.8	0.3
MB	n/a	n/a	n/a	n/a	9.16	61.37	61.4	2.1

Figure 1

The final equation used to calculate the sound level pressure is the following (after adjustment):

$$L_E(s) = 10\ \log_{10}(\ 10^{C+\Delta E} + S^{A/10}10^{B+\Delta E/10}\ )$$

Equation (2)

This study gave the elements to calculate sound pressure levels of road sections and then of the whole city as detailed in the methodology.
Moreover, GIS has proved to be a powerful tool in order to model noise propagation (Accolti, y otros, 2011; K.T. Tsai, 2009).

The study takes place in Bogotá, Colombia, a rapidly developing country where a large proportion of the inhabitants travel by bus. The bus fleet is dominated by numerous old and noisy vehicles. The Colombian law includes noise level limits for different activities' zones. Even though the legislation exists, it seems that the defined noise limits for Bogotá are routinely exceeded.

3. METHODOLOGY

This part presents the methodology used to identify areas that are likely to exceed legal noise limits. It describes the steps followed to generated predicted sound levels in many locations across the city. The methodology is divided into two sections: the first part explains how the noise pollution for an entire road network was obtained. The second part is the development of a map illustrating this information using a Geographic Information System.

Data: Calculation of road sections' emissions

Traffic volumes for buses and cars were calculated for each principal road section of the network using a 4 step transportation model. Average speeds of buses and cars are also known for each road section.

Using equation (2), the noise level emitted is obtained applying the coefficients and speeds corresponding with the category of the vehicle studied. This noise level is calculated for each type of vehicle and road section.

Then, using the following equation, the pressure P_1 was obtained. It allows to convert sound pressure level in sound pressure.

$$P_1 = P_0 . 10^{L_E(s)/20}$$

Equation (3)

P_0 is the atmospheric pressure of 2x10-5 Pa.
$L_E(s)$ is the sound pressure level.
The pressure P_1 was multiplied by the number of vehicles per category present on the road section (calculated by the 4 steps transportation model). This process was done for both vehicle types: cars and buses. This enabled us to obtain the total sound pressure for each segment.

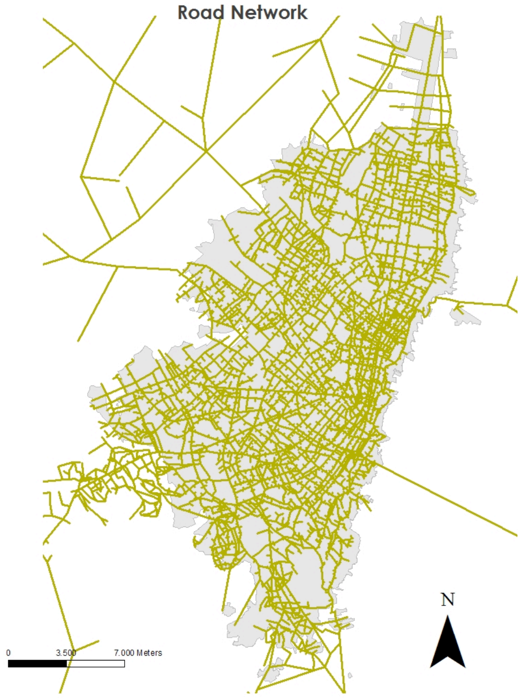

Figure 2: Map of the road network used

Use of GIS: model logic

The use of ArcGIS allowed the representation of the acoustic propagation from each road section acting as a linear source. The precedent calculations gave us the emission of each road section. Emissions were assigned to each link from the Bogotá road network layer.
Sound propagation by distance from source is shown in this equation:

$$dB_2 = dB_1 + 10\log_{10}(\frac{D_2}{D_1})$$

Equation (4)

However, the whole study was done with sound pressures as it permits to sum them and, at the end, all results were converted into decibels.

Coefficients were calculated at a distance of 15 meters from the source.
Also, D_1 = 15m and P_1 is the sound pressure emitted by the source, the link.

The sound pressure part of the propagation equation is specific to each source, implying that the calculation of noise propagation must be carried out one link at a time. To achieve this, ArcGIS ModelBuilder was used to calculate an individual emission effect for each source and then aggregating at the citywide level. The model developed selects another source for each round and calculates its spatial propagation with equation (4).
The equation was applied to each source using the “raster calculator” tool and the attributes of the initial layer. The distance D_2 is the one obtained using “Euclidian Distance” tool. Due to the large number of links, almost 90 groups of sources were created corresponding to different ranges of emissions. The average emission (according to the range) was assigned to each group.
At the end, the sound pressure obtained for each cell of the map was converted into sound level.

Considerations in the logic of the model

Sources are modeled lines (links). A rectangular geometry of 1000m of width was created on both sides of each link to take into account this distance.

During the implementation of the model, another issue appeared: how to treat link intersections. For this study we considered that noise pressure is the sum of the sound pressures caused by each link at the intersection but it is not exactly the case in the reality. So, after applying the model to one group level, we selected the intersections of the rectangular areas surrounding each link of the group. With GIS tools, the number of original rectangles constituting the intersection can be obtained. The value of the cells included in these intersections is multiplied by this number (x times the initial noise pressure).

The following map shows the number of buffer intersections, source of errors for the model.

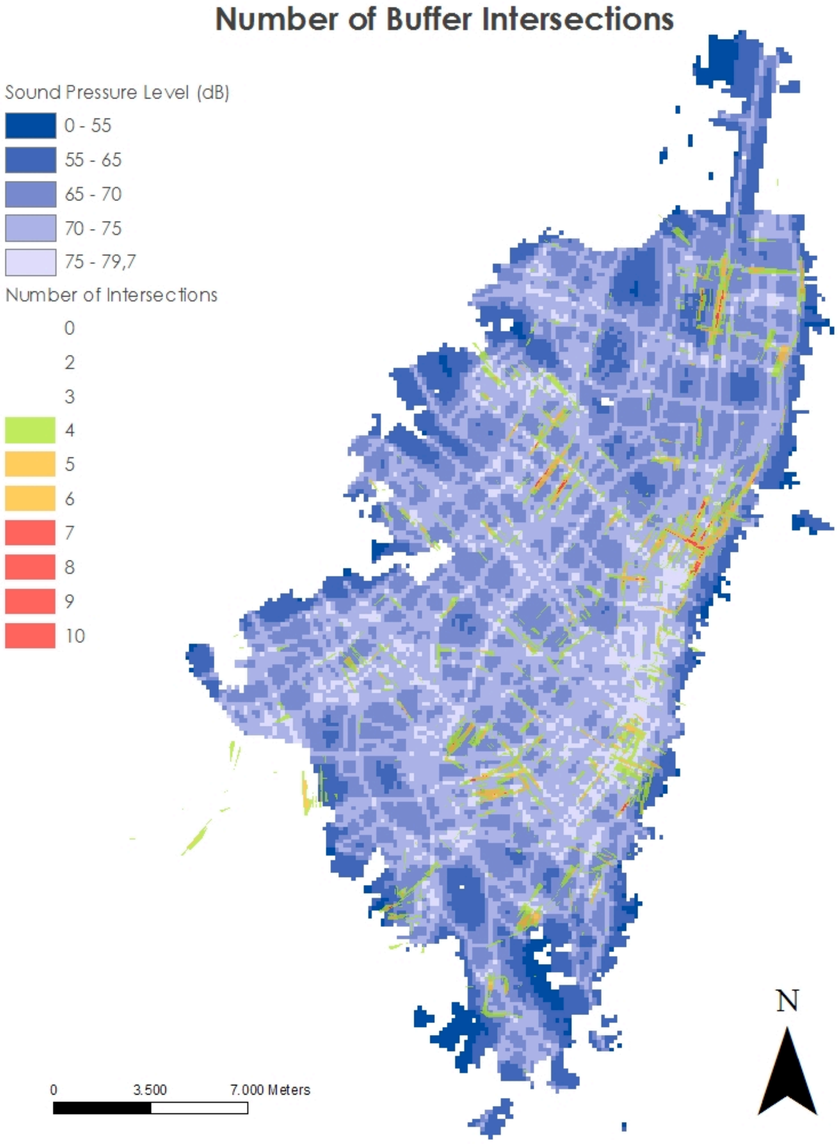
Number of Buffer Intersections
Sound Pressure Level (dB)
0 - 55
55 - 65
65 - 70
70 - 75
75 - 79,7
Number of Intersections
0
2
3
4
5
6
7
8
9
10
0
3.500
7.000 Meters
N

Figure 3

4. RESULTS

A continuous map of Bogotá was developed with in each cell the value of the sound pressure level at this point. The legend stresses the different sectors' legal limits.

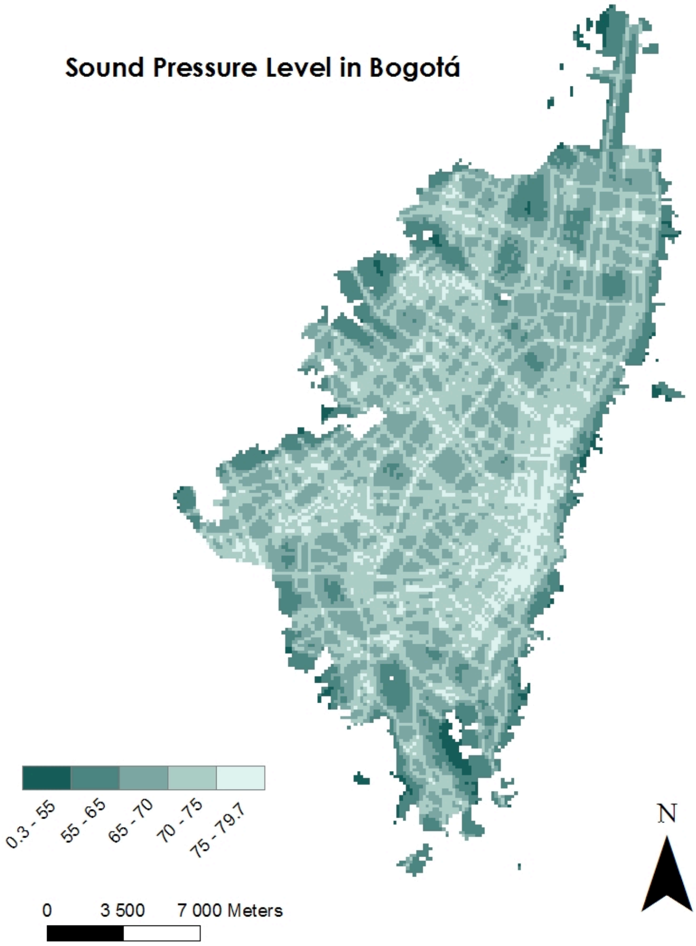

Figure 4: Total Sound Level Pressures modeled for Bogotá

To determine how much of the city is exceeding legal limits, national limits were used. These ones depend on the type of sector: A, B, C3, C2 and C1.

Table 1: Legal limits and zones

Zone	Sound Level Limit (dBA)	Description
A	55	Hospitals, Libraries, Nurseries
B	65	Education: universities, schools Parks, Residential areas
C3	65	Offices, Institutions
C2	70	Commercial areas, Sport centers
C1	75	Industrial areas

The key question was: how much of each zone was exceeding its legal limit?
Percentages of area for each type of area were obtained as following:

Table 2: Results for each zone

Zone	% SPL > Limit	% SPL < Limit
A	99,4	0,6
B	86,2	13,8
C3	95,7	4,3
C2	53,2	46,7
C1	5,3	94,7

These results stress the critical situation of Bogotá. Due to the model we can't rely on the exact value of the sound pressure level (groups of emissions and intersections). But, it is an interesting tool to define where measures should be taken to control and then apply the legislation.

5. CONCLUSIONS

The methodology proposed in this paper provides a high-quality tool to identify areas where sound levels are likely to exceed legal limits. The results of the study applied to Bogotá suggest that most of the city seems to present bad noise or sound conditions. These high sound levels are very likely to affect the activities of the sector and the health of people working or living in these areas.
The model allows us to identify the areas where strict controls should be implemented in order to apply the law and protect citizens. It stresses the lack of concern by authorities about this noise issue. One of the reasons is that controls are expensive.
We are looking forward to expand the model, applying it at a micro scale to analyze smaller areas. Besides, other noise sources should be investigated such as industries. Also, field measures should be carried out to improve the process.

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