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Geoprocessing applied to the assessment of environmental noise: a case study in the city of Sorocaba, São Paulo, Brazil

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Abstract Noise mapping has been used as an instrument for assessment of environmental noise, helping to support decision making on urban planning. In Brazil, urban noise is not yet recognized as a major environmental problem by the government. Besides, cities that have databases to drive acoustic simulations, making use of advanced noise mapping systems, are rare. This study sought an alternative method of noise mapping through the use of geoprocessing, which is feasible for the Brazilian reality and for other developing countries. The area chosen for the study was the central zone of the city of Sorocaba, located in São Paulo State, Brazil. The proposed method was effective in the spatial evaluation of equivalent sound pressure level. The results showed an urban area with high noise levels that exceed the legal standard, posing a threat to the welfare of the population.

Keywords Environmental noise · Noise mapping · Geoprocessing · Urban planning

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Introduction

In developing countries, the expansion of urban mesh has caused great disparity in the progress of its regions, particularly by the phenomenon of population growth. Besides the socioeconomic implications, derived from an unorganized development, the environmental quality also started to show signs of deterioration.

Noise is now a prominent factor in the urban environment that has deteriorated the quality of life, and traffic is in one of its main sources (Zannin et al. 2002). It causes significant health effects, such as cardiovascular problems, hypertension, increased levels of diabetes, changes in social behavior and induces depressive tendencies (WHO 2001).

Besides, this type of pollution is often ignored by most people, being taken as part of the routine of urban centers.

In some countries, acoustic zoning has been introduced as the basis technical tool for the evaluation and control of environmental noise (Piccolo et al. 2005). Through Directive 2002/49/EC (European Union 2002), member countries of the European community are required to establish noise mapping in cities with over 250,000 inhabitants. In countries like the UK, complete environmental noise mapping of their municipalities are already available via Internet. It can be accessed by the population and helps public management (DEFRA 2008).

In Brazil, urban noise is not yet recognized as a major environmental problem by the government, although noise complaints can be cited among the major issues dealt with by the environmental departments of large cities such as Rio de Janeiro and São Paulo (Pinto and Mardones 2008).

With the approach given by the Brazilian legislation, control and monitoring of noise shall be implemented by municipalities, allowing the existence of specific municipal laws or just obeying the federal law that dictates the subject.

The Brazilian Technical Norm NBR 10151 (ABNT 2000) establishes the basic procedures for the measurement of noise and sets standards for equivalent sound pressure level, depending on the land use. It does not obligate, however, to carry out the noise mapping. This technical standard was introduced into the Brazilian legislation board by Resolution 001/90 of the National Environmental Council (CONAMA 1990), and its standards should therefore be obeyed.

Noise mapping

After the adoption of Directive 2002/49/EC by member countries of the European community, noise mapping acquired high importance as a tool to support decisions on land use planning, being an integral part of municipal master plans. It allows visualizing areas with critical noise levels and those who have good sound quality (Baltazar et al. 2006).

Cho et al. (2007), on a study in the Republic of Korea, carried out noise mapping through a computer modeling system that uses information from sound pressure level measured in the field, along with the coordinates of the sampled sites, over three-dimensional topographic models that represent both the natural and building topographies. Their study showed results that can be effectively used for directly monitoring and assessing environmental noise.

Acoustic simulation models have also great importance in studies that consider noise in urban areas. Such models take into account the physical effects of sound propagation (reflection, absorption, diffraction, etc.) along with traffic and environmental information, as in the study presented by Pinto and Mardones (2008). With this technology, they were able to demonstrate an excellent means to deal with urban noise.

However, it is rare to find cities in Brazil that have topographic databases, considering not only terrain but also buildings, which is a major factor in the above-cited methods. Surveys of traffic and environmental information are also hardly found, with the exception of large cities.

Such methods happen to be excellent tools for noise assessment. Nevertheless, with regard to the available databases, Brazil is still far from its effective use. Therefore, it is essential to develop methodologies that are compatible with the reality of the country and able to concretely help urban planning.

Geoprocessing

Geoprocessing is a set of techniques based on the study of spatially distributed information in order to describe the characteristics of the phenomenon under investigation at the whole area of interest. It also allows periodical updates over the database, which enables the spatiotemporal analysis (Yilmaz and Hocanli 2006).

This work aimed to describe the spatial behavior of environmental noise from field measurements through the use of geoprocessing techniques and thus define a methodological procedure for its assessment.

Area of study

Because of proximity to the Metropolitan Region of São Paulo, Sorocaba became one of the leading economic expansion areas of the State of São Paulo since 1960, which induced significant population flows. The city's population now sums more than 600,000 inhabitants.

The study was carried out in the central zone of the city, according to the municipal master plan. The area of the study (gray polygon in Fig. 1)

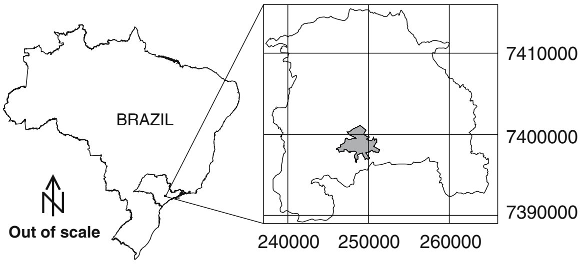


Fig. 1 Central zone of Sorocaba, São Paulo, Brazil

is approximately 10 km^2 and is characterized by the coexistence of commercial establishments, services, and diversified industries, in addition to the preservation of historically consolidated residential uses. There is also an intense flow of people and vehicles, predicting noise as a component of urban life.

Regarding noise, there is no specific municipal legislation on the subject. Hence, it obligates the city to comply with federal law, Resolution 001/90 of the National Environment Council, which refers to the standards established by the NBR 10151 Technical Norm.

Field measurement procedures

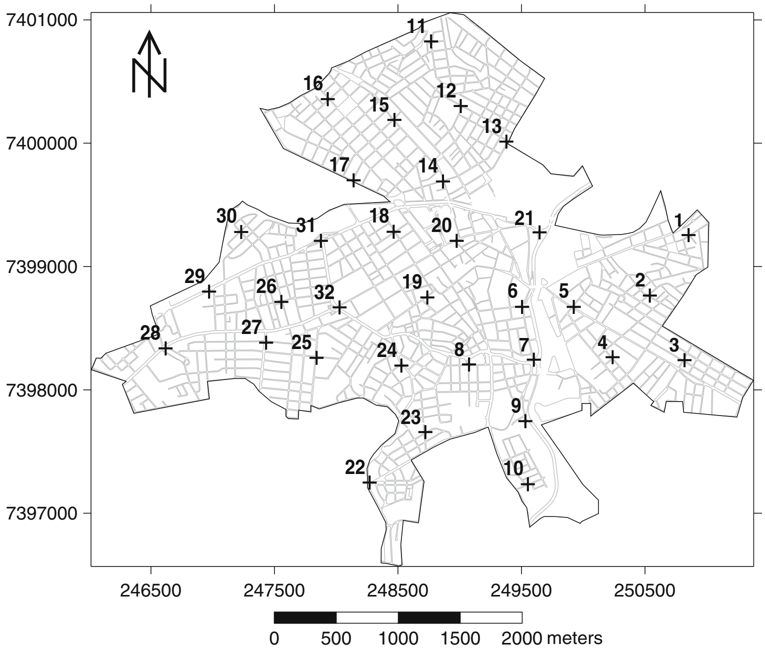
The sampling points were defined to ensure a regular sampling network. To do so, a triangular network was generated, with vertices 600 m apart, defined as the measurement points. A total of 32 points were created, representing a density of three to four points per square kilometer.

Some points defined in the office suffered minor adjustments in the field because of difficulties of access, for example, when a point was created in the middle of a block. Figure 2 shows the sampling points' locations.

The measurement period was defined to represent the daily peak times. The periods of highest concentration of public transport vehicles were acquired from the Department of Transportation of the city, which ended to be between 6 and 8 A.M. and between 4 and 7 P.M. Public transportation was considered an indicator of the peak period.

Field work was divided into three campaigns because the limited period for sampling did not allow completing the measurement in a single day. Each campaign was composed of 11 points at maximum, carried out on Wednesdays of April

Fig. 2 Sampling points



2008, and each point was sampled in the morning (between 6 and 8 A.M.) and in the afternoon (between 4 and 7 P.M.) of that same day. The reason to elect the Wednesdays of April was to represent the noise without interference from atypical periods, such as weekends or school holidays, resulting in noise levels that the population is regularly exposed.

The measurement used a global positioning system to assign the coordinates of each sampling point and a digital decibelimeter, with a compensation circuit A, calibrated in a laboratory that is certified by the National Institute of Metrology (INMETRO 2008).

The measurement length at each point was 5 minutes, with the decibelimeter set up on the fast A scale approximately 1.2 m off the ground and at least 2 m away from any reflecting surface (ABNT 2000). The instrument readings were written down on a spreadsheet every 10 s, resulting to 30 records for each point. The equivalent sound pressure level (L_{eq}) was calculated as follows (Eq. 1):

$$L_{\mathrm{eq}} = 10 \log \frac{1}{n} \sum_{i=1}^{n} 10^{(L_i/10)} \tag{1}$$

where:

L_i is the sound pressure level in decibels (A), read every 10 s;

n is the total number of readings.

The equivalent sound pressure level (L_{eq}) for each point was calculated in the morning and in the afternoon. The arithmetic average of these two values was used for analysis, named hereafter as "equivalent sound pressure level average" (L_{Aeq}).

Spatial analysis procedures

Initially, some useful statistics were calculated to characterize the distribution of data, such as measures of position (mean and median), dispersion (variance and standard deviation), and skewness (Pearson's asymmetry index), using Microsoft Excel 2007 (Microsoft Corporation 2006).

Next, a geostatistical analysis was performed. For this, a semivariogram was calculated to investigate the spatial distribution of the values measured in the field, using the following expression (Eq. 2):

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} \left[r(z_i) - r(z_i + h)\right]^2 \tag{2}$$

where:

h is the distance between two pairs of samples in a given direction of a two-dimensional space;

$r(z_i)$ is the value of the variable in the arbitrary point z_i;

$r(z_i + h)$ is the value of the variable at point $z_i + h$;

$n(h)$ is the number of pairs h units apart.

The semivariogram is a function that can be represented graphically, with the distance h at the x-axis and the semivariogram function $\gamma(h)$ at the y-axis.

For this step, the software Surfer 8 (Golden Software 2002) was used, such as for the following interpolation and cross-validation steps.

The values of L_{Aeq} were then interpolated by the use of different techniques. Besides geostatistical interpolation (known as "kriging"), inverse-square distance and minimum curvature models were carried out. These results were tested by cross-validation to obtain the best spatial representation of the measured values.

The cross-validation technique compares the values estimated by an interpolation method and the actual values of the sampled data set. Through a software simulation, the value sampled at a particular location is temporarily discarded of the data set, and then, a new value is estimated using the remaining samples. This procedure is repeated successively for all the samples available, and the new estimated values are compared with the real (Isaaks and Srivastava 1989).

The results of the cross-validation were tested statistically by Pearson's linear regression and by analysis of variance, using the software Microsoft Excel 2007 (Microsoft Corporation 2006).

Table 1 Maximum noise levels allowed by Brazilian legislation (ABNT 2000)

Land use	Maximum allowable level (day) in dB (A)	Maximum allowable level (night) in dB (A)
Cottage and farm areas	40	35
Strictly urban residential area or schools or hospitals	50	45
Mixed area, mostly residential	55	50
Mixed area, with an administrative and commercial role	60	55
Mixed area, with recreational vocation	65	55
Predominantly industrial area	70	60

Results and discussion

The standards set by the Brazilian legislation for the equivalent sound pressure level, which will be the basis for comparison with the results obtained in the study, are presented in Table 1.

For the central zone of Sorocaba, the maximum level allowed was assumed to be 60 dB (A), related to mixed areas, with commercial and administrative roles, at daytime. Figure 3 shows the results of L_{Aeq}, together with the maximum ($L_{\max}$) and minimum ($L_{\min}$) levels measured at each point. The 60 dB (A) legal standard was also drawn for comparison.

It was noted that at only four sampling points (1, 10, 11, and 12), which are located in residential spots, the variable L_{Aeq} did not exceed the maximum allowed level. At the other points, the values situated up to 25 dB (A) above the legal limit. It highlights an area with concern on acoustic characteristics.

During the field survey, vehicle traffic was identified as the predominant source of noise in the area. In terms of intensity of noise in this category, the differences were related, primarily, to the type of vehicle. Trucks, buses, and motorcycles registered the highest levels. In many cases, the conservation status of the vehicle was identified as an aggravating factor for the high sound pressure levels.

The frequency distribution and the main statistics of the variable L_{Aeq} are presented in Fig. 4.

The frequency distribution, along with Pearson's asymmetry index, showed a moderately asymmetric distribution, with values concentrated at the right side of the mean. This becomes important because the mean exceeded the maximum allowable level in more than 10 units of decibels (A).

For the geostatistical analysis, anisotropic semivariograms were generated for the four main directions: N–S, E–W, NW–SE, and NE–SW, and also an isotropic semivariogram. They are presented in Figs. 5 and 6.

The analysis of anisotropic semivariograms (Fig. 5) showed two privileged directions of variation, which are the directions N–S and SW–NE, where the values of the function $\gamma(h)$ increase almost continuously with the distance h until they

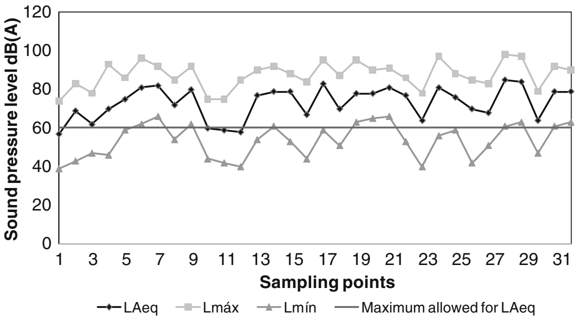


Fig. 3 Results of the noise measurements

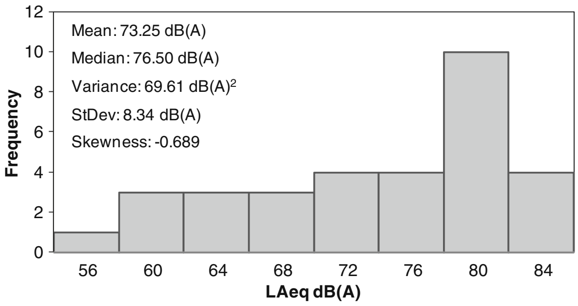


Fig. 4 Frequency distribution and main statistics of the variable L_{Aeq}

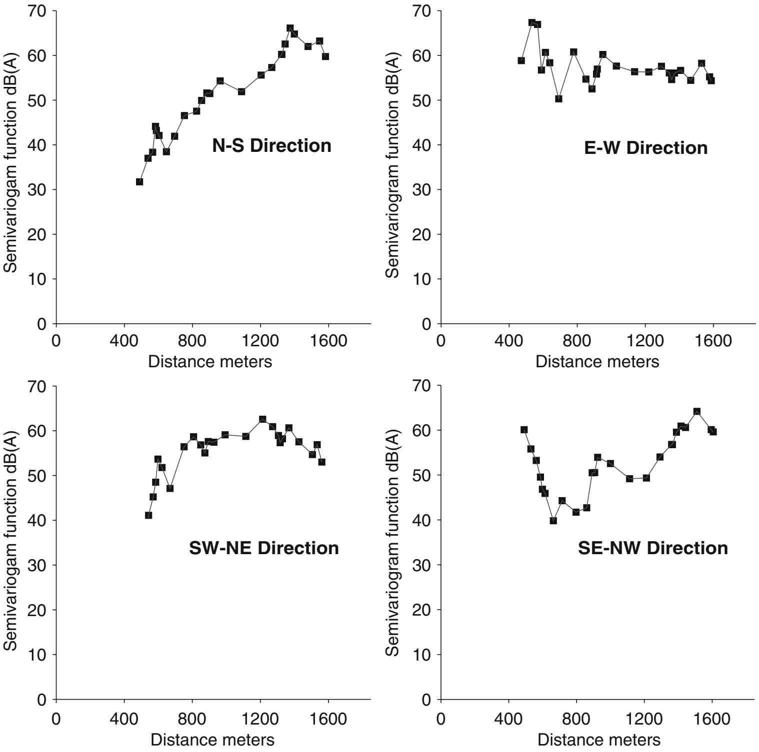


Fig. 5 Anisotropic semivariograms

reach a level where the spatial variability becomes constant.

In other directions, E–W and SE–NW, it was not possible to attribute continuity in the spatial variation of noise due to the erratic behavior of the function $\gamma(h)$.

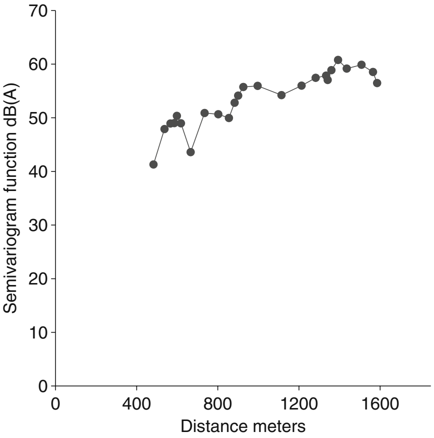


Fig. 6 Isotropic semivariogram

As for the isotropic semivariogram (Fig. 6), some spatial continuity was also observed. Together with the N–S and NE–SW anisotropic semivariograms, a tendency to reach the range around 1,400 m was noted. This distance assigns the limit of the influence zone of a sampled point on its neighbors. The sill, level where the semivariogram function becomes constant, is close to the sample variance, around 65 dB (A), as expected.

In a general analysis, it was possible to identify the existence of a pronounced nugget effect, regardless of the direction of calculation. This effect is noticed by high values of the semivariogram function for values of distance near the origin, demonstrating a great contribution of the random component in the variation of the sampled L_{Aeq}.

This indicates an intrinsic randomness of the phenomenon, showing that under the conditions of the study, the equivalent sound pressure level of an arbitrary point did not make a great influence on the neighboring points. Therefore, the characteristics of the road network (streets, avenues, crossroads, type of asphalt and terrain slope) happened to be more decisive for the spatial variation.

The characteristics of the calculated semivariograms also suggested that the use of kriging in the estimation would not provide a satisfactory result. In fact, the application of kriging over the sample data set generated a model that was not accepted by the cross-validation. The Pearson's linear regression coefficient between sampled values and cross-validation estimated values resulted +0.131, indicating a low correlation between the variables and not validating the model.

The same happened with the inverse-square distance estimator, for which the cross-validation generated a Pearson's linear regression coefficient of around +0.084, indicating a lower correlation compared to the first model.

In contrast, the model generated by the minimum curvature estimator showed a high correlation between sampled values and cross-validation estimated values, supporting the decision to choose it to represent the spatial distribution of the variable L_{Aeq} in the study area. Figure 7 shows the model calculated by this estimator, represented by isolines of L_{Aeq}, at intervals of 5 dB (A).

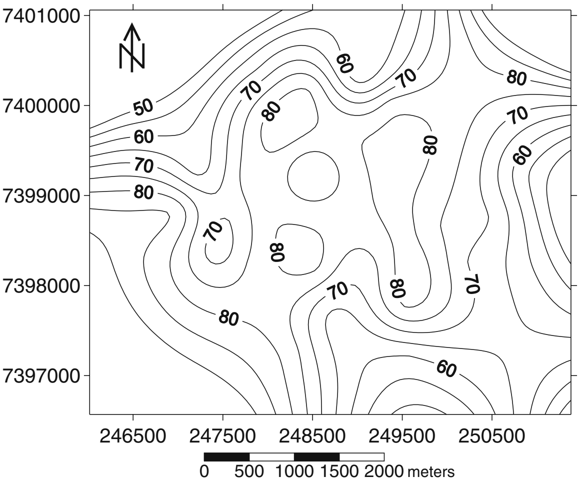


Fig. 7 Model generated by the minimum curvature method

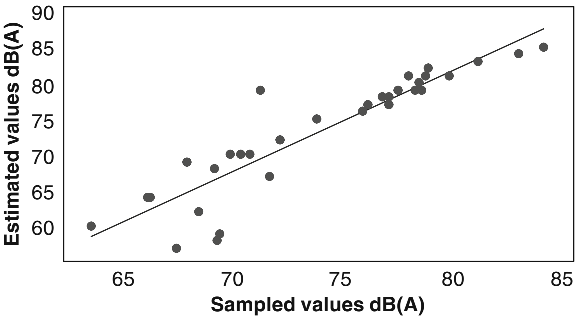


Fig. 8 Dispersion diagram of cross-validation data

Regarding validation, Fig. 8 shows the dispersion diagram of the sampled values against cross-validation estimated values.

This result showed a strong correlation between the variables, which was confirmed by a Pearson's linear regression coefficient value of +0.911, very close to a perfect positive linear correlation. To complement the first test and assure the statistical validation, the analysis of variance resulted in $F < F_{1,62,5\%}$, with a significance level of 5%, also validating the model (Table 2).

Once the model was validated, the surface was gray-scaled, ranging from light to dark tones, representing low to high levels of sound pressure, respectively, thus generating the noise map of the central zone of Sorocaba (Fig. 9).

According to the map, the only noise zone that did not exceed the maximum allowable level of 60 dB (A) was the one represented by the lighter color, which occupies just 7.3% of the total area.

The study showed sound pressure levels that generally increases from the edge to the center of the area. This is due to the fact that bordering areas of the central zone are predominantly occupied by residences.

The zone with the highest sound pressure levels, represented on the map by the darker color, sums 20.4% of the total area and have particular characteristics about the road network:

- The darker region located in central-east portion is along the main avenue of the study area. Particularly at points “A” and “B”

Table 2 Results of analysis of variance for the cross-validation data

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	$F_{1,62,5\%}$
Between samples	8.069	1	8.069	0.164	3.995
Residual	3050.953	62	49.209		
Total	3059.022	63			

(indicated on the map), this avenue connects to other two important roads;

- The darker region indicated with “C” is at the crossroad of an important commercial route;
- The darker region indicated with “D” is at an access route to the central zone. In this critical area, the sloping terrain and the traffic lights induce a greater need for acceleration by the vehicles, which consequently increases the sound pressure levels generated by the engine;
- The darker region indicated with “E” is at the main connection between the central and west zones of the city.

Overall, the assessment showed an urban area with high sound pressure levels that exceed the legal standard and pose a threat to the welfare and health of the population that resides, works, or uses the services of the central zone of Sorocaba.

Conclusions

The proposed methodology proved to be capable of evaluating environmental noise. Taking into account the limitations of the model, which does not consider the characteristics of the sound propagation (noise barriers, loss of energy in transmission, etc.), its results still proved to be satisfactory for the reality of the study area. The noise map was able to highlight the most critical areas in terms of noise and the sound pressure levels that the population is exposed in a peak period of a typical day.

Regarding the analysis procedures, some considerations are necessary and can help planning future assessments:

- For the sampling process, which is the basis for the entire study, the reproduction of a pilot sample before the definitive sampling

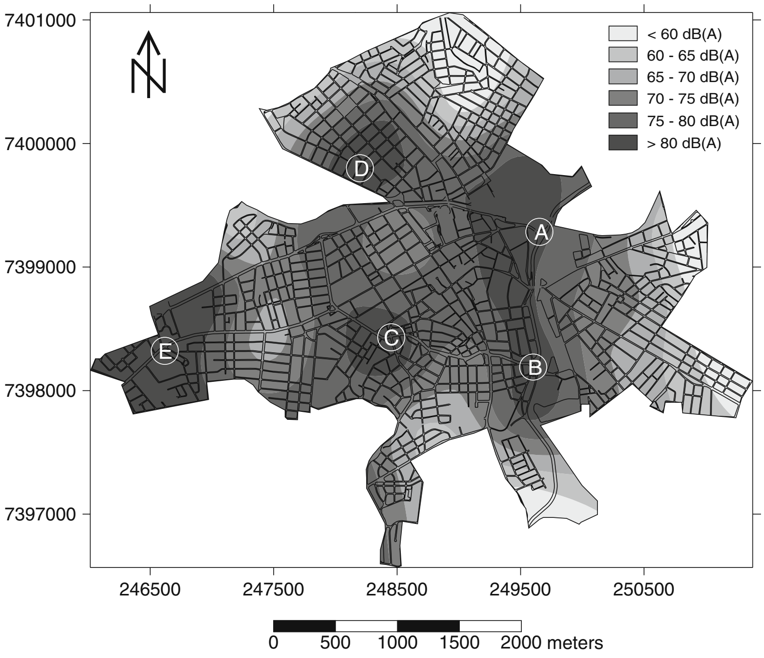


Fig. 9 Noise map of the central zone of Sorocaba, São Paulo, Brazil

provides the surveyor a first experience with the equipment and a preliminary understanding of the phenomenon behavior. It minimizes the probability of errors in this primary stage;
- Statistical analysis proved to be an essential step in the evaluation, which helps understanding the phenomenon and facilitates the interpretation in more refined analysis;
- For the development of geostatistical analysis, it was observed that is necessary to reproduce on the field, with the highest possible fidelity, the regularity imposed by the sampling network. The results of the semivariograms are decisive for choosing the model to be used in the interpolation, hence influence the outcome mapping. It guarantees that the model is able to well represent the variable.

Finally, it was identified that environmental noise is part of daily urban life, a fact predominantly conditioned by traffic conditions. The results confirmed the need to include it as an indicator in environmental planning, and it is expected that the information obtained from this research can provide practical benefits for those responsible for planning this study area and other urban areas with similar characteristics.

References

Associação Brasileira de Normas Técnicas, ANBT (2000). *NBR 10151: Acústica—Avaliação do ruído em áreas habitadas, visando o conforto da comunidade—Procedimento*. Rio de Janeiro, Brazil.

Baltazar, L., Coucelo, C., Guedes, M., Leite, M. J., Passos, C., & Sequeira, N. (2006). Cartografia de ruído. In: *9° Encontro de Utilizadores de Informação Geográfica*. Lisboa, Portugal.

Cho, D. S., Kim, J. H., & Manvell, D. (2007). Noise mapping using measured noise and GPS data. *Applied Acoustics, 68*, 1054–1061.

Conselho Nacional do Meio Ambiente, CONAMA (1990). *Resolução 001, de 8 de março de 1990*. Brasília: Diário Oficial da União.

Department for Environment Food and Rural Affairs, DEFRA (2008). *Noise Mapping England*. http://noisemapping.defra.gov.uk/wps/portal/noise . Accessed 22 May 2008.

European Union (2002). Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002, relating to the assessment and management of environmental noise. *Official Journal of the European Communities, L189*, 0012–0026.

Golden Software (2002). *Surface Mapping System Version 8.00*. Golden, CO: Golden Software Inc.

Isaaks, E. H., & Srivastava, R. M. (1989). *An introduction to applied geostatistics*. New York, NY: Oxford University Press.

Instituto Nacional de Metrologia, Normalização e Qualidade Industrial, INMETRO (2008). *Rede Brasileira de Calibração—RBC*. http://www.inmetro.gov.br/laboratorios/labrbc.asp. Accessed 14 January 2008.

Microsoft Corporation (2006). *Microsoft Office Excel 2007*. Redmond, WA: Microsoft.

Piccolo, A., Plutino, D., & Cannistraro, G. (2005). Evaluation and analysis of the environmental noise of Messina, Italy. *Applied Acoustics, 66*, 447–465.

Pinto, F. A. N. C., & Mardones, M. D. M. (2008). Noise mapping of densely populated neighborhoods—example of Copacabana. In: *Environmental Monitoring and Assessment*. Brazil: Rio de Janeiro.

World Health Organization, WHO (2001). *Occupational and community noise*. Fact sheet 258. http://www.who.int/peh/Occupational_health/OCHweb/OSHpages/OSHDocuments/Factsheets/noise.pdf. Accessed 22 May 2008.

Yilmaz, G., & Hocanli, Y. (2006). Mapping of noise by using GIS in Şanliurfa. *Environmental Monitoring and Assessment, 121*, 103–108.

Zannin, P. H. T., Calixto, A., Diniz, F. B., Ferreira, J. A., & Schuhli, R. B. (2002). Annoyance caused by urban noise to the citizens of Curitiba, Brazil. *Revista de Saude Publica, 36*(4), 521–524.