Spatial Analysis of Accessibility to Support Decision-Making in Urban Investments: a case in Amazonia - Brazil

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ABSTRACT

City planning processes are often supported by decision-making methods that involve selection, evaluation and combination of several factors. Also, nowadays, the accessibility is one important issue for the development of cities. So, factors closely related to the accessibility are very relevant to identify and assess the location of urban facilities, which stresses the interest of evaluating accessibility methods. The main goal of the paper is to present an accessibility evaluation model applied in Santarém, in Brazil, a city located midway between the larger cities of Belem and Manaus. The paper describes the research instruments, sampling method and data analysis proposed for mapping urban accessibility. Basic activities (education, health, services, leisure and commerce) provided by the city were used to identify the main key-destinations. The model was implemented within a Geographic Information System and integrates the individual’s perspective, through the definition of each key destination weight, reflecting their significance for daily activities in the urban area. The results of this model application can support city administration decision-making for new investments in order to improve urban quality of live. In addition, the model can simulate and analyze several planning proposal for the city, e.g., expansion of the transport network, the construction of new education and health services, helping to understand which will be the consequences of those actions.

Keywords: Urban Accessibility Assessment, Geographic Information Systems, Santarém, Brazil

INTRODUCTION

The concept and evaluation of accessibility have been discussed for almost two hundred years. In urban context, that analysis is crucial to conduct a sustainable development process because it is linked with the opportunity of citizens to reach urban facilities. In one of the most interesting texts about accessibility, Hoggart (1973) sustains that accessibility is associated with the interpretation, implicit or explicit, of the easiness of reaching spatially distributed opportunities. In the same line, Ingram (1971) defines accessibility of a place as its characteristic (or advantage) regarding the overcoming of any form of resistance to the movement. This author distinguishes between relative accessibility, which regards the degree of connection between two points on a surface (or network), and integral (or global) accessibility, which refers to the degree of connection between a point and all the other points on a surface (or network). The second proposal, global accessibility, is a very important issue in urban planning process because most of urban investments are capitalized as general investments and not as specific investments.

The way accessibility is evaluated depends on the purpose or objective to be achieved. Morris *et al.* (1979) present an extensive classification and formulation of measures for relative and integral accessibility. In order to clearly set the domain of their study, the global or integral accessibility was defined as the focus of this work. For that reason, it is important that an evaluation model includes: measures of separation between all the points; measures of separation incorporating the effect of distance; measures of separation incorporating network capacity and restrictions; and complex measures of separation and supply/demand. Other contributions (Allen *et al.*, 1993; Geertman and Van Eck, 1995; Love and Lindquist, 1995; Mackiewicz and Ratajczak *et al.*, 1996; Mendes *et al.,* 2005) proposed accessibility measures that somehow can be framed in the classification of Morris *et al.* (1979).

METHODOLOGY

The presentation of the methodology is divided in two subsections: one that identifies the theoretical issues of the adopted multicriteria model for evaluating accessibility (Mendes *et al.,* 2005); the other to explain how the model can be implemented and used to map spatial variation of the accessibility index within a Geographical Information System (GIS).

Multicriteria accessibility model

The proposed multicriteria accessibility evaluation model proposed stands on a measure of separation incorporating the effect of distance. The principal theoretical points and assumptions in this model regarding envisioning accessibility include: i) accessibility evaluation is related to the evaluation of the accessibility to basic activities in a city; ii) the accessibility index is a result of the combination of distances to a set of key-destinations; iii) key-destinations are related to different objectives/purposes and can have different priorities (weights); iv) in an urban context, key-destinations can be reached through streets/roads, and each one can have different resistance to movement (impedance) depending on their characteristics; v) cost-distances to a key-destination are a result of the combination of actual distances and the impedance of network segments; vi) cost-distances to key-destinations can be normalized and weighted to obtain their contribution to the accessibility index.

The assessment of the multicriteria accessibility index of a location A_i is given by equation (1). It denotes the fuzzy set membership function applied to cost-distances by $f(c_{ij})$, and the weight of the key-destination j by w_j.

$$A_i = \sum_j f(c_{ij}).w_j \qquad (1)$$

Equation (1) is essentially a Weighted Linear Combination, one of the aggregation procedures available in the context of multicriteria evaluation (Voogd, 1983). In this multicriteria accessibility index, the assessment of c_{ij} represents the cost-distance to a key-destination *j* from a point *i*.

A very important component of a multicriteria evaluation model concerns the priorities attached to the different key-destinations, i.e. the values of the weights w_j in equation (1). The objective of setting weights is to quantify the importance of key-destinations relatively to one another, in terms of their contribution to the overall accessibility index. Among many methods to derive weight, Mendes (2000) has emphasized two most commonly used: the n-points scale (originally seven-points scale, as introduced by Osgood *et al., 1957*); and a more complex method called Pairwise Comparisons, which was developed by Saaty (2008).

Cost-distances measured to each key-destination can be expressed in different scales, i.e., one can be available to travel longer distances to a key-destination than to another, giving a different meaning to identical measured values. For that reason, it is necessary to standardize them before aggregation. The process of standardization is essentially identical to that of fuzzification in fuzzy sets (Jiang and Eastman, 2000). When fuzzifying distance variables, the linear monotonically decreasing function is one of the most used, for which membership grade μ (i.e., standardized value) is given by equation (2). Control points *a* and *b* are critical points that should be set for each specific situation, considering their inherent meaning.

$$\mu = (x - x_b)/(x_b - x_a) \tag{2}$$

$When\ x > x_b\ ,\ \mu = 0\ ; \quad x < x_a\ ,\ \mu = 1$

When evaluating the accessibility to urban facilities, the value 0 is often adopted for point *a*, assuming that maximum accessibility is only set to points corresponding to facilities locations. However, a value for x_a can be adopted to characterize the effect of near-by (for instance, between the car stop and the facility entrance). The value of x_b represents the maximum distance that a facility may have a positive accessibility. Points located at distances higher than x_b of a facility are considered as being located outside the hinterland of that facility. Those will not contribute to the global accessibility index.

A vector gis-based implementation

The formal model presented before can be implemented within a GIS environment, making use of the available toolbox set. The flowchart of Figure 1 shows the geographical database needs (GIS layers) and the sequence of operations required to complement the attribute table to assess the accessibility index for the network points. The first step is to calculate the OD Matrix from all network points to each key-destination and to store the values as new columns in the attributes table.

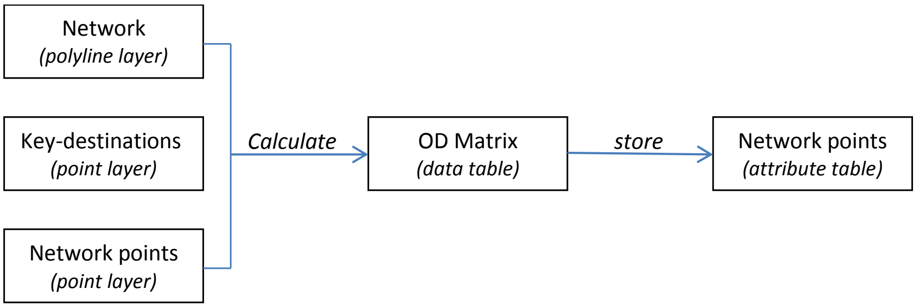

Figure 1 - Vector GIS model to calculate cost-distances

Then, the multicriteria procedure can be implemented. The sequence of operations starts with the standardization (i.e., the application of the selected fuzzy set functions) followed by the weighting. Afterwards, the accessibility index is obtained by the aggregation of the several weighted standardized cost-distance. This procedure is applied at the attributes level. Once again, new columns must be added to the attribute table: two columns for each key-destination (to store standardization results and weighting results and one more for the accessibility index.

Once all calculations are completed, it is possible to generate the accessibility map. Building a triangulated irregular network (TIN) that will cover the study area is the method adopted. Using network points as inputs and setting their accessibility index as Z values, a surface is generated and will show how accessibility values are distributed along the.

In order to use the accessibility evaluation model established in this paper, the model must be "customized" to be applied in a particular context under study. This means: (i) to identify the set of key-destinations; (ii) to establish the weights for each key-destination; (iii) to identify the fuzzy set functions to be used; (iv) and to set the control points a and b for the fuzzy set functions.

CASE STUDY: SANTARÉM, PA - BRAZIL

The city of Santarém is located in the Amazon floodplain, in the Brazilian State of Pará. The town is placed on the right side of the Amazon River at the confluence with the Tapajos River and was founded in 1661. Nowadays, Santarém is municipality with 294,774 inhabitants and occupies a territory of 22,887 km2 (IBGE, 2010). An accelerated urban growth occurred from the 1940s and, by the mid-1970s and until the present day. For that reason, the population of the municipality is majorly urban.

Santarém's downtown had preserved a major role for commerce and leisure activities. Hence, the accessibility evaluation is an important topic in the definition of future facilities buildings locations or in the definition of improvements in the transport infrastructures. The spatial assessment of accessibility to city most relevant facilities in inhabitants' daily activities (education, health, services, leisure and commerce) will be an important contribution to identify urban areas with lower level of accessibility.

Santarém road network and impedance

In a GIS environment, the first step was to generate the map of the streets/roads network and to extract the network points to be evaluated (figure 2). Those points will be used as origins in the accessibility evaluation process, as their distribution revealed to be adequate to cover the studied area.

Since a network is used to measure distances between origins and key-destinations, an impedance factor was define combining available data and local observation as follow: if the network segment is paved then no impedance factor is applied; if the network segment is not paved, the distance for travelling on this segment is doubled, corresponding to an effective reduction of the travelling speed to half, comparing to a paved segment. Circulation restrictions were also included in the final network model.

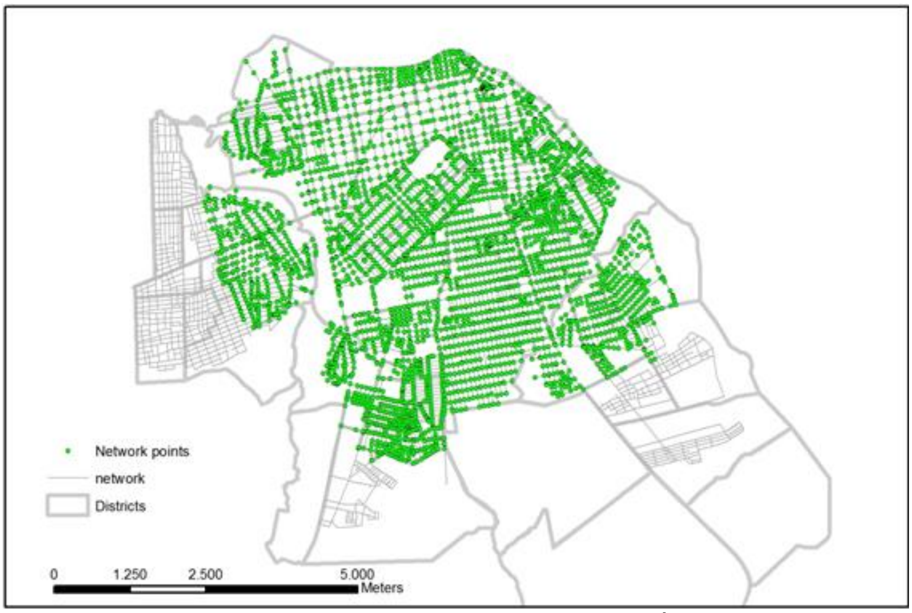

Figure 2 - Network points map for Santarém

Key-destinations in Santarém, fuzzy set functions control points and weights

In order to apply the methodology, a survey was prepared to gather all the data/parameters needded. The survey was firstly undertaken as a pilot test in only two districts, through a structured questionnaire that included the reasons and destinations listed previously by specialists. Then the survey was applied to a panel of specialists, technicians, professionals and a large random group of residents. It was composed by two phases: the first one to identify the location of the relevant key-destinations in the city of Santarém and to identify the modes of transportation in the city; the second one to obtain the data required for the aggregation process.

From the results of the survey, key-destinations were identified and then were grouped into functionalities, forming homogeneous sets of key-destinations: education, health, services, leisure and commerce. Thus, all functionalities were populated by the most relevant key-destinations of the urban area, i.e. schools, hospitals, services buildings, public recreational facilities and shopping areas. The figure 3 shows the maps with the functionalities location adopted in the study. Tables 1a and 1b show the structured organization of the key-destinations.

The information required to define fuzzy set functions and weights for the several key-destinations was not directly available and, for that reason, an empirical approach was implemented. Then, the second phase of the survey was launched, as referred in the previous section, to define the key-destinations relevance (weights) and the maximum distance that interviewed were willing to travel to each one (value of x_b, as define in the equation 2). This phase of the survey was taken in 24 districts of Santarém, which represented 50% of city districts and 84% of the number of households, equivalent to 46,239 households. The research was household, based assuming one person per household. A binomial probability sample was used, with 95% confidence level error estimated at 10%, with, 400 households interviewed. The relevance of functionalities and key-destinations was assigned by all the interviewees by scoring each item in a scale of 0 to 100 points. This process intends to capture the perspective of the participants about the importance of each key-destination for the realization of their daily activities.

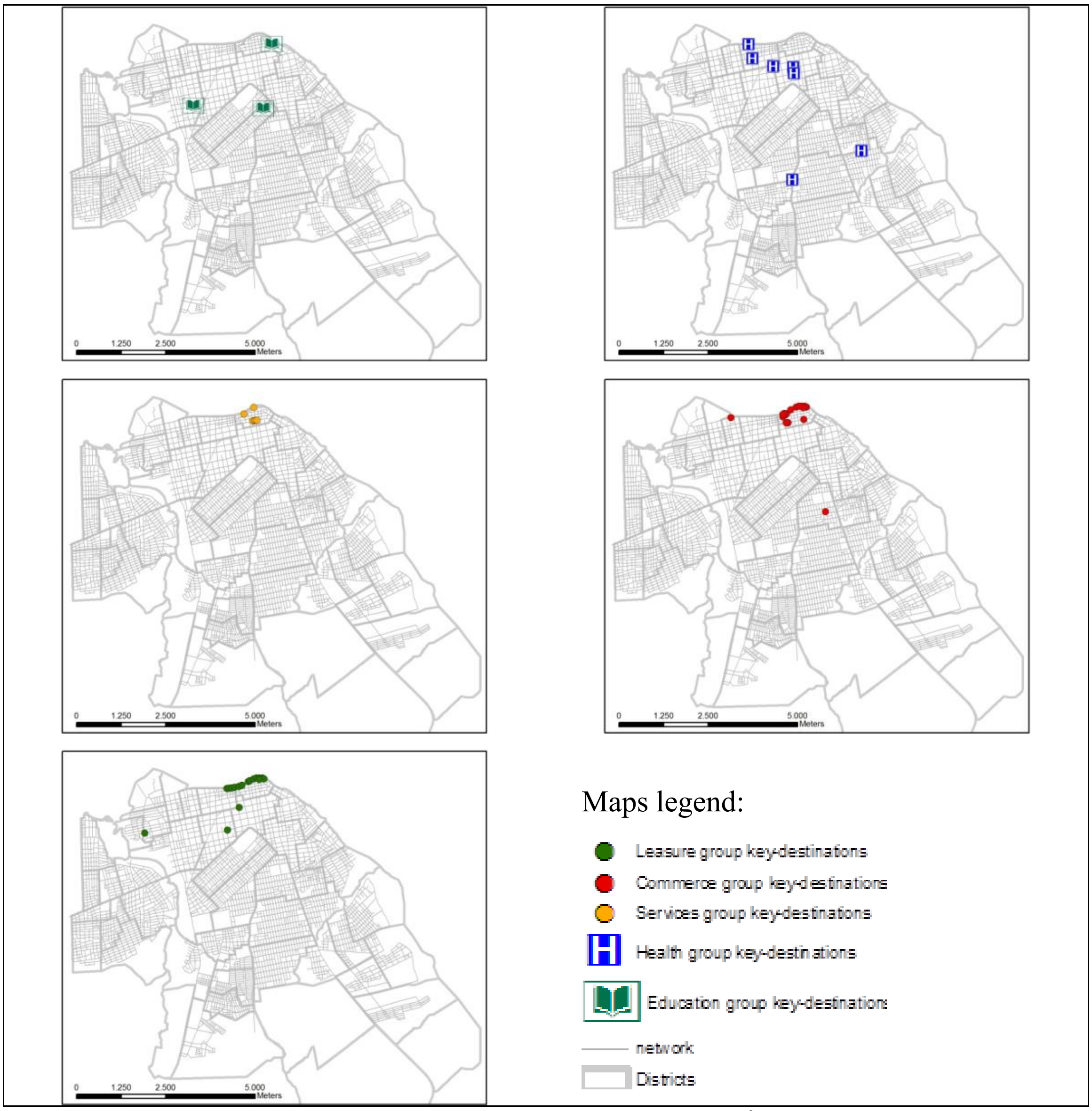

Figure 3 - Key-destination maps for Santarém

Table 1a - Weights and control distances for functionalities and key-destinations for Santarém

Functionalities	Weights	Key-destinations	Weights	Min. Distance (m)	Max. Distance (m)
Education	0.14	Frei Ambrósio School	0.38	721	2770
		IESPES College	0.15	1261	3794
		Integrated Colleges of Tapajós and Tapajos High School	0.47	1503	3764
Health	0.2	Aldeia/Fátima Health Center	0.08	598	1460
		Livramento/S. José Health Center	0.06	3271	4579
		Imaculada Conceição Hospital	0.08	1677	3362
		Municipal Hospital	0.46	1525	3629
		Regional Hospital of West Pará	0.07	850	2695
		Unimed Hospital	0.25	1311	3697

Table 1b - Weights and control distances for functionalities and key-destinations for Santarém

Services	0.23	Bank of Brasil	0.18	1004	3556
		Itaú Bank	0.38	1689	3528
		Bradesco Bank	0.18	1121	3511
		Caixa Econômica Bank	0.11	1962	4764
		Central Post Office	0.07	470	2370
		Bookkeeper of Rui Barbosa street	0.08	1528	4416
Commerce	0.26	Shopping Centre of Santarém	0.62	987	3804
		Municipal Market	0.07	299	1792
		CR Supermarket	0.14	695	3821
		Candilha Fair	0.08	1017	4060
		Mercadão 2000 Fair	0.09	609	2959
Leisure	0.17	Santarém waterfront	0.57	785	3942
		Church of the Peace	0.25	681	3106
		Assemblies of God Church	0.08	507	2472
		Mariscada Bar	0.06	681	2517
		Mascote Restaurant	0.04	643	2382

Using data compiled from the interviewees answers, weights for key-destinations and functionalities (groups) were obtained: for each evaluated item, the average value of points assigned was calculated and then transformed in a percentage corresponding to the portion of all points assigned in the group. Interviewees were also asked to point out the minimum and maximum distances that corresponds to full and no accessibility for each key-destination. As described in equation (2), those values are used to determine the control points for the standardization process.

Accessibility mapping

Applying the proposed model to calculate accessibility indexes for all points within a GIS platform is possible when taking advantages of database management. All key-destinations data must be stored in a table in order to perform further calculations that require standardization and weighting. Control points (minimum and maximum distances) must be assigned to each key-destination to allow the standardization of distance values through the fuzzy function. Then, the shortest distance to each key-destination must be identified and stored in the attribute table of the point layer. This step is performed using a tool for network analysis that generates OD Matrices. Network points are designated as origins and all the key-destinations (points) as destinations. The results are the shortest path over the network from each origin to each destination. To transpose those values into the attributes table of the network points layer, new columns were added and unique column identifier assigned in order to keep the relationship with the key-destinations. The existent one to one relationship between identifiers of network points and key-destinations identifiers is used to ensure that the values transfer is applied successfully. This step was ran twice in order to obtain an OD matrix using each version of the network, i.e., including or not pavement impedance.

As the next calculation steps are associated to the standardization of values and the index calculation, once again, new columns were added to the network points attribute table: one column for each key-destination to store the standardized values and one extra column to store the final accessibility indexes values. The standardization was performed applying the chosen fuzzy function formula to each distance value using the “Field Calculator” tool. With all distances standardized, the accessibility indexes were finally calculated using the same tool to apply the aggregation formula from the proposed model.

With the conclusion of the calculation process, the map production started. To generate a continuous surface that can illustrate how the accessibility to key-destinations varies over the study area, a triangulated irregular network (TIN) was created. The network points were used as mass points, covering the study area, and the accessibly index values was designated as Z values. Using those parameters, the resulting TIN “filled” the study area with accessibility indexes values. Figures 4 shows the accessibility index map obtained by changing the TIN representation as a graduated color ramp that varies from red (lowest values) to green (higher values).

Case study conclusions

The implementation of the methodology in Santarém indicates that an adequate number of key-destinations could be easily adopted to evaluate the accessibility index. Moreover, working in a GIS environment and mapping the index give the opportunity to analyse the spatial distribution and to understand how levels of global accessibility index to key-destinations vary along the studied area.

A detailed analysis of the map shown in figure 4 highlights the following issues:

- The concentration of key-destination for several functionalities in the central area of the city results in high level of accessibility for that area of city;
- About 2km outside the central area, some facilities are distributed along a peripheral arc;
- In the outer peripheral area (more than 2.5 km away from downtown), there are none relevant facilities for the city;
- The accessibility values found in the central area and in the area inside the arc of 2 km are relevant and identifies good level of accessibility to the most important facilities;
- In contrast, outside the 2.5km peripheral arc, accessibility to the facilities is very low;
- The spatial distribution of the accessibility index highlights the maintenance of the importance of downtown area (the old town) and confirms that daily activities of inhabitants imply making also long journeys.

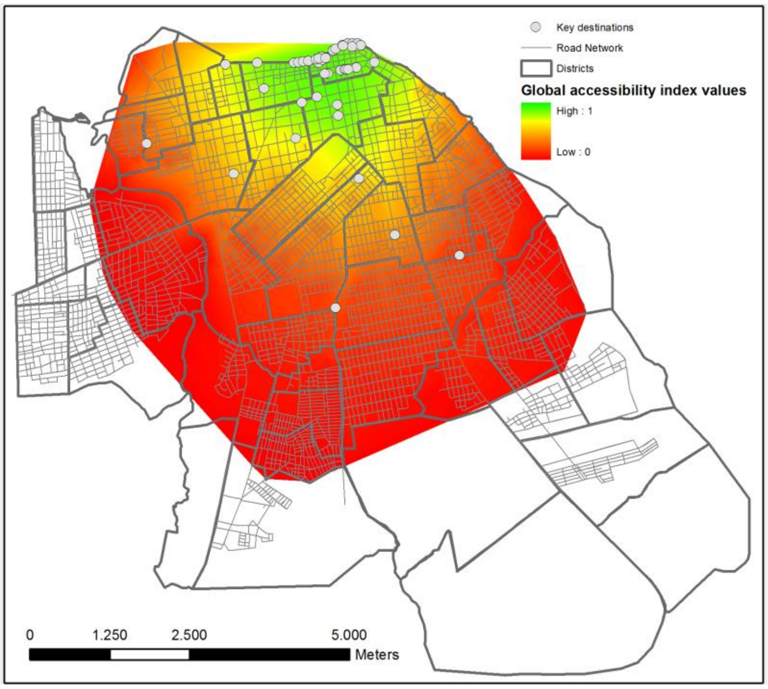

Figure 4 - Map of Accessibility Index for Santarém with pavement impedance

For better understanding the results differences achieved when pavement impedance is including or not in the calculation process, figure 5 is presented. It is the result of the algebraic difference between the map where pavement impedance was take into account and another when it is not. It can be seen that global accessibility indexes values can differ in worst cases almost 0.2, near 20% of the full scale. It confirms that details about the network that has influence on accessibility must be integrated in the evaluation process.

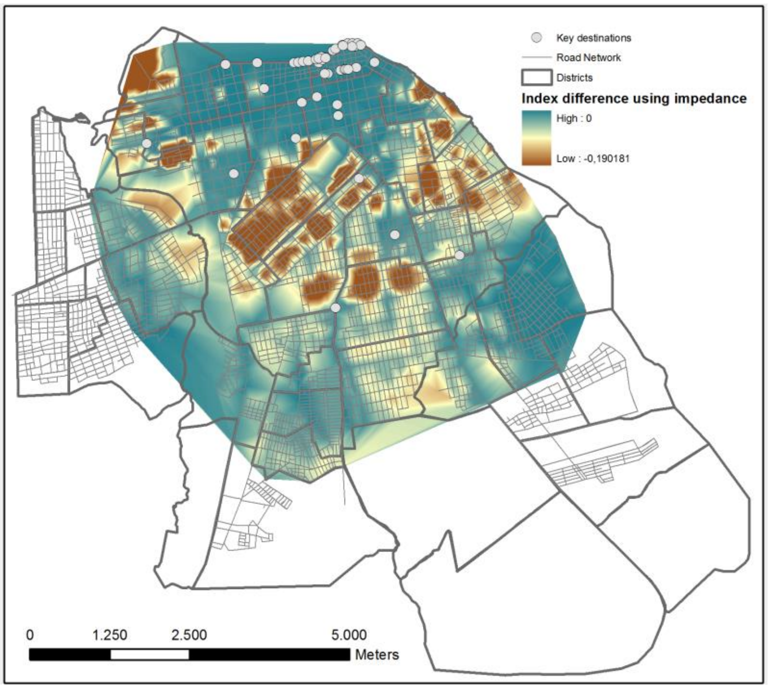

Figure 5 - Map showing index differences setting or not pavement impedance on the network

CONCLUSIONS

In this paper a multicriteria accessibility evaluation model was developed within a GIS environment. The proposed model calculates an accessibility index given by the weighted summation of cost-distances to a number of key-destinations. Relevant elements in this model include:

- The calculation of cost-distances making use of a road network with friction that represents the resistance to movement.
- The standardization of cost-distances using fuzzy set membership functions that, when calibrated, give a better representation of the effect of distance in the evaluation.
- The combination of cost-distances taking into account the relative weight of key-destinations in the evaluation.
- The implementation in a GIS environment, taking advantage of the map algebra and visualization toolbox.

In that context, a tool for an easy and ample assessment of the accessibility to most relevant facilities, exploring urban spatial distribution, was achieved through the proposed methodology and its application. Moreover, it helps to identify the relationships between street patterns and urban morphology related to big traffic generators/attractors, i.e. hospitals, schools, services, leisure or shopping areas. In such way, the method can be used for monitoring and supporting transport policies and facilities location.

Hence, the results of this model application can support city administration decision-making for new investments in order to improve urban quality of life. In addition, the model can simulate and analyze several planning proposal for the city, e.g., expansion of the transport network, the construction of new education and health services, as well as helping to understand which will be the consequences of those actions.

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