A GIS extension model to calculate urban heat island intensity based on urban geometry

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Abstract

This paper presents a simulation model, which was incorporated into a Geographic Information System (GIS), in order to calculate the maximum intensity of urban heat islands based on urban geometry data. The methodology of this study stands on a theoretical-numerical basis (Oke's model), followed by the study and selection of existing GIS tools, the design of the calculation model, the incorporation of the resulting algorithm into the GIS platform and the application of the tool, developed as exemplification. The developed tool will help researchers to simulate UHI in different urban scenarios.

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1 Introduction

Man changes the natural environment, modifying space and materials and, consequently influencing on the energy balance of the Earth. Thus, thermal fields emerge in cities as a result of the phenomena associated with the urbanization itself. Among climatic issues resulting from urbanization, one of the most discussed by researchers is the formation of urban heat island (UHI). UHI is one of the problems of cities that may generates many undesirable effects, such as discomfort in people, health problems, and, in some cases, higher energy consumption and pollution. In general, the UHI results from urbanization features, such as the air pollution, the anthropogenic heat, the existence of impermeable surfaces, the thermal properties of materials and the geometry of the surfaces.

The urban geometry is treated as one of the most influential factors in the formation of heat islands. In many studies (Oke, 1981; Oliveira Panão et al., 2009; Marciotto et al., 2010: Memon et al., 2010; Levermore and Cheung, 2012), urban geometry is measured by H/W ratio (height/width), which is a parameter that considers the height of buildings and the track width related to a street.

Regarding the heat island phenomenon, which has been observed in several cities in the world, some of the main studies published are those of the researcher Timmothy R. Oke, in the 70s and 80s. In that period, Oke created an innovative approach to the issue, by establishing correlations between urban planning variables and the climate of the city, treating it as a closed thermodynamic system and evaluating it from an energy balance calculation.

Oke (1981) established a simplified model for the calculation of the maximum intensity of urban heat islands, based on the value of H/W ratio. Due to this simplified approach and its geometric conception, it is possible to promote an adaptation of Oke’s model to a computational platform, in such a way that it expands the possibilities of analysis and facilitates its application by different researchers. In this context, the association of such a tool to Geographic Information Systems (GIS) is noteworthy, because of its ability to store topological relationships between spatial features (represented, for example, by points, lines or areas) and storing attributes in tabular data, as well as containing the most diverse information.

Besides having numerous analysis tools incorporated into commercial packages, the GIS increasingly assumes prominence, because of the fact of being a platform on which to develop and incorporate new techniques and methods of territorial planning (Silva et al., 2004).

Considering these facts, in this research a GIS platform was chosen for the development of an algorithm designed to calculate UHI based on Oke´s model. For this purpose, it was defined a criteria for the calculation of urban geometry, and this tool allowed the automation of the process.

This paper is organized as follows: firstly the review about Urban Geometry and Heat Island; secondly the description of Material and Methods and The Subroutine Development; thirdly An Application and Conclusions section.

2 Urban geometry and heat island

The UHI is considered to be the difference of air temperature values in the urban environment in relation to data recorded outside the city. The variation of urban geometry can influence the increase or decrease of this temperature difference, the wind speed and direction, the form of radiation received by shortwave and released heat through long waves.

In order to represent the urban geometry, the relationship between the height of the building and the width of the street canyon, also called aspect ratio (H/W ratio), is widely used as an indicator. The H/W ratio was used by Oke (1981) in experiments with scale models in order to simulate the urban canyon. The term ‘urban canyon’ characterizes the set of streets that cut through dense blocks of buildings, especially skyscrapers, resembling the natural canyon.

The higher the H/W ratio, the smaller the area of visible sky. Therefore, reducing the dissipation of long-wave radiation and, consequently, lowering the air-cooling in urban areas.

The geometry of the canyon type changes the energy balance, leading to a positive thermal change. A larger surface area of multiple reflections leads to an increased absorption of shortwave radiation. The reduction of the visibility of the sky leads to a decrease of long-wave radiation loss. The wind speed reduction causes the decrease of the total heat transfer of turbulence, causing an increase in air temperature (Oke, 1982).

Studies on urban climate consider that the UHI is greatest when the wind speed is small (typically under anticyclonic condition; a clear sky and zero wind speed). At the nighttime with a clear sky, the UHI effect is even more intense. In urban studies of heat islands, models or computer programs are often used to simulate real and hypothetical scenarios, mainly checking the different situations of urban density.

The urban heat island phenomenon is a consequence of many factors. The most important of which are summarized as follows (Oke et al., 1991):

- the canyon radiative geometry contributes to the decrease in long-wave radiation loss from within the street canyon due to the complex exchange between buildings and the screening of the skyline;
- the thermal properties of materials, which increase storage of sensible heat in the fabric of the city;
- the anthropogenic heat released from combustion of fuels and animal metabolism;
- the urban greenhouse, which contributes to the increase in the incoming long-wave radiation from the polluted and warmer urban atmosphere;
- the canyon radiative geometry, which decreases the effective albedo of the system because of the multiple reflection of short-wave radiation between the canyon surfaces;
- the reduction of evaporating surfaces in the city, which means that more energy is put into sensible heat and less into latent heat; and
- the reduced turbulent transfer of heat from within streets.

According to Oke (1984) and Svensson et al. (2002), three types of models can be applied for climate related research in urban environments: numerical, physical, and empirically based models.

For energy balance check and prediction of heat islands, many are researchers have performed numerical simulations (Atkinson, 2003; Fortuniak, 2003; Kanda et al., 2005; Bruse, 1999; Han et al., 2007; Zinzi et al., 2012; Fahmy et al., 2012; Santo et al., 2012) and empirical basis simulations (Jusuf and Hien, 2009; Balázs et al., 2009; Svensson et al, 2003; Chen et al., 2008; Grimmond and Oke, 2002).

Empirical models are primarily based on observations of the surface energy balance (SEB). Their objective is to reproduce the energetic of the canopy layer, using statistical relationships derived from observations (Masson, 2006). They include statistical algorithms, parameterizations, engineering formulae and qualitative conceptualization. Among the empirical models, statistical approaches are among the most common methods to reveal relationships between the UHI intensity and the meteorological and other physical parameters which influence its formation (Balázs et al., 2009).

Oke (1981) performed considerations of geometry for the development of a simple empirical model (Eq. 2.1), able to predict the maximum intensity of heat island on a location. Empirical models are based primarily on observations of surface energy balance (SEB) in order to reproduce the energy flow of the cover layer, using statistical relationships derived from observations (Masson, 2006). They include statistical algorithms, parameterization, engineering formulas and qualitative concept. Among the empirical models, peripheral approaches are among the most common methods to reveal the relationship between the intensity of UHI and meteorological parameters and other physical influencing their formation (Balázs et al., 2009).

Oke's model (1981) adjusted for the H/W ratio is shown in Eq. 2.1 (with R^2=0,89).

$$\Delta T_{u-r(\max)} = 7{,}45 + 3{,}97 \ln(H/W) \quad (2.1)$$

where:

$\Delta T_{u-r(\max)}$ is the maximum urban heat island;

H/W is the relationship between height and width.

Oke (1981) analyzes the geometry as a good measure of urban structural change effecting on the heat island. However, these results also include other causes of urban thermal changes, which are often automatically linked to changes in geometry and cannot be isolated (as high-rise buildings with the greatest anthropogenic heat flux, with different materials of high thermal admission, etc.).

According to Montávez et al. (2008) the Oke's model (Eq. 2.1) seem to work quite well in the case of North American and European cities (data used for fitting the model). They argue that for other cities with different climates, such as Korean and Japanese cities, the Oke's model is not able to explain the lower values of UHI intensity. The very different thermal admittances of these places are presumably the reason (Johnson et al., 1991).

According to the study of Theeuwes et al. (2014), the relationship between the aspect ratio and the UHI is very complex. These authors found that the UHI is controlled by two counteracting processes. First, by the process of trapping long-wave radiation, which has an increased effect on the UHI. Long-wave radiation are most trapped when buildings are the highest and streets are the narrowest. Secondly, the process of shadowing has a decreased effect on the UHI within the urban canopy. As streets narrow, less solar radiation reaches the inner part of the canyon, leading to less heating during the day. This causes the nighttime temperature and thus the UHI to stabilize and, in some cases, even decrease when streets become narrower.

Some models that are developed to analyze urban climate are based on a grid network of cells (Unger et al., 2011; Bruse, 1999). In these model types, the resolution becomes smaller so that the representation of the urban environment suits the cell grid format. Thus, these models are often used to simulate urban environments of mesoscale. So, models that use GIS platform seem to be more advantageous for the representation of urban geometry, by using spatial representation tools of vector control. Thus they broaden the representation of different building formats and other urban elements. Some researchers have developed models of the urban thermal environment with GIS methods for different scales of analysis and objectives, such as air temperature forecasting, human thermal comfort, winds dynamics (Jusuf and Hien, 2009; Unger et al., 2011; Svensson et al., 2003; Chen and Ng, 2011).

As the urban heat island is a highly complex phenomenon, the calculation tools select only some parameters for input and output, simplifying the energy balance calculation process in the urban layer. In most cases, a parameter is isolated to facilitate the interpretation of their influence on urban temperatures.

3 Methodology

This paper presents the followings steps: approach to the theoretical-numerical base, description of the development of the subroutine and an application example of the developed tool.

The discussed theoretical-numerical basis demonstrates that the H/W ratio is one of the ways to describe the urban geometry and can be related to the development of a nocturnal heat island via simplified modeling of the urban thermal environment. Thus, the parameter chosen for urban geometry calculation was the H/W ratio and the model used to estimate maximum heat island intensity was the Oke's model (Eq. 2.1).

For the development of the subroutine, we have applied the ArcGIS 10. Firstly, the methodology includes the recognition of the commands and tools of the ArcGIS 10 for the development of a subroutine calculation. Therefore, the algorithm was based on a logical sequence of tools that meet the spatial and numerical relationships necessary for the calculation of urban geometry. Subsequently, the value of H/W ratio is determined and the calculation of maximum UHI intensity is easily accomplished by incorporating Oke's equation into the algorithm.

The computational code was written in Visual Basic language and incorporated into ArcGIS 10 via a macro. This enabled agility to the code verification tests, which were decisive in the choice of the input and output objects and the applied tools of spatial and numerical relationships.

The subroutine runs by the recognition of inputs such as street axes, buildings, height of these buildings and a distance radius of building-axis, the identification of average height of the canyon (H) and the average width of the canyon (W). Then, determination of H/W ratio is performed and the output data is the maximum UHI intensity related to each block

For an application of the tool, presented in topic 5, a hypothetical scenario was represented, aiming to feature buildings of different heights. The results are shown both, numerically in table and graph (originating from ArcMap) and in three-dimensional form (simulation in ArcScene). The subroutine was incorporated into ArcMap. The ArcScene was only used to simulate the three-dimensional image based on the output file generated from within ArcMap.

4 The subroutine development

The development of the algorithm focused on the interpretation of the urban environment in the GIS, and the implementation of spatial associations to result in a value of urban geometry. From this value, the maximum heat island intensity calculation is easily accomplished by Oke's model.

The user is requested for the following input data: location of street axes (lines), perimeters of buildings (polygon), height of these buildings (number associated with the object polygon) and the distance radius of building-axis (single value). This last parameter is the value that will be used to select the buildings for the calculation of H/W ratio of each of the street axes. The initial input file, therefore, must have a minimum of two shapefiles: the objects 'polygons' and 'lines' (Fig. 4.1).

Fig.4.1. Objects required as input (polygons of buildings and street centerlines) in GIS.

The first step of the built-in subroutine is a process of spatial associations. Solid lines of axes are divided into fragments based on their intersections (blocks). Based on a radius value entered by the user, the subroutine selects the buildings that ‘belong’ to each block (Fig. 4.2 a). Each building is linked to its block (Fig.4.2 b) which, in turn, is associated with the axis lines edging them (Fig. 4.2 c).

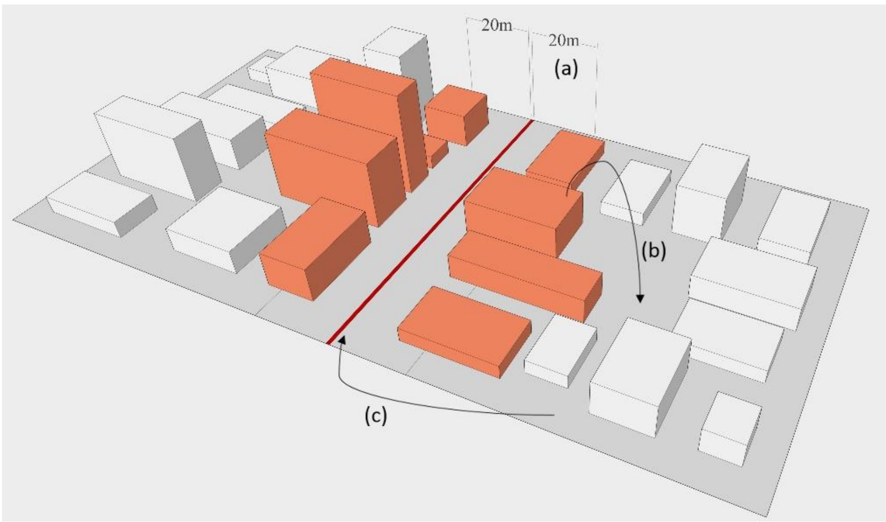

Fig.4.2. Spatial associations made to the axis relative to buildings (a. 20 m radius example); buildings with the block (b); and the block with the axis (c).

Thereafter, numerical associations are performed. The calculation of H is the mean height of all buildings on both sides (Eq. 4.1). The calculation of W is performed based on the sum of the mean values away from the buildings to the axis, of the right and left sides (Eq. 4.2). Thus, the value of the maximum intensity of the heat island is obtained in accordance to Eq. 2.1).

$$H = \frac{h1 + h2 + h3 + \cdots + hx}{x} \tag{4.1}$$

$$W = \frac{Dr1 + Dr2 + Dr3 + \cdots + Drx}{y} + \frac{Dl1 + Dl2 + Dl3 + \cdots + Dlz}{z} \tag{4.2}$$

where:
H is the average height;
h is the height of each building;
W is the average width;
Dr is the distance of each building to axis, from block on the right side;
Dl is the distance of each building to axis, from block on the left side.

Finally, the output data provided by GIS are: average height, average width, H/W ratio and maximum UHI.

5 An application

Only for example purposes, this article presents the tool application developed in a hypothetical scenario. The supplied input data are: eight blocks in orthogonal layout (Fig. 5.1); radius for selection of buildings for each line-block of 25m and height of buildings classified as low (4m), medium (10m) and high (40m) density.

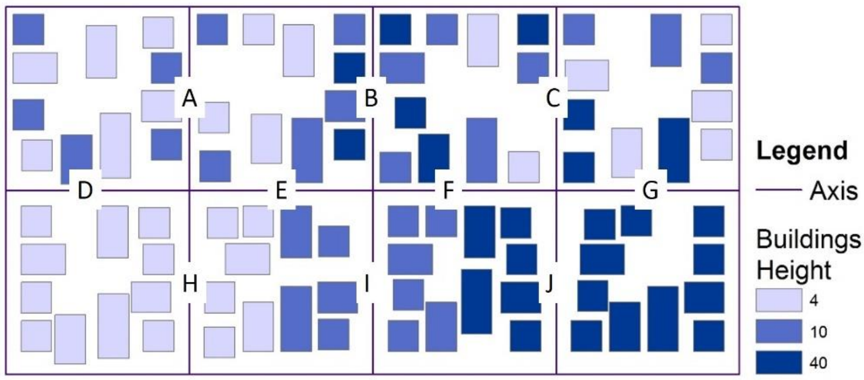

Fig. 5.1 Hypothetical scenario of input for the simulation with identification of the axes.

To the applied subroutine (as described in topic 4 The development subroutine) the output data provided for that scenario are presented in Table 5.1 and graph of Fig. 5.2. The blocks A, B, C, D, E, F and G show heights of buildings heterogeneously distributed. Blocks H, I and J exhibit more standard configuration.

Given that the blocks H, I and J have a little variation of W among themselves but different patterns on their heights of buildings (4, 10 and 40m respectively), the maximum UHI values was 0.17, 3.88 and 9.05, respectively.

It is also important to emphasize that the data originated from the lines edges should not be considered by the absence of urban geometry data that may characterize them as urban canyons.

Table 5.1. Output data of the subroutine

Axis	H med	W med	H/W ratio	UHI máx.
A	7,5	12,27	0,61	5,50
B	25	12,39	2,02	10,24
C	20,75	12,25	1,70	9,54
D	5,5	21,72	0,25	2,00
E	11,5	25,72	0,45	4,25
F	20,5	15,34	1,33	8,60
G	31	20,32	1,52	9,12
H	4	25,05	0,16	0,17
I	10	24,56	0,40	3,88
J	40	26,74	1,50	9,05

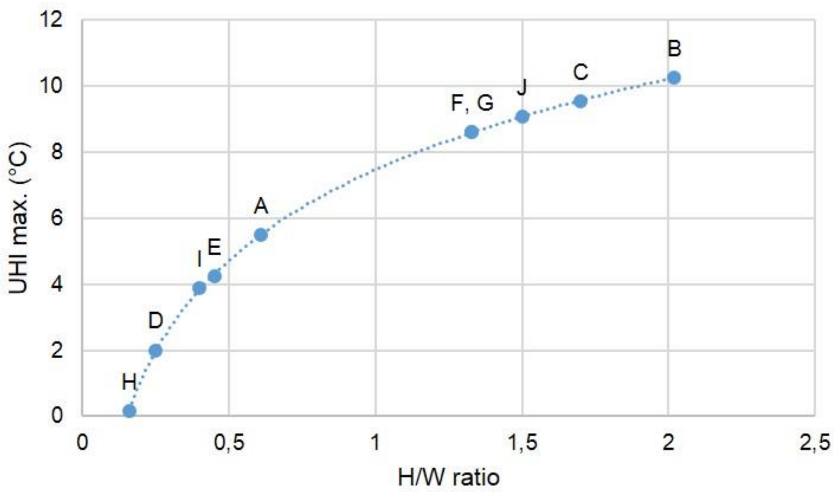

Fig. 5.2 Graph of 10 points of UHI maximum values, resulting from the simulation

A 3D simulation in ArcScene could be performed from the maximum UHI data obtained by simulation (Fig. 5.3).

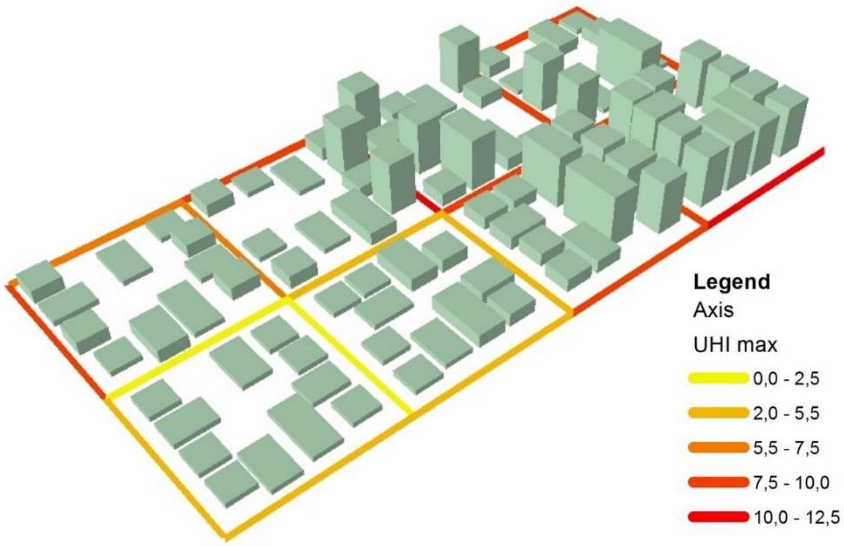

Fig. 5.3 3D simulation of results in ArcScene.

This simulation suggests that, based on the Oke's model, for an urban area that has a variation of H/W ratio between 0.16 and 0.61, the maximum intensity of UHI values stays in the range from 0.17 to 5,5. When H/W ratio varies in the range from 1.33 to 2.03, the resulting values of maximum intensity of UHI are between 8.60 and 10.24. It is noted that the model suggests the presence of larger variation in the intensity of UHI for the lower values of H/W ratio than for the higher.

The results of this simulation also show that very similar values of maximum intensity of UHI (8.60 and 9.05) can be obtained in two very different scenarios: average H of 20.5 and average W of 15.34 with variation of buildings heights (F axis); and average H of 40 and average W of 26.74 with a standard building height (J axis).

The application of this tool in existing urban areas could expand the discussion on the applicability of Oke's model in different countries, as is placed by Montávez et al. (2008).

Some studies involving the calculation of H/W ratio only consider the width of the street, or add the measures of sidewalks, or may be based only on an aerial photo reference. This tool developed can calculate more accurately the variation of the distances between building facades, considering that there are neighborhoods and cities where there is a big difference in frontal distances between neighboring buildings.

Because it is a calculation tool which isolates the role of urban geometry, there is a limitation of the analysis that is only based on this parameter, discarding others that influence the heat island. But it is also easy to verify that one of the advantages is the simulation speed and the fast insertion of input data.

6 Conclusions

It was developed a subroutine incorporated into the GIS in order to calculate the maximum intensity of urban heat islands based on urban geometry data. An application was described, presenting the spatial and numerical associations that were necessary to adapt a simple empirical model, which is widely known and used in urban climatology area.

The developed tool will help researchers to simulate UHI in different urban scenarios and suggests further discussion about the influence of different urban geometry settings in the formation of heat islands.

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