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# ANNUAL MEAN URBAN HEAT ISLAND VERSUS 2D SURFACE PARAMETERS: MODELLING, VALIDATION AND EXTENSION

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**Összefoglalás** – Feltételezésünk az, hogy az alföldi városok átlagos évi hősziget intenzitása megközelíthető a felszíni jellemzőik alapján. Tanulmányunk célja – szegedi és debreceni hőmérsékleti és felszínborítottsági adatok alapján – egy többváltozós modell készítése az átlagos hősziget területi eloszlásának megbecslésére, e modell validálása, majd kiterjesztése más olyan, hasonló földrajzi adottságú városokra, ahol nem áll rendelkezésre hőmérsékleti mérés.

**Summary** – Our assumption is that the mean daily maximum heat island of towns situated on a plain can be assessed on the basis of their surface features. Based on temperature and surface cover data from Szeged and Debrecen, the aim of our research is to construct a multiple variable model for estimating the spatial distribution of the mean heat island, the validation of this model and then to extend our results to other towns situated in a similar environment with no temperature measurements available.

*Key words*: urban heat island, urban surface parameters, geoinformatic methods, Szeged, Hungary

## 1. INTRODUCTION

Urban environments differ significantly from the surrounding natural lands, because they have different surface geometry, material- and air composition, and the anthropogenic heat emission also affects them. This leads to a local-scale alteration of climate: e.g. the formation of the urban heat island (UHI). This is a positive thermal alteration, namely that the town is usually warmer than its surroundings. The effect has dual characteristics: in summer it means a problem because of the slowly cooling air at night, but in winter this same influence is advantageous, since the heating demand of buildings and the length of heating period decreases in the urban areas (*Unger,* 1997). Furthermore, the composition of urban vegetation is changed and a postponement of phenological phases is observable (*Lakatos and Gulyás,* 2003). Its investigation is important because of the large number of inhabitants.

The aim of our research is to calculate a statistical estimation for the intensity of the annual mean maximal heat island. Its research can provide important information for example for urban planning (*Kuttler,* 1998).

The quantitative determination of the role of factors affecting the development and intensity of UHI is difficult because of the complex vertical and horizontal structure of the town and because of the artificial emission of heat and pollutants. Detailed data collection is also complicated and it demands significant technical investments. Our assumption is that satellite images of the settlements situated on plain (simple morphology, no orographical influence) can serve as a tool to estimate the annual mean UHI, because some parameters (e.g. the built-up ratio) of the modified urban surface can be calculated with the help of these images.

According to the aim of this research we construct a multiple variable model for the estimation of the spatial distribution of the mean heat island using the surface cover data of Szeged and Debrecen. Then we extend our results to other towns situated in a similar environment with no temperature measurements available.

## 2. STUDY AREAS

Szeged and Debrecen are situated on the Great Hungarian Plain, on Holocene sediments with a gentle relief. According to Trewartha's classification Szeged and Debrecen belong to the climatic type D.1 (continental climate with longer warm season), similarly to the predominant part of the country.

According to the geographical position it is possible to divide the Hungarian towns into three categories: located in a valley, at the meeting point of mountainous area and plain, and on the plain. From the point of view of urban climate development, in the case of the first two categories it is very difficult to separate the effects of topography and human impact. Szeged and Debrecen belong to the third category, so they have favourable conditions for urban climate research. For this reason the results of systematic measurements and analysis in these towns can be a basis of general conclusions (*Unger,* 1997).

The investigations are focused on the built-up areas of the towns, which mean about 30 $km^2$ areas in case of both towns. The towns have different structures: Szeged has one centre and an avenue-boulevard system, and the river Tisza flows across it. Debrecen is less structured and has more centres.

## 3. TEMPERATURE MEASUREMENTS

For the information on the UHI structure and intensity temperature data were collected by mobile measurements in Szeged and Debrecen (*Fig. 1a-b*). In order to systematise the collected datasets the study areas were divided into 500 m x 500 m grid-cells. The same grid size of 0.25 $km^2$ was applied in some other urban climate projects (e.g. *Park,* 1986; *Long et al.,* 2003; *Lindberg et al.,* 2003). The study areas consist of 107 (25.75 $km^2$) and 105 cells (26 $km^2$) in Szeged and in Debrecen, respectively. They cover the inner and suburban parts of the towns. In both towns one rural cell was used as a reference area for the comparison of temperature data.

The required data were collected with measurement cars on assigned routes, in a one-year-long period between April 2002 and March 2003). Such mobile measurements are wide-spread in studying urban climate parameters (e.g. *Oke and Fuggle,* 1972; *Moreno-Garcia,* 1994; *Santos et al.,* 2003).

In the study areas the representative temperature pattern derives from the measurements, which took place every 10th days. This means the measurements were taken

35 times in Szeged and Debrecen at the same time. The three-hour measurements were carried out under all weather conditions except rain. Based on experiences from previous studies the data collection took place at the expected time of the daily maximum development of the UHI, at 4 hours after sunset (*Oke,* 1981; *Boruzs and Nagy,* 1999).

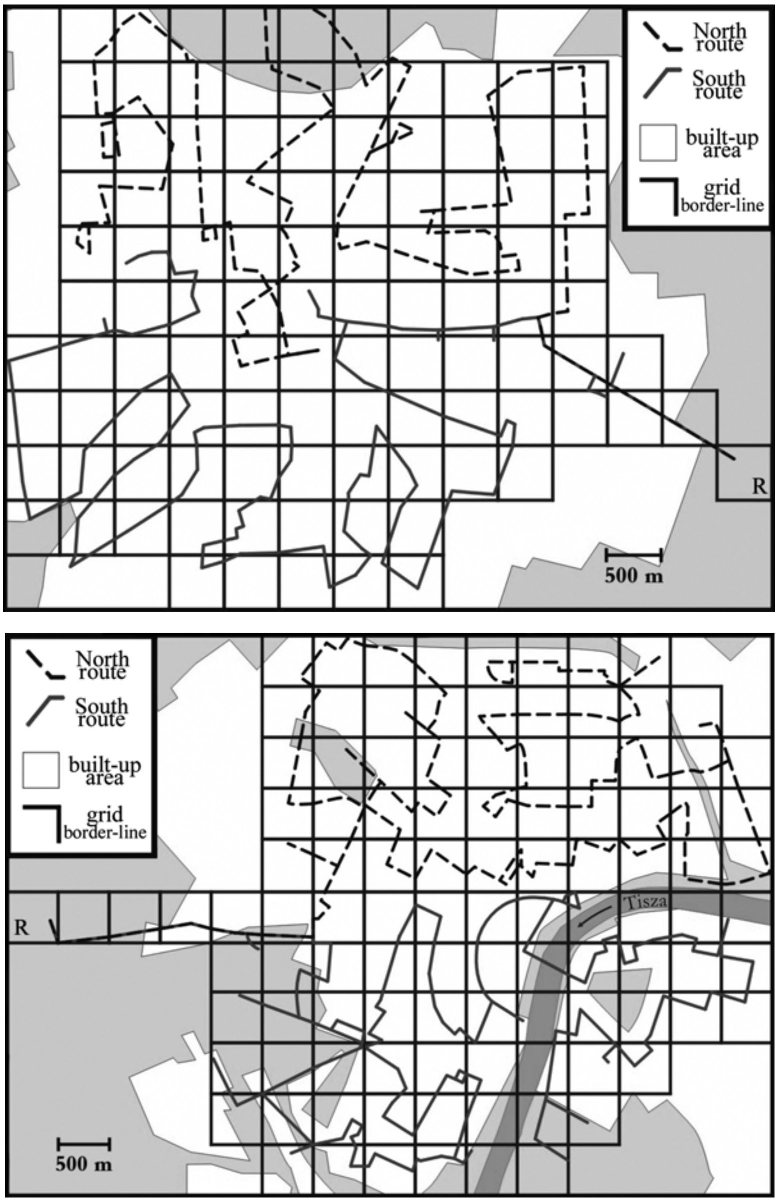


*Fig. 1* Routes of the mobile UHI measurements (*a*) in Debrecen and (*b*) in Szeged (R = rural cell)

The areas were divided into two sectors because of the size of the study areas and the length of the measurement routes. The routes were planned to touch all the cells at least once both ways (*Fig. 1a-b*). The temperature was measured by an automatic sensor connected to a digital data logger. The sensor measured the values every 10 seconds. It was placed on a bar, 0.6 m in front of the car and 1.45 m above the ground because of the thermic disturbing effect of the car. The car's speed was 20-30 $kmh^{-1}$ in order to provide the necessary ventilation to the sensor and a proper density of data. Accordingly there are data from every 55-83 m along the measurement routes. The values logged at the rare stops (e.g. red light, barrier) were later deleted from the database. The measured temperature data were averaged in each cell. In the hours after sunset the linear change of temperature was applied to the calculation of the measured data, with the assumption that it is only approximately valid in the suburban areas because of the different cooling gradients (*Oke and Maxwell,* 1975).

In our case the UHI intensity ($\Delta T$) is defined as follows (*Unger et al.*, 2004):

$$\Delta T = T_{cell} - T_{cell\,(R)}$$

where $T_{cell}$ = temperature of the given urban cell; $T_{cell(R)}$ = temperature of the rural cell.

## 4. BUILT-UP RATIO AND FURTHER SURFACE PARAMETERS

The built-up ratio (*B*) characterizes the town horizontally. This parameter of land-use (streets, pavements, parking lots, building roofs, etc.) was determined for each grid cell using GIS (Geographical Information System) methods combined with remote sensing analysis of Landsat satellite images (*Unger et al.*, 2001) not only for the study areas used for the temperature measurements but also for their extensions of 1.5 km in every direction. The nearest-neighbour method of resampling was employed, resulting in a root mean square value of less than 1 pixel. Because the geometric resolution of the image was 30 m x 30 m, small urban units could be assessed independently of their official (larger scale) land-use classification. The satellite images were taken in 2003, so they provide accurate data for the actual built-up conditions. Normalised Vegetation Index (*NDVI*) was calculated from the pixel values, according to the following equation (*Gallo and Owen,* 1999):

$$NDVI = (IR - R) / (IR + R)$$

where IR is the pixel value of the near-infrared band (0.72-1.1 μm) and R is the pixel value of the visible red band (0.58-0.68 μm). The value of *NDVI* is between -1 and +1. It depends on the quantity of biomass. If there is rich vegetation in the area, the $NDVI \approx 0.5\text{-}1$ (this means a full vegetation cover, e.g. forest). If there is grass vegetation in the area, the value of the $NDVI \approx 0.2\text{-}0.5$. If there is water surface, then the value approaches -1. With this index it is possible to determine the proportions of water, built-up and vegetated surfaces in percent by cells.

*Fig. 2* shows the relation between the mean heat island intensity and the built-up ratio in Szeged and Debrecen together, so 212 element pairs were used. A strong positive relationship can be seen between the two parameters, namely the temperature difference increases as the built-up ratio increases. The strength of the linear relationship is supported by the value of the deterministic coefficient at the used element number ($R^2 = 0.2855$, n = 212).

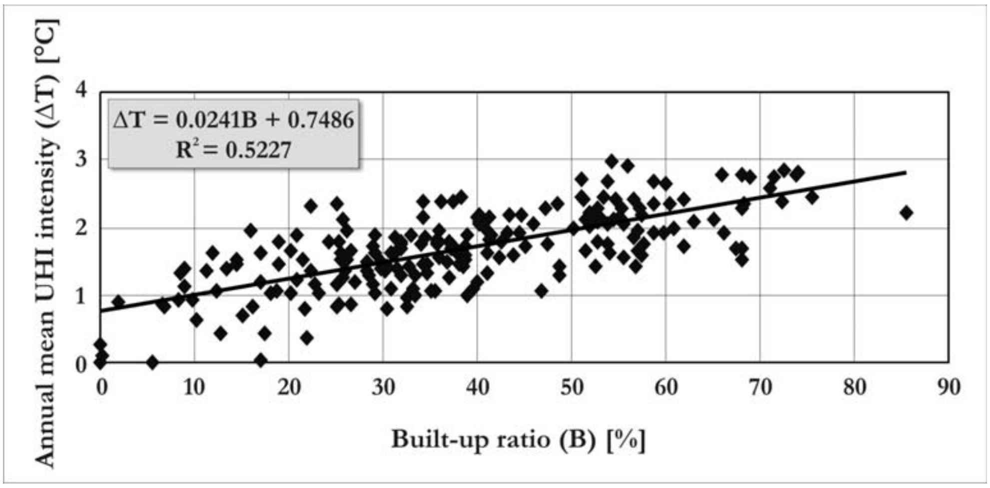


*Fig. 2* Relationship between heat island intensity and built-up ratio in Szeged and Debrecen together (n = 212)

The values of the built-up ratio can vary between 0% and 100%. In our case, in the study towns a built-up ratio of 2-84% was found. For example, in the case of Szeged *Fig. 3* shows the relation between the spatial distribution of the heat island and the built-up ratio, as the heat island intensity follows the change of built-up values. The distribution of the UHI intensity is roughly concentric, which is the consequence of the structure of the town.

It is important to consider the surroundings of the cells, because the temperature of the surroundings influences the temperature of a given cell, and *B* changes rapidly from the city centre. A set of predictors can be determined from the surface built-up ratio and its areal extensions in the following way, similar to *Bottyán and Unger* (2003):

- parameter value in the grid cell *B* with $\Delta i^2 + \Delta j^2 = 0$
- mean parameter value of all grid cells $B_1$ with $1 \leq \Delta i^2 + \Delta j^2 < 2^2$
- mean parameter value of all grid cells $B_2$ with $2^2 \leq \Delta i^2 + \Delta j^2 < 4^2$

Here, *i* and *j* are cell indices in the two dimensions, and $\Delta i$ and $\Delta j$ are the differences of grid cell indices with respect to a given cell. The obtained zones of predictors cover the entire investigated area and their extensions in Debrecen and Szeged. Now we have three predictors to build a linear statistical model. This procedure creates the right conditions for applying our model to predict the UHI intensity in other cities with different size. *Fig. 4* shows the structure of the constructed $B$, $B_1$, $B_2$ parameters.

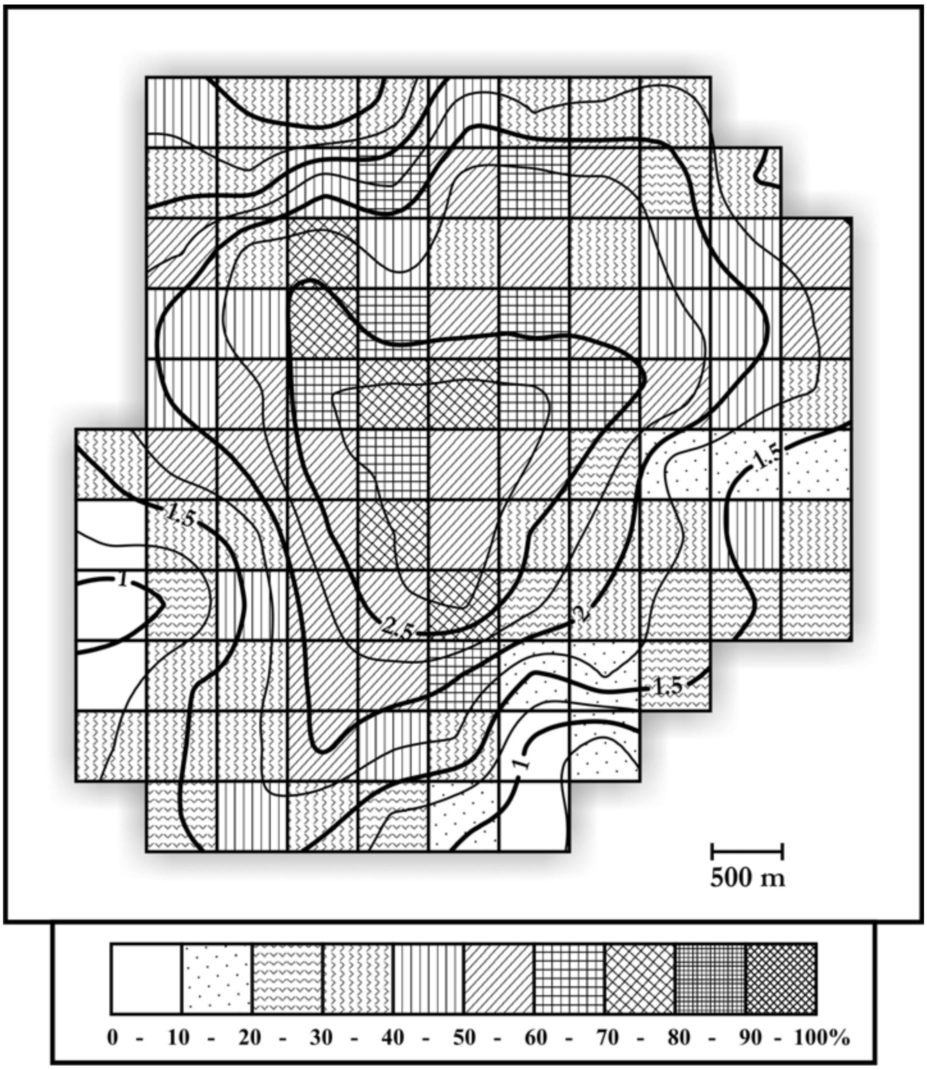


*Fig. 3* Spatial distribution of the built-up ratio and the UHI intensity (in °C) in Szeged (the 4 cells in the westernmost part of the study area are not shown)

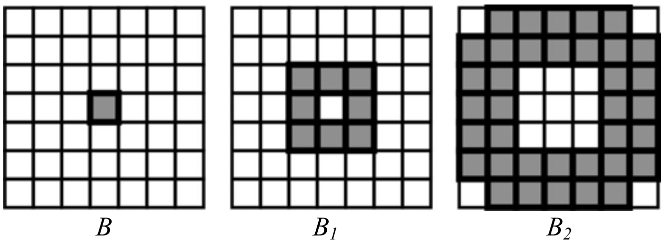


*Fig. 4* The cells which take part in the calculation of $B$, $B_1$, $B_2$ parameters

## 5. CONSTRUCTION OF THE MULTIPLE-PARAMETER MODEL

The task is to quantitatively define the relationship between the above-mentioned urban surface parameters and the annual mean UHI intensity. As mentioned earlier our aim is to create a general multiple-parameter model on the basis of data from Szeged and Debrecen, which can be used for the estimation of heat island structure in other towns situated on a plain.

The elements of our multiple-parameter model:

- $\Delta T$, as variable parameter (°C),
- $B$, $B_1$, $B_2$, as invariable parameters (%).

The multiple regression analysis of the Statgraphics Plus software was used to compute a model equation for the spatial distribution of the intensity of the annual mean heat island:

$$\Delta T = 0.0040 \cdot B + 0.0167 \cdot B_1 + 0.0267 \cdot B_2$$

The three parameters are responsible for the development of the temperature excess in more than 90% ($r^2 = 0.94$). In the data of Szeged and Debrecen, used together (212 element pairs) in creating the model, the value of $B$ is between 0% and 84%, the value of $B_1$ is between 3% and 63%, the value of $B_2$ is between 12% and 49%, and the value of $\Delta T$ is between 0°C and 2.96°C.

Our model results can be considered appropriate, if the values of the study area are in the same interval. Henceforth this general model can be extended to other, different-sized towns, where the environmental situation, like topography and climate, is similar to that of Szeged and Debrecen. As mentioned earlier only the satellite images of the settlements are necessary for this, from which the built-up ratio and its areal extensions can be determined as predictors.

## 6. VALIDATION

Between September 2002 and January 2005 temperature measurements were taken in some towns situated on plain (Hajdúböszörmény, Hajdúdorog) by *Szegedi* (2005). These towns are situated near Debrecen, so they have similar topography and climate, but they are smaller than Debrecen. These towns both have avenue-boulevard systems, which is favourable for the development of the regular heat island structure type.

Hajdúböszörmény has 29,000 inhabitants and its (mostly urban) study area consists of 56 cells (14 km$^2$). Here the annual mean UHI intensity is 0.9°C in the centre according to the temperature measurement. The estimated annual $\Delta T$ is also 0.9°C (*Fig. 5*). 10,000 people live in Hajdúdorog and it has a study area of 35 cells (8.75 km$^2$). The annual mean UHI intensity is 0.3°C in the centre according to the temperature measurements. The estimated annual $\Delta T$ is also 0.3°C (*Fig. 5*).

So there is a good correspondence between the measured and estimated intensity values.

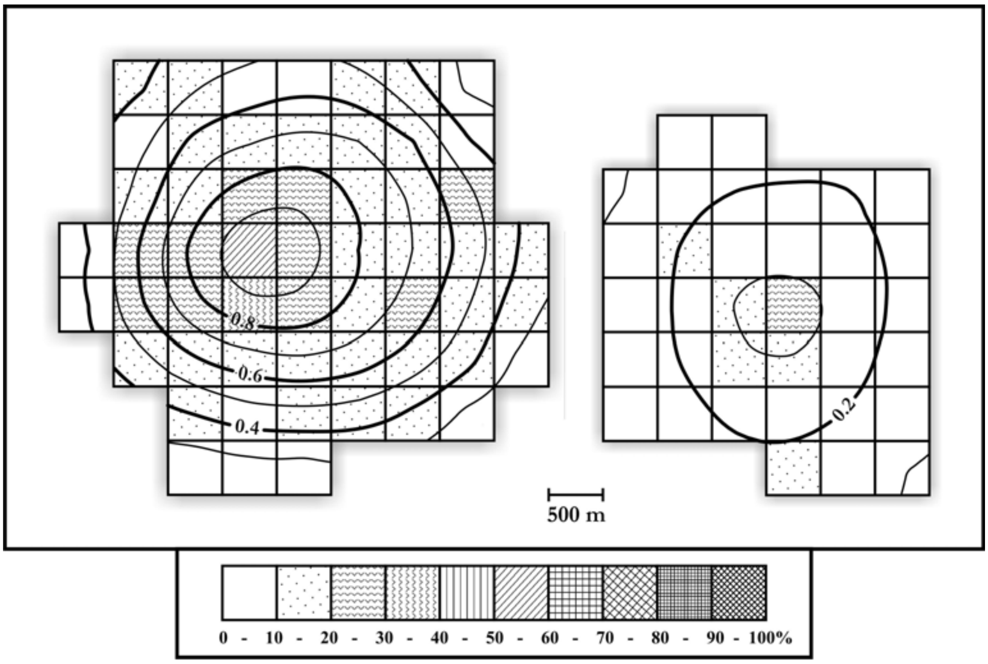


*Fig. 5* Spatial distribution of the predicted mean UHI intensity (in ºC) for Hajdúböszörmény and Hajdúdorog

## 7. APPLICATION − EXTENSION

Presently sixteen towns with different size and population situated on a plain (Great Hungarian Plain) are examined in order to extend our model results. Three towns are not situated in Hungary: one is in Serbia and two in Romania. The towns studied are as follows: Arad, Baja, Békéscsaba, Cegléd, Hódmezővásárhely, Karcag, Kecskemét, Kiskunfélegyháza, Makó, Nagykőrős, Nyíregyháza, Orosháza, Szabadka (Subotica), Szolnok, Temesvár (Timisoara) and Pest (east side of Budapest, which is an almost plain area).

In this section, as examples, we show some of our results on the modelling of the spatial distribution of the annual mean UHI intensity in the case of Kecskemét and Békéscsaba.

Kecskemét has 109,000 inhabitants with a (mostly urban) study area of 61 cells (15.25 $km^2$). According to our model equation it has a rather regular heat island development with a center in the historical city centre and with a largest value of about 2.9°C (*Fig. 6*).

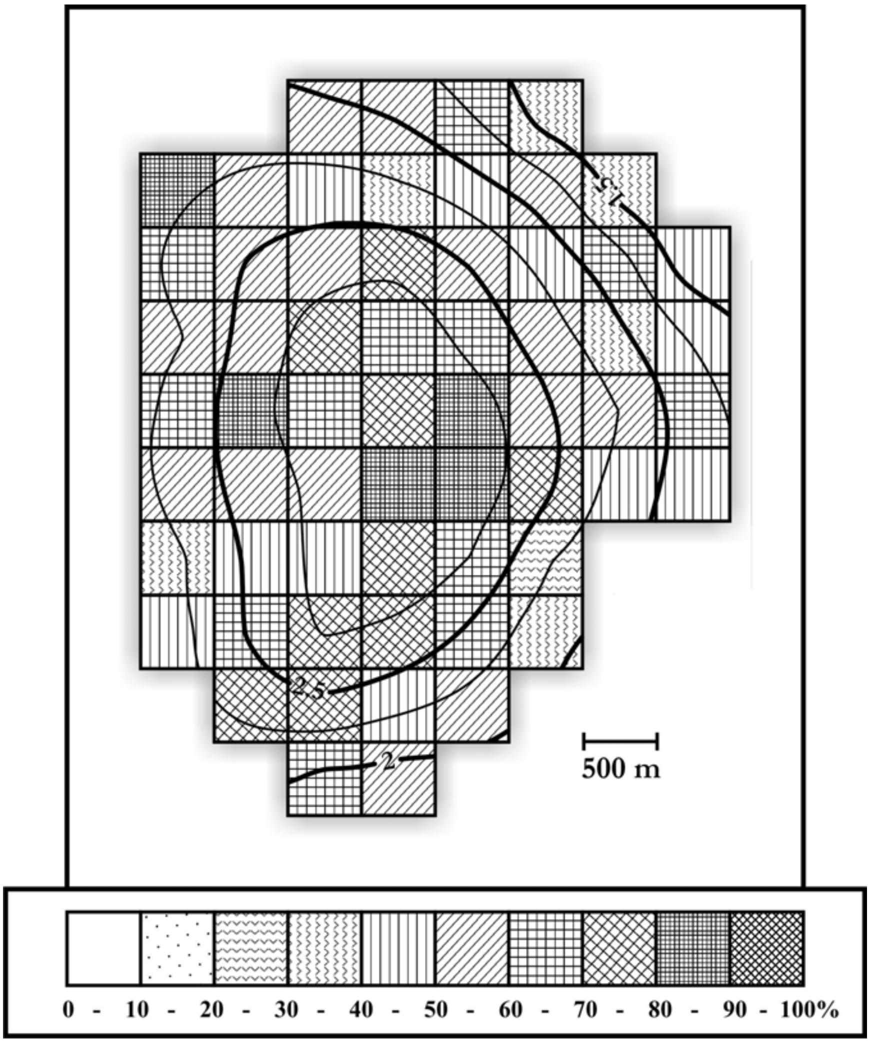


*Fig. 6* Spatial distribution of the predicted mean UHI (in ºC) intensity in Kecskemét

64,000 people live in Békéscsaba and its study area consists of 73 cells (18.25 km$^2$). As *Fig. 7* shows, it also has a regular heat island structure type with a largest value of about 1.8°C.

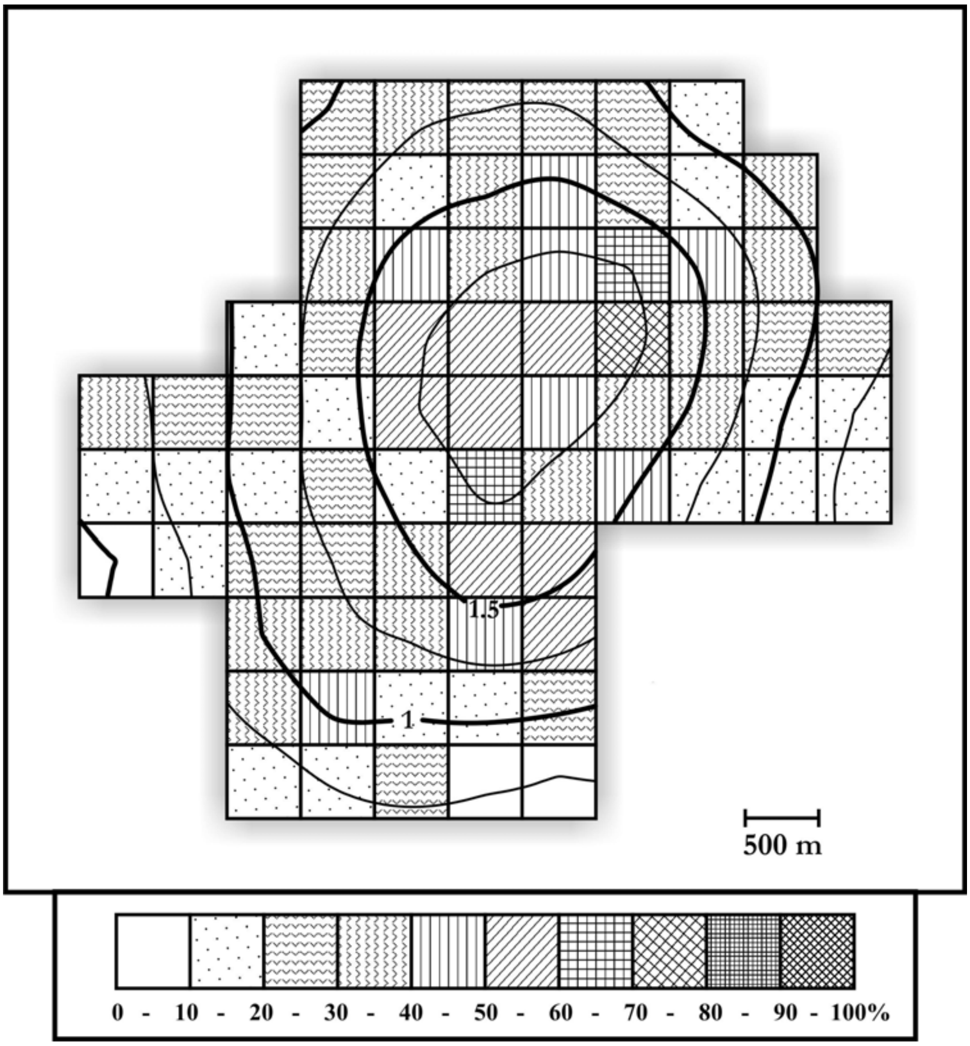


*Fig. 7* Spatial distribution of the predicted mean UHI intensity (in ºC) in Békéscsaba

## 8. CONCLUSIONS

This study presents a general multiple-parameter model based on surface cover parameters. There is a good correspondence between the measured and estimated intensity values. It can be used for the estimation of heat island structure in the case of towns situated on a plain. The knowledge of the estimated structure of mean UHI may provide useful basic information for the development projects of towns.

Our further aims are the verification of the model with temperature measurements, the extension of the model for other towns and to follow up the changes in the built-up ratio.

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