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A multivariate linear regression model of mean maximum urban heat island: a case study of Beregszász (Berehove), Ukraine

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Abstract—The aim of the research presented in this study is to elaborate a multivariate linear regression model that describes the spatial structure of the mean maximal development urban heat island (UHI) formed under favorable synoptic conditions on the basis of surface parameters. Temperature data were gathered in a small town, Beregszász, Zakarpattia, Ukraine. As a first step, a one-year-long UHI measurement campaign has been carried out using mobile techniques in order to obtain data for the description of the UHI in the study area. Two surface parameters (ratio of non-evaporating surfaces in the environment of the measurement sites and distance of measurement sites from the center of the settlement) have been selected first. The two surface parameters had to be quantified next. On this basis, relationships between surface parameters as independent variables and UHI intensities as dependent variables could be traced by performing a multivariate linear regression. Results have showed that the two chosen parameters have strong impact on UHI development in our study area. Spatial structure and intensity of UHI can be estimated with an accuracy of 0.4 °C within the built-up area of the town using our MLR model. The high resolution surface parameter database and the UHI estimating model enable the prediction of heat load of smaller spaces and town parts. This procedure helps the reduction of heat load and the determination of the location of green areas important for urban planning as well.

Key-words: multivariate linear regression model, non-evaporating surfaces, urban heat island

1. Introduction

Settlements differ from natural environment significantly, due to altered surface geometry, different composition, and structure of urban atmosphere. Anthropogenic heat emissions should be taken into consideration as well (*Oke,* 1997). As a result, a local or meso gamma scale phenomenon, the urban climate develops (*Arnfiled,* 2003; *Oke,* 1973; *Orlanski,* 1975). Built-up areas are characterized by higher air and surface temperatures than close-to-natural areas in their neighborhood what is called urban heat island (UHI). The thermal difference between the town center and its rural environment determines the intensity of the urban heat island. UHI intensities have a special diurnal and annual course with maxima 3–5 hours after sunset and in late summer – early autumn (*Landsberg,* 1981). Additionally, UHI intensities change according to synoptic conditions as well: clear skies with calm weather are advantageous for the development of a strong UHI. This way, synoptic conditions determine the UHI intensities at a given point of time, while maximal (or potential) intensities can develop under favorable synoptic conditions. These factors are dynamic conditions of UHI development. Spatial pattern of the absolute or the mean maximal UHI is determined by static factors, the characteristics of the urban surface (*Bottyán* and *Unger*, 2003; *Bottyán et al.,* 2005*; Chen et al.,* 2011; *Ginnaros et al.,* 2013). Therefore, for studying the effects of static conditions on the spatial structure of UHI, favorable synoptic conditions are suitable. Investigations on heat islands give important information for town-planning (*Kuttler,* 1998), because the phenomenon influences the comfort sense of town dwellers (negatively in summer, positively in winter) essentially, alters the composition of urban vegetation, and can cause phenologic phase shifting (*Oke,* 1975).

Beyond determination of the characteristics of urban heat islands, recent studies focus on examination of their evolving factors in big cities. Our study area, Beregszász (Berehove) with its population of 26,000 belongs to the group of settlements which gain much less attention from this aspect. However, a high ratio of the population of Central and Eastern Europe live in small settlements, where heat islands can develop (*Fig. 1*), but there are much less studies in that field. Additionally, many rapidly growing independent suburbs of cities fall into that size category as well.

The main aim of the study presented here is to analyze the relationships between spatial structure of UHI and its formative surface parameters. There are many surface parameters that have an effect on UHI development. The hypothesis was that the most important parameters are the distance of a given site in the settlement from the geometrical center and the ratio of non-evaporating surfaces in that site.

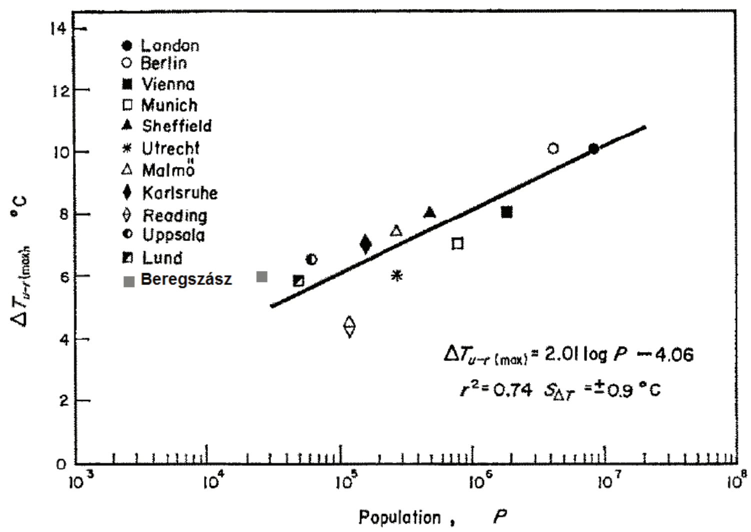

Fig. 1. Relationship between maximum observed heat island intensity ($T_{u\text{-}r(max)}$) and population *(P)* for European settlements indicating the position of Beregszász from this aspect (modified after *Oke,* 1973).

Other aim of our studies is to build an empirical estimating model for the spatial pattern of the mean maximal development UHI using the before mentioned surface parameters. The model could make possible the description of the spatial structure of the mean maximal development UHI for settlements of that size and structure category. Results can provide basic information on spatial pattern of the thermal excess in a given small settlement for spatial planning, forming urban spaces and green areas to utilize the advantages and prevent the drawbacks of the heat island phenomenon.

The examination of effects of surface parameters on UHI development requires high resolution spatial temperature data gathered under synoptic conditions what makes possible the strong development of UHI. For this reason, measurements were carried out under anticyclone synoptic conditions with clear skies and calm weather.

While examination of satellite images (*Bartholy et al.,* 2009) are more capable for heat islands of big cities (*Oke,* 1975; *Park,* 1986; *Kislov* and *Konstantinov,* 2011; *Lee* and *Baik*, 2010) (e.g., New York, Montréal, Moscow, Soul, Budapest), in the case of Beregszász, due to its size, the adaptation of a mobile measurement method (*Elansky et al*., 2012) used by researchers of the University of Szeged (*Unger et al.,* 2000) and Debrecen (*Szegedi,* 2000) seemed to be adequate. The difference between the two methods is that satellite images make possible the determination of heat surplus in surface temperatures, while the latter one allows the measurement of heat excess in air temperatures.

Our mobile temperature measurements have provided abundant data for the characterization of UHI in Beregszász (Berehove). On this base, a multivariate linear regression model can be applied to analyze the role of some surface parameters in development of UHI in our study area.

2. Study area and methods

2.1. Location and climate of Beregszász (Berehove)

Beregszász (Berehove) (48.1°N, 22.3°E) lies 117 m above sea level. The southwestern part of the town can be found on a flat, alluvial plain, only occasionally interrupted by small hills. The town is situated on an almost flat terrain without great water bodies, what is advantageous from the aspect of the examination of the spatial development of urban heat island. It is located in the Zakarpattia Oblast (province) in Western Ukraine, near to the Hungarian border. It is the administrative center of the Berehivskyi Raion (district) with a population of 26,000.

The climate normal was calculated based on the Climate of the Carpathian Region Project dataset *(Lakatos et al., 2013)*. The town and its environment belong to Köppen's climate region Cfb on the basis of the climate parameters (*Table 1*.). The annual course of precipitation reaches its maximum in June and July. Prevailing wind direction is north-easterly.

Table 1. Annual and monthly means and sums of meteorological parameters at the weather station of Beregszász (Berehove), 1961–2010 (*Anon,* 1992; *Lakatos et al.,* 2013).

Beregszász (Berehove)	
Annual mean temperature (˘C)	9.8
Temperature range (˘C)	21.8
Mean temperature in January (°C)	–2.7
Mean temperature in July (˘C)	20.2
Annual mean precipitation (mm)	682
Annual mean wind speed (m s^{-1})	2.1
Sunshine duration per year (h)	1998

2.2. UHI measurements

Since the spatial pattern of the heat island is influenced by different urban morphological types significantly (*Szegedi,* 2006; *Unger et al*., 2004; *Molnár et al., 2006*), we had to integrate the highly complex urban morphology into our model. Along a measurement route 42 measurement sites were selected, which are representative on one hand and quite smoothly cover the settlement on the other hand (*Fig. 2*). Temperature data was gathered 36 times along the route using mobile measurement techniques from January to December in 2005 by

Marguca V. and Kakas M. A measurement session was carried out using mobile measurement techniques in 2010 as well (n=10), under meteorological conditions advantageous for UHI development. This dataset was used as independent data in validating the established empirical model.

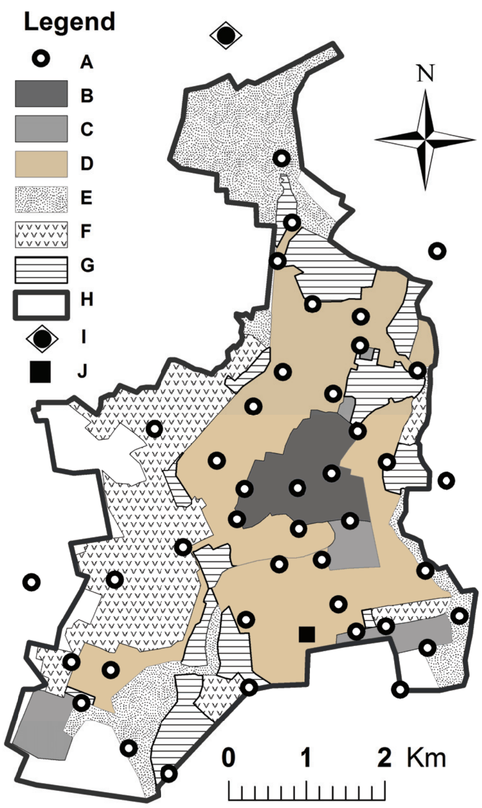

Fig. 2. UHI measurement sites (**A**) and urban morphological types in Beregszász (Berehove):**B**–historical town center with 3–5 storied buildings, **C**– 5–8 storied apartment houses, **D**—1-2 storied detached houses, **E**—open low-rise built-up area, **F**—industrial area, **G**—green areas inside the town, **H**—border of the study area, **I**—rural measurement site (reference point), **J**—weather station.

Measurement days were chosen according to the weather conditions within the decades: nights with rain and/or strong winds were excluded, since these conditions prevent the development of UHI. Measurements started approximately 3 hours after sunset, when heat island development is the most dynamic. Temperatures were recorded manually at each measurement site (*Table 2*).

Table 2. Observed meteorological parameters during the UHI measurements at the weather station of Beregszász (WMO station code is 33634; 48.19°N, 22.64°E, 122 m above sea level)

Measurement date	Air temperature (°C)		Cloudiness (octas)	Wind speed ($m\ s^{-1}$)		UHI max	UHI mean
2005	**19 : 00**	**01 : 00**	**19 : 00**	**19 : 00**	**01 : 00**		
January 5	2.8	3.5	7	0	0	0.9	0.5
January 17	–2.1	–3.1	0	0	1	5.0	1.6
January 25	–1.3	–1.4	4	1	2	2.2	1.2
February 4	–5.1	–5.4	2	2	3	4.1	3.0
February 16	0.3	0.8	0	0	1	1.8	1.1
February 21	2.6	1.1	1	1	0	4.0	1.7
March 3	–1.4	–0.8	2	2	1	0.9	0.4
March 15	3.5	1.6	6	1	0	2.2	1.0
March 22	0.1	1.4	0	2	1	2.6	1.5
April 5	9.3	8.1	0	0	1	4.9	2.7
April 18	11.3	10.4	8	3	4	0.5	0.3
April 27	10.4	12.6	0	0	1	2.8	1.6
May 5	13.7	12.8	4	1	2	0.9	0.7
May 12	8.0	5.3	0	0	1	1.7	0.9
May 23	19.4	17.8	0	0	0	3.9	2.1
June 07	12.8	12.2	0	1	0	1.9	1.3
June 14	17.1	15.5	0	0	0	4.6	1.4
June 22	20.1	19.0	7	2	3	2.0	1.1
July 8	18.2	16.9	0	1	0	4.9	2.4
July 18	23.4	22.3	0	1	0	2.1	1.6
July 21	15.5	14.1	0	1	1	4.9	1.4
August 2	23.2	22.7	0	0	1	3.3	1.9
August 12	18.1	17.7	0	0	0	2.3	1.4
August 22	20.2	19.6	6	2	3	0.8	0.4
September 6	12.7	12.0	0	0	1	4.5	2.6
September 13	18.5	16.6	0	1	0	1.7	0.9
September 22	14.2	15.9	0	0	2	6.6	4.1
October 04	14.9	16.7	1	0	1	3.6	1.6
October 11	9.0	8.1	0	0	0	3.9	1.7
October 25	14.4	13.9	7	2	3	1.7	0.3
November 03	3.3	1.5	0	1	0	4.2	2.5
November 15	7.7	7.4	8	3	4	1.4	0.6
November 22	–2.2	–3.0	0	0	1	2.7	1.8
December 07	5.1	4.3	5	1	3	0.7	0.4
December 13	0.6	0.5	6	0	1	1.0	0.6
December 21	–5.0	–5.9	1	2	1	3.2	2.5

From the numerous methods developed for urban climate examinations, mobile techniques were used in order to get abundant comparable data for Debrecen and settlements involved in the research. Sensors of a digital thermometer were mounted on a car (with a resolution of 0.1 °C) at a height of 1.5 m, which is a common practice in UHI measurements. An important problem is that measurements should be carried out at exactly the same time in each grid. This is impossible using mobile techniques. The difference between the first and the last grid is 90 minutes, which is a considerable time span from the aspect of the change of temperatures in the different parts of the city. In order to get comparable temperature data during the measurements, we visited each grid two times: first on the way to the end of the route (the reference site, measurement site 42) and the second time on the way back. In this way we gained two temperature values for each grid. Since on the way back we visited the grids in reversed order, calculating the averages for the grids we gained values for the same time (the reference time). The reference time was four hours after sunset, since according to the literature, heat island intensity reaches its maximum 3–5 hours after sunset. Since the aim of the research was to trace the spatial pattern of urban heat island, only favorable conditions for heat island development were taken into consideration during the first campaign: measurements were carried out in anticyclone conditions. *Fig. 2* shows locations of measurement sites. UHI intensities (Δt values) were calculated using the following formula:

$$\Delta t = t_{urban} - t_{rural} , \tag{1}$$

where t_{urban} means temperature values measured at urban sites and t_{rural} means temperatures measured at the reference site outside the town.

2.3. Determination of surface parameters

The role of two surface parameters (presumably the most important ones) influencing the heat island development have been examined in the present study.

These are:

- Ratio of non-evaporating surfaces *(NES)* in the environment of measurement sites;
- Distance between measurement sites and the geometrical center (48.20°N, 22.64°E) of the town. Distances between measurement sites and the geometrical center of the town (km) were calculated, and distances were determined for the grid points of the network of the town as well.

Since non-evaporating surfaces store more heat during daytime than the close-to-natural evaporating surfaces, the air above built-up areas is warmer than over their surroundings. For this reason, quantification of the ratio of non-evaporating surfaces is necessary.

Close-to-natural evaporating areas are surfaces covered by vegetation (wood, shrub, lawn etc.) or bare soil. Non-evaporating surfaces are mainly artificial objects (buildings, pavements, other constructions). We have found that satellite images are the most suitable for parameter estimation. Thus, the ratio of non-evaporating surfaces was assessed visually using high-resolution, true color images of Google Earth. A grid network of 15.4×15.4 m was set on the images with the measurement points at the centers of the grids, and characteristic surface types for each grid were determined. The land cover was determined at 109,500 points with a spatial resolution of 15.4×15.4 m, which gives more detailed data than a grid network with 500×500 m resolution used by other researchers *(Kislov et al.,* 2011; *Unger et al*., 2000).

It was an important question to decide what size of environment of measurement points influences the heat island intensity most strongly. We have tested four variations by statistical analysis:

—NES_1 – 9 grid points represent an area of 2134 m^2 around the measurement point;
—NES_2 – 25 grid points cover an area of 5930 m^2;
—NES_3 – 49 grid points represent an area of 11,621 m^2 around the measurement point;
—NES_4 –81 grid points cover an area of 19,210 m^2.

As a first step, the size of the environment, which influences the heat island intensity most strongly around the measurement sites was determined statistically. For this reason, *NES* values of the 4 chosen areas were correlated with the mean maximal heat island intensities of measurement sites, and significant correlation was found in every case (*Table 3*).

Table 3. Connection between the ratio of non-evaporating surfaces (*NES*) and UHI intensities, *r*– correlation coefficient

Period	NES_1 *r*	NES_2 *r*	NES_3 *r*	NES_4 *r*	**Sign. level**
Δ*t*-annual	0.57	0.64	**0.70**	0.67	1%
Δ*t*/heating	0.56	0.64	**0.69**	0.67	1%
Δ*t*/non-heating	0.54	0.59	**0.68**	0.61	1%

The strongest relationship was found between NES_3 and the UHI, so the 11,621 m^2 area influences heat island intensities of Beregszász most remarkably. Maps were completed on the basis of the ratio of non-evaporating surfaces in Surfer 8.0 (*Fig. 3*). This statistical software offers several types of interpolation methods, from which we have chosen the widely used Kriging-procedure. Ratio of non-evaporating surfaces reaches its maximum in the center of the town, however, there are some patches with high ratio of artificial (non-evaporating) surface cover around the center near the edges of the settlement. They are industrial areas and housing estates. The distance of the measurement points from the town center was determined by using the differences of coordinates of the previously mentioned grids.

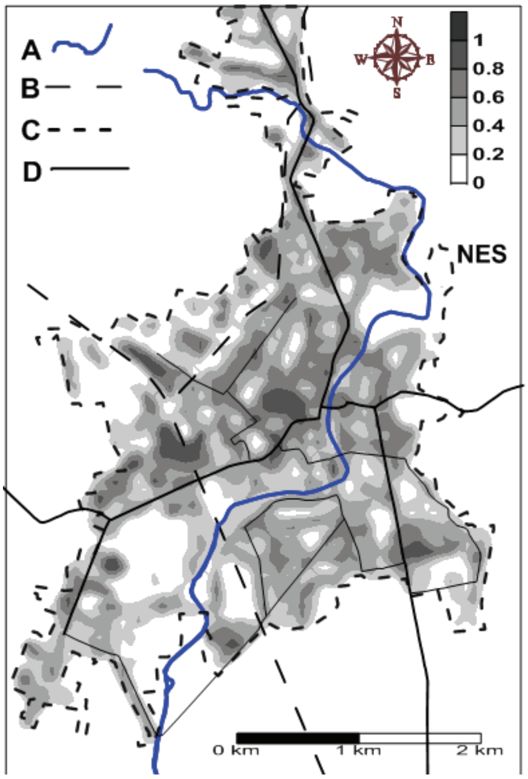

Fig. 3. Spatial pattern of the of non-evaporating surfaces in Beregszász: A– Vérke canal, B–railroad line, C– border of built-up area, D– main road line.

Correlations between variations of *NES* (NES_1-NES_4) and distances from the geometrical center of the town were determined. In this way, possible linear dependence between explanatory variables was traced. In the case of dependence between explanatory variables, one of them was ignored in order to create an independent system of explanatory variables. This method minimized the possible multicollinearity (*M*) of explanatory variables incorporated into the model. Value of *M* shows the magnitude of the non-separable effect of factor variables. In this way, the coefficient of multiple determination can be divided into the partial effect of each factor variable and the joint effect of the factor variables. In our case, the value of *M* was 0.37 which cannot be regarded as significant. This value was tested using the variance inflation factor (VIF):

$$VIF_i = \frac{1}{1 - R_i^2} \ . \qquad (2)$$

This factor shows how many times greater the actual variance of the estimated coefficient of variable *i* is than it would be with the complete exclusion of multicollinearity. Value of *VIF* in our case is 1.58 suggesting slight multicollinearity that determines the estimation strength of the model not significantly.

2.4. The statistical model applied

Beside basic statistical analysis (average, correlation), we have attempted to build an empirical model to investigate relationships between heat island intensities and surface parameters. We have applied the multivariate linear regression (MLR) method in the model, which is deemed to be advisable for solving similar kind of problems by other researcher's (*Bottyán et al*., 2005; *Hjort et al*.,2011; *Szymanowski* and *Kryza,* 2012).The MLR equation is

$$Y = a + b_1 X_1 + b_2 X_2 + ... + b_i X_i \ , \ i=1,2,\ldots,n \qquad (3)$$

where Y is the dependent variable, a is a constant, X_i is independent variable, b_i is the partial regression coefficient of independent variable number, and n is the number of independent variables taken into consideration (*Ezekiel* and *Fox,* 1959).

Fitting of the multiple regression equation was performed using the method of least squares. Calculations were carried out using SPSS software pack. Establishment of the linear model was made suing the software SPSS applying the Enter method. Kolmogorov–Smirnov tests proved that distribution of dependent and independent variables involved in the model is not different significantly from normal distribution what is a condition of correlation and regression calculations.

3. *Results and discussion*

3.1. Characteristics of the mean maximal UHI

Mean maximal diurnal UHI intensities culminated in the center of the settlement of Beregszász with 2.3 °C during the studied period, while maximal observed UHI intensity reached 6.1°C, in accordance with the results of *Oke* (1973). Development of the UHI is supported by high ratio of non-evaporating surfaces, compact built-up structure with two storied buildings, and high traffic density beside the central part of studied area.

A map of mean maximal UHI intensities have been prepared by calculating the average maximal UHI intensities for each measurement sites (*Fig. 2*). The following main characteristics of the UHI can be determined (*Molnár et al.,* 2006; *Molnár, 2007*):

- Highest mean maximal UHI intensities over 2.3 °C form the "peak" in the center of the town.
- Thermal excess decreases gradually from the center towards the outskirts of the town. The phenomenon "plateau" cannot be identified due to the small size of the settlement, presumably.
- Thermal excess over 1 °C on the slopes of the low mountain ridge bordering the town from the East is linked to the UHI.
- Low intensity fringes (around 1 °C) of the UHI of Beregszász reach the small, previously independent villages around the town (Beregardó on the north and Búcsú on the southwest) and a housing estate on the southeastern border of the town.
- Mean maximal UHI intensities around the weather station of Beregszász reach 1.2 °C what should be taken into consideration in the processing of datasets measured there.
- Low intensity borders of the mean maximal UHI reaches far over the borders of the built-up area of the town due to the impacts of airflows.

3.2. Structure of the multivariate model

Our main aim was to elaborate a universal model for estimation of spatial pattern of mean maximal heat islands on the base of meteorological and morphological data of Beregszász.

The input parameters of the multivariable model are

- heat island intensity as a dependent variable (°C),
- ratio of non-evaporating surfaces as an independent variable (*NES* – given in %), and
- distance of measurement sites from the geometrical center of the town as an independent variable (D – given in meters).

The following model equation has been created for the spatial structure of annual mean maximal heat island intensity using multivariate regression process of SPSS software:

$$\Delta t_{annual} = 1.642 - 0.00026 \times D + 0.54 \times NES \, . \tag{4}$$

It has been proved that the two parameters play an important role in development of the temperature excess (r^2 = 0,766). The value of *D* partial correlation coefficient is prominent in the model (r^2 = 0,766), since it is much higher than the other parameter (*NES* – r = 0.477), which means that it may play much more important role in the formation of UHI. Spatial structure of UHI in Beregszász has been described on the base of UHI intensities calculated by the model. It can clearly be seen in the map that ratio of non-evaporating surfaces determines the alteration of air temperature much obviously in the built-up area than on the outskirts (*Fig. 4*). Where *NES* values are above 40%, isotherm lines run parallel with them, otherwise isotherm lines diverge. The reason for this is the irregular shape of the borderline between the built-up and close-to-natural areas in the town, probably.

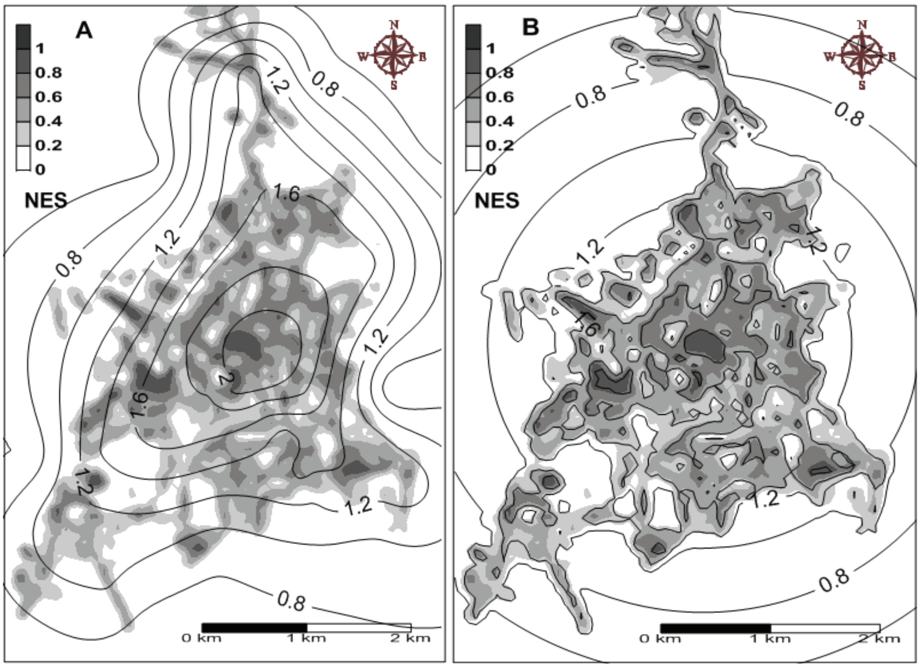

Fig. 4. Spatial structure of non-evaporating surfaces, measured (A) and estimated (B) mean maximal UHI intensities (difference between isotherms is 0.2 °C) for the studied period.

Empirical estimation model equations were created for the summer period (April 16 – October 15), winter period (October 16 – April 15), and sunny (under 4 octas) and cloudy days (over 4 octas).

Differences can be found in the empirical model of heat island intensities in the heating and non-heating periods. Values of r^2 indicate that the two built-up factors determine the „strength" of heat excess developed in the town relatively weakly in the winter period. *Table 4*. presents the multivariate linear regression equations created for heating and non-heating periods. The disparity of partial correlation coefficients emphasizes the higher importance of distance from the center probably in the cold season, since decreasing evaporation rates weaken the impact of evaporating surfaces on the energy balance in the heating season.

Table 4. The multivariate regression equations of heat island intensities at measurement sites, the surface parameters influencing them, and the partial correlation coefficients built in the equations for Beregszász. r^2 is the coefficient of multiple determination, the other applied notations are the same as in *Table 3*.

	Equation of multivariate linear regression	*r2*	**Partial correlation coefficients**	
			D	***NES***
Δt/heating	$= 1.652 - 0.000274 \times D + 0.709 \times NES$	0.650	–0.665	0.513
Δt/non-heating	$= 1.679 - 0.000273 \times D + 0.319 \times NES$	0.732	–0.737	0.309

Correlation analysis was carried out to verify our model. Mean maximal UHI intensity values estimated by the model were correlated to mean maximal UHI intensities calculated on the base of results of a campaign of ten measurements carried out in 2010. There is a significant connection between the two datasets (r=0.86, n=41) at a level of significance of 0.1. Maximal error of the model was 0.4 °C, standard deviation of error was under 0.2 °C.

4. Conclusions

Our attempt to elaborate a model describing the spatial pattern of UHI in a small town has proved to be successful from methodological aspects. The multivariate linear regression model created by the integration of two surface factors as ratio of non-evaporating surfaces and distance of measurement points from the settlement center describes the structure of UHI in our study area well. A part of spatial pattern of thermal excess developed in the built-up area could not be interpreted by the regression model, what can be a result of measurement bias on one hand and factors not taken into consideration in the model on the other hand. A continuation of this research for this reason could be to integrate new surface parameters into the model like sky view factor (SVF) and aspect ratio (H/W), which can have a significant impact on UHI formation as well.

According to literature and our previous examinations, the limit of the development of urban heat island is under 1,000 inhabitants. Our results provide better knowledge on spatial structure of UHI in small settlements. It is important, since small settlements have different structures from cities making it impossible to study the spatial and temporal characteristics of those heat islands on the basis of simple extrapolation of results for big cities.

Most advantageous location of new buildings and green areas can be found using UHI maps. Human comfort conditions of public spaces could be improved by the establishment of smaller parks in central areas of the town, while heating energy demand could be decreased by more compact built-up in residential areas. This way our results could be applied in spatial planning.

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