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Simulation of the mean urban heat island using 2D surface parameters: empirical modelling, verification and extension

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ABSTRACT: The spatial distribution of the annual mean urban heat island (UHI) intensity was simulated applying empirical models based on datasets from urban areas of Szeged and Debrecen, using simple and easily determinable urban surface cover variables. These two cities are situated on the Alföld (Great Hungarian Plain) and have similar topographic and climatic conditions. Temperature field measurements were carried out, Landsat satellite images were evaluated, and then one- and multiple variable models were constructed using linear regression techniques. The selected multiple-parameter models were verified using independent datasets from three urban settlements. In order to obtain some impression of the mean UHI patterns in other cities with no temperature measurements available, the better model was extended to urban areas of four other cities situated in geographical environments similar to Szeged and Debrecen. The main shortcoming of typical empirical models, namely that they are often restricted to a specific location, is overcome by the obtained model since it is not entirely site but more region specific, and valid in a large and densely populated area with several settlements. Copyright © 2009 Royal Meteorological Society

KEY WORDS mean urban heat island; satellite images; NDVI; urban surface cover parameters; geoinformatic methods; multiple-variable linear regression; empirical model equation; verification; extension

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1. Introduction

Urban environments differ significantly from the surrounding natural lands because they have different surface geometry, material and air composition, and they provide sources of significant artificial heat release from buildings, traffic and people. This modification leads to a local-scale alteration of climate: e.g. the formation of the urban heat island (UHI). This is a positive thermal alteration: the city is usually warmer than its surroundings. Heat islands are of different types: UHI under the surface, on the surface, in the urban canopy layer (UCL) and in the urban boundary layer (Oke, 1982). This study looks at the heat island in the UCL where most human activities usually take place. Its magnitude or intensity (marked ΔT) is defined as a temperature difference between the air within the UCL (at a few metres above ground) and that measured in the background rural area at similar heights. In general, the UHI in the UCL is weak or absent in the daytime but increases rapidly after sunset, reaching its maximum 3–5 h later. Thereafter it gradually declines through the rest of the night (Oke, 1981, 1987). In middle latitude cities this UHI effect has dual characteristics: in summer it can increase the energy needs of air-conditioners and cause thermal stress for city-dwellers because of the slowly cooling air at night. On the other hand, in winter this same influence is advantageous, since the heating demand of buildings and the length of the heating period decrease. Furthermore, the composition of urban vegetation is changed and there seems to be a shift in phenological phases (e.g. Landsberg, 1981; Kuttler, 2006). Because of the large number of city dwellers and urban planning considerations, research on the UHI is an important issue, and is, therefore, rather complex and extensive worldwide.

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. The range of numerical models is very broad and they are continuously being developed and refined (e.g. Masson, 2006). They are used for simulating the wind field, pollutant dispersion, thermal climate and its effects on energy demand and human comfort. Physical models can be applied for studies on surface roughness, flow and dispersion patterns, radiative transfer and surface energy balance (e.g. Kanda, 2006). Empirical models include statistical algorithms, parameterizations, engineering formulae and qualitative conceptualization. These types of models assume stationarity and temporal representativeness of the training sample. Their advantage is that they are based on observed

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statistical properties, but their disadvantage is that they are often restricted to a specific location.

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 (including variables describing surface properties) which influence its formation. Thus, these models may provide useful quantitative information on the roles of the above mentioned parameters in the development and spatial distribution of the UHI (e.g. Oke, 1981; Park, 1986; Kuttler *et al.*, 1996; Unger *et al.*, 2001b; Fortuniak, 2003; Bottyán *et al.*, 2005; Alcoforado and Andrade, 2006; Giridharan *et al.*, 2007).

The spatial distribution of ΔT exhibits strong seasonal and diurnal variations as a result of meteorological and urban characteristics and location (Oke, 1987). Simplifying the factors of location (topography, water bodies) to a flat area and considering the annual mean UHI, its form and size are mainly a result of the urban factors (Lowry, 1977; Unger *et al.*, 2001a). The quantitative determination of the role of factors affecting the UHI intensity is difficult because of the complex vertical and horizontal structure of the cities. As an example, Table I gives a short review on studies which simulate ΔT using partly or entirely urban surface features as independent variables. It is to be mentioned that the weakness of most of the studies listed is the lack of validation.

As the studies mentioned in Table I show, detailed data collection is complicated and requires significant technical investment. Our assumption is that satellite images of the settlements situated on a plain (with simple morphology, no orographical influence) can serve as a tool to estimate the annual mean UHI intensity, because some parameters (e.g. covered or built-up surfaces) of the modified urban environment can be easily determined through the evaluation of these images.

The objectives of this study are threefold: (1) simulation of the spatial distribution of the mean UHI intensity applying one- and multiple parameter empirical models based on datasets from urban areas (Szeged and Debrecen) containing temperature values as well as simple and easily determinable surface cover variables; (2) verification of the selected multiple parameter models using independent urban datasets, and, (3) extension of the better model to other urban areas situated in geographical environments similar to those of Szeged and Debrecen with no temperature measurements available.

Experiments to model the spatial distribution of canopy layer ΔT for relatively large (several dozens of km^2 or more) urban areas are rather scarce. To the authors' knowledge, only a few examples are to be found in the literature. Some of them are listed in chronological order as follows: a numerical model for a 140 km^2 area of Christchurch, New Zealand (Tapper *et al.*, 1981); empirical models for a ~120 km^2 area of Lodz, Poland (Fortuniak and Klysik, 1998); for a ~700 km^2 area of Göteborg and its wide surroundings (Svensson *et al.*, 2002); for a ~30 km^2 area of Szeged, Hungary (Bottyán and Unger, 2003); for a ~30 km^2 area of Debrecen, Hungary (Bottyán *et al.*, 2005) and a numerical model

Table I. Survey of studies using statistical models for simulation of UHI intensity (ΔT) using partly or entirely urban surface factors.

Dependent variable	Independent variable	Reference
Seasonal mean ΔT	Terrain parameters, density of urbanisation, building height	Goldreich (1970)
Mean ΔT	Areal ratios of land-use types	Park (1986)
ΔT	Built-up area, height, wind speed, time, temperature amplitude	Kuttler *et al.* (1996)
ΔT	Proportionality factor (depends on artificial surface ratio, wind speed)	Fortuniak and Klysik (1998)
ΔT for T_{avg}, T_{max}, T_{min}	Normalised Difference Vegetation Index, surface temperature (satellite-based)	Gallo and Owen (1999)
Annual and seasonal mean ΔT	Distance from the city centre, built-up ratio	Unger *et al.* (2000)
Seasonal mean ΔT	Built-up ratio, water surface ratio, sky view factor, building height	Bottyán and Unger (2003)
Mean ΔT	Artificial surface ratio, natural surface ratio, roughness, Normalised Difference Vegetation Index, thermal admittance, artificial heat flux	Szymanowski (2003)
Seasonal mean ΔT	Built-up ratio	Bottyán *et al.* (2005)
ΔT	e.g. green area ratio, sky view factor, built area ratio, total height-to-floor area ratio, surface albedo, proximity to sea	Giridharan *et al.* (2005)
ΔT	e.g. green area ratio, water surface area ratio, built-up ratio, altitude	Alcoforado and Andrade (2006)
Seasonal mean ΔT	e.g. green area ratio, total floor area ratio, sky view factor, surface albedo, proximity to sea, altitude	Giridharan *et al.* (2007)

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for a ∼400 km^2 area of Rome, Italy (Bonacquisti *et al.*, 2006). The present study, which is more region than site specific, can be regarded as an attempt to partly compensate for this deficiency.

2. Study areas

On the basis of their geographical situation, Hungarian cities can be divided into three classes: cities located (1) in a valley, (2) at the junction of a mountainous (or hilly) area and a plain, and, (3) on a plain. From the point of view of urban climate development, separation of the effects caused by topography and human activity is very difficult for cities in the first two classes. Cities in the third class, however, have favourable conditions for clear urban climate development. Thus, results of systematic measurements and analysis in this type of cities can lead to general conclusions (Unger *et al.*, 2001a; Bottyán *et al.*, 2005).

All the investigated cities are situated on the Alföld (Great Hungarian Plain), on Holocene sediments with a gentle relief, so they belong to the third category mentioned above (Figure 1). The area of the plain is about 100 000 km^2 and is shared by six countries (Hungary, Slovakia, Ukraine, Romania, Serbia and Croatia). According to Trewartha's (1980) climate classification, the whole plain belongs to the climatic type D.1 (continental climate with longer warm season).

Datasets from Szeged (population 165 000) and Debrecen (population 204 000) were used to construct empirical models. The measurements and modelling focused on the urbanized areas, about 30 km^2 for both cities. They have different city structures: Szeged has one densely built central area and an avenue-boulevard street system (Unger *et al.*, 2001b). Debrecen has a less regular street network and its most densely built areas are located in different parts of the city (Bottyán *et al.*, 2005). For verification purposes datasets from three settlements near Debrecen (Hajdúböszörmény, Hajdúdorog and Hajdúnánás) were used (Figure 1).

According to our project plan, the annual mean UHI patterns of 15 cities with different sizes and population, situated on the Great Hungarian Plain, were to be modelled regardless of the existing country borders. The studied cities are as follows: Baja, Békéscsaba, Cegléd, Hódmezovásárhely, Karcag, Kecskemét, Kiskunfélegyháza, Makó, Nagykoros, Nyíregyháza, Orosháza and Szolnok in Hungary; Arad and Timisoara in Romania; and Subotica in Serbia. In this paper only four of these cities (Karcag, Békéscsaba, Kecskemét and Arad, in increasing size order) are presented as examples. The characteristics of the investigated settlements are presented in Table II.

3. Dependent variable: UHI intensity

For the information on the UHI intensity (as a dependent variable) and its pattern, temperature data were collected by mobile measurements in the urban areas of Szeged and Debrecen (Figure 2(a) and (b)) divided into 0.5 × 0.5 km grid cells. The same cell size of 0.25 km^2 was applied in several other urban climate projects (e.g. Park, 1986; Svensson *et al.*, 2002). According to Oke (2004), the circle of influence on a screen level (∼1.5 m) temperature is believed to have a typical radius of about 0.5 km. So this 0.5 × 0.5 km mesh is reasonable to simulate night temperatures in urban canopies. The study areas consisted of 107 cells (25.75 km^2) in Szeged and 105 cells (26 km^2) in Debrecen, and covered the inner and suburban parts of the cities. One rural cell in both cities was used as a reference area for the comparison of temperature data. These cells (labelled R) are located outside of the cities and their areas can be characterized as agricultural, consisting of mainly vegetable gardens, non-irrigated wheat and maize fields (Figure 2(a) and (b)). These cells were also regarded as rural in previous urban climate studies in Szeged and Debrecen (e.g. Unger *et al.*, 2001b; Bottyán *et al.*, 2005).

The required data were collected with cars on assigned routes, in a 1 year period between April 2002 and March 2003. This type of mobile measurement is widespread

Table II. Characteristics of the investigated settlements and their divison by the study purposes.

Purpose	Settlements	Population	Geographical coordinates	Elevation (m)	Study area (km^2)	Mean January temperature (°C)	Mean July temperature (°C)	Mean annual precipitation (mm)
Model construction	Szeged	165 000	46.0°N, 20.0°E	84	26.75	−1.8	20.3	496
	Debrecen	204 000	47.5°N, 21.5°E	121	26.25	−2.6	20.8	566
Verification	Hajdúböszörmény	29 000	47.5°N, 21.5°E	121	12.25	−2.6	20.8	556
	Hajdúnánás	18 000	48.0°N, 21.5°E	97	6.75	−2.6	20.7	542
	Hajdúdorog	10 000	48.0°N, 21.5°E	110	4.25	−2.7	20.7	548
Extension	Karcag	23 000	47.0°N, 21.0°E	87	8.50	−2.2	21.3	520
	Békéscsaba	65 000	46.5°N, 21.0°E	90	20.75	−1.6	22.6	555
	Kecskemét	110 000	47.0°N, 19.5°E	122	30.25	−1.8	21.9	518
	Arad	191 000	46.0°N, 21.0°E	111	39.50	−1.2	21.6	631

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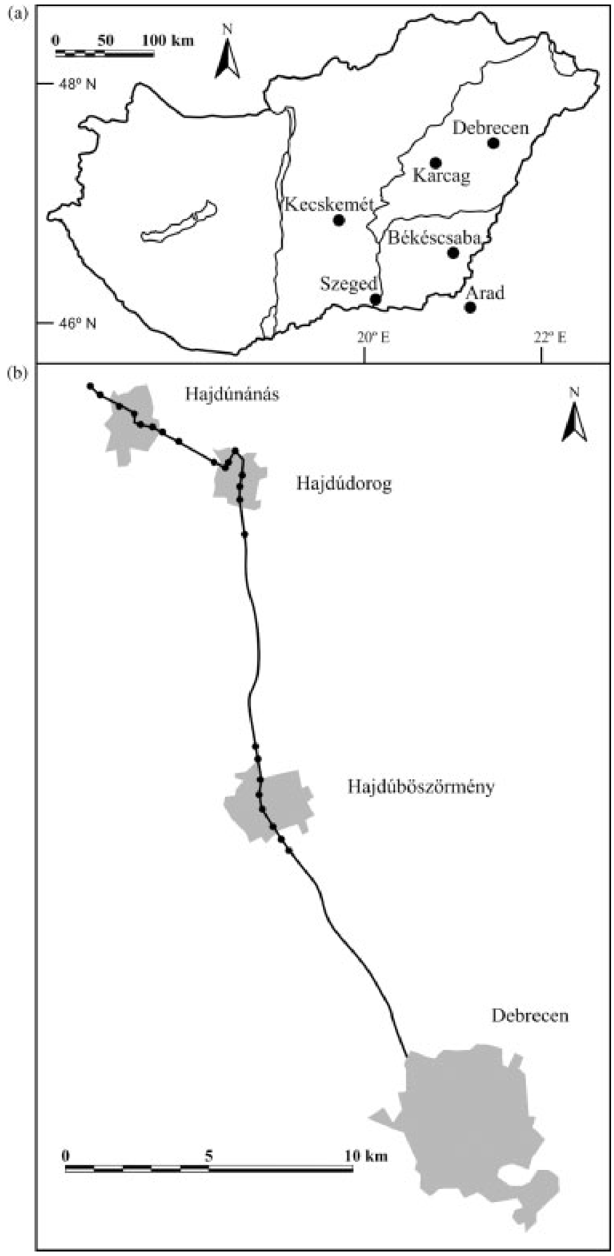

Figure 1. Location of the investigated cities on the Alföld (Great Hungarian Plain) with the outline of Hungary (a) and the towns near Debrecen with sections on the measurement route (b).

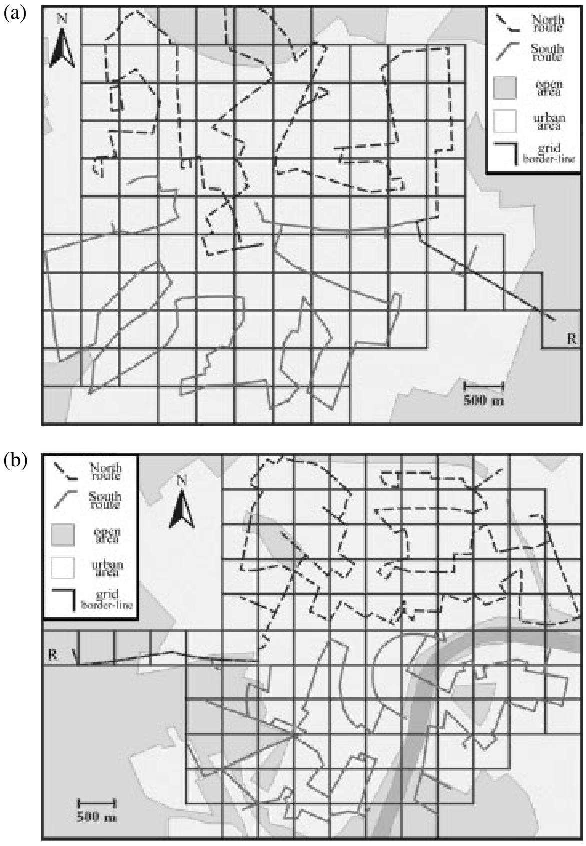

Figure 2. Study areas with grid network and routes of the mobile UHI measurements (a) in Debrecen and (b) in Szeged (R = rural cell).

in observing urban climate parameters (e.g. Oke and Fuggle, 1972; Moreno-Garcia, 1994). The measurements took place at a frequency of about 10 days in Szeged and Debrecen simultaneously, altogether 35 times in both cities, and they took 3 h to complete. They were carried out under all kinds of weather conditions except rain. Rainy conditions and the resulting wetness in the surface layer make the urban–rural temperature differences disappear. The exclusion of rainy days might result in a bias in the value of the annual mean ΔT, but it is probably rather small because of the relatively dry and warm climate of the investigated region (Section 2 and Table II). Based on experiences from previous studies, data collection took place at around the expected time of the daily maximum development of the UHI, which is 4 h after sunset (Unger, 2004; Bottyán *et al.*, 2005). This value is also supported by other studies (e.g. Oke 1981, 1987).

The study areas were divided into two sectors because of their size and the length of the measurement routes. The routes were planned to cover all the cells at least once both on the way there and back (Figure 2(a) and (b)) in order to make time-based corrections (Unger, 2004). The temperature was measured every 10 s by an automatic sensor connected to a digital data logger. It was placed on a bar 1.45 m above the ground and 0.6 m in front of the car to avoid the thermal disturbance of the car's engine. The speed was 20–30 km h^{-1} in order to provide for the necessary ventilation for the sensor and a proper density of data. This provided data from every 55 to 83 m along the measurement routes. The values logged at the unintentional stops (e.g. red lights, cross-roads) were later deleted from the datasets. The temperature data measured during each night were averaged by cells. Consequently, a single temperature value was assigned to every cell. A linear change of temperature was applied to the time adjustments of the data measured in the hours after sunset, with the assumption that it is only approximately valid in the suburban areas because of the different cooling gradients (Oke and Maxwell, 1975). This linear change was monitored using the continuous records of the automatic weather station at the University of Szeged located near the city centre (Unger *et al.*, 2001b). Height-dependent temperature corrections are not an issue as the areas are very flat (with only a few metres of elevation difference).

In our case the UHI intensity (ΔT) by cells is defined as follows (Unger *et al.*, 2001b):

$$\Delta T = T_{\text{cell}} - T_{\text{cell (R)}} \tag{1}$$

where T_{cell} = (average) temperature of an urban cell, $T_{\text{cell(R)}}$ = (average) temperature of the rural cell. Annual mean ΔTs were determined by averaging the ΔT values of the 35 measurements by cells.

4. Independent variables

As independent variables for estimating the UHI field, 2D urban surface cover data and distance from the city boundary were determined for each element of the 0.5×0.5 km mesh in the study areas in Szeged and Debrecen.

4.1. Surface cover parameters

The artificially covered surface ratio (streets, pavements, parking lots, roofs), or built-up ratio, (B_0), horizontally characterizes the surface of a settlement. This parameter was determined for each cell using GIS (Geographical Information System) methods combined with the remote sensing analysis of Landsat satellite images (Unger *et al.*, 2001b), not only for the study areas used for the temperature measurements, but also for their extensions of 1.5 km in every direction (see the last paragraph in this section). The accuracy of the polynomial geometric correction was less than 1 pixel (total RMS error was 0.3), and nearest neighbour resampling method was employed to get new pixel values in the new grid system. The geometric resolution of the images was 30×30 m. The satellite images were taken in 2003, so they provide accurate data on the current built-up conditions. Normalized Difference Vegetation Index (NDVI) was calculated from the pixel values, using the following equation (Gallo and Owen, 1999):

$$\text{NDVI} = (IR - R)/(IR + R) \tag{2}$$

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 depending on the quality of the surface cover (vegetation, water) (Lillesand and Kiefer, 1987). The vegetation has relatively high near-infrared reflectancy and low red reflectancy, therefore the index is positive. Its value depends on the amount of biomass, so in an area with grass vegetation, the value of the NDVI ≈0.2–0.5. If there is rich vegetation, the NDVI ≈0.5–1 (this means a full vegetation cover, that is the pixel is completely covered with vegetation and the thickness of this vegetation is significant (e.g. forest)). In the case of bare rock, asphalt and concrete, the value is around zero, since the reflectancies of red and near-infrared are nearly equal. Water surface has high red reflectancy and low near-infrared reflectancy, for this reason the value approaches −1. So, the ratio of water, built-up and vegetation surfaces in each cell can be determined with this index.

It is important to consider the surface conditions around the cells, because the wider surroundings can influence the temperature of a given cell. In order to take the effect of the surroundings into account, a set of derived variables (concentric areal extensions around the cells) can be defined from the built-up ratio in the following way, similar to Bottyán and Unger (2003) and Bottyán *et al.* (2005):

- parameter B_0 = built-up ratio value (%) in the grid cell with $\Delta i^2 + \Delta j^2 = 0$
- parameter B_1 = average built-up ratio value (%) of all grid cells with $1 \leq \Delta i^2 + \Delta j^2 < 2^2$
- parameter B_2 = average built-up ratio value (%) of all grid cells with $2^2 \leq \Delta i^2 + \Delta j^2 < 4^2$

Here, *i* and *j* are cell indices in the two dimensions, and Δi and Δj are the differences of cell indices with respect to a given cell. Figure 3 shows the considered cell structure for the calculation of parameters B_1, B_2. The distinction of urban and rural cells based on an arbitrary value of B_0: if $B_0 < 5\%$ then the cell is considered rural, otherwise urban. The obtained zones of surface variables cover the entire study areas and their 1.5 km wide extensions in the investigated settlements (see Sections 6 and 7). The 1.5 km wide extensions are needed in the

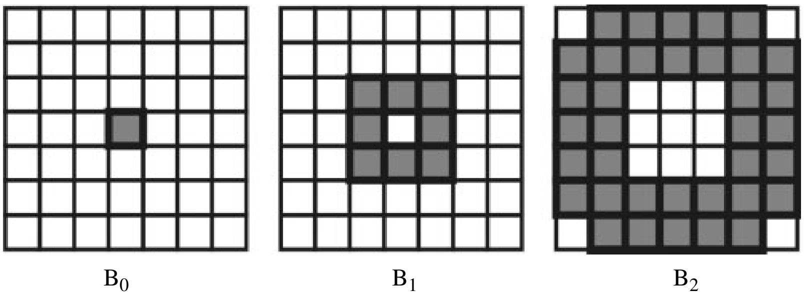

Figure 3. Cells which take part in the calculation of B_0, B_1, B_2 surface parameters.

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calculations of B_1 and B_2 parameters for cells near the edges of study areas.

4.2. Distance from the city boundary

Unger *et al.* (2000) and Svensson *et al.* (2002) draw attention to the relationship between the distance and the UHI intensity. The distance (from the city centre or from the boundary) can be regarded as a parameter that characterizes the location of a place inside the city. Unger *et al.* (2000) presented a relatively strong ($R^2 = 0.7$) linear relationship between the annual mean ΔT and the distance from the city centre in Szeged based on datasets from 1999 to 2000.

Fortuniak (2003) found a logarithmic dependence of ΔT on the distance (D) from the city boundary, so assuming that the city population (P) is proportional to the urban area this relationship explains the logarithmic relation between the population and the maximum UHI intensity proposed by Oke (1973) and Park (1986). That is, considering the areas with the same building structure and design in the suburbs and in the centre, a reduced ΔT can be experienced in the suburbs compared to that in the centre.

In the present study the distance from the city boundary (D in m) is considered. This D is defined as the distance between a given cell inside the study area (with a built-up ratio of B_0) and the nearest cell with a built-up ratio of less than 5% outside the study area (Figure 4).

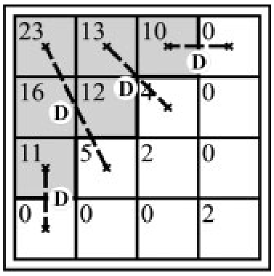

Figure 4. Examples for the determination of the distance (D) (thick line is the border of the study area, thin line is the cell border, numbers are the built-up ratios by cells in %).

4.3. Combined parameters

In order to take into account the common roles of distance (D) and the above-mentioned surface parameters (built-up ratio (B_0) and its areal extensions (B_1, B_2)) in the formation of the UHI, some new combined urban parameters were constructed (marked by apostrophes: B_0', B_1' and B_2'). Based on the work of Fortuniak (2003), distance is considered as $\ln D$. So the combined parameters are generated by multiplying (or weighing) the surface parameters by the logarithmic distance by cells:

- parameter $B_0' = B_0 \times \ln D$,
- parameter $B_1' = B_1 \times \ln D$,
- parameter $B_2' = B_2 \times \ln D$,

The dimension of the obtained parameters should be '% m' because of the multiplication, but it could better and simpler be regarded as 'dimensionless'.

5. Construction of the multiple-parameter models

5.1. Connection between the independent variables and ΔT

In the study areas of Szeged and Debrecen a range of 0–85.5% was found for the built-up ratio. Figure 5

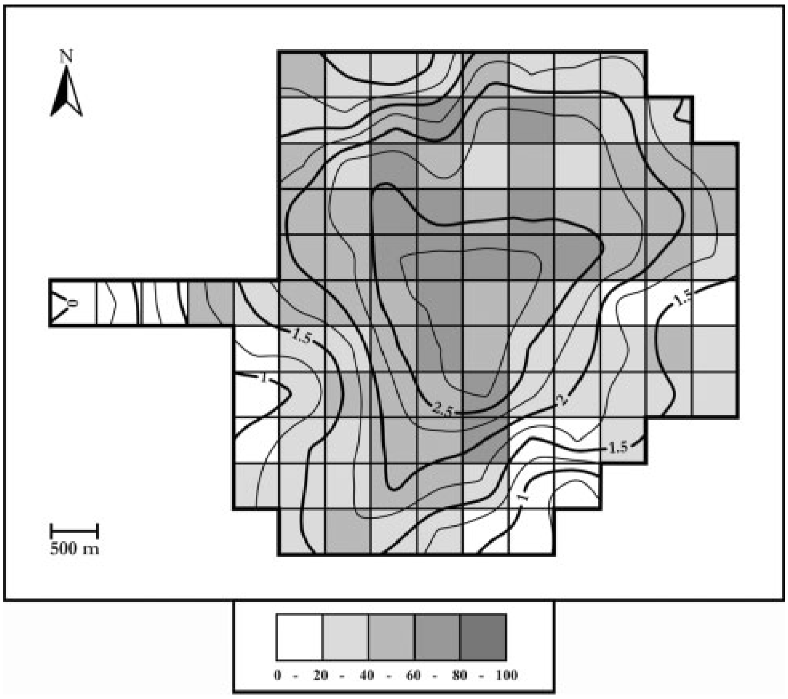

Figure 5. Spatial distribution of the built-up ratio (%) and the mean UHI intensity (°C) in Szeged (2002–2003).

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shows the connection between the spatial distribution of the annual mean ΔT and B_0 for Szeged (Debrecen not shown): UHI intensity values follow the change of built-up values, so the distribution of the intensity is roughly concentric, which is the consequence of the rather concentric structure of the city. Here and in the following figures the standard Kriging method and linear variogram model of Surfer 8 software were used to interpolate the temperature values by cells and for the spatial tracing of the isotherms (for details on the method see Chiles and Delfiner, 1999; Emery, 2006).

The relative roles of the chosen independent variables on the development of mean UHI intensity patterns were investigated separately, using datasets from Szeged and Debrecen together (212 element pairs), where the elements of the one-parameter models are the following:

–ΔT (mean of the 35 measurements), as variable parameter (°C),
–B_0 or D or $\ln D$, as invariable parameter (%).

The first part of Table III contains the obtained simple one-parameter model equations and the related statistical measures. As the values show, a relatively strong positive relationship can be observed between the annual mean ΔT and the built-up ratio by cell, namely the temperature difference increases as the built-up ratio increases. There are also positive relationships in the cases of D and $\ln D$, which means ΔT increases as distance from the city edge increases. These parameters explain 91.7, 91.4 and 92.2% of the variation in the urban heat island intensity distribution, respectively.

5.2. Two multiple-parameter models approaching ΔT

First, the relationship between the three surface cover parameters (B_0, B_1, B_2) and the annual mean UHI intensity were determined quantitatively. As mentioned earlier, our aim was to construct a general multiple-parameter model based on data from Szeged and Debrecen which can be used for the estimation of mean ΔT patterns in other settlements situated on a plain. The elements of the first multiple parameter model are the following:

–ΔT, as variable parameter (°C),
–B_0, B_1, B_2, as invariable parameters (%).

Stepwise multiple regression analysis of the SPSS 11 software was used to compute the first model equation (for details on the method see Cohen *et al.*, 2003):

$$\Delta T = 0.008 \times B_0 + 0.019 \times B_1 + 0.020 \times B_2 \qquad (3)$$

As the second part of Table III shows, B_1 is the most important parameter. Using B_2 and B_0, only slight improvements can be achieved (0.6 and 0.3%, respectively). The three parameters altogether explain 97.1% of the variation in the urban heat island intensity distribution across the studied cities. Model 1 has a root mean square error of estimation of 0.3 °C and the significance level is less than 0.001.

Second, the relationship between the obtained combined urban surface parameters and the annual mean UHI intensity were determined. The elements of the second multiple-parameter model are the following:

–ΔT, as variable parameter (°C),
–B_0', B_1', B_2', as invariable parameters (‘dimensionless’).

The second model equation takes the following form:

$$\Delta T = 0.001 \times B_0' + 0.002 \times B_1' + 0.003 \times B_2' \qquad (4)$$

At the construction of Model 2, B_1 is again the most important parameter. Involving more invariable parameters, B_2 and B_0, the explanation only slightly improved (0.6 and 0.2%, respectively). These three parameters also explain the variation in ΔT in the same order as at Model 1 (97.1%). Model 2 also has a root mean square error 0.3 °C and the significance level is less than 0.001 (see last part of Table III). Figure 6 presents the difference maps of observed – modelled ΔT in Szeged and Debrecen. These differences are under 0.5 °C in most parts of the investigated areas for both cities. Areas with differences larger than 0.5 °C only cover a few cells.

Both three-parameter models mean 5–6% improvement on the one-parameter models.

Table III. Obtained model equations and their related statistical measures: deterministic coefficient (R^2), improvement in explanation (ΔR^2), root mean square error (RMSE), significance level (p) ($n = 212$).

Invariable parameters	Modell equation	R^2	ΔR^2	RMSE (°C)	p
B_0	$\Delta T = 0.040B_0$	0.917	–	0.514	<0.001
D	$\Delta T = 0.001D$	0.914	–	0.522	<0.001
$\ln D$	$\Delta T = 0.238 \ln D$	0.922	–	0.499	<0.001
B_1	$\Delta T = 0.04434B_1$	0.962	–	0.347	<0.001
B_1, B_2	$\Delta T = 0.02780B_1 + 0.01934B_2$	0.968	0.006	0.321	<0.001
B_1, B_2, B_0	$\Delta T = 0.008183B_0 + 0.01902B_1 + 0.01970B_2$	0.971	0.003	0.308	<0.001
B_1'	$\Delta T = 0.005770B_1$	0.963	–	0.378	<0.001
B_1', B_2'	$\Delta T = 0.003537B_1 + 0.002614B_2$	0.969	0.006	0.349	<0.001
B_1', B_2', B_0'	$\Delta T = 0.001032B_0 + 0.002455B_1 + 0.002629B_2$	0.971	0.002	0.306	<0.001

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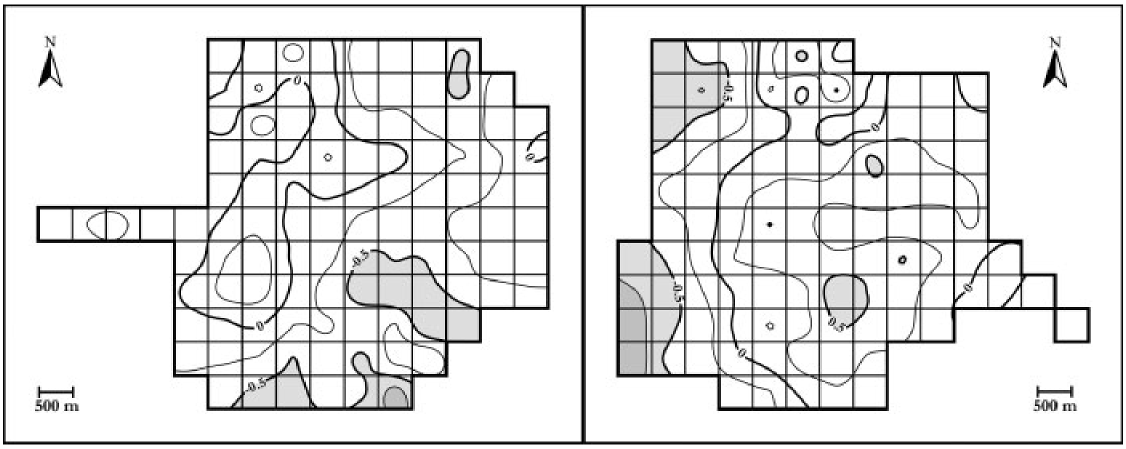

Figure 6. Patterns of observed – modelled (Model 2) difference in ΔT (°C) in Szeged (a) and Debrecen (b). Areas with difference ≥ 0.5°C marked by shading.

Based on the ranges of the applied datasets from Szeged and Debrecen, the obtained model equations can be regarded as valid in the intervals presented in Table IV. These equations have no constant: therefore, if the invariable parameters are equal to zero, the equations give an UHI intensity of zero. It is in line with the experience that the unbuilt or barely built areas do not generate any temperature excess.

6. Model verification

In order to test the obtained model equations properly, we need to use temperature datasets independent from those of Szeged and Debrecen which represent data observed in settlements having similar environmental conditions.

Between September 2003 and January 2005 mobile temperature measurements were taken simultaneously in three towns (Hajdúböszörmény, Hajdúdorog and Hajdúnánás) situated on a flat area. The measurements were carried out by Szegedi (2005) under different weather conditions, altogether 24 times. These settlements are situated near Debrecen, so they have similar topography and climate, but they are smaller than Debrecen (Figure 1). They have avenue-boulevard-like street structures, which are favourable for the development of a regular heat island structure type. The observed mean ΔT values are available as average values referring to the numbered route sections (Figure 7). These route sections were established according to the land-use types of these towns. Rural sections are numbered 1 and 7 but they are not shown on Figure 7. Table V contains the mean observed and estimated UHI intensities by Model 1 and Model 2 for these sections by settlement.

Table IV. Validity intervals of the obtained models based on the datasets of Szeged and Debrecen (together).

Parameter	Min.	Max.
B_0 (%)	0	85.5
B_1 (%)	0.1	63.1
B_2 (%)	8.1	49.7
B_0' (−)	0	675
B_1' (−)	0	498
B_2' (−)	0	390
D (m)	0	3162
ΔT (°C)	0	2.96

Hajdúböszörmény has 29 000 inhabitants and its (mostly urban) study area consists of 49 cells (12.25 km^2). Here the annual mean UHI intensity is 0.9 °C in the centre according to the temperature measurement, and the estimated ΔTs are 1.11 and 1.02 °C, respectively. Hajdúnánás has a population of 18 000 and its study area consists of 27 cells (6.75 km^2). The observed mean ΔT is 0.7 °C in the centre, while the estimated values are 0.50 and 0.48 °C, respectively. With a population of 10 000, the smallest town, Hajdúdorog, has a study area of 17 cells (4.25 km^2). Here the observed and estimated mean UHI intensities are 0.3 °C, as well as 0.39 and 0.34 °C in the centre, respectively (Figure 7, Table V).

According to Table V there are two sets of 15 element pairs of (observed – ΔT_{obs} and modelled – ΔT_{mod1} and ΔT_{mod2}) UHI intensity for verification purposes. The fitted linear regression lines for modelled versus observed values are:

$$\Delta T_{\mathrm{mod1}} = 0.83\Delta T_{\mathrm{obs}} + 0.11\ (R^2 = 0.774) \quad (5)$$

$$\Delta T_{\mathrm{mod2}} = 0.84\Delta T_{\mathrm{obs}} + 0.06\ (R^2 = 0.816) \quad (6)$$

The coefficients (0.83 and 0.84) suggest a slight underestimation in the modelled ΔT values partly compensated with the constants (0.11 and 0.06) compared to the ΔT_{obs} values. In both cases the values of the coefficient of determination (R^2) mean significant relationship between these elements even at 1% level ($n = 15$). So there is good correspondence between the measured and estimated values in both models.

7. Model extension

In order to extend the estimation of annual mean patterns of UHI intensity to other settlements, one of the obtained

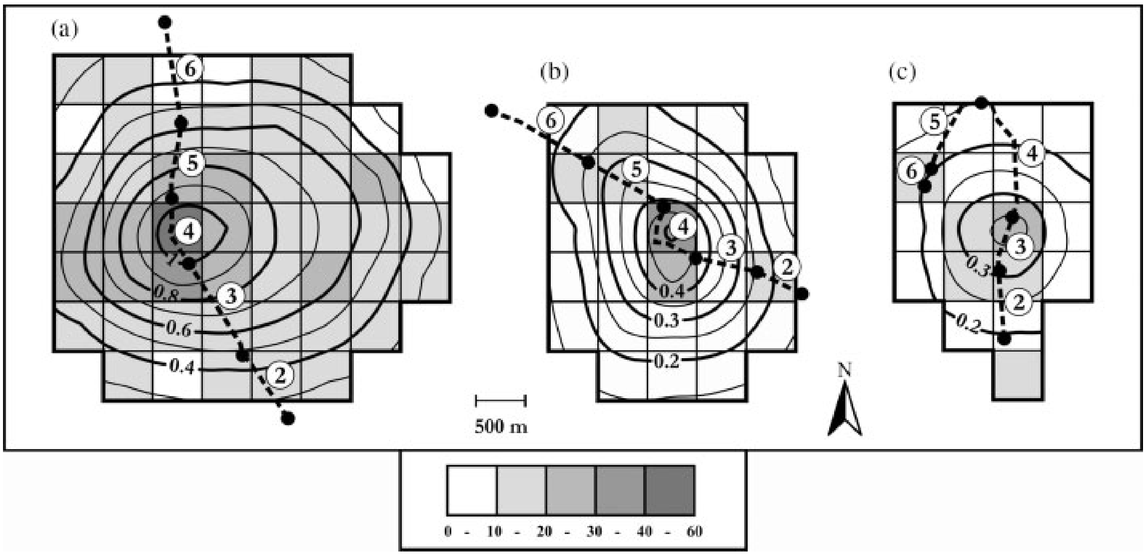

Figure 7. Spatial distribution of the built-up ratio (%) and the predicted (Model 2) mean UHI intensity (°C) for Hajdúböszörmény (a), Hajdúnánás (b) and Hajdúdorog (c) with sections on the measurement route (for explanation of numbers see Table V).

Table V. Mean observed (Szegedi, 2005) and modelled UHI intensities by land-use types (as numbered sections) in the three settlements used for verification (see also Figure 7).

Settlement	Land use type	Observed ΔT (°C)	Modelled ΔT (°C) by Model 1	Modelled ΔT (°C) by Model 2
Hajdúböszörmény	Urban edge, sparsely built (2)	0.45	0.38	0.37
	Suburban (3)	0.75	0.80	0.74
	Centre (4)	0.90	1.11	1.02
	Suburban (5)	0.75	0.81	0.76
	Industrial, sparsely built (6)	0.40	0.51	0.42
Hajdúnánás	Urban edge, sparsely built (2)	0.25	0.25	0.20
	Suburban (3)	0.50	0.38	0.34
	Centre (4)	0.70	0.50	0.48
	Suburban (5)	0.50	0.39	0.35
	Urban edge, sparsely built (6)	0.25	0.24	0.18
Hajdúdorog	Suburban (2)	0.10	0.30	0.25
	Centre (3)	0.30	0.39	0.34
	Low lying area, reed plot (4)	0.10	0.29	0.23
	Suburban (5)	0.10	0.21	0.11
	Urban edge, sparsely built (6)	0.10	0.25	0.20

multiple-parameter models has to be selected. The statistical measures of these models are very similar or the same (R^2, RMSE, p), but during the verification process Model 2 had a slighly better estimation for ΔT values measured in the towns we used for verification purposes than Model 1. Therefore Model 2 will be applied for the above-mentioned extension.

This general model can be extended to other, different-sized settlements, where the environment, like topography and climate, is similar to that of Szeged and Debrecen. As mentioned earlier, only certain Landsat satellite images of the settlements are necessary, from which the built-up ratio and its areal extensions (weighing with the long-distance from the city border) can be determined as independent variables for this purpose. The obtained model equation can be considered applicable and appropriate for other cities of different size, if the invariable parameter values of the study areas are within the intervals given in Table IV.

In this section the results of the modelling of the spatial distribution of ΔT are presented with examples in the cases of four selected cities, namely Karcag, Békéscsaba, Kecskemét and Arad (Romania), with a population range between 23 000 and 191 000 (Table II).

The smallest city, Karcag is located in the eastern part of Hungary (Figure 1) with a study area of 34 cells (8.5 km^2) (Figure 8). The number of inhabitants is 23 000. According to the simulation it has a rather regular UHI form slightly stretched out in S–N direction with a centre in its most densely built-up areas with a largest ΔT of about 0.95 °C (Figure 8).

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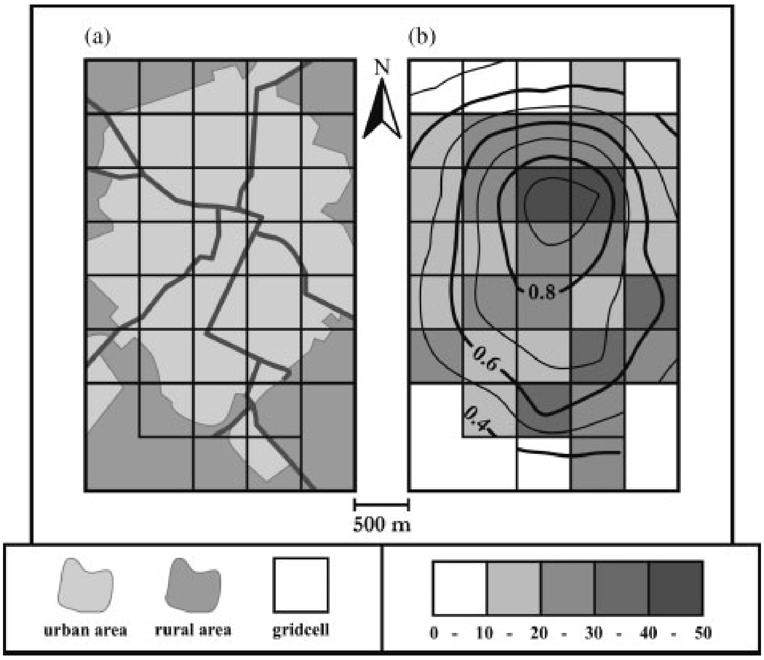

Figure 8. Study area with grid network and the main traffic lines (a), as well as spatial distribution of the built-up ratio (%) and the modelled mean UHI intensity (°C) (b) in Karcag.

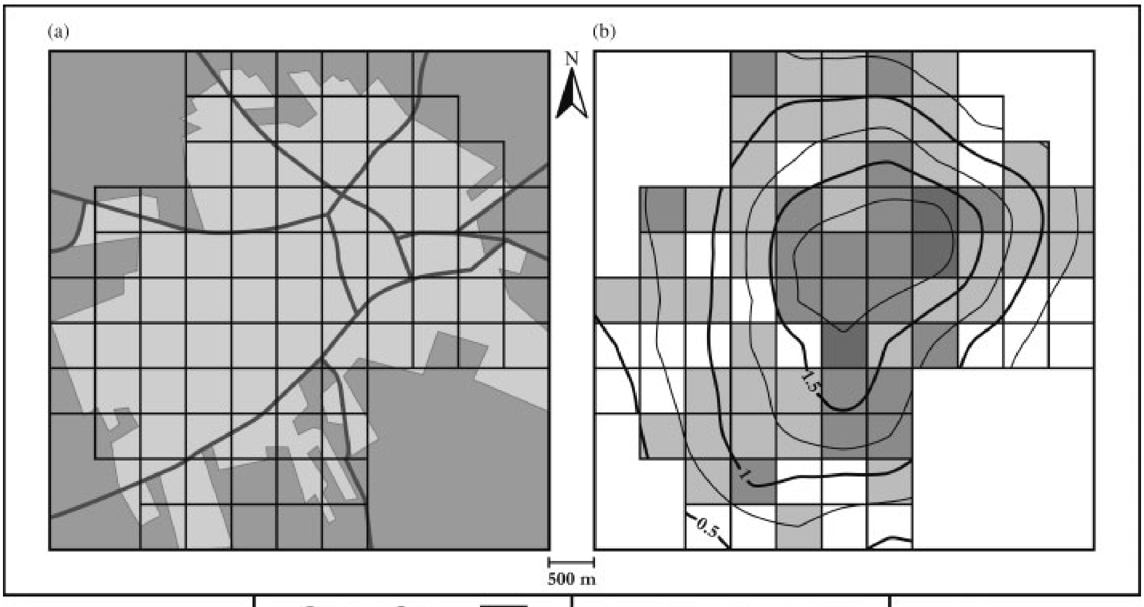

Figure 9. Study area with grid network and the main traffic lines (a), as well as spatial distribution of the built-up ratio (%) and the modelled mean UHI intensity (°C) (b) in Békéscsaba.

Somewhat larger, Békéscsaba (population 65 000) is situated in the south-eastern part of Hungary (Figure 1) with a study area of 83 cells (20.75 km^2) (Figure 9). The simulated heat island in Békéscsaba has a concentric structure with a largest ΔT value of about 1.8 °C (Figure 9).

The selected medium-sized city, Kecskemét (population 110 000) is located in the central part of Hungary (Figure 1) with a study area of 121 cells (30.25 km^2) (Figure 10). According to Model 2 it has a rather regular UHI development with a centre in the historical city core (reaching 80–90% built-up ratio) and with a largest ΔT of about 2.7 °C (Figure 10).

The largest city used for modelling purposes, Arad, is situated in Romania near the border of SE-Hungary (see Figure 1). It has a population of 191 000 and its slightly streched study area consists of 158 cells (39.5 km^2) (Figure 11). The simulated mean ΔT pattern is also

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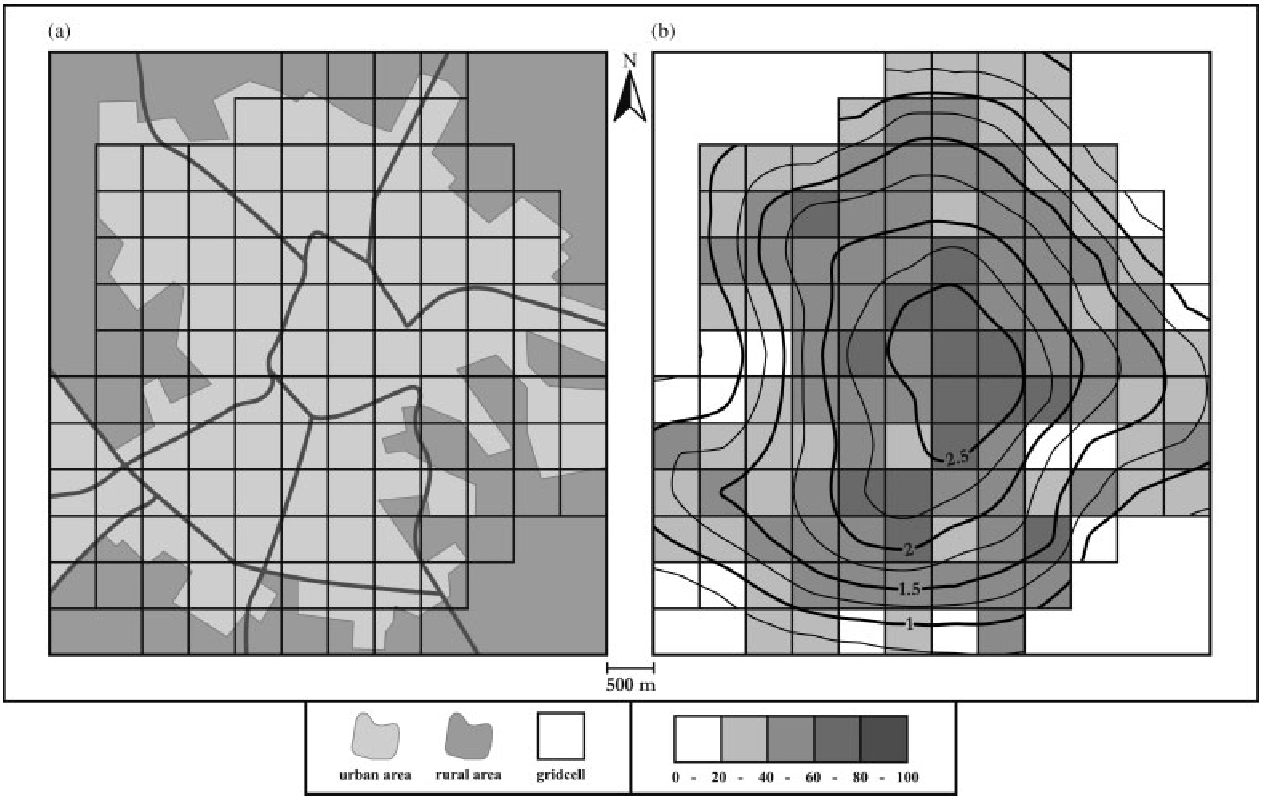

Figure 10. Study area with grid network and the main traffic lines (a) as well as the spatial distribution of the built-up ratio (%) and the modelled mean UHI intensity (°C) (b) in Kecskemét.

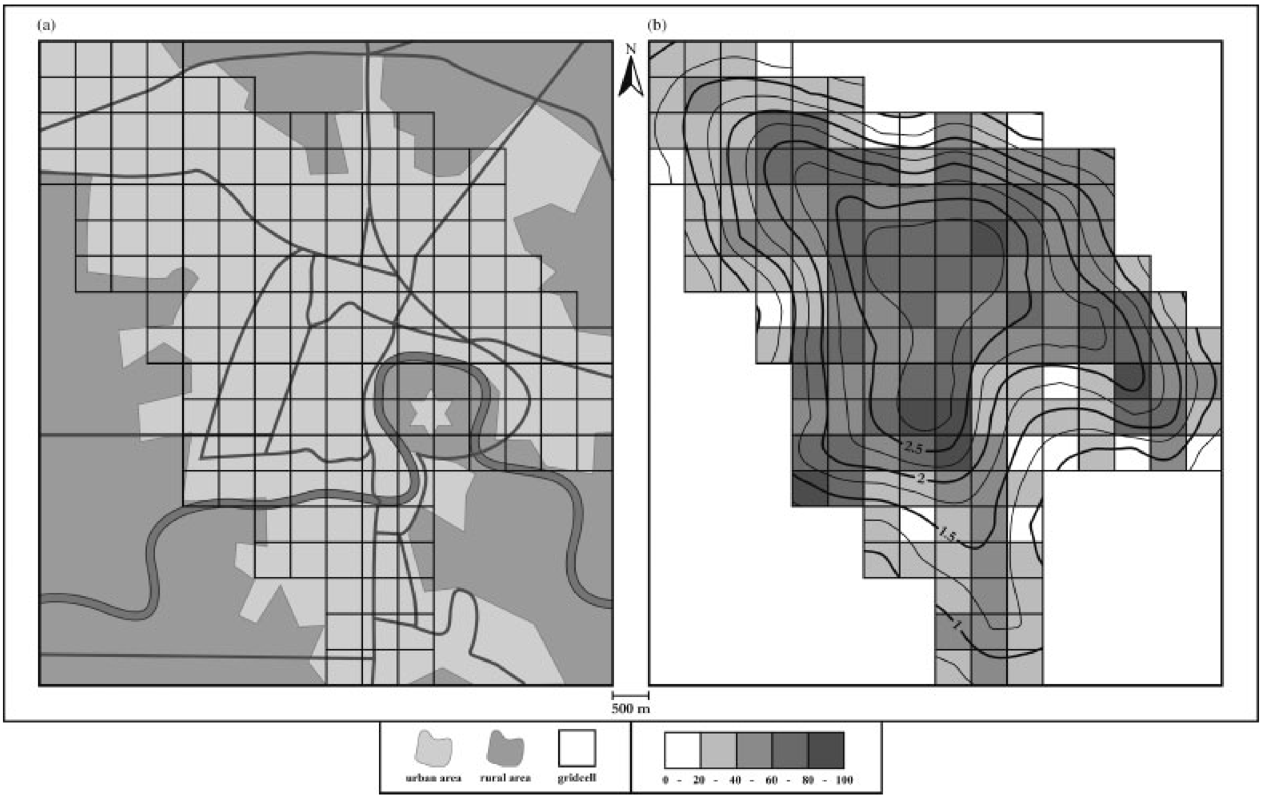

Figure 11. Study area with grid network and the main traffic lines (a) as well as spatial distribution of the built-up ratio (%) and the modelled mean UHI intensity (°C) (b) in Arad (Romania).

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concentric but it has large extensions in the directions of NW, SE and S (Figure 11), where densely built neighbourhoods are found reflecting the lesser concentric urban structure of the city. Therefore, the city has a mean UHI maximum of about 2.9 °C.

8. Conclusions

This study presented and compared several one-parameter and multiple-parameter models based on surface cover and temperature information obtained by the evaluation of satellite images and mobile surveys and then arranged into a 0.5 km × 0.5 km mesh in the urban areas of Szeged and Debrecen, Hungary. Spatial distribution of the annual mean UHI intensity as predictant was simulated using simple and easily determinable urban surface cover variables as predictors. According to the additional temperature measurements in other settlements used for validation purposes, there is a good correlation between the measured and estimated intensity values.

There are plenty of empirical models for assessing the temperature patterns in urban areas (see Table I). The main shortcoming of typical empirical models is that they are often restricted to a specific location. They are constructed directly from the statistical characteristics of the observed UHI in isolated locations using a comparison of the modelled results to the same datasets which were applied to develop the model equations. This shortcoming does not affect this study since our Model 2 is more region than site specific, valid for a large and relatively densely populated geographical area (Alföld - Great Hungarian Plain, about 100 000 km^2) with several settlements. Moreover, the model was trained against the spatial distribution of UHI intensity across the cities using generic independent variables. These settlements have similar topographic and climatic conditions to those of the base cities of the model (Szeged and Debrecen).

Therefore, the presented empirical model can be regarded as a useful tool for estimating the mean heat island patterns for cities situated on a plain and in the same climate type. The knowledge of the estimated structure of mean UHI may provide useful basic information for the development projects of neighbourhoods or cities. It is to be noted that in other regions of the world where the climate conditions (e.g. wetness) and the resulting artificial heating patterns are different, the developed model could fail.

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