Urban surface parameter (SVF, roughness) calculation using 3D urban database

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1. Introduction

Studying the altered urban environment is important because of the high number of the involved inhabitants. The surface cover and geometry differ from the rural surfaces, and the water and energy balances are modified (Oke 1987). Urban climate research focuses on this modified local climate. This is a priority topic since the prediction of the possible impacts of global climate change for urban areas is impossible without an in-depth knowledge of the features of urban climate. The two most important modifications of the climate in these areas are the altered thermal environment and the different airflow conditions, and booth of these climate modifications are primarily connected with the alteration of the geometry and material characteristics of the surface (Oke 1987).

The thermal modification often appears in urban temperatures higher than in the surrounding rural areas (urban heat island − UHI). The largest UHI, which is the strongest urban-rural temperature contrast, generally appears at night, while during the daytime the difference is moderate or absent. The main reason of the UHI is the urban-rural difference in the nocturnal cooling processes, which are primarily forced by outgoing long wave radiation. In urban areas the 3D geometrical configurations of the surface plays an important role in the restriction of long-wave radiative heat loss, and contributes to intra-urban temperature variations below roof level (Oke 1981). The sky view factor (SVF) is the most appropriate parameter describing the urban geometry (Oke 1987). SVF is defined as the ratio of the radiation received (or emitted) by a planar surface and the radiation emitted (or received) by the entire hemispheric environment (Watson and Johnson 1987).

Due to the increased drag of the surface the average wind speed is lower in the cities than in the surrounding rural areas (Oke 1987). For describing the geometry or texture of the surface and as a consequence its roughness several parameters are known (Grimmond and Oke 1999). The connection between the wind and the drag force of the obstacles (buildings, vegetation) can be characterized by the zero-plane displacement height (z_d) and the aerodynamical roughness length (z_0) (Counihan 1971). These are the key parameters in studying the airflow over urban areas.

There are several options to calculate SVF values in urban environment (see Unger 2009, Chen et al 2012 for brief reviews). One way is the application of computer algorithms that requires a 3D surface database about the examined area. These methods can be separated by the input data used (raster or vector). Most of them utilize high resolution raster digital surface models containing the terrain and the buildings for computing patterns of continuous sky view factor. Their advantage is that the roof of buildings can be managed more easily; however the accuracy of the results is significantly affected by the selection of the resolution of the input data (Gál et al. 2009). There are some examples for vector-based methods as well (Gál et al. 2009, Souza et al. 2003, Matzarakis and Matuschek 2010). These scripts calculates the SVF values more accurately because the buildings are in vector format, thus the locations of the building walls are unequivocal and do not depend on the resolution.

The determination of the roughness length (z_0) and displacement height (z_d) is not straightforward and remains problematic and there are numerous ways for their assessment or calculation. Three generalized classes of these methods are available: (1) micrometeorological methods using field observations of wind and turbulence, (2) roughness classification methods using roughness classes and visual estimation, (3) morphometric (or geometric) methods using measures of surface morphometry. The last group of the methods are the most appropriate for a precise mapping process. There are several morphometric methods using surface morphology data (Counihan 1971, Bottema 1997, Grimmond and Oke 1999). These methods are based on empirical relations from wind tunnel studies concerning flows over regular building arrangements and there are only a few examples of their generalization.

The roughness parameters are widely used for wind speed reduction in urban sites where in site measurements are not available. Wind speed at 2 or 10 m above ground level is a key input parameter for microclimate modelling for example in ENVI-met (Lahme and Bruse 2003, Égerházi et al. 2013) or in RayMan model (Matzarakis et al. 2007, and it is also applied for calculation or modelling human thermal comfort parameters (Kántor and Unger 2011).

The aims of this study are (i) to present a new automatic software method for calculation of sky view factor and roughness parameters, and (ii) to apply these methods in a medium sized city (Debrecen, Hungary).

2. Study area

The study area is located in Debrecen (47.5°N, 21.5°E). The city lies at a height of 120 m above sea level on nearly flat terrain in the Great Hungarian Plain that is favorable for UHI development. It is the second largest city in Hungary with a population of 220 000. The city's region belongs to the Köppen's climate type Cfb on the basis of the 1961–90 climate normal, but it has a significant year-by-year fluctuation. The annual amount of precipitation is about 550 mm and its variation shows a maximum in May and June. Generally, the summer is sunny and warm, with an average temperature above 20°C. The winter is cold; it is around −2°C and it is often snowy. The wind speed is usually around 3 ms^{-1} and the prevailing wind direction is northeasterly (Bottyán et al. 2005).

The study area was divided to 1 km x 1 km grid and the roughness parameters were calculated for the center points of each grid (Fig. 1). The SVF varies at the local scale therefore it is not reasonable to present its intra-urban variation in the entire city area. So three grid cells representing the most important built-up types of the city were selected (Fig.1): compact midrise, open midrise and open low-rise.

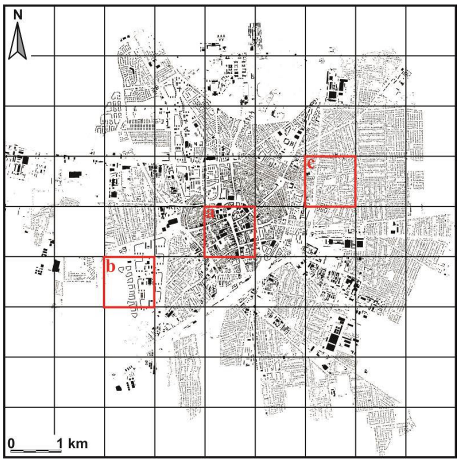

Fig. 1 Study area with the 1 km grid for roughness calculation and the areas (in red squares a: compact midrise, b: open midrise, c: open low-rise) for SVF calculation.

Detailed building and tree-crown databases were used as inputs for the SVF and roughness calculations in the study area. These databases were calculated with a tree-crown mapping tool (TCM) (Gál et al. 2013). This standalone automatic software tool was developed in C++ language and it is compatible with Windows and Linux environments. As an input data for the evaluation 4-band digital aerial photographs were used, made by the Hungarian Institute of Geodesy, Cartography and Remote Sensing in 2007. The resolution of the photographs is approximately 0.5 m and they have 4 spectral bands (3 VIS and 1 NIR). The building and tree-crown databases were evaluated for the whole study area and Fig. 2 illustrates a small part of it in the center of Debrecen.

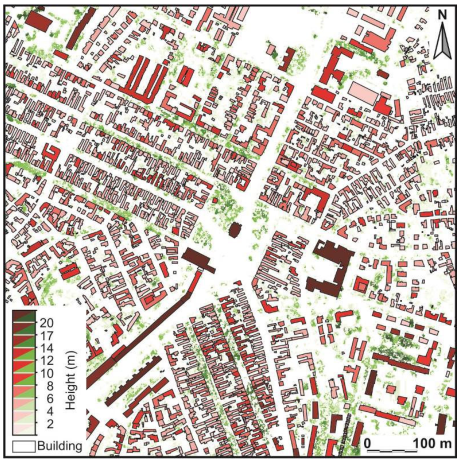

Fig. 2 Building and tree-crown databases in the center of the whole study area.

3. Calculation methods

3.1 SVF mapping tool

The calculation of the SVF is based on a modified form of the equation by Unger (2009) and Gál et al (2009). It takes into account the effect of different object types on the SVF. These objects are: building (B) with the highest elevation angle (β) in a given direction from a given point, tree (T_1) with the highest elevation angle (β + γ) in the same direction, and tree (T_2) with the highest zenith angle (δ) of the crown overlapping the point where the SVF calculation was made (Fig. 3).

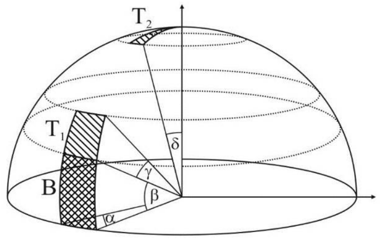

Fig. 3 Polygons on the hemisphere corresponding to a building (B) and to the two types of tree-crowns (T1 and T2).

The value of the SVF for a given point is equal to one minus the sum of the view factors (VF) of different objects (B, T_1, T_2) in all directions (ω):

$$SVF = 1 - \left(\int_0^{2\pi} VF_B \, d\omega + \int_0^{2\pi} \tau \cdot VF_{T_1} d\omega + \int_0^{2\pi} \tau \cdot VF_{T_2} d\omega \right) \quad (1)$$

where τ is the transparency of the tree crowns. This transparency is considered to be constant and it describes the average transparency of the different tree species in the study area. In order to estimate the transparency we carried out field measurements and we obtained a τ value of 0.863591 (Gál and Unger 2014).

The calculations of the three different view factors were based on the equation for the calculations of SVF in a regular circle basin given by Oke (1987). For a regular basin, where β is the elevation angle from the centre to the wall, the SVF value (referring to the basin centre) is: $SVF_{basin} = \cos^2\beta$. So the view factor of a basin with the same elevation angle β is $VF_{basin} = 1 - \cos^2\beta = \sin^2\beta$. Therefore, if we have a regular circular building around the point of interest the view factor of this building is $VF_B = \sin^2\beta$. Similarly, the view factor of the first type trees is calculated using the angle γ with the following equation: $VF_{T1} = \sin^2(\beta + \gamma) - \sin^2\beta$ (Fig. 3). For the second type trees δ is used for calculation: $VF_{T2} = \sin^2 90° - \sin^2(90° - \delta) = 1 - \sin^2(90° - \delta)$.

In real situations the angular height of the objects are not equal in all directions, therefore the projection of the objects on the hemisphere is not a circle. In this case the three angular heights vary as a function of the direction (ω), so the Eq. 1 is modified:

$$SVF = 1 - \left(\int_0^{2\pi} \sin^2\beta \, d\omega + \int_0^{2\pi} \tau \cdot \left(\sin^2(\beta + \gamma) - \sin^2\gamma\right) d\omega + \int_0^{2\pi} \tau \cdot \left(1 - \sin^2(90° - \delta)\right) d\omega \right) \quad (2)$$

To develop a computer algorithm, the utilization of Eq. 2 is not appropriate therefore the SVF value of this equation is estimated by using discrete sections of the hemisphere. The width of these sections is defined by the rotation angle α (Fig. 3) that determines the resolution of the calculation. If the value α decreases, the resolution, and precision of the method increases if the hemisphere is divided in small parts, since these describe the real layout of the objects around the point of interest more precisely.

Using the angle α the Eq. 2 can be approximated with Eq. 3, where n is the number of divisions of the circle (n = 360°/α). In all directions only the elevation angles (β, γ, δ) (Figures 5 and 6) have to be determined for the calculation using building and tree-crown database.

$$SVF = 1 - \left(\sum_{i=1}^{n} \frac{\alpha}{2\pi} \cdot \sin^2\beta_i + \sum_{i=1}^{n} \tau \cdot \frac{\alpha}{2\pi} \cdot \left(\sin^2(\beta_i + \gamma_i) - \sin^2\beta_i\right) + \sum_{i=1}^{n} \tau \cdot \frac{\alpha}{2\pi} \cdot \left(1 - \sin^2(90° - \delta_i)\right) \right) \quad (3)$$

For the implementation of this calculation we developed a new software method in Java language. It is compatible with Windows and Linux platforms also, and it does not need any GIS software to operate [30]. This software reads the geometry and attributes information from the input building and tree crown shape files. For each SVF calculation points it scans the elements of the building and tree-crown databases with a projection line in a given (user defined) distance. The first direction of scanning line is North and then rotated clockwise by (user defined) angle α. The software calculates the highest elevation angles β and γ, and the largest zenith angles δ for all scanning lines; also it calculates the view factors for the different objects (B, T_1, T_2). The software applies a user defined constant transparency value (τ) during calculations. The calculation time is significantly low, the calculation of the SVF for one point takes approximately only 0.6 s in a common PC (Core i3 processor and 4 GB memory).

3.2 Roughness mapping tool

In our earlier research we have developed a new implementation for roughness calculation (Gál and Unger 2009). With this approach the calculation of the roughness parameters is possible not only for regular arrays of buildings and houses but also for an irregular building groups as well as real urban sites (Gál and Unger 2009). The basis of the roughness length (z_0) computations is in accordance with the method of Bottema (1997). His basic model equation was originally designed for regular building groups:

$$z_0 = (h - z_d)\exp\left(-\frac{\kappa}{\sqrt{0.5 \cdot C_{Dh} \cdot \lambda_F}}\right) \quad (4)$$

where C_{Dh} is the drag coefficient for isolated obstacles and it is considered constant (0.8) Bottema (1997), and λ_F is the frontal area ratio of an elementary area. The formula of the zero displacement height (z_d), which is necessary for Eq. 3, is a simple power-law approximation of regular-group-model: $z_d = h \cdot (\lambda_P)^{0.6}$, where λ_P is the plan area ratio of an elementary area. In the case of irregular arrangements it gives an approximate value for z_d without taking the volume of the buildings and their recirculation zones into account.

The basis of the calculation of the input parameters is the building block; therefore the buildings touching each other were merged into blocks. As a next step we divided the study area into polygon-shape areas based on these blocks, which is a certain kind of extension of the approach used by Grimmond and Oke (1999). Each polygon consists of the set of points closer to the central building block than to the other blocks.

We defined the total surface area or lot area (A_T) as the area of a polygon. The sum of the areas of building footprints is the plan area for buildings (A_{Pb}). For the tree-crown parts in each polygon we done the same in order to obtain the plan area for trees (A_{Pt}). The wind flow blocking attributed to the tree-crowns can be described using the porosity (p), which is a simple ratio of the perforated area to a total area of an obstacle (Heiser and DeWalle 1988). This p value for buildings is 0 but for deciduous trees it is characteristically 0.2 at winter and or 0.6 at summer owing to the variation of leaf cover. Using the porosity values the plan area ratio (λ_P) referred to a polygon is:

$$\lambda_P = (A_{Pb} + (1 - p) \cdot A_{Pt}) / A_T \quad (5)$$

In order to determine the frontal area ratio (λ_F) we have to compute the frontal area of each building and tree-crown. The frontal areas of buildings and trees depend on the direction of the airflow. The basis of the calculation is the frontal projection of the buildings and the tree-crowns within a lot polygon. This frontal projection could be calculated using projection lines with a given resolution (Δx). For each lines two height values are obtained: z_t for trees and z_b for buildings. The frontal area for buildings (A_{Fb}) is the sum of the $\Delta x \cdot z_b$ values in each projection lines. The calculation of the frontal area of tree-crowns (A_{Ft}) is similar (sum of $\Delta x \cdot z_t$) if the value of z_t is higher than the value of z_b. In the case when the projection of a building is higher the tree-crown is neglected from the calculation, because it has insignificant effect for the airflow compared to the building. The frontal area ratio referred to a polygon (and to an orientation) is:

$$\lambda_F = (A_{Fb} + (1 - p) \cdot A_{Ft}) / A_T \quad (6)$$

The calculation of the volumetrically averaged building height needs the volumes (V_{b1}, V_{b2}, V_{b3}, …, V_{bn}) and heights (h_{b1}, h_{b2}, h_{b3}, …, h_{bn}) of each building and also of tree-crowns (V_{t1}, V_{t2}, V_{t3}, …, V_{tn} and h_{t1}, h_{t2}, h_{t3}, …, h_{tn}) in each building block:

$$h = \frac{\sum_{i=1}^{n} V_{bi} \cdot h_{bi} + \sum_{j=1}^{n} \left(V_{tj} \cdot (1-p)\right) \cdot h_{tj}}{\sum_{i=1}^{n} V_{bi} + \sum_{j=1}^{n} \left(V_{tj} \cdot (1-p)\right)} \quad (7)$$

The final step is to take into account the effect of the surrounding areas. For this purpose we applied the concept of fetch (Liu et al 2009). With this concept the effect of the source area (Schmid 1994) for the airflow can be included into the calculation of the roughness parameters. In their work (Liu et al 2009) the roughness length was calculated with four different morphometric methods in an elliptical area. The major and minor axis of these fetch were 500 and 150 m, respectively. The major axis was parallel to the wind direction, and the near endpoint of the windward placed fetch was at the measurement site (Fig. 4).

Fig. 4 Illustration of the fetch in an urban area (the cross shows the measurement site).

In our new method we use the similar approach. The roughness calculation refers to a point grid with an arbitrary resolution. For each point the roughness parameters are calculated with the following formulas:

$$z_0 = \frac{\sum_{i=1}^{n} z_{0i} \cdot A_i}{\sum_{i=1}^{n} A_i}, \qquad z_d = \frac{\sum_{i=1}^{n} z_{di} \cdot A_i}{\sum_{i=1}^{n} A_i} \qquad (8)$$

where A_i is the overlapping area, z_{0i} is the roughness length, z_{di} is the displacement height of each lot polygon from the group of the polygons overlapping with the fetch (Fig. 4).

4. Results

4.1 Intra-urban SVF patterns

The main characteristics of the spatial patterns of the calculated SVF values in the three different urban areas are significantly different. In compact midrise area (Fig. 5a) the dominant range of SVF is 0.1–0.5, and only a few wide streets and urban squares have higher values. The dominance of the low SVF indicates that the long wave emission of surface mostly blocked in the urban canopy layer, thus at night time the cooling rate is moderate compared to the rural area.

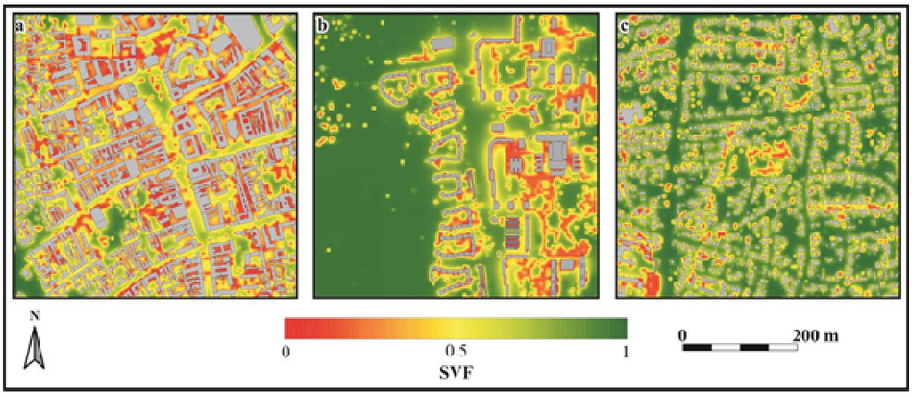

Fig. 5 Spatial patterns of the SVF in the three different urban areas (a: compact midrise, b: open midrise, c: open low-rise).

In open midrise area (Fig. 5b) the buildings are not smaller than the compact midrise area, but the dominant range of the SVF decreased significantly. The values around 0.1–0.5 appear only in the close proximity of the buildings or in the urban parks with significant tree cover. Most of the streets the typical values are around 0.5–0.7. This difference indicates that the radiation balance and thermal reactions of this area are not so different from the rural ones like in the case of the compact midrise area.

In the open low-rise area (Fig 5c) the typical SVF values are around 0.4–0.7, only some parts – with significant tree crown cover – have 0.1–0.3 values. The streets have 0.5–0.8 values and most of the backyards have same or higher SVF because in these areas mostly low vegetation is present. These SVF values indicate that this kind of urban areas has the least modified thermal properties and radiation balance within the presented types.

4.1 Roughness parameters in the study area

In the urbanized area of Debrecen the two most important roughness parameters shows almost concentric shape (Fig. 6). The zero displacement height (Fig. 6a) increases in the edge of urban area and in the mostly open low-rise areas of the city it is around 2-5 m. In the edge of the inner city there is a rapid increase and in the city core its value reaches 12 m.

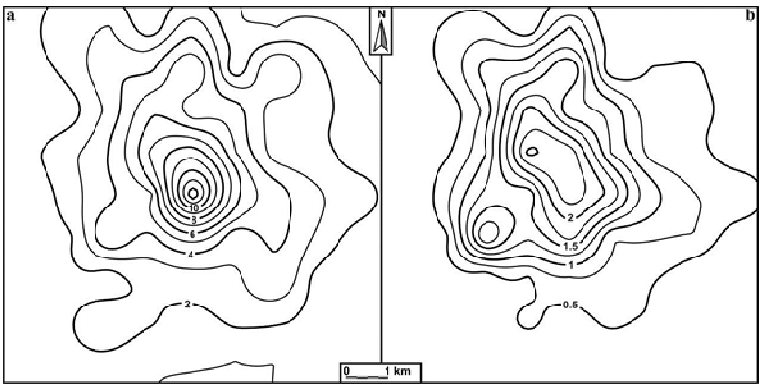

Fig. 6 Spatial distribution of displacement height (a) and roughness length (b) in m.

Roughness length increases rapidly in the edge of the city (Fig. 6b), the highest z_0 values appear in the center and in the open midrise areas (thanks to the 10-story buildings). In the center it reaches 2.5 m and in most of the city core it is larger than 1.5 m.

Acknowledgment

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References

Bottema M., 1997: Urban roughness modelling in relation to pollutant dispersion. *Atmospheric Environment*, **31**, 3059–3075

Bottyán Z., Kircsi A., Szegedi S., Unger J., 2005: The relationship between built-up areas and the spatial development of the mean maximum urban heat island in Debrecen, Hungary. *International Journal Climatology*, **25**, 405–418

Chen L., Ng E., An X., Ren C., Lee M., Wang U., He Z., 2012: Sky view factor analysis of street canyons and its implications for daytime intra-urban air temperature differentials in high-rise, high-density urban areas of Hong Kong: a GIS-based simulation approach. *International Journal of Climatology*, **32**, 121–136

Counihan J., 1971: Wind tunnel determination of the roughness length as a function of fetch and density of three-dimensional roughness elements. *Atmospheric Environment*, **5**, 637–642

Égerházi L.A., Kovács A., Unger J., 2013: Application of microclimate modelling and onsite survey in planning practice related to an urban micro-environment. *Advances in Meteorology*, Paper 251586

Gál T., Lindberg F., Unger J., 2009: Computing continuous sky view factor using 3D urban raster and vector databases: comparison and an application for urban climate. *Theoretical and Applied Climatology*, **95**, 111–123

Gál T., Unger J., 2009: Detection of ventilation paths using high-resolution roughness parameter mapping in a large urban area. *Building and Environment*, **44**, 198–206

Gál T., Unger J., 2014: A new software tool for SVF calculations using building and tree-crown databases. *Urban Climate*, **10**, 594–606

Grimmond C.S.B., Oke T.R., 1999: Aerodynamic properties of urban areas derived from analysis of surface form. *Journal of Applied Meteorology*, **34**, 1262–1292

Kántor N., Unger J., 2011: The most problematic variable in the course of human-biometeorological comfort assessment – the mean radiant temperature. *Central European Journal of Geosciences*, **3**, 90–100

Lahme E., Bruse M., 2003: Microclimatic effects of a small urban park in densely built-up areas: Measurements and model simulations. *Proc. 5th International Conference on Urban Climate, Lodz, Poland,* P.5.1

Liu G., Sun J., Jiang W., 2009: Observational verification of urban surface roughness parameters derived from morphological models. *Meteorological Application*, **16**, 205–213

Matzarakis A., Matuschek O., 2010: Sky View Factor as a parameter in applied climatology – Rapid estimation by the SkyHelios Model. *Meteorologische Zeitschrift*, **20**, 39–45

Matzarakis A., Rutz F., Mayer H., 2007: Modelling radiation fluxes in simple and complex environments - application of the RayMan model. *International Journal of Biometeorology*, **51**, 323–334

Oke T.R., 1981: Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. *Journal of Climatolgy*, **1**, 237–254

Oke T.R., 1987: *Boundary layer climates*. London-New York: Routledge

Schmid H.P., 1994: Source areas for scalars and scalar fluxes. *Boundary-Layer Meteorology*, **67**, 293–318

Souza L.C.L., Rodrigues D.S., Mendes J.F.G., 2003: The 3DSkyView extension: an urban geometry acces tool in a geographical information system. *Proc. 5th International Conference on Urban Climate, Lodz, Poland,* O.31.3

Unger J., 2009: Connection between urban heat island and sky view factor approximated by a software tool on a 3D urban database. *International Journal of Environment and Pollution* **36**, 59-80

Watson I.D., Johnson G.T., 1988: Graphical estimation of sky view-factors in urban environments. *Journal of Climatology*, **7**, 193–197