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Detection of ventilation paths using high-resolution roughness parameter mapping in a large urban area

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Abstract

In this study, an urban roughness mapping method is presented on the example of a large study area in Szeged, Hungary, as an example. With this roughness mapping procedure, the potential ventilation paths of the city can be located. Our calculations of the roughness parameters are based on a 3D building database; however, this new approach using the lot area polygons provides more detailed results than other recent studies. The detected ventilation paths could play a significant role in the development of the urban heat island circulation and result in the reduction of air pollution in the central parts of the city. Based on our results, we can mark out the areas where the city government should keep the advantages of the ventilation paths considering the human comfort aspects of the urban climate, thus providing important input data for urban planning procedures.

Keywords: 3D building database; Frontal area; Roughness length; Displacement height; Porosity; Urban roughness mapping

1. Introduction

In urban areas, the surface geometry and characteristics have been changed compared to the original natural surfaces. In urban environments, the water and energy balances are modified which often results in higher urban temperature compared to the surroundings (urban heat island, UHI). The UHI has a marked diurnal variation: the largest urban–rural contrast appears at night, while during the daytime the temperature difference is moderate. The cities are about the roughest surfaces; the enhanced drag effect of the urban surface on the air flow is one of their most important features. Due to the larger roughness of the surface, the average wind speed is lower in the cities than in the surrounding rural areas [1]. The regional wind tends to hinder the formation of the UHI and modifies its spatial structure [2].

In direct analogy with the well-known land-sea breeze system, the city generates a local air flow, the so-called country breeze. Its driving force is based on the fact that a city is commonly warmer than the rural background. For the development of the country breeze, the regional winds need to be very weak, so anticyclonal weather conditions are ideal for this flow system. The horizontal temperature (and therefore pressure) gradient can be sufficient to induce low-level breezes across the urban–rural boundary, which converge in the center from all directions. There is uplift in the center of the city and also a counter-flow in the higher air layer (Fig. 1). The vertical thermal structure is as important as the urban–rural thermal differences, since the vertical instability also promotes this 3D circulation [1]. Unlike the land-sea breeze system, there is no diurnal reversal of flow because the city is usually warmer than the countryside. If the inflow is strong enough to penetrate the city by overcoming the frictional drag of the complex urban surface, the winds can be slightly stronger compared to the surrounding areas [1]. In short, this is the urban heat island (-induced) circulation (UHIC) [4].

During the day, the country breeze can be observed above the roof level (in the urban boundary layer), since the building roofs are the hottest parts of the cities due to the insolation. At that time, the instability of the air makes the vertical movement easier so the small horizontal thermal gradient (weak UHI) is sufficient to drive this

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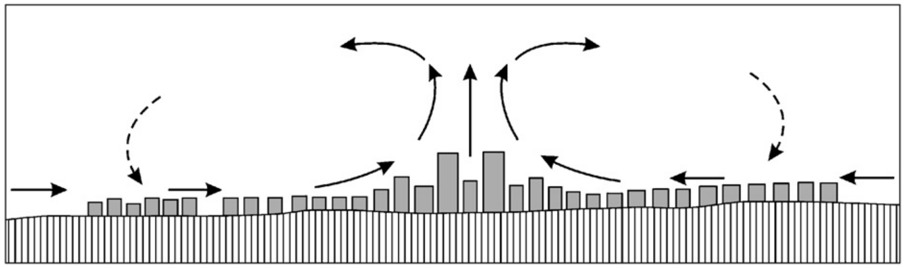

Fig. 1. Schematic shape of the urban heat island circulation (modified after [3]).

system. At night, the thermal difference is significant under the roof level among the buildings (in the urban canopy layer, UCL); therefore, the country breeze can be found here [5]. Owing to the high surface roughness of the city, the development of the nocturnal country breeze needs significant thermal difference between the urban and rural surface.

In reality, the UHIC is a relatively unstable and intermittent system with flow patterns rather than continuous mono-directional air movements [5]. The general effect of different factors such as meteorological conditions, existing buildings and other obstacles causes certain directions to be more prominent. As Haeger-Eugensson and Holmer [6] showed, at night the advective inflow by the UHIC plays a significant regulating role in the development and strength of the UHI, since the intrusion of the cool air into the city decreases the urban–rural temperature contrast, thus weakening its driving forces itself.

This meso-scale circulation could offer a potential for the improvement of the urban air quality [5,7]. The depth of the inflow in the UHIC system depends on the roughness of the surface. If the city has parts where the roughness is lower than in the other areas and these are interconnected the country breeze can reach the inner parts of the city and it can reduce the accumulated pollution. These are the so-called ventilation paths.

For describing the geometry or texture of the surface and as a consequence its roughness, several parameters are known. The roughness parameters describe how effective a surface area is in transforming the energy of the average wind, flowing over it, into turbulent motion in the boundary layer above Davenport et al. [8]. The most commonly used parameters are the zero-plane displacement height (z_d) and the aerodynamical roughness length (z_0) [9,10]. The connection between the wind and the drag force of buildings can be characterized by z_0. It is a key parameter for studying the urban atmosphere, as it can be utilized for example in pollutant dispersion modeling and in large-scale flow models to provide a momentum boundary condition for determining the wind patterns [2,11]. Further known parameters, which are partly necessary for the calculation of z_d and z_0, are the plan area ratio (λ_P), building plan area density referring to the height z ($\alpha_P(z)$), frontal area ratio (λ_F), complete aspect ratio (λ_C), height-to-width ratio (λ_S), average height weighted with frontal area (z_H), depth of the roughness sublayer (z_r) (e.g. [12–15]), roughness volume density ($\rho r(z)$) [16] and the effective height (h_{eff}) [17]. Burian et al. [18] gave a comprehensive review of the most common morphological parameters and their calculation for a sample area around the downtown of Los Angeles, CA. In their work, a 3D urban dataset, land use/cover information, a Digital Elevation Model (DEM) and roads were integrated and analyzed using a geographic information system (GIS). Mean parameter values were calculated for the entire area and for each land use type, and, in addition, in some cases on spatial grids and as a function of height a.g.l. This work was extended for a larger area around Houston, TX [18].

Grimmond and Oke [13] mentioned a coefficient p that was allowed for the porosity of trees. Some sort of porosity for the UCL can also be introduced that can be a useful tool for roughness mapping.

If we evaluate the roughness parameters in a large urban area, we have the opportunity to find the potential ventilation paths essential for enhancing the efficiency of the country breeze. Matzarakis and Mayer [17] and Mayer et al. [19] summarize the supposed requirements of the ventilation paths with the following points: (a) aerodynamic surface roughness length lower than 0.5 m, (b) negligible zero-plane displacement, (c) sufficiently great length in one direction, at least 1000 m, (d) sufficiently great width, minimum width is double to four times the height of the lateral obstacles, but at least 50 m, (e) the edges of paths should be comparatively smooth, (f) the width of the obstacles in a path should not be greater than 10% of the width of the path, (g) the height of the obstacle in a path should not be greater then 10 m, (h) obstacles within a path should be oriented so that their greatest width is parallel to the axis of the path, (i) single obstacles within a path should have a ratio of height to horizontal distance between two successive obstacles of 0.1 for buildings and 0.2 for trees.

Based on these requirements, there is an opportunity to give some advice for the local government on how to promote the intrusion of the cool and clean air and to decrease air pollution level in urban environments. The most important points suggested by Barlag and Kuttler [5] are the following:

(i) almost straight free paths must be kept to the center of the city;

(ii) surface roughness along these free paths must be kept low;
(iii) surfaces in these areas should have a cooling effect on the air moving slowly towards the center; and
(iv) pollution should be minimized in the areas from which air moves to the center and along the paths.

The overall purpose of this study is the presentation of an urban roughness mapping method in a large study area using morphometric methods (see Section 2) and a 3D building database in Szeged, Hungary. The specific objectives are: (i) to describe the application of the roughness parameter calculation method in irregular building groups, (ii) to present the calculation of porosity in the UCL, and (iii) to find potential ventilation paths in the study area using the calculated urban roughness parameters.

2. Methods for the determination of roughness parameters

The determination of the roughness length and displacement height is not straightforward and remains problematic. There are numerous ways for z_0 and z_d assessment or calculation. Three generalized classes of these methods are available [8,13,20]:

(i) micrometeorological (or anemometric) methods using field observations of wind and turbulence;
(ii) roughness classification methods using roughness classes and visual estimation; and
(iii) morphometric (or geometric) methods using measures of surface morphometry.

The most common micrometeorological methods use data of field observations of one or a few installed and instrumented tall towers for the computation of roughness length and the zero-plane displacement height based on the log-law:

$$\frac{\bar{u}(z)}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z - z_d}{z_0}\right), \tag{1}$$

where $\bar{u}(z)$ is the time-averaged wind speed at height z, u_* is the friction velocity and κ is von Karman's constant (0.4) [10,12,21]. For this equation, we need wind speed data from at least three heights well above the average heights of the obstacles in the surface [22]. The estimated roughness values vary with the wind direction and are sensitive to errors [23]. This method is unsuitable for detailed roughness mapping in large urban areas since it is rather cost-intensive; numerous towers need to be installed, which could bring significant difficulties concerning the obtaining and operating of field sites in agreement with the local authorities.

The estimation of the roughness in a given location is based on earlier measurement of the roughness values in a similar terrain elsewhere [8]. The well-known Davenport method uses eight roughness classes and it uses the eye as integrator of photographs or land use maps [8,24]. The advantage of this method is the error will not be more than a single roughness class width [8]; however, there are only two roughness class for built up areas [25], therefore it is adaptable with difficulties in urban environments.

There are several morphometric methods which are based on surface morphology data. The simple ones use only the average heights and density of the roughness elements in the cities (e.g. [10,12]). More sophisticated methods include the computation of the frontal area ratio, which combines the mean height, width and density of the roughness elements [13]. The results of these methods provide more accurate approximations for the roughness parameters (e.g. [9,21]). Petersen [22] has been found that the Lettau [9] and the Counihan [10] methods are only acceptable in the case of up to moderately inhomogeneous situations.

The above-mentioned 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. Bottema and Mestayer [26] present a method for roughness mapping in a 2.7 km × 2.2 km-large urban environment where the building arrangements are mainly irregular. Their method is based on a cadastral database (vector-based building database) and the buildings are represented by a polygonal ground plan to which the heights (a.s.l.) of the building base and roof are assigned. The spatial basis of the computation of roughness parameters is a 2D grid cell called rugoxel (roughness pixel) with sizes between 50 and 450 m. After the necessary splitting process, all polygons are convex and fit within one rugoxel. The applied z_0 and z_d formulas are referring to these rugoxels and give average values.

Ratti et al. [2] calculate the λ_P, z_H, λ_F from urban digital elevation model (DEM) using expressions found in the literature (e.g. [13]); however, their computation is applied for small (400 m × 400 m) sample areas in London, Berlin and Toulouse.

The definitions of the basic geometric variables used in the following sections for computations of z_0 and z_d are as follows:

- Plan area ratio or fraction λ_P = (total plan area of the buildings)/(total site area).
- Frontal area ratio or fraction $\lambda_F(\theta)$ = (total frontal area of the buildings (θ))/(total site area) [2,14]. The angle θ represents the flow direction, because λ_F is a function of orientation.
- Volumetrically averaged building height h = (sum of (height of the building × building volume))/(total of the building volumes) [26].

2.1. Roughness length and the zero displacement height for irregular building groups

The basis of the roughness length computations is in accordance with the method of Bottema [12] and Bottema and Mestayer [26]. Their basic model equation was

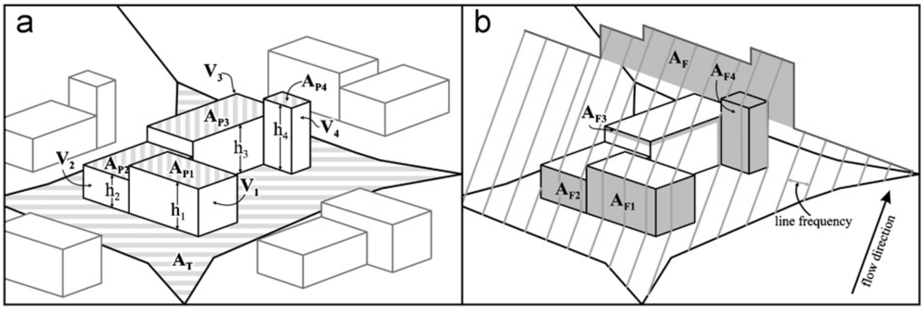

Fig. 2. (a) Input parameters for the roughness calculation for an irregular building group and (b) frontal area calculation with parallel lines in a certain direction (for explanation see the text).

originally designed for regular building groups:

$$z_0 = (h - z_d)\exp\left(-\frac{\kappa}{\sqrt{0.5C_{Dh}\lambda_F}}\right), \quad (2)$$

C_{Dh} is the drag coefficient for isolated obstacles and it is considered constant (0.8) [26,27], and λ_F is the frontal area ratio for a rugoxel. With some approximations and neglections [26], it can be applied in the case of irregular building groups. Substituting the constants, the Eq. (2) can be written in a slightly simpler form:

$$z_0 = (h - z_d)\exp\left(-\sqrt{\frac{0.4}{\lambda_F}}\right). \quad (3)$$

The next formula of the zero displacement height, which is necessary for Eq. (3), is a simple power-law approximation of regular-group-model:

$$z_d = h(\lambda_P)^{0.6}, \quad (4)$$

where λ_P is the plan area ratio of a rugoxel. 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 [26].

For the application of these equations, we need some input parameters. As a real city does not mainly consist of regular arrays of buildings and houses, Fig. 2 shows these parameters for an irregular building group. The basis of the calculation of these input parameters is the building block; therefore, the buildings touching each other were merged into blocks (Fig. 2a).

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 [13]. Each polygon consists of the set of points closer to a 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 (Fig. 2a). The sum of the areas of building footprints (A_{P1}, A_{P2}, A_{P3}, …, A_{Pn}) is the plan area (A_P), so the plan area ratio referred to a polygon is $\lambda_P = A_P/A_T$. Similar approach was used by Burian et al. [14] but they referred the λ_P values to a uniform 100 m × 100 m grid mesh and a non-uniform grid mesh based on land use types bordered by the street network. In the case of the first mesh, several buildings crossed the grid cell boundaries; in the second case, the polygon areas contained several buildings. In our approach, the polygons were smaller and contained only connected (contacting) buildings.

In order to determine the frontal area ratio we have to compute the frontal area of each building (Fig. 2b). The sum of the frontal areas of buildings (A_{F1}, A_{F2}, A_{F3}, …, A_{Fn}) is the frontal area (A_F). This frontal area of a building block depends on the direction of the view (or direction of the airflow). The frontal area ratio referred to a polygon (and to an orientation) is $\lambda_F = A_F/A_T$. In the work of Burian et al. [14], the calculations were not possible for the uniform mesh because several buildings were larger than the grid cells and, as mentioned above, several buildings crossed the grid cell boundaries.

The calculation of the volumetrically averaged building height needs the volumes (V_1, V_2, V_3, …, V_n) and heights (h_1, h_2, h_3, …, h_n) of each building (Fig. 2a) in each block:

$$h = \frac{\sum_{i=1}^{n} V_i h_i}{\sum_{i=1}^{n} V_i}. \quad (5)$$

2.2. The porosity of the urban canopy layer

One way to interpret the urban porosity could be a ratio quantifying the open air volume in the canopy layer. So, it is a measure of how penetrable the area is for the airflow and could be defined as the ratio of the volume of the open air and the volume of the UCL referring to the same area. In other words, it gives an impression on the relationship of the penetrable and impenetrable parts of an air layer over a certain area. According to this definition, this parameter is dependent on the height of UCL and it is independent of orientation. The building plan area density ($\alpha_P(z)$) defined by Burian et al. [14] can also applied for this purpose because it gives information on how much of the air volume is occupied by buildings.

There are two possible ways to compute urban porosity. The first way is less precise, however easy to evaluate for urban areas, while the second one is much more accurate but the computation is rather time-consuming.

Porosity evaluation with the first method is based on the input parameters of building volumes, lot areas and the height of the entire UCL (h_{const}), which is defined as a constant. This constant value is based on the survey of the building heights in the entire study area. The basis is that the number of buildings higher than the UCL height has to be significantly low in the entire area. So, the equation of this type of urban porosity ($P_{h-\mathrm{const}}$) of a spatial unit (as a lot area) is the following:

$$P_{h-\mathrm{const}} = \frac{A_\mathrm{T} h_\mathrm{const} - V}{A_\mathrm{T} h_\mathrm{const}}, \tag{6}$$

where V is the sum of the building volumes located at the actual lot.

The second method of porosity computation is based on variable UCL heights by spatial units. For each spatial unit of the investigated area, the height of the UCL (h_UCL) has to be determined as the height of the highest building within the given lot area. Based on these values, the equation of this type of urban porosity ($P_{h-\mathrm{var}}$) of a spatial unit is the following:

$$P_{h-\mathrm{var}} = \frac{A_\mathrm{T} h_\mathrm{UCL} - V}{A_\mathrm{T} h_\mathrm{UCL}}. \tag{7}$$

3. Roughness mapping in the urban area of Szeged

3.1. Study area and the 3D building database

Szeged (46°N, 20°E) is located in southeast Hungary, in the southern part of the Great Hungarian Plain at 79 m above sea level on a flat plain (Fig. 3). According to Trewartha's classification, Szeged belongs to the climatic type D.1 (continental climate with longer warm season), similar to the predominant part of the country [28]. While the administrative area of Szeged is 281 km^2, the urbanized area is only around 30 km^2. The avenue-boulevard structure of the town was built to the axis of the river Tisza. The number of inhabitants is about 160,000.

In earlier urban climate investigations, temperature measurements for identifying the UHI were taken in a 25.75 km^2 sized area of Szeged (Fig. 3). Our study is partly based on the earlier results therefore we used the same study area (e.g. [29–31]).

As a result of earlier projects, there is a 3D building database available for the study area. This data source is based on local municipality data of building footprints. In addition, the individual building heights were evaluated by photogrammetric methods. This means that more than 22,000 individual buildings with their main parameters (footprint area, building height) are available for this study. The creation of the 3D database is described in details in Unger [31,32].

3.2. Details of the roughness calculations

Fig. 4 summarises the main steps of roughness mapping in the study area. Firstly, we have aggregated the contacting buildings in the database to building blocks. That resulted in more than 11,000 blocks, each containing the interlocking buildings. Based on these building blocks,

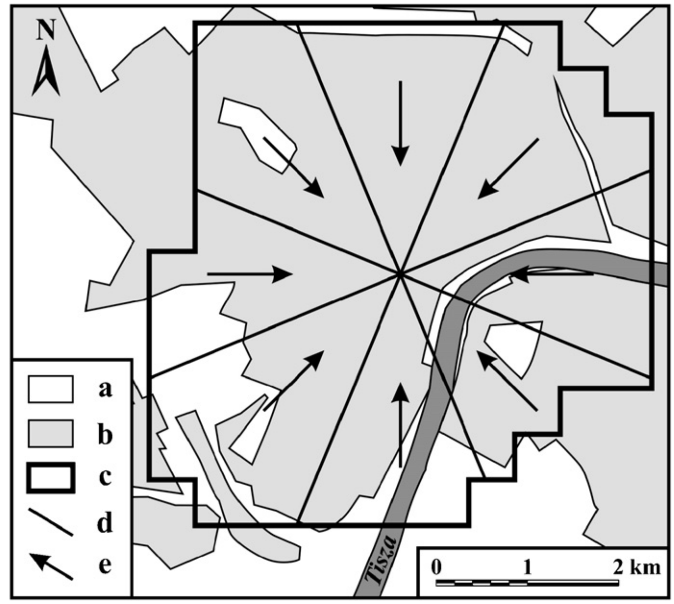

Fig. 3. Study area and the calculation zones (45° wide) for the frontal area: (a) rural area, (b) urban area, (c) border of the study area, (d) border of the frontal area calculation zone, and (e) direction for the frontal area computation.

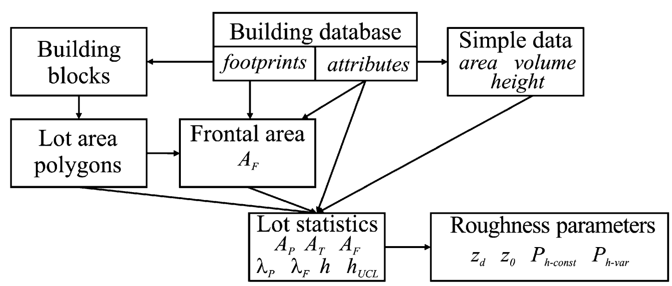

Fig. 4. Schematic description of the roughness mapping procedure.

the determination of the lot areas described in Section 2.1 is achievable with ArcView 3.2 software by using the assign proximity function of the Spatial analyst module. All of the roughness parameter calculations were carried out for these lot polygons (units) (Fig. 5).

The values of some roughness parameters depend on the wind direction because of the application of the direction-dependent frontal area ratio (A_F) as an input. Therefore, the calculation methods of these parameters are also direction-dependent. Generally, these roughness parameters are computed for several directions and the obtained results are averaged giving the final value [2]. As our main objective is the mapping of the ventilation paths conducive to the heat island circulation, we evaluated these roughness parameters in radial directions within each calculation zones (Fig. 3). For the sake of simplicity eight zones with a width of 45° were selected, similarly to Burian et al. [14], but the number of zones can be larger according to the selected width of the zones (e.g. 12–30°, 16–22.5°, 24–15°, etc.).

Fig. 5. Lot area polygons (units) in a part of the study area in Szeged, as an example (a: building blocks, b: border of the building footprint within the building block, and c: lot area polygons).

The frontal area calculation in ArcView is a more complex task than the calculation of the footprint area, the building volume and other simple parameters. Therefore, we have constructed a simple Avenue script for this calculation. Before the evaluation, a shape file needs to be created, containing lines parallel with the given radial direction and covering each frontal area calculation zone (see Figs. 2b and 3). The distance between the neighboring lines is 5 m. The algorithm is searching for the highest building elevation in each lot using the line–building intersections for each line. Based on these elevation values and the line frequency (5 m), the frontal area is computable (see Fig. 2b).

With the frontal area calculation, all of the input parameters for the z_0 and z_d calculation (Eqs. (2)–(4)) are at our disposal. The obtained values refer to the lot area polygons in the investigated area.

The porosity values are calculated with Eqs. (6) and (7). For the $P_{h-\mathrm{const}}$ calculation, we surveyed the heights of the buildings in the study area and defined h_{const} as 40 m (P_{h-40}). For the $P_{h-\mathrm{var}}$ calculation, we defined h_{UCL} as the height of the highest building within a given lot (its maximum is 63.4 m and its mean is 6.59 m for the study area).

4. Spatial distribution of the calculated parameters and the potentional ventilation paths

As a result of our calculations, we got the values of the roughness parameters referring to the lot area polygons. Based on this database, we can analyze the spatial distributions of these parameters in order to trace the potential ventilation paths.

Firstly, we have located the ventilation paths with the three most important requirements mentioned in Section 1: (a) z_0 value has to be lower than 0.5 m, (b) z_d value is negligible and (c) sufficiently great length in one direction (>1 km) [17]. On the basis of the relevant literature, urban areas with low building height and density (which are mainly residential or light industrial) have a displacement height of less than 3 m on average [13,14,18]. Thus, we consider the z_d value as negligible, if it is lower than 3 m.

The analysis is based on the maps showing the spatial distributions of these roughness parameters. In order to take the other six properties suggested by Matzarakis and Mayer [17] into consideration, our approach dividing the study area in polygons is not appropriate. Based on the z_0 values, Fig. 6a shows the supposed ventilation paths that have sufficiently great length in one direction in the investigated area. According to the z_d values (Fig. 6b), the supposed ventilation paths have near negligible zero-plane displacement values.

Secondly, taking into account the fourth (d) important requirement (sufficiently great width, at least 50 m) in order to locate the ventilation path more accurately, we applied a 50 m × 50 m mesh in each zone (see Fig. 3). The boundaries of these grid cells are parallel or rather rectangular to the main directions referred to the zones (Fig. 7). Because of their size, these cells accomplish the criterion (d). We selected those polygons that fulfil the criteria (a) and (b) by Matzarakis and Mayer [17] and marked the 50 m × 50 m cells of which most of the area is inside these selected polygons. Miao et al. [15] presented a similar raster-based map to present the spatial distribution of the surface roughness; however, our composite map is more detailed. As a result, we got a composite map where the cells are differentiated based on different roughness categories and on the openness to the surrounding areas in the proper directions (Fig. 8).

As Fig. 8 shows, the areas with low roughness are clearly recognizable. Remembering also the criterion (c) and the airflow directions by zones leading to the center, potential paths can be found in the northern zone (~1.3 km long), in the eastern zone (~1.5 km long), in the south-eastern zone (~1 km long), in the south zone (~1 km long), two in the south-western zone (~1.9 and 1.5 km long, respectively), in

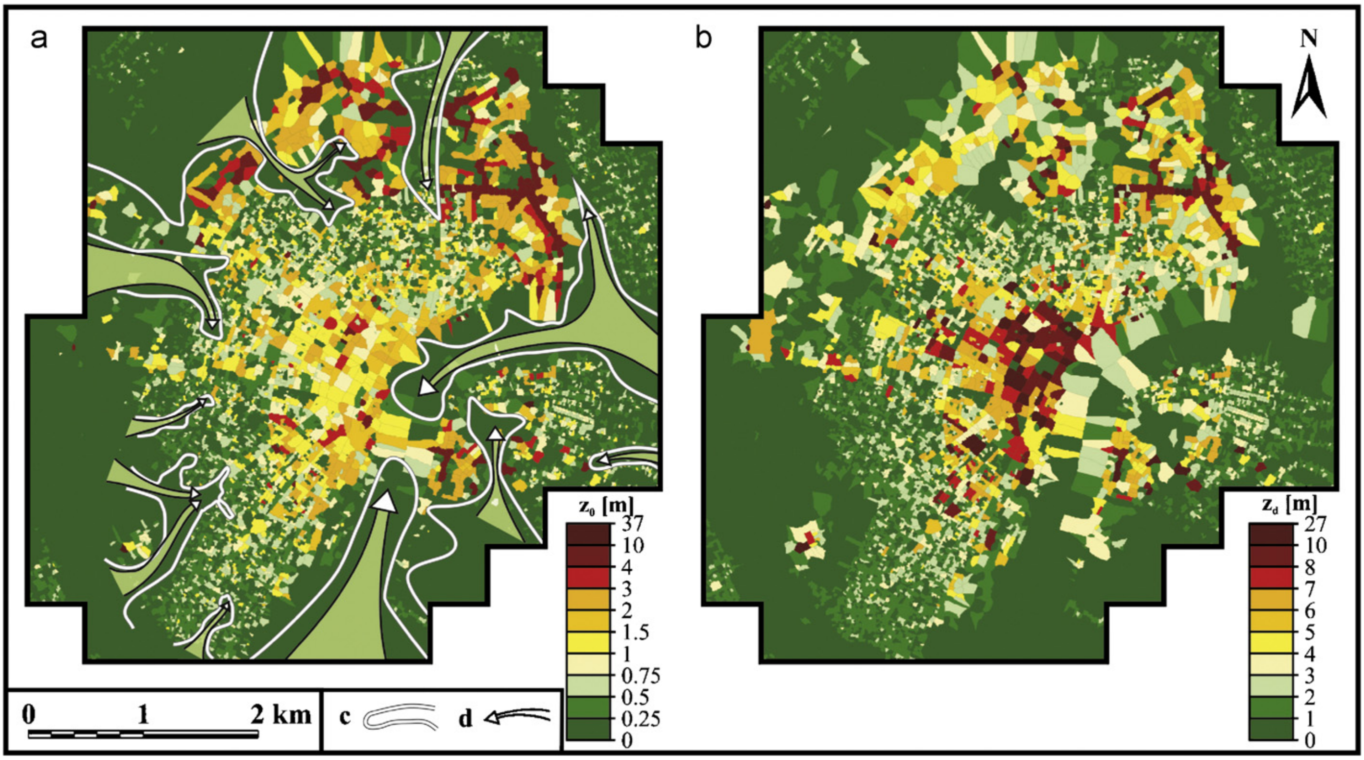

Fig. 6. (a) Spatial distribution of the roughness length (z_0) values and the supposed ventilation paths, (b) spatial distribution of the zero-plane displacement height (z_d) in the investigated area (c: border of a continuous area with z_0 values lower than 0.5, d: supposed ventilation path).

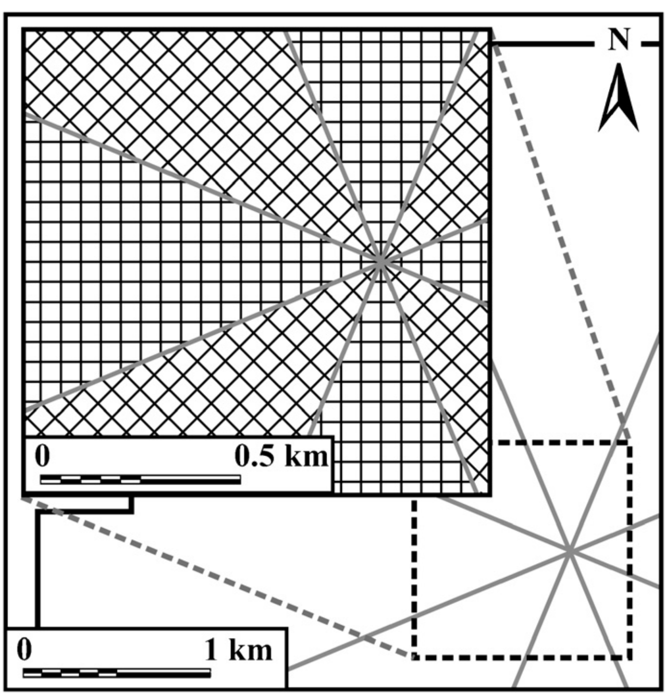

Fig. 7. A sample area illustrating the sheme of the 50 m × 50 m mesh.

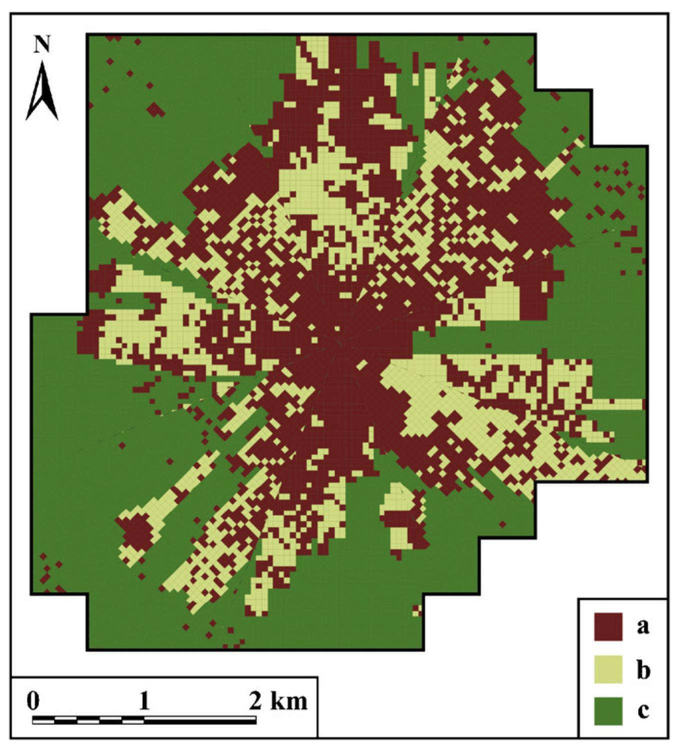

Fig. 8. Composite map with the cells of the 50 m × 50 m mesh — a: cells that do not fulfill the criteria (a) and (b), b: cells that fulfill the criteria (a) and (b) but not (c), c: cells that fulfill the criteria (a) (b) and (c).

the western zone (~1.3 km long,) and in the north-western zone (~1.5 km long).

We also examined the spatial distribution of the P_{h-40} (Fig. 9a) and $P_{h-\mathrm{var}}$ (Fig. 9b). Studying the two figures we find that the spatial distribution of the first parameter is similar to the spatial distribution of the z_0. The shapes of the possible ventilation paths based on P_{h-40} values in Fig. 9a (not shown) would be similar to the shapes in Fig. 6.

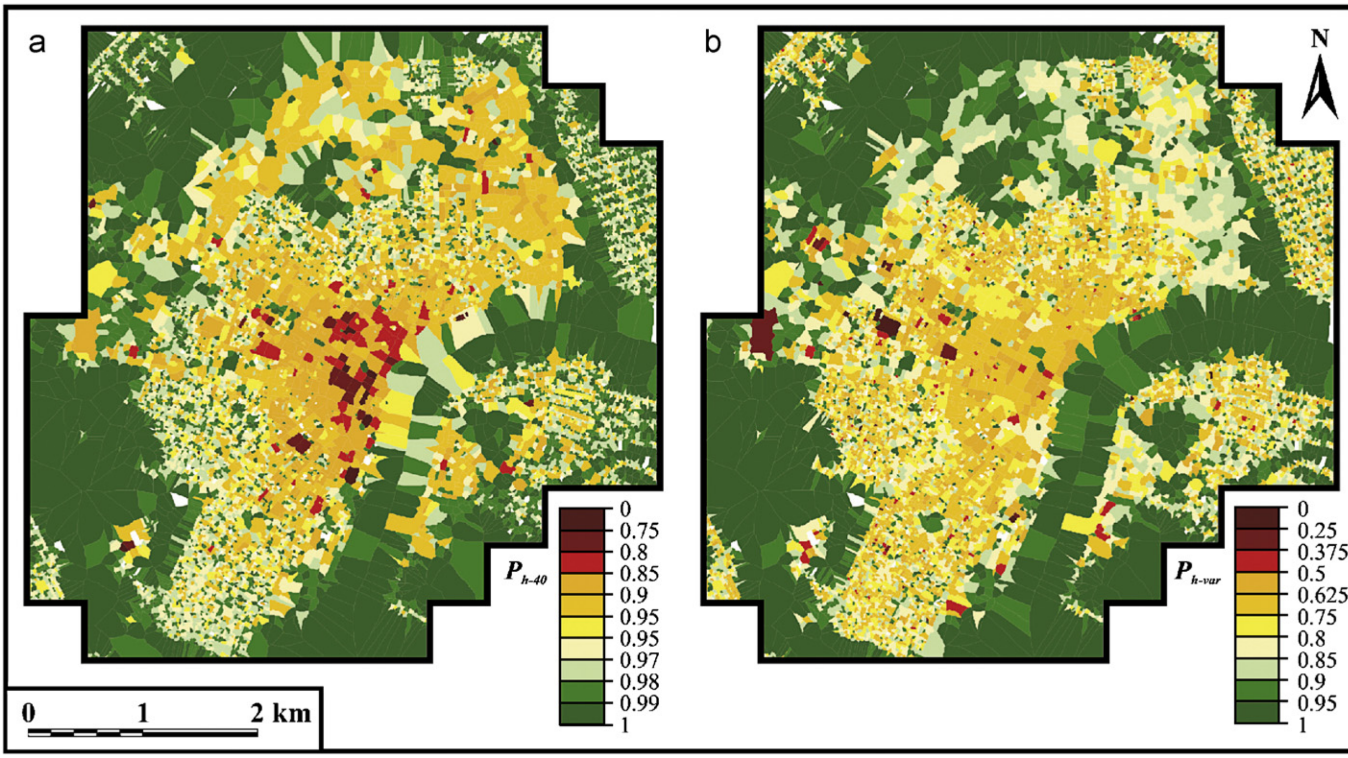

Fig. 9. Spatial distribution of the porosity values in the investigated area: (a) P_{h-40} and (b) $P_{h-\text{var}}$.

According to Fig. 9b, we can identify new areas which can play a role in the city ventilation. For instance, on the east side of the town there is an area with high blocks of flats and large green areas between them. Because of this special built-up style, this area of large housing estates can also be regarded as a potential ventilation path despite the relatively high roughness length values.

5. Conclusions

We have calculated the most important roughness parameters in the study area. The calculation is based on a 3D building database and it is more detailed and more extended than those in other recent studies in this topic (e.g. [2,14,26]). This calculation based on the lot area polygons is a new approach and according to our knowledge there are no similar examples in the literature.

Investigating the spatial distribution of the calculated parameters, we could locate the potential ventilation paths. These ventilation paths could play an important role in the development of the urban heat island circulation and as a result in the reduction of air pollution in the inner part of the city.

Based on our results, we could set out the areas where the city government should have to consider the advice of Barlag and Kuttler [5] to keep the advantages of the ventilation paths regarding the human comfort aspects of the urban climate.

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