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Determination of Ventilation Channels In Urban Area: A Case Study of Wrocław (Poland)

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Abstract—Urban areas are among the roughest landscapes in the Earth and its aerodynamical properties are responsible for a lot of processes and phenomena of urban climate, such as surface drag and pollutant dispersion. These properties can be quantitatively expressed by various parameters, with zero plane displacement height (z_d) and roughness length (z_0) as the most frequently applied. Based on remotely gathered (LIDAR scan) height data and morphometric methods of roughness calculations, the comprehensive procedure to determine ventilation channels in urban area is proposed and implemented on the example from Wrocław, Poland. Morphometric analysis of urban structure allowed establishing a proper database of aerodynamic parameters of the city. Then a series of maps of the city showing the distribution of two roughness parameters were prepared. GIS tools were used to carry out the analysis of roughness data, assuming various directions of wind flow. It enabled to determine the locations of potential ventilation paths in the city which, if combined, form large ventilation channels. They may have a significant role in improving air quality and be a valuable source of information for local government responsible for the appropriate development of the city.

Key words: Morphometry, roughness parameters, ventilation paths and channels, Wrocław.

1. Introduction

Even though the consequences of urban climate and urban environment in general and their strong impact on people living in urbanized areas are well known, city dwellers expect comfort and confidence that the surrounding environment has as little negative influence on them as possible. Among the main factors driving the concern about their health are air pollution and bioclimatic conditions formed as the inadvertent outcomes of modified aerodynamic properties of cities. Harmful compounds found in the air accumulate in large quantities in urban areas where human activity is intensified not only as the result of enhanced emission of pollutants in these areas, but as the effect of the strong surface drag in rough structures and limited effective dispersion of pollutants.

City as one of the most complex anthropogenic structures is characterized by a great diversity of space. From micro- and mesoclimatological point of view it is a real mosaic of climates formed by buildings, artificial surfaces, green areas, elements of hydrographic networks and many other objects of various shapes and sizes. Urban areas form very rough surfaces and aerodynamic roughness of cities exceeds that of essentially all other types of landscape element which are essential for resistance to the wind field. The process of urbanization influences local changes of the surface and physical–chemical properties of the atmosphere, leading to the aerodynamic and other modifications of climate (Szymanowski, 2004). Roughness parameters are essential in understanding many processes occurring in urban atmospheres such as surface drag, shearing stress, wind profile forms and turbulence characteristics, as well as such phenomena as wind shear over cities, vertical motions, the depth of urban boundary layer and pollutant dispersion in and above urban canopies (Arnfield, 2003).

There are numerous methods used to determine aerodynamic properties of the Earth's surface. Roughness is a characteristic of space and can be described by various parameters. The most important and most commonly used are: z_0, called roughness length, and z_d, called zero plane displacement height (Oke, 1987). Dependence of z_d and z_0 on the height, shape, area, density and distribution of spatial objects was analyzed using wind tunnels, analytical works, terrain models and terrain observations (Wieringa, 1993; Bottema, 1995a, b, 1997). Roughness changes

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with the density and height of buildings achieving maximum values in the central areas of cities (Klysik, 1998a, b; Grimmond and Oke, 1999a, b; Lewińska, 2000). The calculation of roughness parameters z_d and z_0 for Wrocław were conducted by Szymanowski (2004) using the simplified method of Lettau (1969), and by Suder (2009) (for center of the city) and Netzel (2011) (for the whole area of the city) using the algorithms of Gál and Sümeghy (2007) based on the method of Bottema and Mestayer (1998).

In the urban atmospheric boundary layer, which is located above urban canopy layer, the wind speed changes according to a logarithmic wind profile. The closer to the objects on the Earth's surface is, the greater friction becomes, thus the wind speed is reduced. In neutral air stability, the roughness length is defined as the height where wind speed equals to zero. About 25 % down from this level, there exists a surface which is identified with the ground level for the undeveloped surface, and it is called the zero plane displacement height. It is a hypothetical basis of the logarithmic profile (Oke, 1987).

Mostly, for determining the zero plane displacement height and the roughness length, one of the following two groups of methods are used (Grimmond and Oke, 1999a, b):

1. morphometric (or geometric)—approach these methods use algorithms that relate aerodynamic parameters to morphometric surface. Then, it is recommended to carry out the lab tests and verify the models. Grimmond and Oke (1999a, b) divided morphometric methods into three sets. The first uses the simplest, "rule of thumb" method which is based on the height of buildings. The second set uses height and the plan area ratio (λ_P—for definition see Fig. 2). The third group uses height and frontal area ratio (λ_F—for definition see Fig. 2),
2. micrometeorological (or anemometric)—approach these methods use data from measurements of wind or turbulence to calculate aerodynamic parameters contained in theoretical relations derived from the logarithmic wind profile Grimmond *et al.* (1998) reviewed various anemometry-based methods for evaluating aerodynamic roughness parameters.

Morphometric methods have several very important advantages. The most important of them are low cost compared to wind-based methods and the relative ease of calculation of roughness parameters for each area irrespectively of the direction of the air inflow, e.g. with Geographic Information Systems (Liu *et al.*, 2009). A comprehensive review (Grimmond and Oke, 1999a, b) finds that most morphometric methods yield plausible values of z_0 and z_d and results of many of the 'anemometric' methods are of insufficient quality.

Air circulation affects different aspects of urban environment. Air exchange between urban and rural area strongly influences quality of resident's life. This shows how important it is to conduct a balanced and rational process of urbanization (Lyons, 1986). The recommendation can be a guide for a local government, on steps that should be undertaken to improve air quality (Barlag and Kuttler, 1990; Gál and Sümeghy, 2007; Gál and Unger, 2009). By calculating the aforementioned two parameters it is possible to obtain information about location of ventilation channels, responsible for appropriate ventilation of the city. For example Wong *et al.* (2010) described a simple method for designation of urban ventilation corridors. They used the frontal area index map in least cost path analysis to derive the frequency of occurrence of ventilation areas.

The main goal of this paper is to implement proposal analytical procedure which allows to determine the location of ventilation channels for urban area. Here, ventilation channels are understood as linearized areas of lowered surface drag that may be activated according to appropriate wind direction. In this study we created a database of morphometric parameters of city buildings and for area of their influence (lot area—for definition see Fig. 2). That allowed to calculate the selected parameters of roughness for irregular building groups. Based on these parameters, and on the criteria defined by Matzarakis and Mayer (1992) and Gál and Unger (2009), we prepare a method for locating ventilation channels in the city. We present the experiment for the city of Wrocław.

The whole procedure was based on morphometric methods for calculations of aerodynamical properties of the city and performed in the environment of Geographical Information Systems enhanced by various spatial analysis techniques.

2. Study Area

The study area is located within the administrative boundaries of the city of Wrocław (SW Poland, 51°N 17°E) and represents nearly 293 km^2. The city is inhabited by almost 650,000 people. The altitudes within the city ranges from 103.53 to 155.72 m above sea level (Szymanowski and Kryza, 2009). Majority of the land cover Wrocław consists of green areas (forests, grasslands, wastelands) and agricultural areas which cover over 60 % of the city area. The other dominant elements of landscape are: industrial areas (13 %) and built up areas (17 %). In addition, there are many watercourses, with the largest one the Odra River and the extensive transportation network (Fig. 1).

The climatic conditions of Wrocław are closely related to Polish and European climate. Geographical location in mid-latitudes leads to the alternating effect of different baric systems (oceanic and continental) causing an inflow of mass of either dry or wet air. Such a number of colliding air masses is responsible for dissimilar weather conditions that occur over a year. Typically for mid-latitudes, winds from the western sector are dominant—about 51 % frequency of occurrence. Location of Wrocław in the relative depression of the valley of the river and in the foreland of the Sudety Mts makes the city thermally privileged. Additionally, a large bioclimatic diversity and the well-developed phenomenon of urban heat island can be observed (Drzeniecka-Osiadacz *et al.*, 2010).

3. Data and Methods

Spatial data covering the city of Wrocław were obtained courtesy of the Bureau of City Development (BRW), and provided by airborne LIDAR and

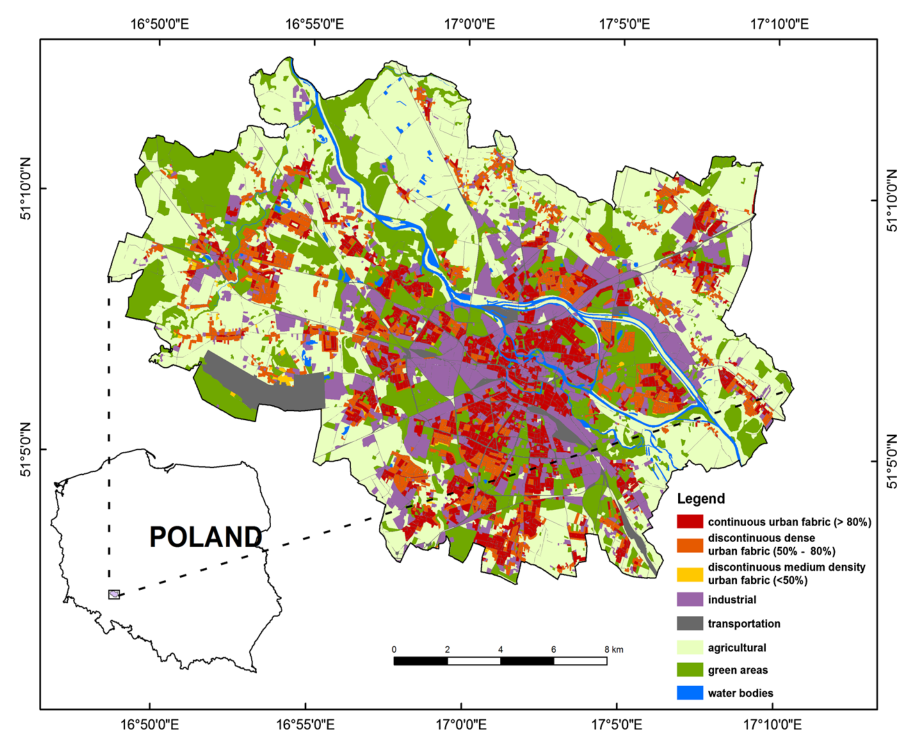

Figure 1
Land use in Wrocław (http://www.gmes.info)

orthophotomaps. It includes information on urban buildings in three dimensions (raster and vector data). Trees are not considered in the analysis. In addition, since the urban topography is mainly flat, terrain is also not considered.

Information about the height of buildings was based on LIDAR data acquired in May 2006th. Accuracy of measurements was 15 cm vertically, and there were two measurements per square meter. Height for each object was recorded in the database as the highest, lowest and average value. The latter will be used in this work. With only this information, it is very difficult to determine the exact shape of the roofs. Therefore, they have a simplified form for City GML level of detail one (http://www.citygml.org).

As a result of correction of input data (obtained from BRW), over 12,000 objects were removed from the layer containing about 145,000 buildings. Those were mostly buildings with zero-height or duplicated items. Subsequent, a database of the simplified buildings in the form of homogeneous groups of roughness elements was created. These groups include single buildings or blocks of buildings given an average height (h). Next, a weight factor was calculated for each object, and that shows the ratio of plan area (A_P) occupied by every building to the surface area of the whole group. As a result, the average height of the entire group (block) reflects the contribution of heights of individual buildings, and calculated by the following formula, (index i corresponds to a current number of a given object):

$$h = \frac{\sum_{i=1}^{n} A_{P_i} \times h_i}{\sum_{i=1}^{n} A_{P_i}}.$$

As a result of conversion of the buildings into the groups, the number of objects was again reduced from 133,000 to 75,000.

In this work, for the analysis of aerodynamic characteristics of the city, morphometric method was used. To calculate roughness length and zero plane displacement height we utilized the formulas proposed by Gál and Sümeghy (2007) and Gál and Unger (2009), who used the expression proposed by Bottema and Mestayer (1998). The approach for regular groups of buildings was expressed by following formula (Fig. 2):

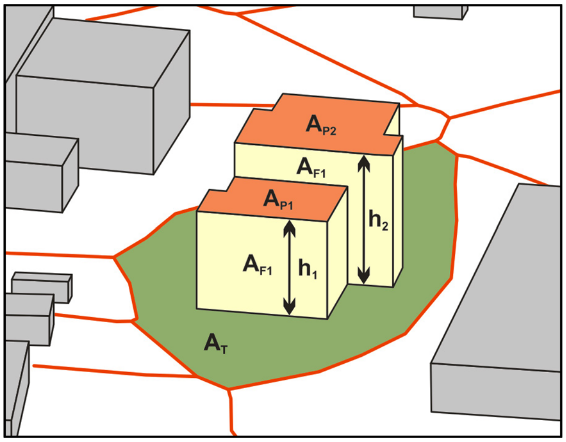

Figure 2
Input parameters for calculation of roughness elements

$$z_0 = (h - z_d)\exp\left(-\frac{k}{\sqrt{0.5 \times C_{Dh} \times \lambda_F}}\right) \rightarrow z_0 = (h - z_d)\exp\left(-\sqrt{\frac{0.4}{\lambda_F}}\right),$$

where: h—averaged height of buildings, z_d—zero plane displacement height, k—von Karman constant (0.4), C_{Dh}—drag coefficient for isolated obstacles (0.8), λ_F—frontal area ratio calculated by the formula:

$$\lambda_F = \frac{\sum_{i=1}^{n} A_{F_i}}{A_T}$$

A_F—frontal area, A_T—lot area.

The calculation of roughness for irregular groups of buildings requires extending the method described above and including the formula that sets a zero plane displacement height (Bottema and Mestayer 1998):

$$z_d = h \times (\lambda_P)^{0.6}, \qquad \lambda_P = \frac{\sum_{i=1}^{n} A_{P_i}}{A_T}$$

where: λ_P—is the plan area ratio, A_P—plan area.

Too big range of influence of an obstacle has a negative effect on the final calculations of roughness parameters. It was necessary to solve the problem arising, when the result should be adjusted to the height of the object and the area which it interacts with (A_T). Maximum range of lot areas designated as 10 times the height of the adjacent object in comparison to the findings for meteorological measurement purposes in urban environment (Oke, 2006). In the case of overlapping neighboring areas, we used the principle to set up the border in the geometrical center, between the edges of the buildings or blocks of buildings.

Depending on the direction of air flow, the frontal area (A_F) of objects changes. Gál and Sümeghy (2007) created a script that, in each zone for eight major geographical directions, calculates the frontal area using information obtained from the intersection of lines (arranged in parallel at 5 m intervals) with buildings. In this work we used a different approach to improve the accuracy of the analysis. The bases of the calculation were line objects (vectors) corresponding to walls of buildings (not grouped in blocks). To each wall we added attributes describing: height, coordinates of the beginning and end of the wall, azimuth, neighborhood (whether there is another building on the left or right side of the wall). Hence, the frontal area of each wall (for all buildings) resisting the wind depending on the flow direction was calculated. Thus, there was no loss of data resulting from the grouping of buildings (more accurate data for height) or applying of the Gál's and Sümeghy's method using lines (for further details on the area).

The calculations of roughness parameters and modeling of ventilation channels for the city of Wrocław were conducted for eight cardinal and ordinal wind directions. We are presented in this paper two specific air flow situations:

– wind from western sector, which is dominant in Wrocław,
– additionally, for perpendicular direction from the north.

Determination of the ventilation channels for the city.

Localization of the sites suitable for ventilation channels in urban canopy is based on the number of dependent variables. The most important ones proposed by Gál and Unger (2009), and based on Matzarakis and Mayer study (1992) are:

(a) the values of roughness length (z_0) are less than 0.5 m,
(b) the values of zero-plane displacement height (z_d) shall not exceed 3 m,
(c) the length of ventilation channel in one direction is greater than 1 km,
(d) the width of ventilation channel is more than 50 m.

To fulfill the basic conditions for creating potential ventilation channels in the city, the objects with the roughness length values greater than 0.5 m or a zero plane displacement height values above 3 m were selected from a database of lots area for the assumed wind direction. Then, using GIS tools we combined lots area being less than 50 m apart, and that allowed us to meet the condition to maintain the adequate width of the channel (Fig. 3). The next step was to determine the course of the potential paths between areas of the city ventilation which are not satisfying the conditions proposed by Gál and Unger. Partially we solved that by applying the procedure that separated overlapping lots area. The boundaries, running in geometrical center between the edges of weakly ventilated polygons were determined. For the lines, we calculated azimuths and the selection was carried out following the desired direction of air flow (Fig. 4):

– a potential ventilation path for wind from the west direction is the line with azimuths from interval 45°–135° or 225°–315°,
– a potential ventilation path for wind from the north direction is the line with azimuths from interval 0°–45° or 315°–360° or 135°–225°.

Subsequent, the most probable channels of ventilation were analyzed, assuming that the air flow will happen where a greater density of lines takes place. For this purpose, we calculated density of the lines representing paths in a moving circular window with a radius of 1 km (Fig. 5). Based on the constituent maps we located ventilation channels of the city (Fig. 6). It should be emphasized, that the localization of these channels is subjective.

4. Results

4.1. Spatial Distribution of Roughness Parameters

Information about the values of roughness parameters assigned to lots area (A_T) of building or blocks of buildings was obtained. The estimates of the zero plane displacement height (Fig. 7) attain usually 5 m

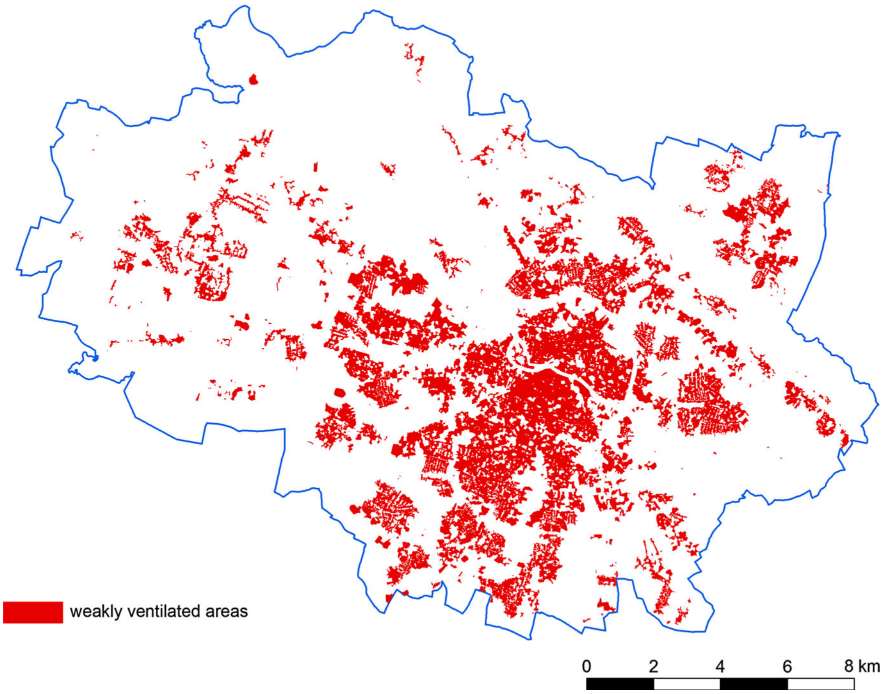

Figure 3
Polygons representing weakly ventilated areas, characterized by $z_d > 3$ m, $z_0 > 0.5$ m and distant by not more than 50 m from the nearest neighbor polygon

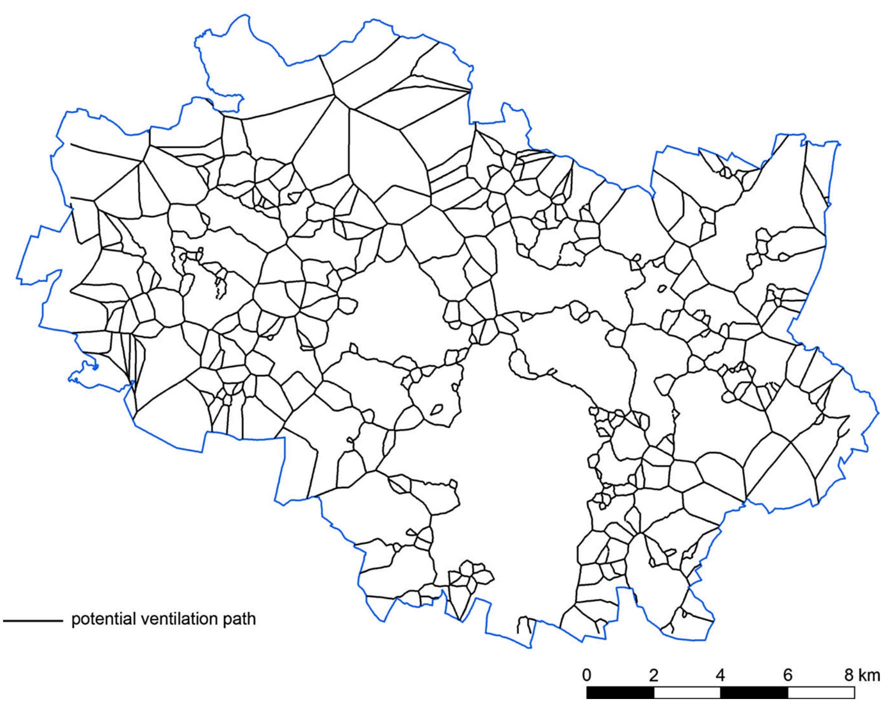

Figure 4
Modeling of the potential ventilation paths of the city

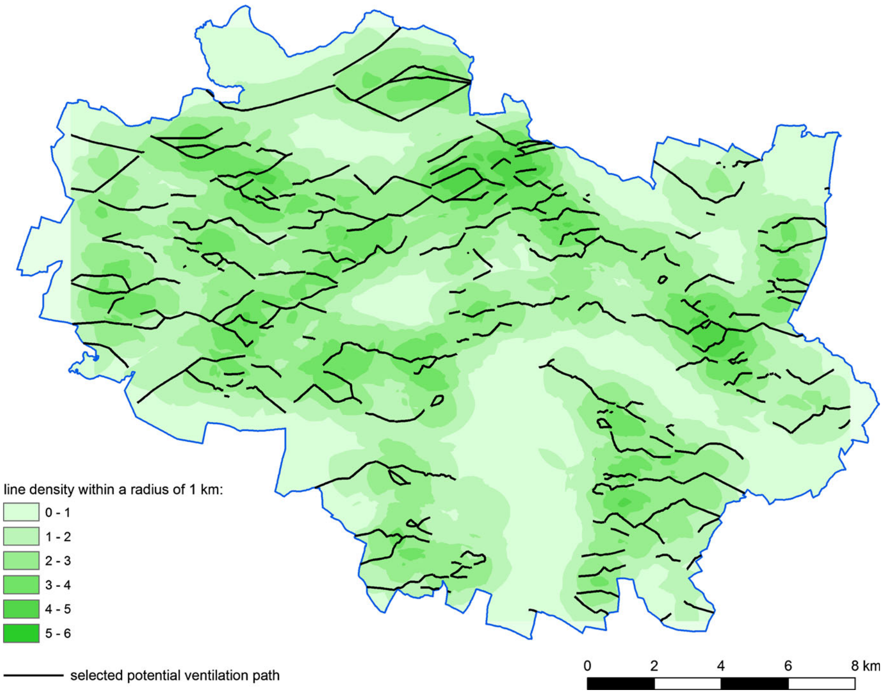

Figure 5
Modeling of the potential ventilation paths in the city for the western airflow

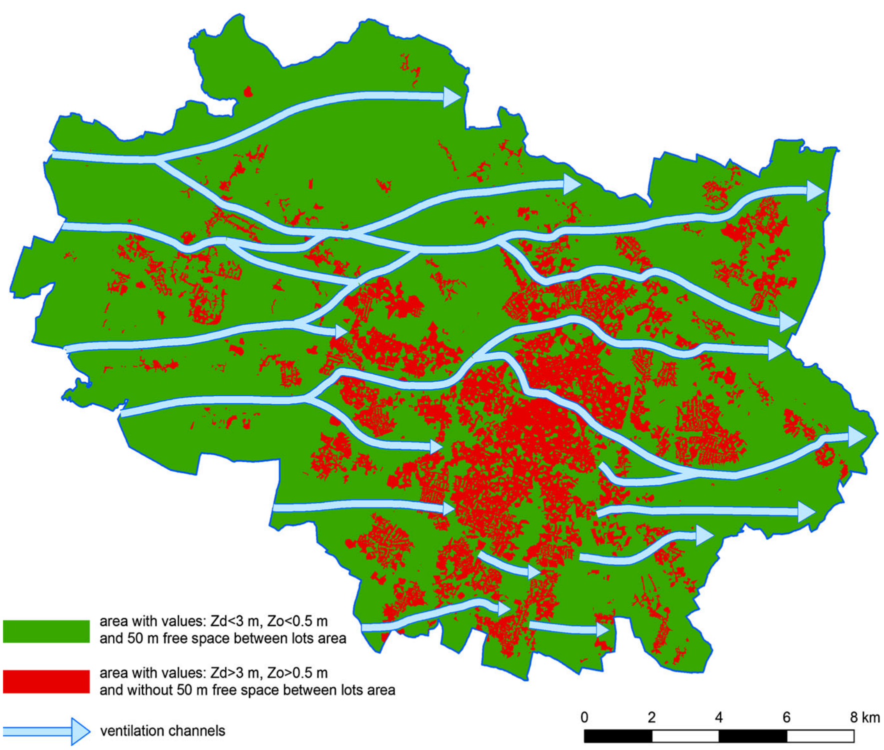

Figure 6
Modeling of the potential ventilation channels in the city for the western airflow

(86.7 % of objects), where the maximum is 25.41 m. The roughness length for the western inflow (Fig. 8), reaches up to 1 m (81 %) for most objects where the highest score was 17.36 m. Assuming the direction of wind from the north the results were very similar: 81.3 % of sites attained values below 1 m, and the highest score was 17.47 m.

The spatial distribution of both roughness parameters has a very similar structure. The largest concentration of high values of z_0 and z_d is observed in the densely built up city center, with a historic center known as the Old Town. That area was the center of Wrocław urban spread and that is the reason why it is characterized by dense buildings (there are many big sacred objects). Historically the city development proceeded in the direction of WNW and ESE and along the Odra River trough. That was connected with the loss of importance of the north–south route for east–west route (Małachowicz, 1985). In addition to these areas the intensity of insular nature of roughness parameters can be observed. This is often associated with tall housing (high residential blocks), built in the last tens of years. Buildings become lower as distance from the city center increase and this affects the less surface drag to incoming air masses.

For the western and northern wind directions, the vast majority of buildings cause movement of the zero plane displacement height by about 1–1.3 m, and the roughness length in most cases is less than 1 m. According to the classification based on the roughness parameters in Grimmond and Oke (1999a, b), Wrocław can be considered as a city of low and medium density and height of buildings.

4.2. Spatial Distribution of Potential Ventilation Channels

The spatial distribution of potential ventilation channels for Wrocław is presented for the airflow from the west in Fig. 6 and from the north in Fig. 9.

With the westerly wind, lots areas characterized by weak ventilation (not meeting the conditions presented by Unger and Gál for localization of ventilation channels) occupy more than 16.5 % area of Wrocław. Located on that area is 34 % of national roads, 46.5 % of local roads, and 23.5 % of provincial roads. In addition, within the study area there is

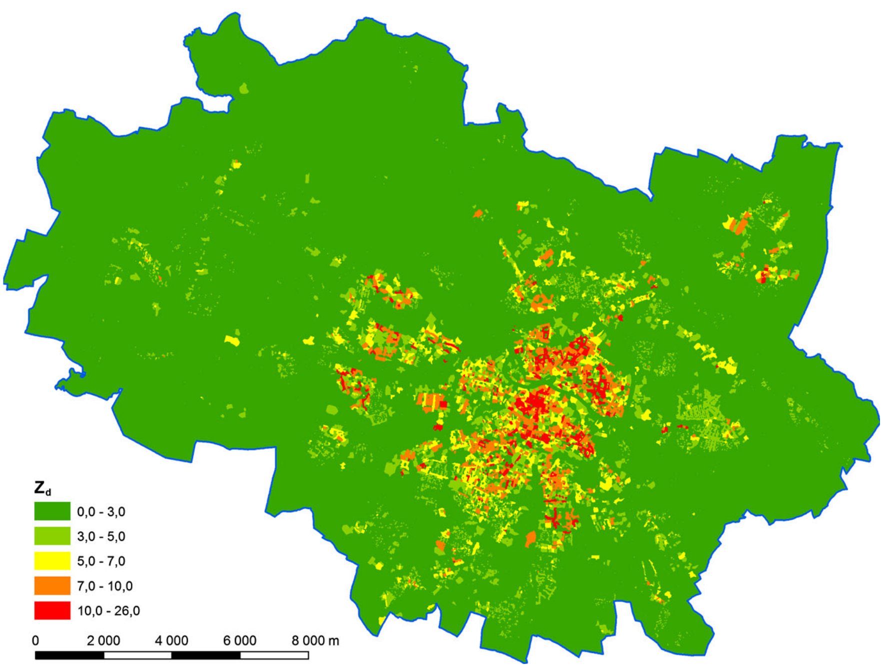

Figure 7
Spatial distribution of zero plane displacement height (z_d) [m] in Wrocław

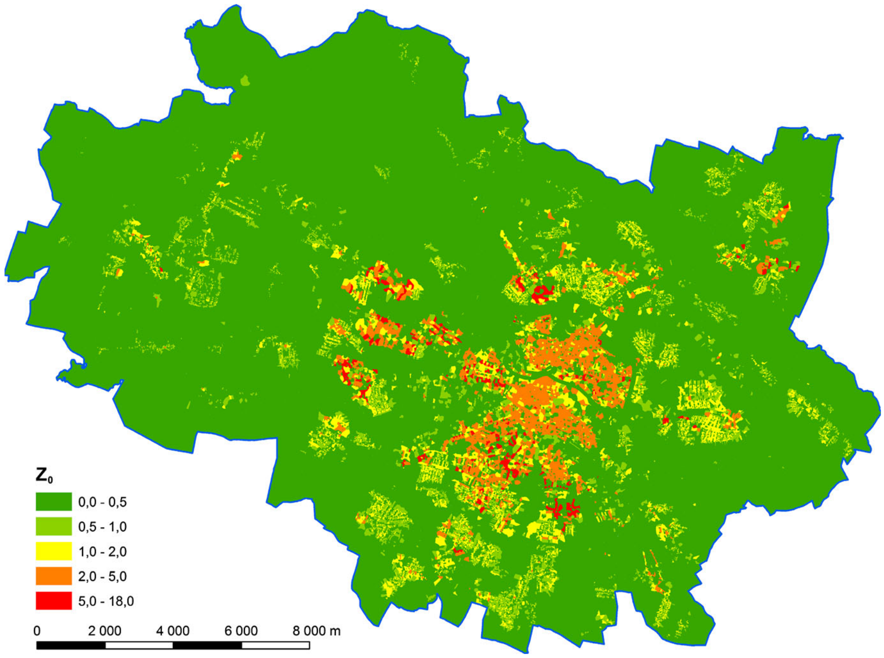

Figure 8
Spatial distribution of the roughness length (z_0) [m] in Wrocław for the western airflow

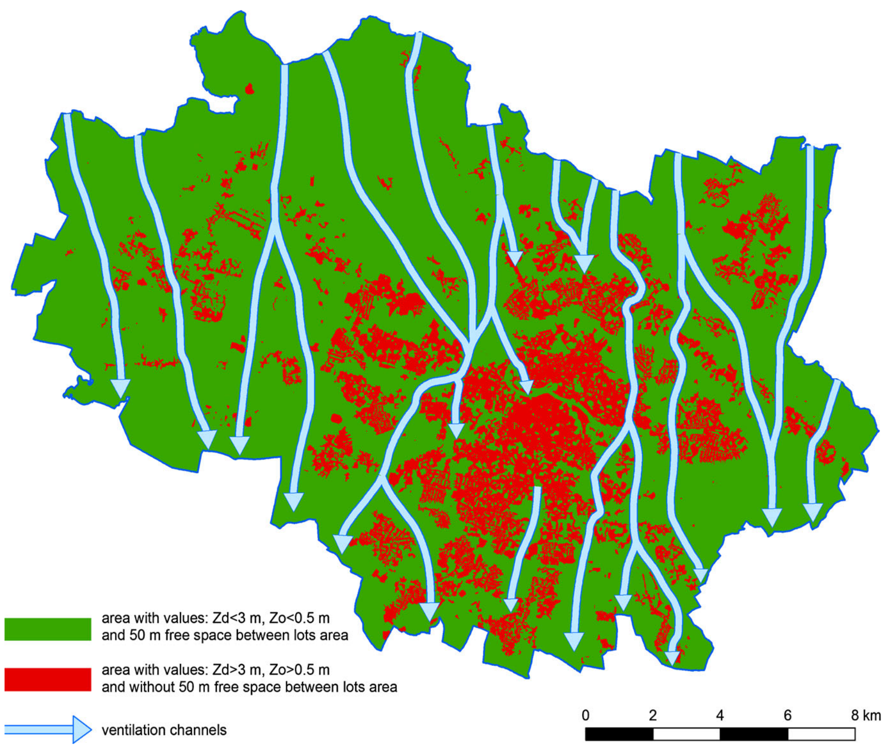

Figure 9
Localization of weakly ventilated areas and ventilation channels in the city for the northern airflow

64 % of all buildings in the city (99 % objects out of all around the city of height over 100 m, 96 % of height 20–100 m, 51 % of 3–10 m ones and only 4.5 % of up to 3 m high). This shows the correlation between the density of roads and buildings, which are the main sources of low emission of pollutants, with areas which prevent the formation of ventilation channels. The results compute for the north wind differ from those presented above by up to 0.3 %.

Despite different directions of air flow, well ventilated areas in Wrocław are located along rivers (mainly the Odra River), large watercourses and the major arteries of transportation (rail lines and large and wide streets). We gained similar results for areas with low buildings or large green areas and agricultural. The longest axis of the city line runs along the direction WNW–ESE but the greatest resistance to air mass is perpendicular to this direction. This is a sector of the city with densely built up tall houses and blocks, with weak conditions for ventilation.

The longest channels of the westerly winds are almost 25 km long, whereas the wind from the north flows through 18 km of the city. The difference is due to the direction of the main axis of the city as described above. This also affects the number of channels, which are localized at the inflow of air from the north. With westerly circulation, we observed very long ventilation channels intersecting the entire city. This is related to the fact that almost the entire length of the Odra River is used for ventilation. Additionally, in the northern part of town there are a lot of detached, widely-spaced houses. Lack of adequate ventilation is detected in the south and southeast of the city. The channels here are shorter than in the rest of the city and do not reveal a continuous waveform. The air flow is impeded by dense buildings in the southern and central part of the built along the streets, mainly aligned to the south. Better ventilation of Wrocław in the eastern and western parts of the city occurs when the inflow of air is from the north.

There are many channels, assuming the inflow from west and north and they encounter along buildings or groups of buildings. As a result of high drag of these objects and the disappearance of ventilation channels may occur. Mainly this is a case in the city center and it is central southern-central part. In other areas, when air masses are encountering strong drag, ventilation channel may change a little its lane and may share or combine with other channels, which is allowed by fluidity of airflow. This means that the areas with relatively low density of buildings have a chance to be ventilated more efficiently.

5. *Summary and Conclusions*

The structure of area for the selected location has specific aerodynamic properties. Utilizing height, shape, area and spatial distribution of roughness elements we get information about the distribution of z_d and z_0, which allows us to generate maps for the city without the need for costly field tests. Use and extension of methods proposed by Gál and Sümeghy (2007) and Gál and Unger (2009) in GIS, allowed creation of extensive and accurate database of aerodynamic parameters for Wrocław. The new method for calculating the frontal area used in this work definitely increased a level of details and the reliability of the results based on that parameter.

Places where surface properties allow low-disturbed air flow, which exist in the city, made it possible to remove pollutants. By identifying areas of low roughness it becomes possible to identify ventilation channels for the city. With the appropriate development in areas where new objects are being created or by deleting existing ones, a successful urban policy takes place, clearly improving quality of life. Procedures of locating ventilation channels used in this work can improve the precision of their determination and help maintain a reasonable quality of the air. This is another step in the development of methods for determining the ventilation channels of the city. The use of the database for research in vector form improves the quality of performance by considering each object in the analysis. The works, which are based on a grid, generalize to some extent the results and are more suitable for mesoscale studies, e.g. Wong *et al.* (2010).

Further research on the roughness parameters for the city of Wrocław will be enhanced by using additional information about objects such as location and height of vegetation resulting from laser scanning. With more detailed information (more accurate spatial data) more precise analysis can be performed and, as a consequence, that improve the quality of the final solutions.

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