Budownictwo i Architektura 24(2) 2025, 133-156

DOI: 10.35784/bud-arch.7013
Received: 30.12.2024; Revised: 25.04.2025;
Accepted: 29.04.2025; Available online: 25.06.2025

Crossref Similarity Check Powered by iThenticate

Orginal Article

Influence of urban changes on the efficiency of ventilation paths

Katarzyna Klemm[1], Weronika Chojna[2], Anna Dominika Bochenek[3]

[1] *Institute of Environmental Engineering and Building Services; Faculty of Civil Engineering, Architecture and Environmental Engineering; Lodz University of Technology; Politechniki Avenue 6, 93-590 Lodz, Poland;*
katarzyna.klemm@p.lodz.pl; ORCID: 0000-0001-8518-4328
[2] *Afterburn; Orla Street 23/34, 90-317 Lodz, Poland;*
wernop00@gmail.com
[3] *Institute of Environmental Engineering and Building Services; Faculty of Civil Engineering, Architecture and Environmental Engineering; Lodz University of Technology; Politechniki Avenue 6, 93-590 Lodz, Poland;*
anna.bochenek@p.lodz.pl; ORCID: 0000-0003-3396-2006

Abstract: The constantly progressing urbanisation of urban areas causes a shortage of land intended for residential development. Open corridor spaces, which often reach the central zones of cities, are becoming very attractive to development companies. At the same time, the still insufficient degree of coverage of cities with local plans contributes to the weakened protection of these areas against investment pressure. Hence the question arises – do the areas of potential corridors designated in planning documents still play such a role? The aim of the work is to determine the impact of changes in spatial development on the effectiveness of the functioning of the western part of the ventilation corridor, running along the Łódka River valley in Łódź (Poland). This area can be considered key from the point of view of shaping aerodynamic conditions, and thus thermal conditions, in the city. The assessment of the corridor's effectiveness was carried out using two methods: a visual estimation method, using data from Corine Land Cover, and a morphometric method based on data provided by the Łódź Geodesy Centre. Aerodynamic roughness length parameters were determined for 1990 and 2018, and then compared with the adopted criteria characterising ventilation corridors. The final part compares the results obtained using the adopted methods and determines the impact of changes on air flow and the efficiency of the ventilation corridor.

Keywords: urban area, city of Łódź, ventilation corridors, visual estimation method, morphometric method

1. Introduction

Cities have become the primary place of residence for an increasing number of people. In 2006, the number of people living in cities exceeded that of rural residents, and this tendency continues to rise [1-7]. One of the negative consequences of these changes is uncontrolled city development, the degradation of historical urban spaces, and the worsening of air quality and microclimatic conditions. It is necessary to introduce solutions consistent with the principles of sustainable development to ensure a high quality of life and safety in cities [8-13].

Proper spatial planning can positively impact climatic conditions in cities, reduce nuisances, and increase the quality of life in these areas. One such solution is air circulation systems in the form of ventilation corridors, which allow masses of air to freely enter urban areas [14]. These areas, being contrasting surfaces, are not only sources of cooler air masses but, when properly designed, also enable a reduction in pollution levels, particularly in city centres. For this reason, they are considered compensation spaces [15]. Such systems should take into account the dominant wind direction, macro-landforms, forested areas, and surrounding sources of pollution. It is also important to consider local conditions, including city topography, spatial planning, and local sources of pollution. The literature discusses the variation in climatic conditions depending on the characteristics of functional zones (Local Climate Zones), which contrast with ventilation corridors [16-17]. This diversity results in, for example, a temperature gradient between the city centre and suburban areas. The higher the gradient, the greater the scale of the Urban Heat Island phenomenon. This leads to modifications of thermal, humidity, and aerodynamic conditions in cities [18-21]. Greenery also plays a key role as a pillar of the air flow system. It contributes positively to filtering air flowing through the ventilation corridor [22-25], transpiration and shading [26], and lowering ambient temperatures [19].

Current methods of defining ventilation conditions in urban areas include both experimental research based on meteorological measurements and model solutions developed alongside advances in computer technology. Geographic Information Systems enable the use of data on terrain morphology and meteorological station measurements, creating tools for understanding local climate characteristics [27-30]. Wind tunnel modelling, a relatively new tool, can potentially provide accurate analyses of aerodynamic conditions. However, limitations include project scale, computational requirements, and potentially high study costs [31-32]. Another option is CFD realistic simulations, which consider air flow in highly urbanised structures. Although computationally demanding, they are unsuitable for large-scale climatic studies [33-35].

Unfortunately, the role of ventilation corridors is underestimated in spatial planning. Open green areas are attractive to investors seeking to build on available land, diverting attention from the important role these spaces play [36].

2. City ventilation systems

Ventilation corridor systems have a positive impact on climatic conditions in cities [37]. Air exchange with rural areas regulates temperature differences and the concentration of pollutants in the atmosphere. These systems are created based on the individual characteristics of each city and are adapted to existing conditions. The most important factors in ventilation corridor planning are the dominant wind direction, the shape of the urban space, the placement of green areas, and natural conditions [38-39].

Natural topography is the most common factor determining the location of a ventilation system. River valleys that run along dominant air flow directions create favourable conditions for ventilation. In addition, due to wet soils and the risk of flooding associated with surface waters, these areas are not preferred for development. This forms a natural barrier to construction, which ensures low aerodynamic roughness length in the surrounding valley. Water areas often occur alongside greenery, which positively affects air quality due to its filtering properties and its role in improving water retention. An example of such planning is the city of Kraków, where seven out of eleven designated ventilation corridors are river valleys [40]. In Łódź, the entire ventilation system was created based on small valleys of surface and underground rivers [41].

Another natural factor in developing ventilation systems is the presence of forested areas that perform the function of air regeneration. While tall vegetation can obstruct wind flow, it has a positive impact on air quality. Therefore, it is beneficial to locate corridors close to forests and extensive green areas. Forests produce significant amounts of oxygen; the air within them has beneficial thermo-humidity properties and contains specific bactericidal substances. The improvement of the aerosanitary condition occurs not only within the regeneration area but also in its vicinity [42].

The occurrence of thermally contrasting surfaces, such as tall green areas (Łagiewnicki Forest) and watercourses (the Bzura and Sokołówka valleys), has a positive effect on the intensification of air exchange in Łódź. Thanks to its large surface area and dense tree cover, it can also perform a regenerative function (Fig. 1) [43].

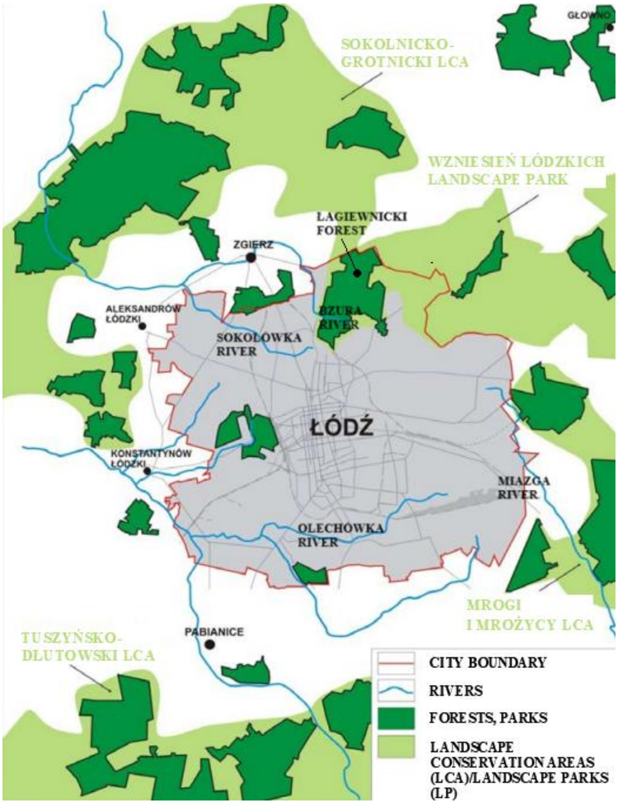

Fig. 1. Air regeneration areas and the main water network in Łódź. *Source*: [43]

Anthropogenic forms can also function as ventilation corridors. The linear layout of communication routes allows for the transport of air into the city; however, with the development of motorisation, they have also begun to emit large amounts of pollutants. Therefore, the ventilation system should not be based solely on the street layout. Another solution is to use railway areas. While their regenerative role is limited, these vast terrains, often surrounded by greenery, create suitable conditions for the transport of air masses [44-45].

Warsaw is an example of a city whose ventilation system is based on river valleys, natural spaces, and railway areas (Fig. 2). It consists of nine corridors running radially from the city borders towards the centre. Although not all of the routes align with the dominant wind direction, their radial arrangement allows for the utilisation of breeze circulation potential. The main role is played by the Vistula Corridor, through which air masses flow primarily from the north, north-west, and south-east. In the central and northern parts, the aim is to preserve riverside greenery, and the supply area for this corridor is the Kampinos Forest. Despite in-depth analyses of the urban heat island in Warsaw and an awareness of the role of ventilation in mitigating the urban climate, most ventilation corridors remain under threat from development pressure. Local planning documents permit the construction of new buildings within them, which may negatively affect air quality in the city [7,46].

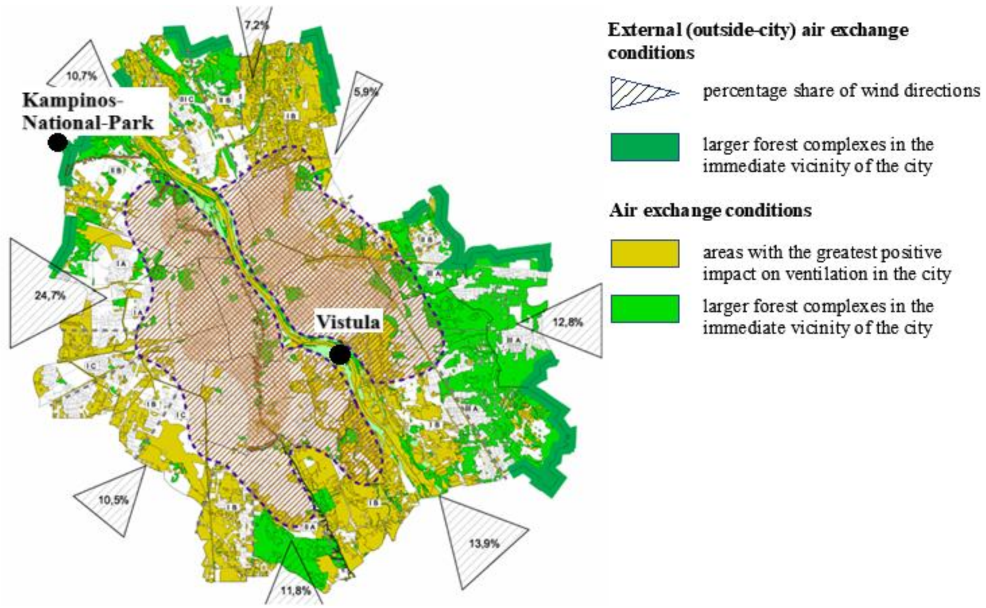

Fig. 2. External (outside-city) air exchange conditions in Warsaw. *Source*: [47]

In the most densely built-up cities in the world, ensuring efficient air circulation in the city centre is a major challenge. Ventilation corridors extend beyond the area of compact and tall buildings, which is why it is important to plan solutions on a smaller scale along communication routes and through the appropriate location of buildings. Hong Kong may serve as an example for other cities due to its well-prepared air circulation strategy. Nevertheless, recommendations should be individually adjusted to different structures due to the diversity of urban climates [48].

Urban air corridors can be classified according to the type of air they transport [49].

Clean air corridors connect places of differing temperatures but with low levels of air pollution. In weather conditions with low wind speeds, the air temperature equalises within the corridor.

Cold air corridors connect spaces with varying levels of pollution and without significant temperature differences. In weather conditions with low wind speeds, pollutants are transported from the city towards rural areas within the corridor.

Ecological corridors lack structural continuity but maintain functional continuity. These areas allow the migration of plants, animals, and fungi in urbanised environments [50]. Under appropriate conditions, they can also function as ventilation corridors.

Free air flow should be ensured in cities through designated open areas. For such a space to function as a ventilation corridor, it must meet the following general conditions [7]:

- the layout of the space should coincide with the dominant wind direction,
- the space should be free of urban barriers that inhibit the free flow of air,
- the corridors should allow air to flow in both directions – to introduce regenerated and cooled air into the area, and to allow contaminated and heated air to flow out,
- the corridor area should contain green spaces. However, vegetation introduced in the corridor should be limited in height and density, as the presence of tall vegetation can reduce wind speed.

Based on the literature review, it can be concluded that there are few studies specifying the detailed conditions that ventilation corridors should meet in highly urbanised areas. One significant work on this topic is the research by Matzarakis and Mayer [49], which defines quite precisely the requirements an area should meet in order to perform a ventilation role:

1. The aerodynamic roughness length must be less than 0.5 m.
2. The zero displacement height should not exceed 3 m.
3. The corridor length must be at least 1000 m in one direction.
4. The width of the corridor must be at least four times the height of the side obstacles, but not less than 50 m.
5. Corridor boundaries should be free of obstacles.
6. The width of barriers in the corridor area, such as buildings or tall trees, should be less than 10% of the corridor width.
7. The height of barriers should be less than 10 m.
8. Barriers within the corridor should be placed parallel to the airflow to minimise their impact.
9. The height-to-distance ratio between individual objects should be a maximum of 0.1 for buildings and 0.2 for trees.

3. Study area: fragment of the ventilation corridor

The constantly progressing urbanisation of urban areas causes a deficit of land designated for residential development. Open corridor spaces that often extend into the central parts of cities are becoming very attractive to development companies [51-53]. Simultaneously, the still insufficient level of coverage of cities with local plans contributes to the weakened protection of these areas against investment pressure. This raises the question: do the areas of potential corridors designated in planning documents actually still fulfil such a role?

In the following study, the effectiveness of the western section of one of the ventilation corridors in Łódź will be assessed. The corridor runs along the Łódka River valley, which can be considered a key area in terms of shaping aerodynamic conditions, and thus thermal conditions, in the city (Fig. 3).

The study area is a fragment of the ventilation corridor running along the Łódka River valley, bounded by a communication route to the east, railway areas and allotment gardens to the west. The northern boundary runs along the ventilation corridor, and the southern boundary follows the main communication routes. The study area covers 616.62 ha.

The area was selected due to its location within the ventilation corridor of the Łódka Valley, which is one of two designated corridors bringing fresh air into the city centre – the Łódź Metropolitan Zone. The fragment was chosen based on its position relative to the dominant westerly inflow of air masses (Fig. 4), specifically the surroundings of J. Piłsudski Park. The green areas play a regenerative role for air masses coming from the west. Another reason for choosing this area is the high degree of urbanisation within the zone bordered by the railway bypass.

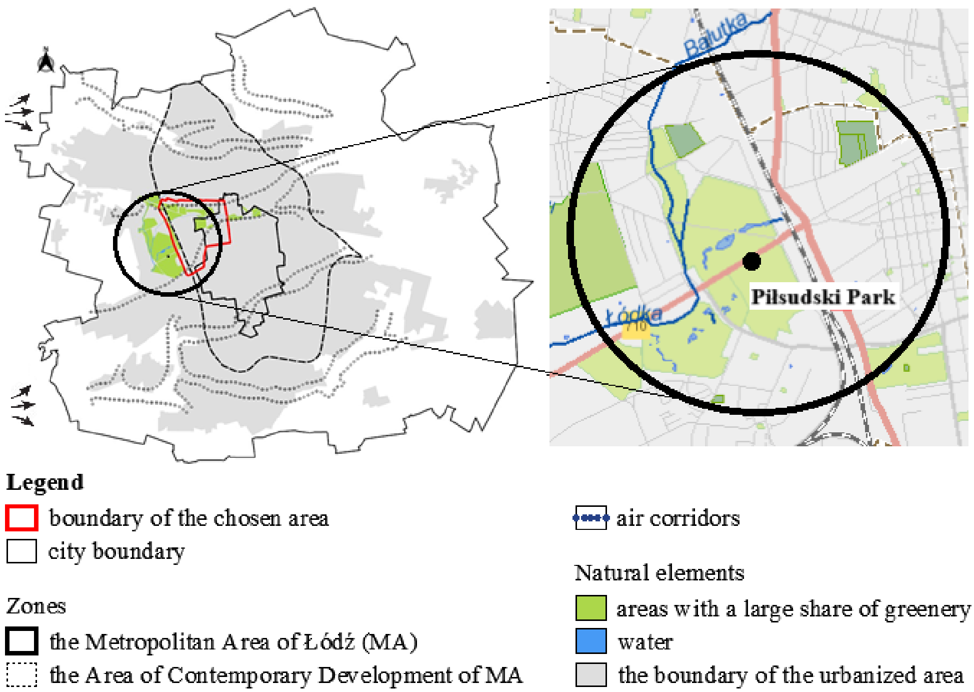

Fig. 3. Location of the study area within the city structure. *Source*: own study based on [41]

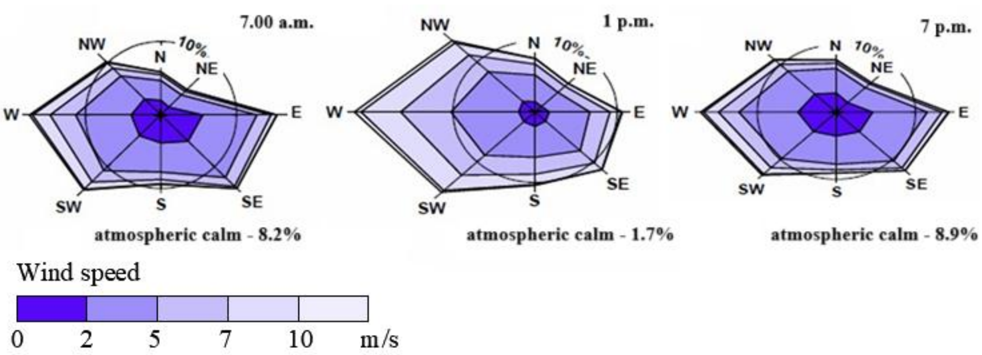

Fig. 4. Frequency of winds from particular directions in Łódź in 1951–1990 (in percentage). *Source*: own study based on [54]

The study area is located within the Metropolitan Zone and the Contemporary Development Area of the Metropolitan Zone. The former was developed in Łódź up to 1939 and primarily encompasses the downtown area, mainly consisting of tenement buildings. The dominant land use in this area is service and residential. Green areas occupy only a small percentage of the terrain. The latter – the Contemporary Development Area of the Metropolitan Zone – is another part of the city, bounded by the ring railway. This area is dominated by residential, service, and service-production developments. Due to its historical growth, this part of the city has a diverse character and structure, with development beginning before 1939 and continuing to the present day.

An important factor ensuring the proper functioning of ventilation corridors is the presence of terrain with a high share of greenery. Over 25% of the selected area is covered by green spaces. These are concentrated in the northern and western parts of the study area and largely exhibit linear continuity, which is a favourable feature for ventilation purposes. In addition, greenery is also found alongside other land uses. Areas with a high proportion of permeable surfaces include multi-family housing estates. The presence of vegetation has a positive effect on the microclimatic conditions in these zones. A negative aspect, however, is the lack of designated green spaces among city centre buildings, which hinders the possibility of introducing spatial modifications.

Over the course of 120 years, development has progressed intensively in the study area (Fig. 5). In 1903, the urbanisation boundary was mainly confined to the present-day Metropolitan Zone. In 1906, following the construction of the bypass railway, the decision was made to extend the city limits to include nearby villages (Żubardź, Doły, Widzew, Dąbrowa, Rokicie, Karolew, and Brus). At that time, the area of Łódź was 38.1 km² [55]. Until 1929, development continued in the central area. The newly incorporated areas were developed in a dispersed manner, with buildings concentrated along individual streets. Subsequent transformations mainly complemented the existing built environment, while the northern part of the area expanded. In the post-war period, the focus shifted to the construction of large-scale multi-family housing estates. Apartment buildings were erected adjacent to existing developments, significantly covering the study area. From 1991 to the present day, changes have mainly taken the form of infill development or revitalisation processes. The limitation of development dispersion observed in the area is a positive trend for maintaining sustainable conditions for urban expansion.

Fig. 5. Development of buildings in the years 1903–2019. *Source*: own study based on historical maps from the Mapster website

4. Methods for assessing the ventilation corridor

The type of terrain over which air flows has the greatest influence on airflow. Its impact is determined by topography, the density and type of development, as well as the presence of vegetation cover. The influence of terrain type on wind movement is characterised by the aerodynamic roughness length. It is defined as "*the ratio of the projection of the building base on the horizontal plane to the total calculation area (e.g. 1 km²), multiplied by the average height of the building*" [56-59]. This relationship is expressed experimentally as (Eq. 1) [60]:

$$z_0 = 0.5h\frac{A_P}{A_T} \tag{1}$$

where: z_0 – aerodynamic roughness length, h – average building height, A_P – building area, A_T – total area.

Among the parameters defining surface roughness, the aerodynamic roughness length (z_0) is most commonly used [61]. There are three basic methods for determining this parameter: micrometeorological, visual estimation, and morphometric.

The micrometeorological (anemometric) method is based on data from direct wind speed measurements, from which vertical wind speed profiles are determined using a logarithmic formula. This method involves high data acquisition costs and is highly sensitive to data errors, which is why it is not commonly used for determining ventilation corridors.

The visual estimation method determines aerodynamic roughness length using eight Davenport classes, modified by Wieringa [61-62]. This method is relatively easy to use, but the results are characterised by low precision. In relation to built-up areas, the aerodynamic roughness length classes take into account only two values.

The morphometric method is the most common approach for determining and assessing ventilation corridors in cities. It uses building data from the Geographic Information System (GIS) to assess aerodynamic roughness length using GIS software. This method is the most effective due to its low data acquisition cost, high precision, and relatively simple calculation procedure [61].

The ventilation corridor fragment was analysed using the visual estimation method, based on land classification data from the Corine Land Cover project for 1990 and 2018, as well as the morphometric method, using data provided by the Łódź Geodesy Centre.

4.1. Determination of aerodynamic roughness length parameters using the visual estimation method

The visual estimation method is based on classifications of typical aerodynamic roughness length values derived from experimental studies. Several classifications have been developed, but the most commonly used is the Wieringa classification (Tab. 1) [63]. The creation of a visual aerodynamic roughness length model was made possible using Corine Land Cover data for the years 1990–2018, concerning land cover, sourced from the website of the Chief Inspectorate for Environmental Protection (https://clc.gios.gov.pl) and made available on a European scale through the Copernicus Land Monitoring Service (https://land.copernicus.eu/en). This programme, created on the initiative of the European Environment Agency, gathers harmonised information on the state of the environment in EU countries and ensures the coherence of information at the international level. Corine Land Cover data provides information on land use changes in Europe from 1990 to 2018. Land cover mapping is carried out with accuracy corresponding to a map at a scale of 1:100,000. Data are obtained from various sources, such as orthophotomaps or topographic maps of the area [64].

This project clearly illustrates the impact of human activity, industrial and transport development, and changes in the urban, agricultural, and forested landscape on the natural environment over a period of approximately 30 years. The data is organised into three levels. The first divides the space into five main groups: anthropogenic areas, agricultural areas, forests and semi-natural ecosystems, wetlands, and water bodies. The second level further divides these into 15 land cover forms, and the third level into 44 land groups, offering the most detailed classification. In Poland, there are 31 land cover classes, each assigned a unique code and an associated aerodynamic roughness length parameter [64].

Figures 6-7 show the development of the study area in the context of Łódź according to Corine Land Cover in 1990 and 2018. This programme involves generalisations that may distort the actual function of the area, including a minimum polygon area of 25 ha. Nevertheless, changes in development over time are clearly visible.

The main changes in the city have occurred in the expansion of loose urban development and the transport network, linked to the construction of motorways and the development of the railway network. Development has become increasingly chaotic and dispersed compared to the relatively compact form seen in the 1990s. Continued unplanned expansion may have negative consequences – economically, due to the need for extended infrastructure, and environmentally, due to the reduction of natural areas and the obstruction of airflow through the city.

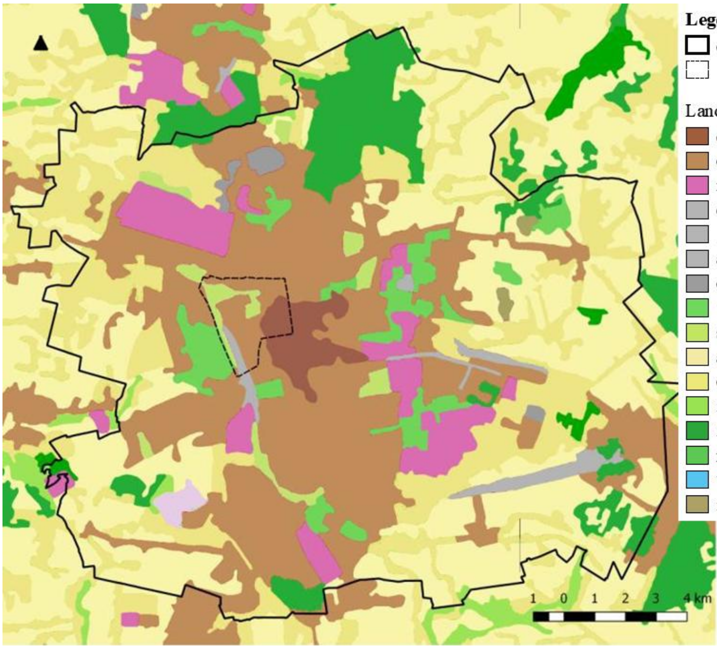

Fig. 6. Development of the area of Łódź according to Corine Land Cover in 1990. *Source*: own study based on CLC data

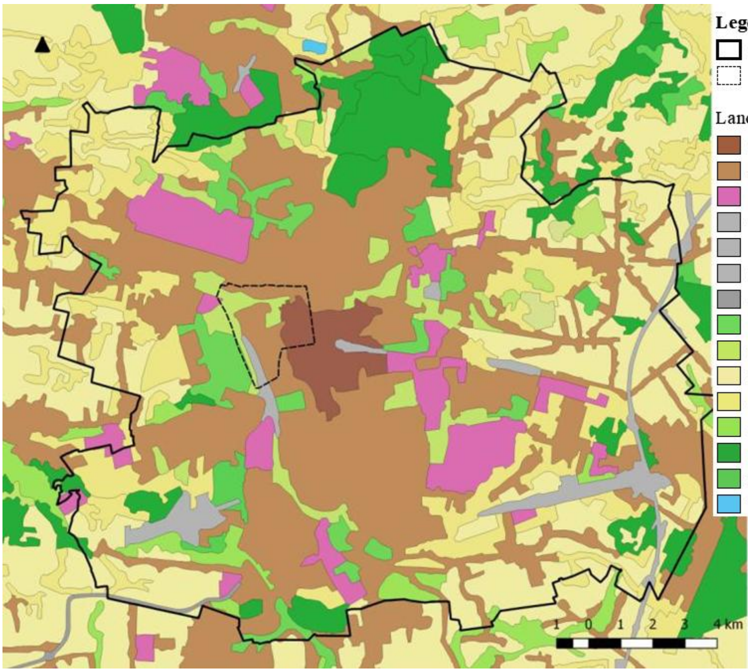

Fig. 7. Development of the area of Łódź according to Corine Land Cover in 2018. *Source*: own study based on CLC data

In the further part of the study, individual classes defined according to Corine Land Cover were assigned an aerodynamic roughness length coefficient. For this purpose, computer-aided techniques were used – specifically, Quantum GIS software. Corine Land Cover developed its own aerodynamic roughness length classification, which was compared with the classification by Wieringa (Tab. 1).

Table 1. Aerodynamic roughness length classification of Corine Land Cover classes. *Source*: own study based on [62,65]

<table>
<tr><th>CLC code</th><th>Description</th><th>Aerodynamic roughness length according to CLC</th><th>Wieringa's aerodynamic roughness length classification</th></tr>
<tr><td>111</td><td>Compact development</td><td>1.2</td><td>2.0</td></tr>
<tr><td>311</td><td rowspan="3">Forest areas</td><td rowspan="3">0.75</td><td rowspan="6">0.5</td></tr>
<tr><td>312</td></tr>
<tr><td>313</td></tr>
<tr><td>141</td><td rowspan="3">Park greenery, forests and shrub vegetation</td><td rowspan="3">0.6</td></tr>
<tr><td>324</td></tr>
<tr><td>334</td></tr>
<tr><td>112</td><td rowspan="5">Sparse urban development, industrial, commercial, sports and recreational areas, construction areas</td><td rowspan="5">0.5</td><td rowspan="2">1.0</td></tr>
<tr><td>121</td></tr>
<tr><td>133</td><td rowspan="3">0.5</td></tr>
<tr><td>142</td></tr>
<tr><td>123</td></tr>
<tr><td>242</td><td rowspan="3">Mixed crop areas, complex cropping systems</td><td rowspan="3">0.30</td><td rowspan="4">0.25</td></tr>
<tr><td>243</td></tr>
<tr><td>244</td></tr>
<tr><td>221</td><td rowspan="4">Vineyards, annual crops, permanent crops</td><td rowspan="4">0.10</td></tr>
<tr><td>241</td><td rowspan="3">0.10</td></tr>
<tr><td>222</td></tr>
<tr><td>223</td></tr>
<tr><td>122</td><td>Communication areas</td><td>0.075</td><td rowspan="11">0.03</td></tr>
<tr><td>211</td><td rowspan="5">Arable land, wetlands</td><td rowspan="5">0.05</td></tr>
<tr><td>212</td></tr>
<tr><td>213</td></tr>
<tr><td>411</td></tr>
<tr><td>421</td></tr>
<tr><td>321</td><td rowspan="4">Natural pastures, heathlands</td><td rowspan="4">0.03</td></tr>
<tr><td>322</td></tr>
<tr><td>323</td></tr>
<tr><td>231</td></tr>
<tr><td>124</td><td rowspan="2">Airports, sparsely vegetated areas</td><td rowspan="2"></td></tr>
<tr><td>131</td><td></td></tr>
</table>

CLC code	Description	Aerodynamic roughness length according to CLC	Wieringa's aerodynamic roughness length classification
132		0.0005	0.005
332			
333			
335	Glaciers and eternal snows	0.001	
422	Peat bogs, salt pans	0.0005	
412			
423			
331	Beaches, dunes	0.0003	
511	Water areas	0	0.0002
512			
523			
522			
521			

The Wieringa classification was used to create the aerodynamic roughness length model due to its widespread application. The results are presented for 1990 (Fig. 8) and for 2018 (Fig. 9).

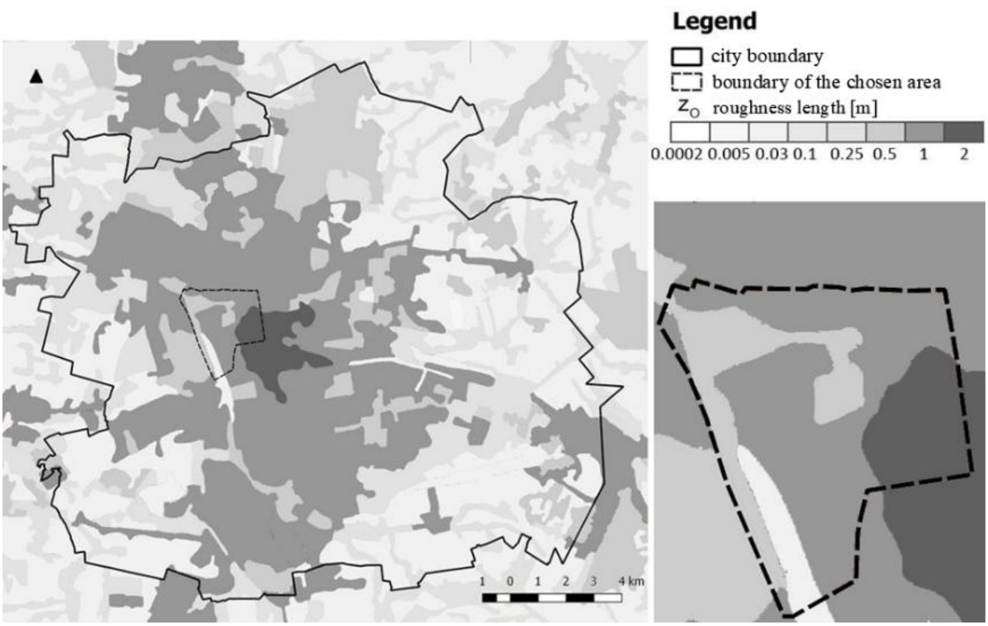

Fig. 8. Aerodynamic roughness length for the study area and the city of Łódź in 1990, determined by visual estimation. *Source*: own study based on CLC data

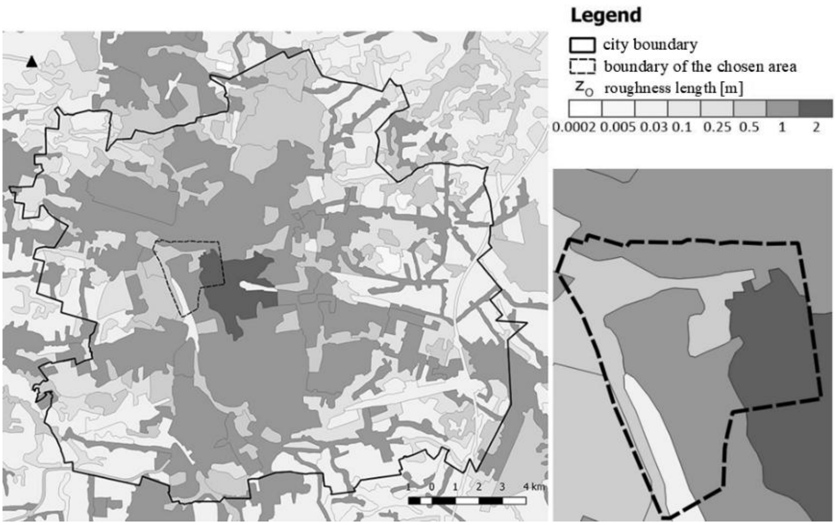

Fig. 9. Aerodynamic roughness length for the study area and the city of Łódź in 2018, determined by visual estimation. *Source*: own study based on CLC data

The largest changes in aerodynamic roughness length can be observed in the western part of the analysed area. Due to increased development density, the area characterised by the highest coefficient values has expanded. At the same time, the existing urban green belt has been extended. In the remaining parts of the area, the coefficient values have remained unchanged.

The next stage involved identifying areas that meet the corridor efficiency criteria (Fig. 10-11). According to Matzarakis and Mayer, the following key criteria were adopted [49]:

- aerodynamic roughness length value < 0.5 m,
- corridor width ≥ 50 m,
- corridor length ≥ 1 km.

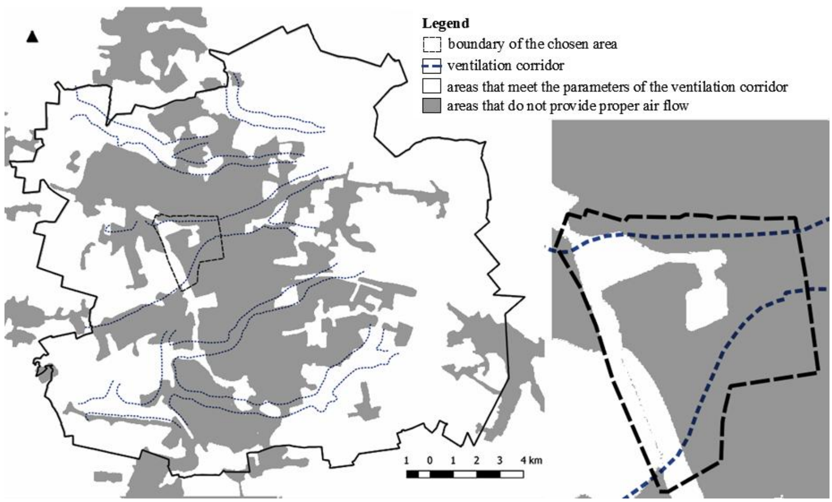

Fig. 10. Areas meeting the ventilation requirements in the study area and the city of Łódź in 1990, determined by the visual estimation method. *Source*: own study based on CLC data

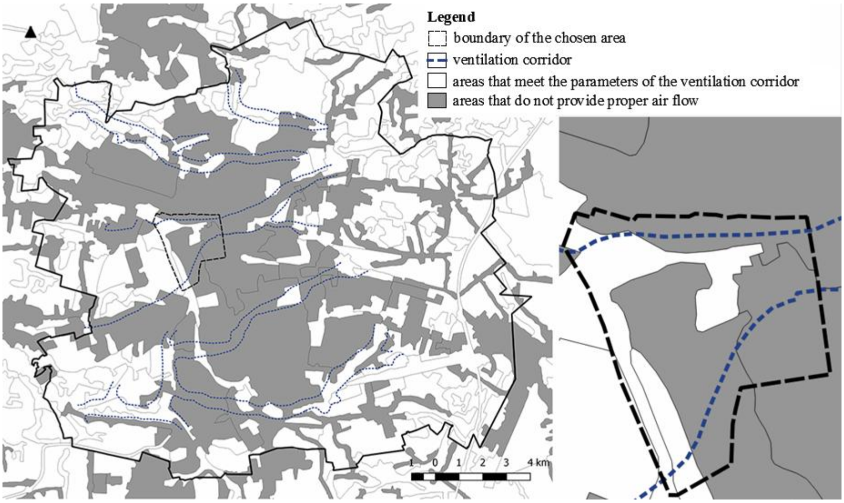

Fig. 11. Areas meeting the ventilation requirements in the study area and the city of Łódź in 2018, determined by the visual estimation method. *Source*: own study based on CLC data

The area that meets the requirements for ventilation corridors has not changed significantly. Only the expansion of urban green areas has contributed to a slight extension of this zone in the north-eastern part.

4.2. Determination of aerodynamic roughness length parameters using the morphometric method

The morphometric method is based on detailed information about objects that act as obstacles to air flow. It is characterised by easy access to the necessary data and high precision of the obtained results. For the purposes of this study, spatial information was obtained in vector form from a digital database of topographic objects and a base map provided by the Łódź Geodesy Centre. The data included the parameters: length, width, and height of 3,572 buildings in the study area.

Due to the diversity of downtown development in Łódź, particularly in residential and industrial areas, it was necessary to group adjacent buildings. As a result of this aggregation, 1,369 objects were created, for which the average height was calculated using the formula (Eq. 2):

$$h = \frac{\sum_{i=1}^{n} A_{Pi} h_i}{\sum_{i=1}^{n} A_{Pi}} \tag{2}$$

where: A_{Pi} – building area, h_i – height of the object.

The building area (A_P), reference area (A_T), and front area (A_F) were calculated based on the dominant westerly wind direction (Fig. 12). Each parameter was determined using the functions available in the QuantumGIS software.

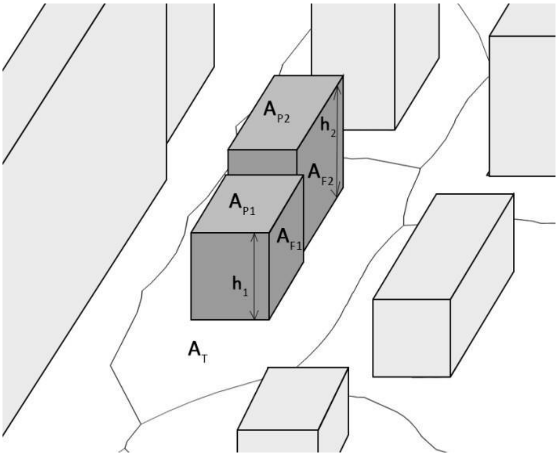

Fig. 12. Parameters used in the calculations with the morphometric method. *Source*: own study based on [66]

The building area was determined using the mathematical function *$area*, which returns the area attribute for each polygon. In the case of grouped objects, these attributes were summed.

Next, for each building or group, a reference surface was assigned using the Voronoi mathematical algorithm. This algorithm determines the perpendicular bisectors between every pair of points and then defines the areas associated with each. Since the algorithm operates only on points, it was necessary to extract the vertices of each building using the geometry tool *Extract nodes*¸ and then determine the reference surface for each of them. To ensure that the surfaces did not intersect the building walls, their geometry had to be densified using the *Densify geometry* tool. The generated polygons were merged within the buildings and groups, and their area was calculated using the *$area* function. More details in: [61].

The frontal area was calculated based on the geographic coordinates of each vertex of the object and its average height. Considering that the air flows from the west, the following formula was applied (Eq. 3):

$$A_F = (y_{max} - y_{min})h \tag{3}$$

where: y_{max} - y-coordinates of the northernmost vertex of the object, y_{min} - y-coordinates of the southernmost vertex of the object, h - height of the object.

Based on the obtained dimensions, the basic terrain roughness coefficients were determined, which are the aerodynamic roughness length (z_0) and the zero displacement height (z_d). The aerodynamic roughness length was calculated using the equation (Eq. 4.):

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

where: h – height of the object, z_d – zero displacement height, k – von Kármán constant (0.4), C_{Dh} – obstacle resistance coefficient (0.8), λ_F - ratio of the building's front area to the reference area.

In its simplified form, the formula can be written as (Eq. 5):

$$z_0 = (h - z_d) exp\left(-\sqrt{\frac{k}{\lambda_F}}\right) \tag{5}$$

The proportion of the frontal area to the reference surface was defined as (Eq. 6):

$$\lambda_F = \frac{\sum_{i=1}^{n} A_{F_i}}{A_T} \tag{6}$$

where: A_F - frontal area, A_T - reference area.

The zero displacement height value was determined using the formulas (Eq. 7-8.):

$$z_d = h(\lambda_\rho)^{0.6} \tag{7}$$

$$\lambda_\rho = \frac{\sum_{i=1}^{n} A_{Pi}}{A_T} \tag{8}$$

where: λ_ρ - share of built-up area, A_P - building area, A_T - reference area.

The aerodynamic roughness length parameters were then calculated for 1990 and 2018 (Fig. 13-14).

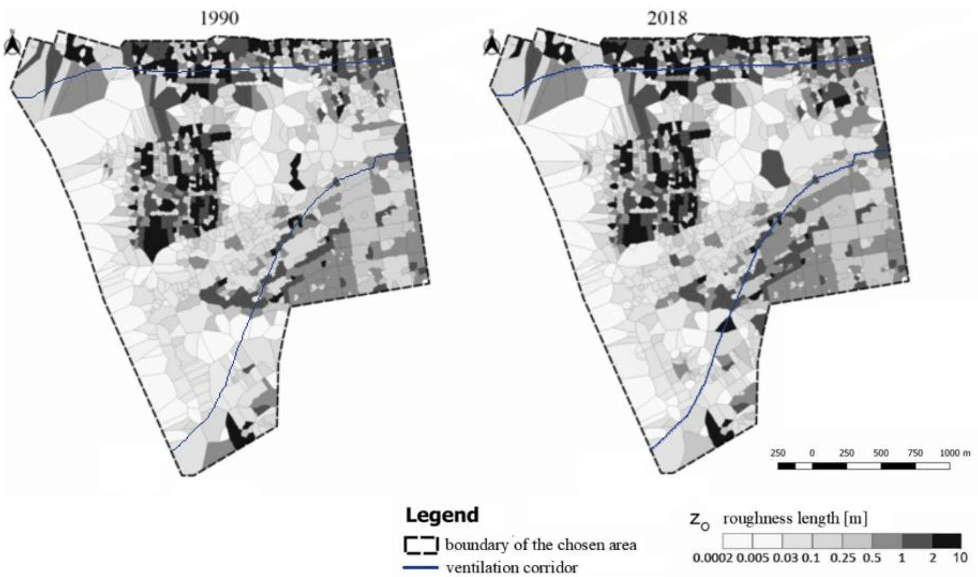

Fig. 13. Aerodynamic roughness length determined using the morphometric method for the study area in 1990 and 2018. *Source*: own study based on CLC data

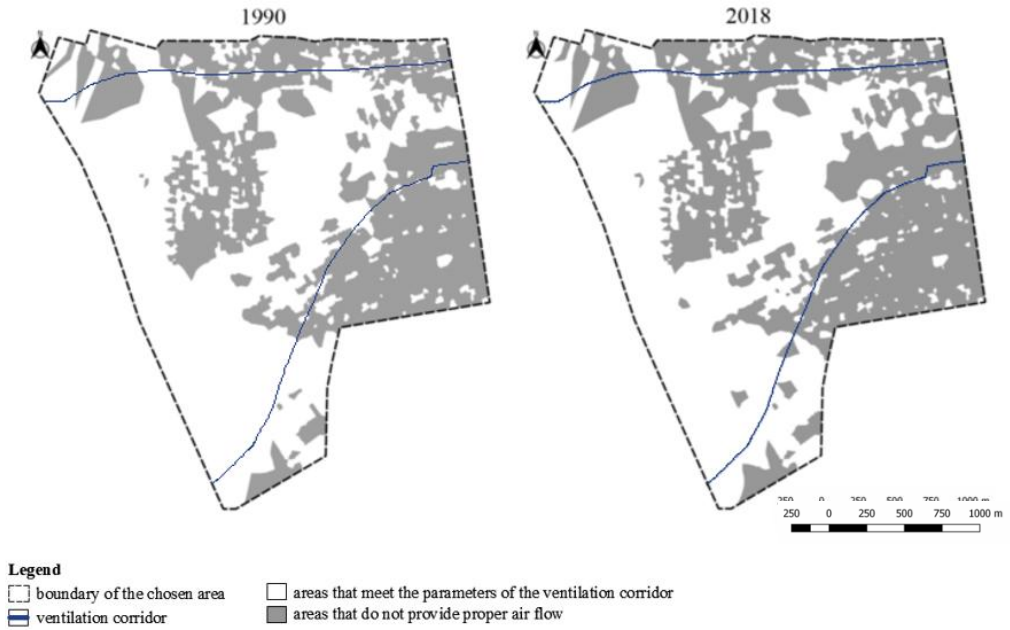

Fig. 14. Aerodynamic roughness length determined using the morphometric method for the study area in 1990 and 2018. *Source*: own study based on CLC data

Similarly to the visual estimation method (Section 4.1), the areas acting as ventilation corridors were designated using the method proposed by Matzarakis and Mayer [49,66-67]. It should be noted that this method considers only the influence of buildings located within the selected area. It does not account for vegetation or terrain features, and therefore aerodynamic roughness length values are underestimated for open areas. It should be assumed that the aerodynamic roughness length in such areas is not less than 0.03 m – corresponding to areas with low vegetation and isolated obstacles.

5. Comparison of results and overall assessment of the corridor

Areas with free air flow, as determined by both the visual estimation method and the morphometric method, include green spaces located in the northern and western parts of the study area, the cemetery, and railway zones. Analyses conducted using the former method showed that open areas and those covered with greenery had low aerodynamic roughness length values, while all built-up areas were excluded from serving as ventilation corridors, regardless of the density or height of the buildings.

It should be noted that only the dominant westerly air flow direction in Łódź was considered. For a comprehensive assessment of the city's ventilation conditions, it is recommended to include additional wind directions in future studies.

Given the characteristics of the terrain – namely, the predominance of built-up areas and the specific size of the analysed fragment – the morphometric method can be considered more precise, as it is specifically designed for analyses in urbanised zones. The visual estimation method is less accurate and is more appropriate for preliminary identification of potential ventilation areas.

The corridors allowing for free westward air flow, as they existed in 2018 and as determined by the morphometric method, are presented in Fig. 15. These areas meet the specific criteria for ventilation corridors. Considering that Piłsudski Park, located west of the study area, meets the ventilation criteria according to the visual estimation method, it was assumed that each of the identified corridors has a length greater than 1 km. However, none of them reach the city centre, contrary to the assumptions outlined in local planning documents. The remaining corridors have been blocked by multi-family housing estates or large-volume individual structures. This situation hinders air exchange between the city centre and peripheral zones. It is worth noting that the situation did not change significantly between 1990 and 2018, as the air corridors were already obstructed by development in 1990.

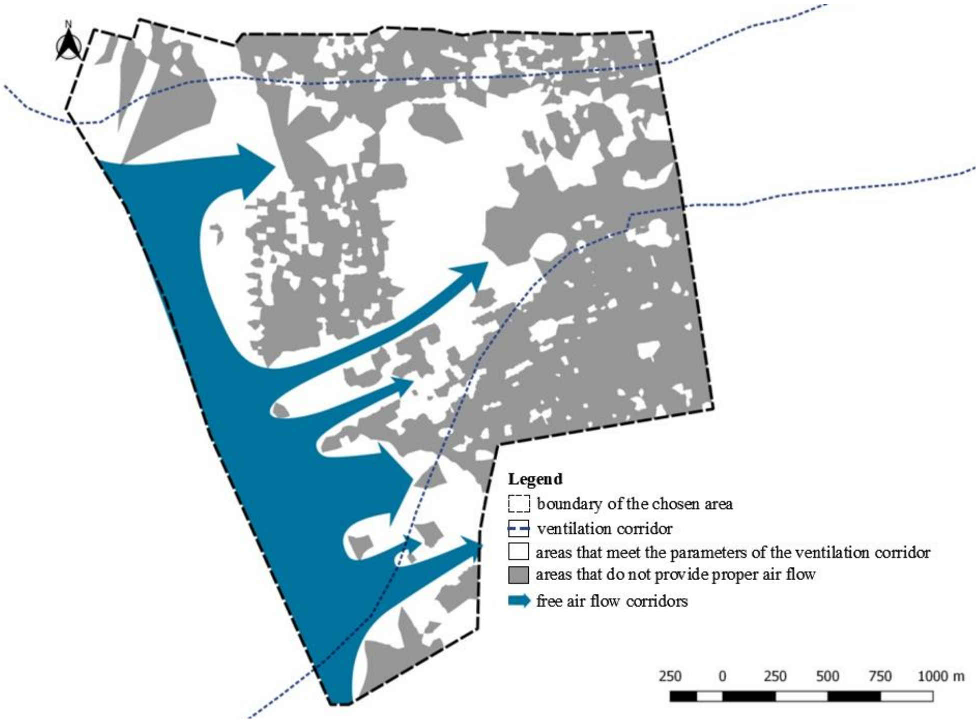

Fig. 15. Free air flow corridors in the study area in 2018. *Source*: own study

The morphometric method provides much more precise results, as it considers the dimensions and surroundings of each building or group of buildings individually. This made it possible to identify areas with good ventilation conditions between buildings – for example, in the service zones between Srebrzyńska Street and Legionów Street (Fig. 16), as well as in the southern parts of the area.

The analyses verified the efficiency of ventilation in green areas located in the northern part and identified additional zones that support air flow. Figure 17 shows how, due to the presence of tall multi-family buildings, air masses flowing over allotment gardens are obstructed.

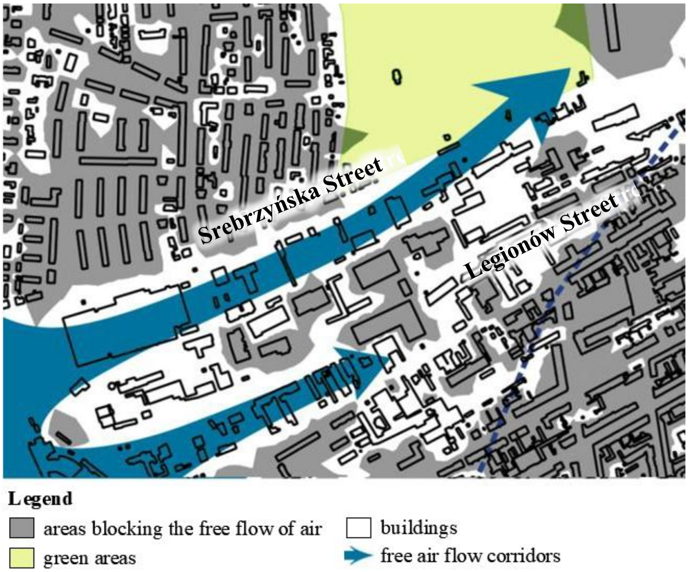

Fig. 16. Air flow over service areas. *Source*: own study

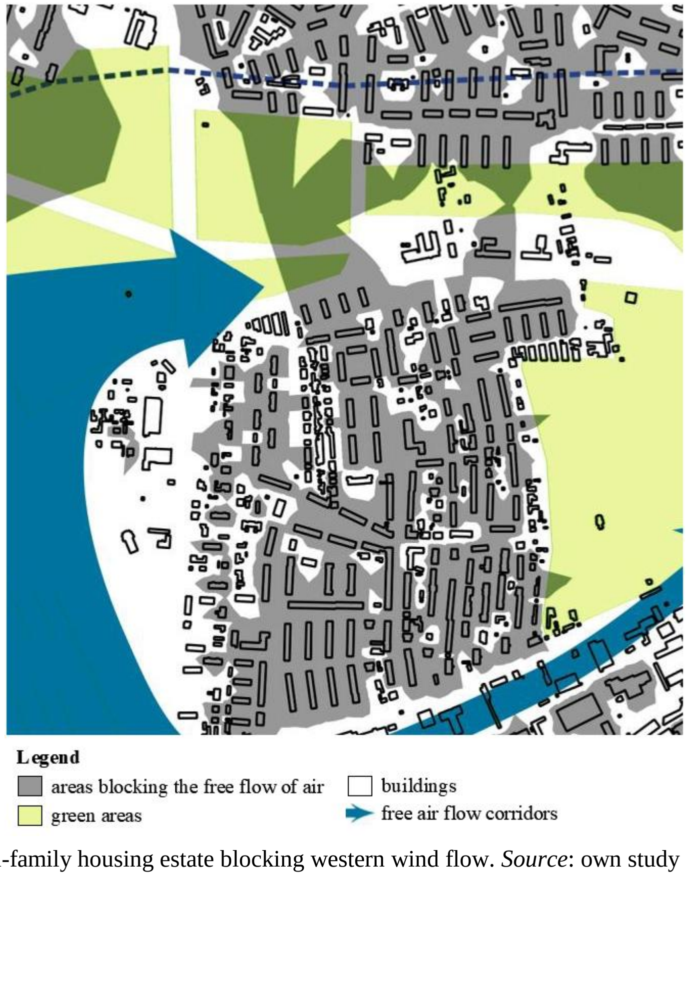

Fig. 17. Multi-family housing estate blocking western wind flow. *Source*: own study

The fragment with a negative impact on the functioning of the corridor is the multi-family housing estate located in the central part of the study area. The dense development of buildings of considerable height (up to 11 storeys) along the north–south axis has created a distinct barrier, hindering the inflow of air from the west into the city.

Within developed areas, the use of the morphometric method is a suitable solution, as it accounts for the parameters and location of each building. This enables the identification of development that obstructs the westerly air flow, as well as that which has an acceptable impact on wind movement. The method also allows for the analysis of a building's influence on its surroundings, which is important because the spatial impact of a structure often exceeds its physical footprint. In the case of large open or green areas, a high level of detail in calculations is not necessary, and determining aerodynamic roughness length using the visual estimation method is sufficient. Despite their differences, both methods can complement each other – the use of aerodynamic roughness length classification is simple and relatively quick, allowing for the identification of main air inflow areas across an agglomeration or region. The morphometric method can then refine the results within highly transformed urban fabric and identify key areas of free wind flow, as well as conflict zones.

6. Conclusions

According to the principles of sustainable development, the spread of urban development should be limited, and already developed areas should be utilised more efficiently – a point emphasised by numerous planning documents. Using the study area as an example, it is evident that until 1990, development occurred in a dispersed manner, which hindered the westward flow of air. Current spatial changes focus on the intensification of development in existing built-up areas. However, in the case of areas functioning as ventilation corridors, this approach is insufficient. The transformation of development should be designed in a way that enhances air flow. The current spatial planning system does not guarantee legal protection for the main areas of air inflow into cities. Although national, regional, and local studies highlight the importance of these zones, they do not provide adequate safeguards. The legal instrument that can protect space from degradation is the local spatial development plan. The number of such plans in Łódź is steadily increasing, which supports the creation and maintenance of spatial order. However, as demonstrated by the example of the study area, the provisions of these plans do not always ensure the free flow of air within ventilation corridors. They often allow the construction of architectural barriers, large-volume buildings, and the intensive development of plots.

The aerodynamic roughness length parameters determined in this study indicate a significant impact of building structures on ventilation conditions. The areas that most obstruct westward airflow are multi-family housing estates, central city buildings, and large-volume structures. Additionally, poorly situated buildings or groups of buildings can create negative aerodynamic effects that reduce the quality of life at the local level. It is essential to avoid locating such structures within ventilation corridors and to maintain appropriate aerodynamic roughness length parameters to ensure these corridors function effectively.

To summarise, the issue of urban ventilation is increasingly addressed in the literature and in planning documents. However, this awareness is not being translated into practical action in spatial planning. Recommendations in city planning documents remain general and fail to provide legal protection for ventilation corridors. It is necessary for local plans to include aerodynamic roughness length indicators for areas designated as ventilation corridors. In the future, detailed analyses of the effectiveness of other ventilation corridors in Łódź should be conducted, taking into account all directions of air inflow. Under weak wind conditions, breeze circulation associated with the urban heat island can aid in ventilating the city. Since air inflow in such conditions can occur from all directions, corridors located in other parts of the city also require protection. In addition to analysing the impact of building structures, particular attention should be paid to potential sources of pollution.

It is important to emphasise the need to raise awareness among landscape planners and municipal officials so that they take into account expert knowledge on aerodynamics in urban environments.

References

[1] Yang X., et al., "Impact of urban heat island on energy demand in buildings: local climate zones in Nanjing", *Applied Energy*, vol. 260, (2020), 1-13. https://doi.org/10.1016/j.apenergy.2019.114279

[2] Adger W. N., et al., "Urbanization, migration, and adaptation to climate change", *One Earth*, vol. 3, (2020), 396-399. https://doi.org/10.1016/j.oneear.2020.09.016

[3] Lee J.-Y. et al., "Future global climate: scenario-based projections and near term information", [in:] Masson-Delmotte V., Zhai P., Pirani A., Connors S. L., Péan C., Berger S., Caud N., Chen Y., Goldfarb L., Gomis M. I., Huang M., Leitzell K., Lonnoy E., Matthews J. B. R., Maycock T. K., Waterfield T., Yelekçi O., Yu R., Zhou B. (eds.), Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, in Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2023, 553-672. https://doi.org/10.1017/9781009157896.006

[4] Pison G., "World population: 8 billion today, how many tomorrow?", *Population & Societies*, vol. 604, (2022), 1-5. https://doi.org/10.3917/popsoc.604.0001

[5] Deuster C. et al., *Demography and Climate Change*, Publications Office of the European Union, Luxembourg, Luxembourg, 2023. https://dx.doi.org/10.2760/26411

[6] Luo F., Yang Y., Zong L., Bi X., "The interactions between urban heat island and heat waves amplify urban warming in Guangzhou, China: roles of urban ventilation and local climate zones", *Frontiers in Environmental Science*, vol. 11(1084473), (2023), 1-13. https://doi.org/10.3389/fenvs.2023.1084473

[7] Błażejczyk K. et al., *Miejska wyspa ciepła w Warszawie*, Instytut Geografii i Przestrzennego Zagospodarowania Polskiej Akademii Nauk, Wydawnictwo Akademickie SEDNO, Warszawa, Polska, 2014.

[8] Elkhazindar A., Kharrufa S. N., Arar M. S., "The effect of urban form on the Heat Island Phenomenon and Human Thermal Comfort: a comparative study of UAE residential sites", *Energies*, vol. 15(5471), (2022), 1-31. https://doi.org/10.3390/en15155471

[9] Vuuren D. P. et al., "The representative concentration pathways: an overview", *Climatic Change*, vol. 109, (2011), 5-31. https://doi.org/10.1007/s10584-011-0148-z

[10] Lopez-Cabeza V. P., Alzate-Gaviria S., Diz-Mellado E., Rivera-Gomez C., Galan-Marin C., "Albedo influence on the microclimate and thermal comfort of courtyards under Mediterranean hot summer climate conditions", *Sustainable Cities and Society*, vol. 81(103872), (2022), 1-19. https://doi.org/10.1016/j.scs.2022.103872

[11] Ampatzidis P., Kershaw T., "A review of the impact of blue space on the urban microclimate", *Science of The Total Environment*, vol. 750(139068), (2020), 1-18. https://doi.org/10.1016/j.scitotenv.2020.139068

[12] Yang X., Zhao L., Bruse M., Meng Q., "Evaluation of a microclimate model for predicting the thermal behavior of different ground surfaces", *Building and Environment*, vol. 60, (2013), 93-104. https://doi.org/10.1016/j.buildenv.2012.11.008

[13] Salata F., Golasi I., De Lieto Vollaro A., De Lieto Vollaro R., "How high albedo and traditional buildings' materials and vegetation affect the quality of urban microclimate. A case study", *Energy and Buildings*, vol. 99, (2015), 32-49. https://doi.org/10.1016/j.enbuild.2015.04.010

[14] Fortuniak K., *Miejska wyspa ciepła*, Wydawnictwo Uniwersytetu Łódzkiego, Łódź, Polska, 2003 (in polish).

[15] Huang J., Wang Y., "Identification of ventilation corridors through a simulation scenario of forest canopy density in the metropolitan area", *Sustainable Cities and Society*, vol. 95, (2023), 1-15. https://doi.org/10.1016/j.scs.2023.104595

[16] Luo Y. et al., "Seasonal cooling effect of vegetation and albedo applied to the LCZ Classification of Three Chinese Megacities", *Remote Sensing*, vol. 15(23), (2023), 1-25. https://doi.org/10.3390/rs15235478

[17] Hu J. et al., "Analysis of the spatial and temporal variations of land surface temperature based on local climate zones: a case study in Nanjing, China", *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 12(11), (2019), 4213-4223. https://doi.org/10.1109/JSTARS.2019.2926502

[18] Sandeepan B. S., Rakesh P. T., Venkatesan R., "Numerical simulation of observed submesoscale plume meandering under nocturnal drainage flow", *Atmospheric Environment*, vol. 69, (2013), 29-36. https://doi.org/10.1016/j.atmosenv.2012.12.007

[19] Son J. M., Eum J. H., Kim S., "Wind corridor planning and management strategies using cold air characteristics: The application in Korean cities", *Sustainable Cities and Society*, vol. 77(103512), (2022), 1-16. https://doi.org/10.1016/j.scs.2021.103512

[20] Ge Q., Kong Q., Xi J., Zheng J., "Application of UTCI in China from tourism perspective", *Theoretical and Applied Climatology*, vol. 128(3), (2017), 551-561. https://doi.org/10.1007/s00704-016-1731-z

[21] Patz J. A., Campbell-Lendrum D., Holloway T., Foley J. A., "Impact of regional climate change on human health", *Nature*, vol. 438(7066), (2005), 310-317. https://doi.org/10.1038/nature04188

[22] Kim J., "Exploring green infrastructure benefits at house and neighborhood scale: case study of Illinois, USA", *Landscape and Ecological Engineering*, vol. 14, (2018), 165-174. https://doi.org/10.1007/s11355-017-0331-0

[23] Guo A. et al., "Quantifying the impact of urban ventilation corridors on thermal environment in Chinese megacities", *Ecological Indicators*, vol. 156(111072), (2023), 1-14. https://doi.org/10.1016/j.ecolind.2023.111072

[24] Ren C. et al., "Creating breathing cities by adopting urban ventilation assessment and wind corridor plan – The implementation in Chinese cities", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 182, (2018), 170-188. https://doi.org/10.1016/j.jweia.2018.09.023

[25] Yim S. H. L., Fung J. C. H., Ng E. Y. Y., "An assessment indicator for air ventilation and pollutant dispersion potential in an urban canopy with complex natural terrain and significant wind variations", *Atmospheric Environment*, vol. 94, (2014), 297-306. https://doi.org/10.1016/j.atmosenv.2014.05.044

[26] Schwaab J. et al., "The role of urban trees in reducing land surface temperatures in European cities", *Nature Communications*, vol. 12(1), (2021), 1-11. https://doi.org/10.1038/s41467-021-26768-w

[27] Jayasinghe C. B., Withanage N. C., Mishra P. K., Abdelrahman K., Fnais M. S., "Evaluating urban heat islands dynamics and environmental criticality in a growing city of a tropical country using remote sensing indices: the example of Matara City, Sri Lanka", *Sustainability*, vol. 16(10635), (2024), 1-30. https://doi.org/10.3390/su162310635

[28] Liu W., Zhang G., Jiang Y., Wang J., "Effective range and driving factors of the urban ventilation corridor effect on urban thermal comfort at unified scale with multisource data", *Remote Sensing*, vol. 13(9), (2021), 1-18. https://doi.org/10.3390/rs13091783

[29] Ng E., Yuan C., Chen L., Ren C., Fung J. C. H., "Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong", *Landscape and Urban Planning*, vol. 101(1), (2011), 59-74. https://doi.org/10.1016/j.landurbplan.2011.01.004

[30] Xie P., Yang J., Wang H., Liu Y., Liu Y., "A New method of simulating urban ventilation corridors using circuit theory", *Sustainable Cities and Society*, vol. 59(102162), (2020), 1-10. https://doi.org/10.1016/j.scs.2020.102162

[31] Klein P., Fedorovich E., Rotach M., "A wind tunnel study of organised and turbulent air motions in urban street canyons", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 89, (2001), 849-861. https://doi.org/10.1016/S0167-6105(01)00074-5

[32] Kubota T., Miura M., Tominaga Y., Mochida A. "Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: Development of guidelines for realizing acceptable wind environment in residential neighborhoods", *Building and Environment*, vol. 43(10), (2008), 1699-1708. https://doi.org/10.1016/j.buildenv.2007.10.015

[33] Yoshie R. et al., "Cooperative project for CFD prediction of pedestrian wind environment in the Architectural Institute of Japan", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 95(9), (2007), 1551-1578. https://doi.org/10.1016/j. jweia.2007.02.023

[34] Unal Cilek M., Cilek A., "Analyses of land surface temperature (LST) variability among local climate zones (LCZs) comparing Landsat-8 and ENVI-met model data", *Sustainable Cities and Society*, vol. 69(102877), (2021), 1-18. https://doi.org/10.1016/j. scs.2021.102877

[35] Gautam K. R., Rong L., Zhang G., Abkar M., "Comparison of analysis methods for wind-driven cross ventilation through large openings", *Building and Environment*, vol. 154, (2019), 375-388. https://doi.org/10.1016/j.buildenv.2019.02.009

[36] Ferreira C. S. S., Walsh R. P. D., Ferreira A. J. D., "Degradation in urban areas", *Current Opinion in Environmental Science & Health*, vol. 5, (2018), 19-25. https://doi.org/10.1016/j.coesh.2018.04.001

[37] Laskowski L., *Wybrane zagadnienia fizyki miasta*, Centralny Ośrodek Informacji Budownictwa, Warszawa, Polska, 1987 (in polish).

[38] Wong M. S., Nichol J. E., To P. H., Wang J., "A simple method for designation of urban ventilation corridors and its application to urban heat island analysis", *Building and Environment*, vol. 45, (2010), 1880-1889. https://doi.org/10.1016/j.buildenv.2010.02.019

[39] Yin J., Zhan Q., Tayyab M., "The ventilation path assessment of urban street in Wuhan", *Polish Journal of Environmental Studies*, vol. 30(3), (2021), 2877-2889. DOI: https://doi.org/10.15244/pjoes/130518

[40] Kraków City Council, *Resolution No. CXII/1700/14 of the Kraków City Council of 9 July 2014 on the adoption of the amendment to the Study of Conditions and Directions of Spatial Development of the City of Kraków*, Kraków, Poland, 2014.

[41] Łódź City Council, *Resolution No. LXIX/1753/18 of the Łódź City Council of 28 March 2018 on the adoption of the Study of Conditions and Directions of Spatial Development of the City of Łódź*, Łódź, Poland, 2018.

[42] Peng L. et al., "Wind weakening in a dense high-rise city due to over nearly five decades of urbanization", *Building and Environment*, vol. 138, (2018), 207-220. https://doi.org/10.1016/j. buildenv.2018.04.037

[43] Wysmyk-Lamprecht B., Stobińska A., Jach K., Miłosz M., *Opracowanie ekofizjograficzne sporządzone na potrzeby studium uwarunkowań i kierunków zagospodarowania przestrzennego*, Łódź, Polska, 2007.

[44] Pan P. et al., "Identification of urban ventilation corridor system using meteorology and GIS technology: a case study in Zhengzhou, China", *Atmosphere*, vol. 15(1034), (2024), 1-19. https://doi.org/10.3390/atmos15091034

[45] Cichowicz R., Dobrzański M., "Analysis of Air Pollution around a CHP Plant: Real Measurements vs. Computer Simulations", *Energies*, vol. 15(553), (2022), 1-18. https://doi.org/10.3390/en15020553

[46] Wicht M., Osińska-Skotak K., "Temporal analysis of urban changes and development in Warsaw's ventilation corridors", *Miscellanea Geographica – Regional Studies on Development*, vol. 20(4), (2016), 11-21. https://doi.org/10.1515/mgrsd-2016-0021

[47] City of Warsaw Office, *Ecophysiographic study for the study of conditions and directions of spatial development of the capital city of Warsaw*, Warsaw, Poland, 2006.

[48] Ng Y. Y., Tam I., Jiang J., Ng K. C. S., Coles J., "Urban climatic map and standards for wind environment - feasibility study. executive summary", *School of Architecture CUHK*, Hongkong, China, 2008.

[49] Matzarakis A., Mayer H., "Mapping of urban air paths for planning in Munchen", *Planning Applications of Urban and Building Climatology*, vol. 16, (1992), 13-22.

[50] Ustawa z dnia 16 kwietnia 2004 r. o ochronie przyrody (Dz. U. 2004, nr 92, poz. 880).

[51] Han L., Zhao J., Zhang T., Zhang J., "Urban ventilation corridors exacerbate air pollution in central urban areas: Evidence from a Chinese city", *Sustainable Cities and Society*, 87(104129), (2022), 1-10. https://doi.org/10.1016/j.scs.2022.104129

[52] Osińska-Skotak K., Zawalich J., "Analysis of land use changes of urban ventilation corridors in Warsaw in 1992-2015", *Geographia Polonica*, vol. 89(3), (2016), 345-358. https://doi.org/GPol.0057

[53] Gu K., Fang Y., Qian Z., Sun Z., Wang A., "Spatial planning for urban ventilation corridors by urban climatology", *Ecosystem Health and Sustainability*, vol. 6(1), (2020), 1-13. https://doi.org/10.1080/20964129.2020.1747946

[54] Fortuniak K., Wibig J., *Atlas miasta Łodzi, Plansza X: Klimat*, Łódź, Polska, 2002.

[55] Stefański K., *Narodziny miasta: rozwój przestrzenny i architektura Łodzi po 1914 roku*, Wydawnictwo Jacek Kusiński, Łódź, Polska, 2016.

[56] Zielonko-Jung K., *Kształtowanie przestrzenne architektury ekologicznej w strukturze miasta*, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, Polska, 2013.

[57] Grimmond C. S. B., Oke T. R., "Aerodynamic properties of urban areas derived from analysis of surface form", *Journal of Applied Meteorology*, vol. 38, (1999), 1262-1292. https://doi.org/10.1175/1520-0450(1999)038<1262:APOUAD>2.0.CO;2

[58] Grimmond C. S. B., Oke T. R., "Heat storage in urban areas: local scale observations and evaluation of a simple model", *Journal of Applied Meteorology*, vol. 38, (1999), 922-940. https://doi.org/10.1175/1520-0450(1999)038<0922:HSIUAL>2.0.CO;2

[59] Bottema M., Mestayer P. G., "Urban roughness mapping – validation techniques and some first results", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 74-76, (1998), 163-173. https://doi.org/10.1016/S0167-6105(98)00014-2

[60] Lewińska J., *Klimat obszarów zurbanizowanych*, Instytut Gospodarki Przestrzennej i Komunalnej, Warszawa, Polska, 1990 (in polish).

[61] Bochenek A., Klemm K., "Wyznaczanie korytarzy przewietrzających przy użyciu metody morfometrycznej dla wybranego fragmentu miasta Łodzi", *Czasopismo Budownictwo i Architektura*, vol. 15(4), (2016), 139-151. https://doi.org/10.24358/Bud-Arch_16_154_14

[62] Wieringa J., Davenport A. G., Grimond C. S. B., Oke T. R., "The revised Davenport roughness classification for cities and sheltered country", *Proceedings of the 3rd European and African Conference on Wind Engineering*, Eindhoven, the Netherlands, 2000.

[63] Klemm K., *Kompleksowa ocena warunków mikroklimatu w luźnych i zwartych strukturach urbanistycznych*, Polska Akademia Nauk, Warszawa, Polska, 2011 (in polish).

[64] Bossard M., *CORINE land cover technical guide - Addendum 2000*, European Environment Agency, Denmark, Copenhagen, 2000.

[65] Silva J., Ribeiro C., Guedes R., *Roughness length classification of Corine land cover classes*, 2007.

[66] Suder A., Szymanowski M., "Determination of ventilation channels in urban areas: a case study of Wrocław (Poland)", *Pure and Applied Geophysics*, vol. 171, (2014), 965-975. https://doi.org/10.1007/s00024-013-0659-9

[67] Gal T., Unger J., "Detection of ventilation paths using high-resolution roughness parameter mapping in a large urban area", *Building and Environment*, vol. 44, (2009), 198-206. https://doi.org/10.1016/j.buildenv.2008.02.008