

Study on transformations in land use in the functional context of extensive city ventilation routes using the example of Bródnowski Ventilation Corridor in Warsaw, Poland

Abstract

Ventilation corridors are critical for regulating the appropriate flow of urban air streams. Details on how they function, especially in a specific location, can be found in local eco-physiographic studies. Such analyses are designed during conceptual work on the conditions and directions of the development of a studied area. Such documentation includes advanced research on the impact of natural conditions on the area's growth and evolution. In Warsaw, Poland, such a study makes it possible to define various natural areas that are essential for the appropriate functioning of the city and increase its inhabitants' well-being. This provides an initial basis for further analysis and motivates researchers to investigate the distribution of natural sites. It inspired the authors to assess the land-use structure in the context of the location of ventilation corridors. Thus, land use and land cover (LULC) modifications were examined in the context of their tendency to aid in the ventilation of the city. The object of the study is the Bródnowski Ventilation Corridor (BVC) – one of several designated for Warsaw in the spatial planning concepts of the 1980s and 1990s. In the research encompassing the years 1982–2020, the authors analysed the land use and roughness determined by the development characteristics and vegetation cover. References were made to current and archival planning documents, aerial photographs, satellite images, and the Topographic Objects Database BDOT10k. The research was prompted by the municipality's intention to urbanize the study area, which will undoubtedly eliminate the ventilation function of the southern part of the corridor and significantly reduce its remaining territory. Analysis of changes in the land cover of the south part of the corridor confirms its marginal importance for the city's ventilation. In this area, ongoing modifications proceed slowly, and urbanization – mainly low-rise and less intensive buildings – is limited. This zone has largely retained and is likely to maintain its favourable features from the point of view of ventilation and air regeneration.

Keywords

Ventilation corridors • urban planning • urban climate • roughness parameters

Introduction

The essential features of a city's climate encompass the deterioration of air quality and the worsening phenomenon of the so-called Urban Heat Island – UHI (Heaviside et al. 2017). The reasons for both problems are well-studied and recognized (Rizwan et al. 2008). In the first case, the origin is the increasing number of pollutant emitters, the source of which may be transportation, industrial facilities, heating with solid fuels, and meteorological conditions (lack of wind, thermal inversion, and many others). However, the factors shaping UHI are much more complex. These include, among others, the city's radiation balance that results from pollution levels and the geometry of urban structures (including building heights and street widths). Additionally, one can mention the increased capacity of building materials to accumulate heat, decreasing evapotranspiration in parallel with reduced green fields, a large share of low albedo surfaces that enable the absorption of solar radiation, and increasing roughness that diminishes ventilation (obstructing the wind blow power). Studies (Fortuniak 2003; Mohajerani et al. 2017; Oke et al. 2017) show that, especially in areas of dense land use, one

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can observe the decreasing wind speed as a function of rising surface roughness.

Large cities' unfavourable aero-sanitary conditions can harm hundreds of thousands of residents by lowering their standard of living. The phenomenon's scale is enormous and requires a comprehensive and long-term strategy for planning the spatial development of urban areas. In this respect, one of the critical action procedures is to change the functional and spatial city structure by designing ventilation corridors. Such passages are linear areas along the lowest land surface that may be activated according to the wind. This phenomenon results from the natural topographic situation of the city. It is enhanced by appropriately shaped vegetation ("green infrastructure") and buildings producing the so-called tunnel effect (Bajorek-Zydroń & Wężyk 2016).

Ensuring urban air exchange and regeneration through a system of ventilation corridors has become a part of urban planning concepts developed for several European cities since the early 19th century. Pioneers include London, Paris, and Vienna (Fortuniak 2003). In the 1980s and 1990s, some recommendations

for shaping the structure of cities, including measures to improve airflow and regeneration, were developed for several German cities, including Munich, Stuttgart, Hamburg, and Frankfurt am Main (Kress 1979; Matzarakis & Mayer 1992). At that time, in 1982, 1992, and 2006, relevant concepts were also developed for wind corridors in Warsaw, Poland.

Implementing the concept of ventilation corridors is increasingly challenging and, in some places, even impossible. The parameters and land development requirements of the areas predestined to play the role of ventilation corridors are increasingly affected by property developers' demands on local authorities, the shortage of investment parcels, and the need for increasing land-use density. The widespread scale of the problem has been highlighted, among others, in the Polish Supreme Audit Office (NIK) report, which assesses the procedures of municipal authorities from 19 Polish cities with regard to strategic planning and the implementation of administrative efforts towards the preservation and expansion of green areas. The report confirmed that, as a result of significant investments encroaching on the natural terrain, one can observe the progressive reduction in the ecological and climatic functions attributed to green areas (NIK 2022).

An analysis of the actions taken by the authorities of large Polish cities, such as Bydgoszcz, Łódź, Wrocław, and Kraków, to update their planning documents (i.e. "Study of conditions and directions for spatial development" – SUIKZP) indicates the efforts made to adapt the earlier concepts of ventilation corridors to the altering conditions or to validate the existing actions and policies by eliminating those that are aimed at enabling air exchange and regeneration (SUIKZP Bydgoszcz 2022; SUIKZP Łódź 2018; SUIKZP Wrocław 2018; SUIKZP Kraków 2014). Similar measures were also taken for Warsaw (KIPiM 2018).

The effectiveness of air exchange in Warsaw depends on internal and external factors. In the former, the usefulness of an area for air exchange depends on the extent of investment, the height and location of civil objects, the coverage of the vegetation area, and the proportion of biologically active space. Spatially connected green fields with low roughness, aided by built-up fields with low ground roughness, are the critical elements of a city ventilation system. In this respect, the land-use structure of Warsaw is diverse and, in general, can be regarded as relatively advantageous. It is determined mainly by the natural character of the vast River Vistula valley. The other areas with the potential for air ventilation are not evenly distributed and contain arable lands, forests, various verdant spaces, street greenery, or even wastelands, as well as some residential sites and road infrastructure. External factors determining the location of Warsaw ventilation corridors are wind direction – the main tendencies and percentage shares of prevailing winds are presented in Figure 1 (WeatherOnline), and spatial links with other biologically active terrains, located in the suburbs, as these are a source of fresh air. In Warsaw, a significant role is played by the large woodland area of Kampinos National Park (located north-west of the city), enhanced by a sizeable arable land area, Mazowiecki Landscape Park (located in the south-east), and Nieporęt or Legionowo Forest (located in the north-east).

The initial document officially introducing solutions to promote air exchange and regeneration in Warsaw was drawn up in 1916. The elaboration titled "Preliminary draft of the regulating plan of Warsaw" (Tolwiński 1948) covered six corridors, including one along the Vistula Valley and five created by various green areas that were spatially and functionally linked. The Prospective Plan of General Spatial Development for Warsaw, established in 1982 (The National Council of Warsaw 1982), contained recreational and climatic zones. The areas included the Vistula River Valley and the zones located on the outskirts of Warsaw

that were spatially connected with open spaces close to the city's core. The next crucial concept was stated in the "Local Spatial Development Plan of Warsaw" and adapted in 1992 (BPRW S.A. 1992). It included nine air corridors running radially from the city's boundaries towards its centre – see Figure 1.

In 2006, the City Council of Warsaw approved a new spatial policy named "Study of Conditions and Directions of Spatial Development" (SUIKZP Warsaw 2006). The authors of the air exchange and regeneration efficiency assessment pointed to declining air exchange efficiency in the areas included in the ventilation corridor system. The main reasons were the excessive spread of built-up areas and the unfavourable arrangement of buildings for ventilation. The efficiency of previous air ventilation corridors, associated with the presence of regions with very good and promising ventilation classes, was assessed as follows: Vistula River Corridor – about 76%, Bródnowski Corridor – 60%, East Railway Corridor – 80%, Wilanowski Corridor – 88%, Podskarpowy Corridor – 80%, Mokotowski Corridor – 70%, Jerozolimski Corridor – 85%, West Railway Corridor – 85% and Bemowski Corridor – about 60%. It is worth noting that despite the declining importance of some corridors for the city's ventilation (e.g. Bródnowski, Bemowski, or Mokotowski corridors), they were still considered significant for the regeneration system (Naftprobud 2001). However, the area preserved for air exchange (SUIKZP 2006) declined by around 13%. The number of air corridors was limited to eight, and the Bródnowski Corridor, which is the area of the presented study, was excluded from the system.

Warsaw's Spatial Policy, established in 2006, was amended in 2010, 2014, 2018, and 2021. These documents emphasized the importance of ventilation corridors as part of the Warsaw Natural System (WNS) and were considered crucial determinants of city land-use changes. However, in this period, the adverse trends were reinforced. The areas of the ventilation corridors became attractive for investment projects. Osiriska-Skotak and Zawlich (2016) studied the directions and rate of development change in nine previous ventilation corridors for the years 1992–2015. The study confirmed the expansion of built-up areas, changing from 15% of the total area in 1992 to 23% in 2015. In particular, the most negative land-use changes, due to industrial and housing development, occurred in the Jerozolimski, West Railway, Wilanowski, Bródnowski, and Mokotowski corridors. The intensification of land development was also confirmed by other authors (Wicht et al. 2016; Wicht et al. 2017; Goch et al. 2017).

As is clear from the above, the system of ventilation corridors for Warsaw is a stimulating object of study. The particular reasons for this are, first, that the corridor concept, at a relatively early stage of preparing spatial plans for Warsaw, transfers to the long period of its practical implementation. Secondly, the concept has been modified several times due to ongoing transformations in the city's spatial development policy, which has negatively affected the functioning of the ventilation system. The last and perhaps most important reason is the constant deterioration of aero-sanitary conditions in the city (Karaczun & Michalak 2019; Gioś et al. 2023). This means that efforts to improve Warsaw's climate, including the maintenance of ventilation corridors, should continue to be one of the priorities in the municipal's spatial policy.

This study aims to analyse changes in spatial policy and land use for the years 1982–2020, relevant to the ventilation capacity of one of the former ventilation corridors of Warsaw, the so-called Bródnowski Ventilation Corridor (BVC). The following assumptions determined the selection of this corridor:

- it used to be one of two significant ventilation corridors in the eastern part of Warsaw (excluded from the system in SUIKZP 2006),
- the area is extremely attractive for investment due to the large share of extensively developed lands,

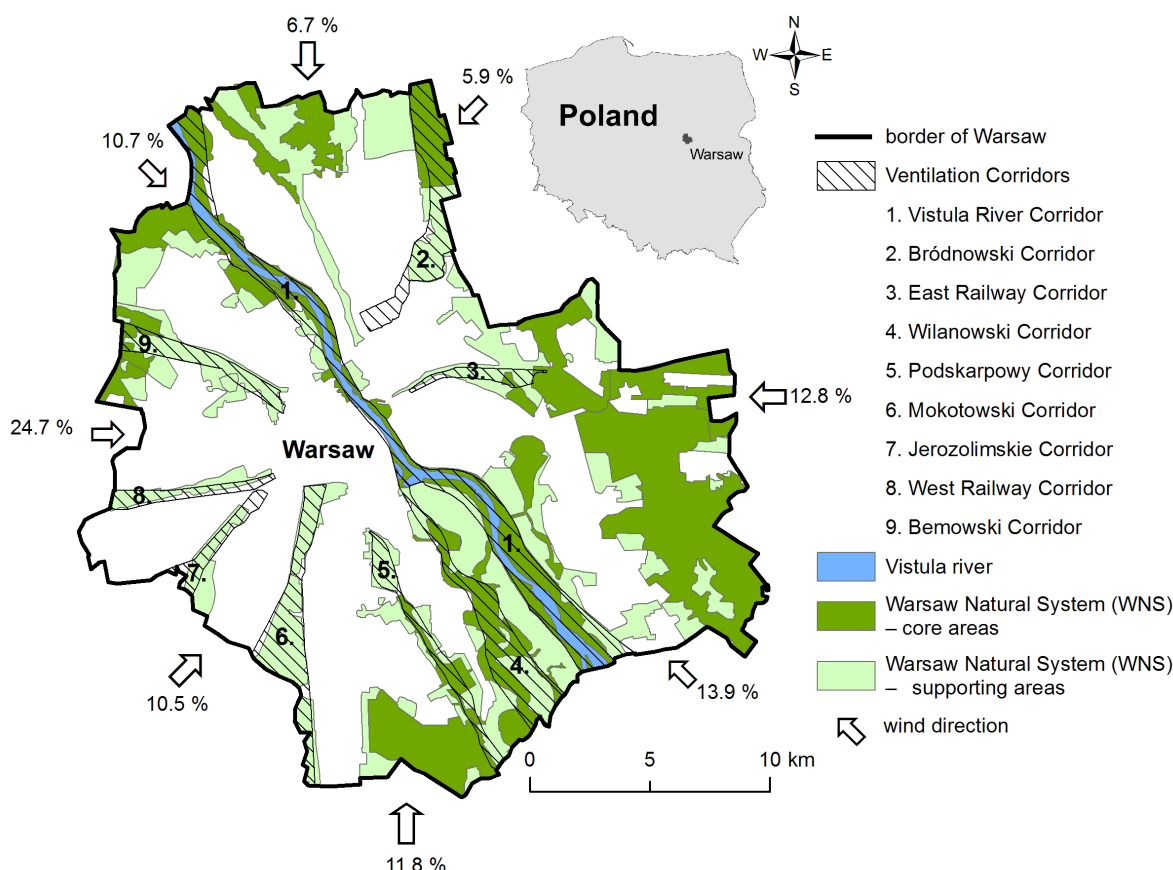


Figure 1. Ventilation corridors established in 1992
Source: own elaboration based on BPRW S.A. 1992.

- it is prone to adverse changes in city policy – adapting planning documents (“Study of Conditions and Directions of the Spatial Development” and available local spatial development plans) that allow land-use changes to be introduced with potentially damaging consequences for air ventilation and regeneration,
- it covers part of the city where aero-sanitary conditions are classified as unsatisfactory.

In our work, we formulated a research hypothesis saying that, due to the growing problems with the air quality in the city and despite ongoing changes in land use, the Bródnowski Ventilation Corridor can still be considered the ventilation system of Warsaw. Its role can be restored by introducing relevant building and land development laws in the appropriate planning acts.

Study area

The study area – the Bródnowski Ventilation Corridor (BVC) – was analysed within the boundaries established in Warsaw's General Spatial Development Plan (BPRW S.A. 1992). At that time, the corridor covered an area of 1151.8 ha, with a maximal length of 11.08 km along the western borderline, or 15.2 km along the eastern borderline and, at its narrowest, a width of 0.35 km. The length and width parameters were greater than the border values defined in publications referencing the ventilation corridors (Matzarakis & Mayer 1992), which indicated a minimal length of 1000 m, and a width four times greater than the height of the lateral obstacles (provided that such a value is not smaller than 50 m).

BVC extends from the Nieporęt and Legionowo forests, located north-east of Warsaw, through the arable lands in the city outskirts to areas with one-family houses, locally multifamily houses, and services-related developments located close to the city centre on the right bank of the Vistula River. Generally (independent of the study period), the urbanization level of the terrain investigated is growing, with extensively developed areas demonstrating a rural and urban character in the northern part of the corridor and a more urbanized area in its southern part. However, such a state is dynamic. For example, green areas were reduced by 14% from 1992 to 2015, and arable lands shrunk by 23% (Osińska-Skotak & Zawalich 2016). This is why the significance of BVC for airflow has been questioned.

BVC's inclination to perform the role of a corridor results from its location relative to the areas supplying Warsaw with fresh air. Land cover and land use also depend on seasonal wind conditions. The meteorological data from the period 1992–2020, obtained for the Okęcie station (<https://www.weatheronline.pl/Polska/Warszawa.htm> – accessed on 12.12.2023) shows that within the analysed area, a mean share of the wind blowing from the northern direction was approximately 7%, whereas from the north-east, it was roughly 6% (Fig. 1). Compared with the other prevailing wind directions, such a percentage is significantly lower.

Roughness calculation for studying aerodynamic properties

An air exchange and regeneration system for city spatial planning should be based on statistical and spatial analysis (Zhu

et al. 2022). A popular method of assessing the aerodynamic characteristics of the city for identifying potential ventilation paths utilizes the morphometric methods of roughness calculation. The roughness of the ground is determined by the type of land cover, including the existing buildings (type, distribution density, height) and vegetation cover. The most popular method of describing roughness parameters consists of calculating roughness length (z_0) and zero-plane displacement height (z_d) (Oke 2002). These two parameters are listed as one of several criteria for designing city ventilation corridors. The overall requirements described in specialized publications (Matzarakis & Mayer 1992; Gál & Unger 2009) are as follows: z_0 should be lower than 0.5 m, z_d – lower than 3 m, the length of ventilation corridor in one direction – over 1 km, the width of the corridor – over 50 m; parameters of obstacles: max width – 10% of the corridor width, height – lower than 10 m, orientation of the most extended front – parallel to the corridor direction.

The spatial variability of roughness length and zero-plane displacement height to determine the locations of potential ventilation corridors was elaborated for Polish cities, including Wrocław (Suder & Szymanowski 2014) and Łódź (Bochenek & Klemm 2016). The methodology applied in these studies was similar and based on formulas proposed in Bottema & Mestayer (1989), which were further developed by Gál & Sümeğhy (2007) and Gál & Unger (2009). The values of roughness parameters in these studies were calculated for numerous single-building areas and regular and irregular groups of edifices. The standard input data used for the roughness calculation included: built-up area, frontal area, reference area, and building heights. In the case of Warsaw, the related studies were conducted by Wicht et al. (2017) and Goch et al. (2017). Both studies present spatiotemporal analysis. In the first case, changes in the spatial distribution of roughness length (z_0) and displacement height (z_d) were calculated for 1992–2011. In the second study, the analysis covered 2002–2016 and concerned changes in building intensity and density, the weighted average number of floors, as well as the Frontal Area Index (A.F. or FAI) (Wong et al. 2010). The studies mentioned focused only on built-up areas. In the present study, the analysis covers all identifiable functions and land cover within the boundaries of BVC.

Data and methods

The initial stage of the study was to analyse changes in the city's spatial policy regarding land-use designation within BVC. Land-use directions are crucial in terms of the long-term development of particular regions. Regarding the primary hypothesis, the most important factors are the properties that may lead to the worsening of ventilation conditions and air regeneration. This concerns, above all, the development of highly intensive build-up areas such as multifamily houses and service buildings.

Therefore, spatial planning documents, valid in a given year, were analysed:

- for 1982 – Prospective Plan of General Spatial Development for the city of Warsaw (The National Council of Warsaw 1982),
- for 2020 – Study of conditions and directions of the spatial development of Warsaw (SUiKZP Warszawa 2018).

For the spatial and statistical analysis, spatial data analysis was performed using ArcGIS version 10.7.1, using the following procedure:

- generate rasters using the planning documents,
- georeference the rasters according to the PUWG-92 cartographic coordinate system,
- vectorize – change the rasters into vector graphics,
- determine the areas with transformations in land-use designation for the years 1982–2020 using the data management tool,

- calculate the changes in land-use designation for the years 1982–2020 using the variation index W_{CA} according to the following formula:

$$W_{CA} = \left[\frac{A_{F2020} - A_{F1982}}{A_a} \right] \times 100 (\%) \quad (1)$$

where: A_{F2020} , A_{F1982} – an area designated for a particular purpose according to the municipal spatial policy in 1982 and 2020 [ha]; a negative value [-] of W_{CA} means a decrease in the area designated for certain functions, whereas a positive value [+] indicates an increase. A_a – the total surface of BVC [ha]

The other aspect of the study was linked with land use and land cover (LULC) changes occurring in the period 1982–2020. It was assumed that they modified the area's roughness, which is considered one of the main aerodynamic properties for identifying potential ventilation functions. Analysing LULC for such a long period was hampered by the limited availability of comparable spatial data. Therefore, changes in LULC within BVC were analysed based on various data sources. Archival data for 1982 was derived from aerial photographs available from the Warsaw City Map Service (<https://mapa.um.warszawa.pl> – accessed on 23.07.2023). As for 1982, the aerial photo coverage was incomplete; we used images from 1987 in some fragments. The data for the year 2020 was obtained from the following sources:

- orthophoto maps from Geoportal (www.geoportal.gov.pl – accessed on 23.07.2023),
- Topographic Objects Database (BDOT10k), available on <http://www.geoportal.gov.pl> (accessed on 23.07.2023).

Quantitative analysis of changes in the ground's roughness affecting the area's ventilation conditions was based on the calculation of the aerodynamic roughness coefficient of the terrain (z_0). As mentioned, this is determined by the characteristics of a development and vegetation cover. The roughness coefficient for certain types of LULC was based on the values applied to similar terrain (Hammond et al. 2012; Wieringa J. et al. 2001) and given in the regulation of the Minister of the Environment on reference values for specific substances in the air (Regulation of the Ministry for the Environment from 26 January 2010). The roughness coefficient related to LULC (Z_x) of BVC for the years 1982 and 2020 was calculated using the formula:

$$Z_{x\ 2020(1982)} = \frac{\sum A_x \times z_0}{A_a} \quad (2)$$

where: A_x – the area of particular types of LULC in 1982 and in 2020 [ha], z_0 – roughness coefficient for a given land-use cover, A_a – total area of BVC [ha].

Transformations in land cover from 1982 to 2020 that impacted the evolution of land climatic conditions were also spatially analysed. Different land cover types were assigned to a given class based on the balance between biologically active areas, ground roughness (z_0), the height of buildings, and vegetation cover (Błażejczyk 2014; Rawski 2017). As a result, one can separate four land classes with different aeration and regeneration properties:

- Class I – good air ventilation, good air regeneration. Terrains are characterized by a high biological ratio (more than 70%), covered with permanent vegetation with low ground roughness (low vegetation). This includes open areas, such as meadows, orchards, arable lands, and surface water zones.
- Class II – medium air ventilation, medium or poor air regeneration. Areas are characterized by medium biological

Table 1. Changes in land-use designation within the area of the Bródnowski Ventilation Corridor (BVC) for the years 1982–2020

Main types of land-use designation	Specific types of land use	Area [ha]		Percentage share [%]		Variation index W_{CA} –	
		$A_F 1982$	$A_F 2020$	1982	2020	for specific types of land use	for main types of land use
Agricultural and horticultural areas	agricultural land for large-scale farming	467.763	0	0.406	0.000	-0.406	-0.627
	agricultural and horticultural land without building development rights	254.317	0	0.221	0.000	-0.221	
Residential areas	majority of single-family houses	3.316	558.116	0.003	0.485	+0.482	+0.531
	majority of multi-family houses	0	56.103	0.000	0.049	+0.049	
Services areas	large retail trade areas (shopping centres)	0	40.836	0.000	0.035	+0.035	+0.025
	sport and recreational areas	35.574	0	0.031	0.000	-0.031	
	education areas	2.394	0	0.002	0.000	-0.002	
	transport services areas	2.059	28.707	0.002	0.025	+0.023	
Main public roads		57.728	69.177	0.05	0.06	+0.082	+0.082
Forest areas	Bródnowski Forest, Marki Forest	172.611	160.537	0.150	0.139	-0.011	-0.011
Special areas	a former Fort Lewicpol, currently a small military unit	14.527	14.527	0.013	0.013	0	0
Cemeteries	the Bródnowski Cemetery, cemetery in Marki	109.946	113.607	0.096	0.099	+0.003	+0.003
Cultivated green areas	allotment gardens	30.396	43.968	0.026	0.038	+0.012	+0.069
	green parks and squares	0.552	65.605	0.000	0.057	+0.057	

Source: own elaboration

activity (40–60%), covered by low-intensity, low-rise buildings (1–2 floors), accompanied by the vegetation of medium roughness and undeveloped sites without vegetation. This includes the areas with single-family housing, allotments, railroad lines, road areas, parking lots, and wastelands.

- Class III – poor air ventilation, good air regeneration. Zones are characterized by high biological activity (more than 70%), covered with permanent vegetation with high ground roughness (predominance of tall vegetation), and no development. This encompasses the terrains of forest parks, trees, or forest cemeteries.
- Class IV – very poor air ventilation, poor air regeneration. Terrains are characterized by low biological activity (less than 40%), covered with compact building sites of high roughness. This encompasses terrains with multifamily residential, commercial, and industrial areas.

Results and discussion

The comparison of land-use designation in the spatial documents prevailing in 1982 and 2020 indicates a complete change in the spatial development of BVC. The General Spatial Development Plan for Warsaw (Spatial Development Plan for Warsaw 1982) assumed rather extensive development and the dominance of agricultural use (mostly individual farms with small areas of state-owned agricultural farms). The study of 2020, however, considered increasing urbanization of the corridor.

The intention was to offsite arable lands and develop residential areas instead. This mainly concerned the deployment of single-family houses. Nevertheless, multifamily house areas were also designed in the southern part of the corridor.

Land use in the spatial documents also considers the areas of forests, cemeteries, and main roads located on the south-western part of the corridor. Currently, the development directions contribute to diminishing the area's significance for ventilation. However, the location of single-family houses can still contribute to the ventilation function, provided that the appropriate indicators are introduced. These include low built-up density and low-rise buildings (1–2 floors). Changes in the designation of areas in the planning documents within the BVC site for the years 1982 and 2020, expressed using the variation index W_{CA} , are shown in Table 1. The functional and spatial structure of the ventilation according to the city's spatial policy of 1982 and 2020 are presented in Figure 2.

For an area to function as a ventilation corridor, the existing state of development is crucial, especially the diversity of land in terms of roughness parameters. Considering the conditions that predestine an area to function as a ventilation corridor, it is desirable to assume a significant proportion of land with a low roughness index value, namely less than 0.5. This condition is fulfilled by land included in classes I and II, adapted in this paper. In 1982, the predominant land use was favourable for optimal air swap. Only the southern part encompassed terrains



Figure 2. Changes in the area designation in the planning documents within the Bródnowski Ventilation Corridor for the years 1982 (2A) and 2020 (2B)

Source: own elaboration

of minor importance for ventilation (high roughness coefficient). However, this turned out to be significant from the point of view of air regeneration. Such a condition was fulfilled for Bródnowski Cemetery and Bródnowski Forest. However, the status of development from 2020 shows primarily progressive urbanization in the southern and central parts of the corridor – see Figure 3.

When analysing the classes with various abilities for shaping climatic conditions established in the work, one can distinguish three areas of main changes (Fig. 3C):

- Area 1 – Located in the southern part, between the Bródnowski Cemetery and Bródnowski Forest, the predominant use of this area in 2020 is multifamily housing, supplemented by commercial and industrial development, the intensity of which has increased since 1982. This direction of change, negative from the point of view of the ventilation function, will undoubtedly continue. Additionally, afforestation of the terrain near the Bródnowski Forest, which was previously covered with grass vegetation, has occurred. Here, one can observe a favourable change regarding air regeneration but a negative one for ventilation.



Figure 3. LULC structure within the boundaries of the Bródnowski Ventilation Corridor in 1982 (3A) and 2020 (3B)

Source: own elaboration

- Area 2 – The opening of the Trasa Toruńska expressway (Toruń Route) led to significant changes in LULC. To the south, intensive large-scale service (commercial) areas have developed in place of agricultural and grassy regions. North of the route, residential development, mainly multifamily housing, is progressing. The above changes are negative both from the point of view of ventilation and regeneration.
- Area 3 – Changes occurred in land cover in the north-eastern part of the corridor, such as the afforestation of grassland and agricultural areas. This was assessed as beneficial from the point of view of air regeneration but the roughness of the ground increased, which restricted ventilation.

The increase in total roughness calculated for the Z_x corridor (0.5151 for 1982 and 0.7278 for 2020) is related to changes that occurred primarily in the southern and central parts of the area (Table 2). The aggregate index poorly illustrates the functioning

Table 2. Changes in land-use and land cover (LULC) and terrain roughness within the area of the Bródnowski Ventilation Corridor for the years 1982–2020

LULC	Site characteristics	Surface area A_x [ha]		Difference in surface area [ha]	Surface variation index [%]	Roughness coefficient z_0	$A_x \times z_0$		Z_x	
		1982	2020				1982	2020	1982	2020
surface water bodies	Bródnowski canal, water reservoirs by shopping centres	1.7591	2.4951	+0.7360	0.0639	0.00008	0.00014	0.0002	0.0000001	0.0000002
arable land crops		107.5858	13.1813	-94.4045	-8.1959	0.035	3.7655	0.4613	0.0032691	0.0004005
forests		169.2150	236.2931	+67.0781	5.8235	2	338.4300	472.5862	0.2938138	0.4102838
groves and trees		31.6657	7.1421	- 24.5236	-2.1291	0.4	12.6663	2.8569	0.0109965	0.0024803
areas covered with shrubs		12.9361	2.6499	-10.2862	-0.8930	0.5	6.4681	1.3250	0.0056154	0.0011503
lawns		627.7656	528.0218	-99.7438	-8.6594	0.035	21.9718	18.4808	0.0190752	0.0160444
vegetation of allotment gardens and orchards		34.7922	35.2404	+0.4482	0.0389	0.4	13.9169	14.0962	0.0120822	0.0122379
cemeteries	Bródnowski Cemetery and part of the Marki Cemetery with high tree groves	107.5420	108.8083	+1.2663	0.1099	1.5	161.3130	163.2124	0.1400466	0.1416956
residential areas of single-family buildings with vegetation		17.0750	85.6975	+68.6225	5.9576	0.5	8.5375	42.8488	0.0074120	0.0371999
residential areas of multi-family buildings with vegetation	low-rise buildings (max 4 storeys)	0.4140	43.7408	+53.5296	4.6473	0.5	0.2070	21.8704	0.0001797	0.0189872
	medium-rise buildings (4–9 storeys)	0	7.0590			2	0	14.1180	0	0.0122568
	high-rise buildings (> 9 storeys)	0	3.1438			5	0	15.7190	0	0.0136467
industrial and storage buildings	low-rise buildings	8.6644	0.9228	-7.7416	-0.6721	1	8.6644	0.9228	0.0075221	0.0008011
commercial buildings	shopping centre M1	0	16.3832	+16.3832	1.4223	2	0	32.7664	0	0.0284467
	other	1.8631	4.7358	+2.8727	0.2494	1	1.8631	4.7358	0.0016175	0.0041115
other buildings	service building (2020) or farm building (1982)	5.9586	3.6159	-2.3427	-0.2034	1	5.9586	3.6159	0.0051731	0.0031392
	Fort Lewicpol	5.3091	5.3091	0	0.0000	0.5	2.6546	2.6546	0.0023046	0.0023046
main public roads		3.6020	19.7105	+16.1085	1.3985	0.002	0.0072	0.0394	0.0000063	0.0000342
paved areas	parking areas, vehicle and pedestrian communication areas	1.0319	24.8497	+23.8178	2.0678	1	1.0319	24.8497	0.0008959	0.0215737
undeveloped grounds	no vegetation	14.6724	2.4182	-12.2542	-1.0639	0.4	5.8690	0.9673	0.0050953	0.0008398
wastelands		0	0.4337	+0.4337	0.0377	0.4	0	0.1735	0	0.0001506
Z_x									0.5151	0.7278

Source: own elaboration

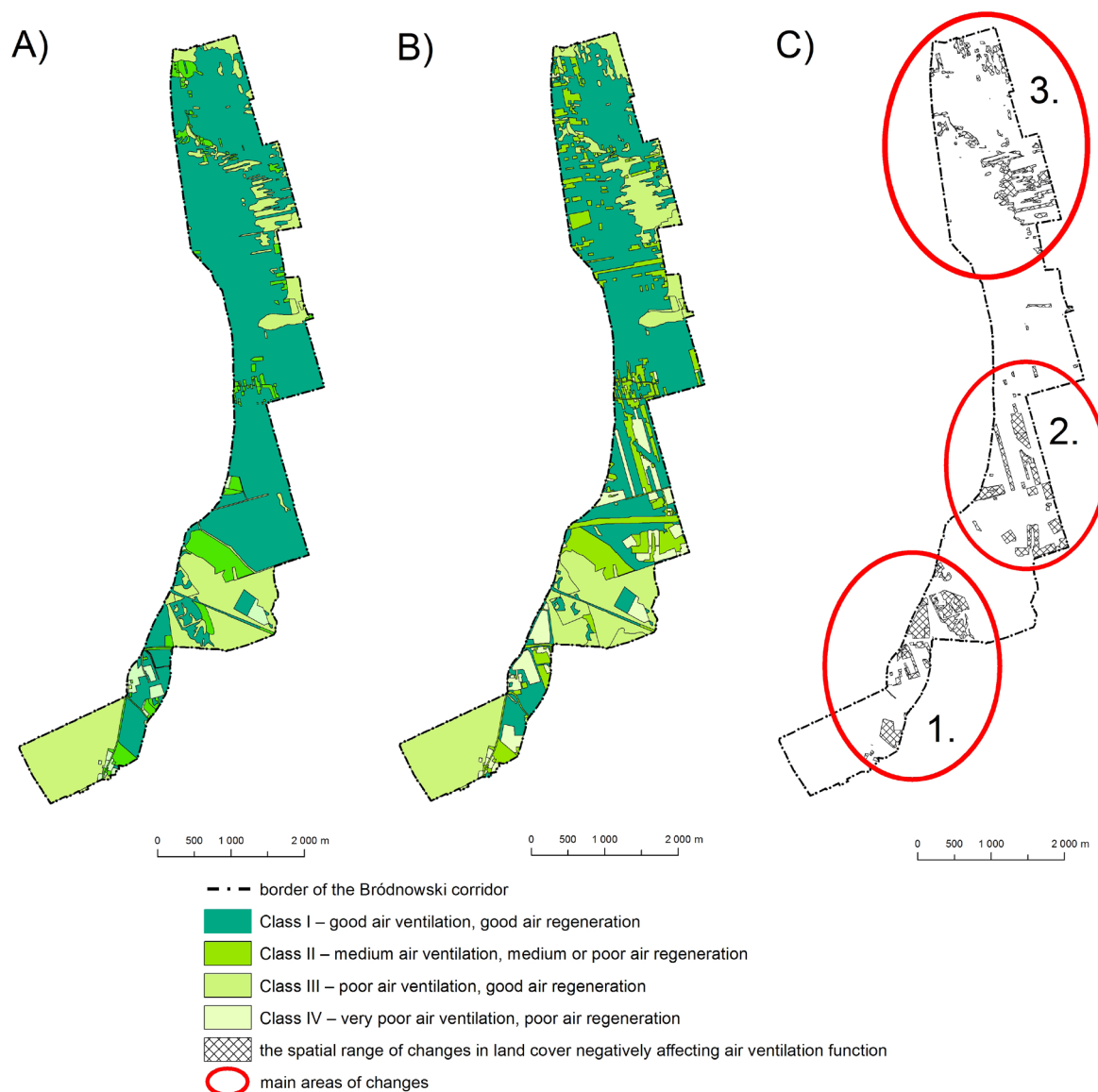


Figure 4. Classes of areas with various abilities for shaping climatic conditions in 1982 (4A) and 2020 (4B); area of main changes (4C)
Source: own elaboration

of the analysed site in terms of ventilation. This is due to the substantial diversity in land development and the relatively large surface. It is more meaningful to explore changes within individual land cover forms (Table 2) and area classes that have various abilities for shaping climatic conditions (Fig. 4).

Conclusions

An analysis of changes in LULC in BVC from 1982 to 2020 shows that the urbanization process is spatially diverse but relatively slow. The area of arable lands is decreasing, whereas (mainly) single-family and multifamily residential areas are increasing. One can also observe minor growth in forest lands. As we can see, the intensity of urbanization has increased towards the southern part of the corridor in the direction of the city centre. The ongoing changes in land cover visibly affect ventilation conditions. The high tree canopy of the cemetery and forest, together with the tall multifamily and commercial development in the southern corridor, have established unfavourable ventilation conditions.

The primary cause is the high ground roughness. This part of the study area seems to be less important for the city's ventilation system but retains some importance for air regeneration. Land cover in the northern and central parts of the corridor has reduced the air circulation function to a lesser extent. Full implementation of the development directions will exacerbate the unfavourable trends in ventilation but may enable the maintenance of positive impacts on air quality and thermal conditions. The prerequisite for maintaining the predisposition to an apparent positive effect on the climate of this city part is an extensive urbanization level, namely the multifunctional development of low-rise buildings (preferably single-family residential houses) with a large share of biologically active terrains (both public and private).

The indicators obtained describing land use and land cover changes in BVC show natural trends associated with large city development. They confirm conclusions from earlier studies on changes in the significance and extent of ventilation corridors for Warsaw. The widened analysis period assumed in the study

allows us to highlight the visible trends referring not only to the ventilation but to the regeneration of the terrain as well.

Regarding the hypothesis formulated in the introduction, we can confirm that the importance of BVC as a potential ventilation corridor has indeed decreased. Nevertheless, changes in the spatial development that are negatively perceived in the perspective of ventilation abilities, are proceeding relatively slowly and are concentrated in the southern part. The spatial range of BVC for the studied period decreased, and such a role can be assigned only to its central and northern parts. We estimate that the corridor's length has potentially shrunk from 15.2 km in 1992

to 6.6 km in 2020, which still adheres to the requirements for such areas. One should emphasize that the directions of development covered by the city spatial policy in a long-term perspective still have a chance to preserve the convenient climate shaping conditions for this part of the city. Nevertheless, it may be connected less with ventilation and more with air regeneration.

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