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Changes in the built-up areas at the aeration wedges of City of Warsaw

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Abstract: The main objective of this paper is to present increasing share of built-up areas at the aeration wedges of City of Warsaw. The idea of Warsaw aeration corridors had been arisen in 1916 and was adapted to the present times in 1992, 2006 and 2018 in the planning's documents which described Warsaw spatial development conditions. The goal for creation these corridors has been to establish the air exchange between areas around the city (especially green areas) and downtown. The analyses were carried out for years: 1992, 1995, 1998, 2001, 2004, 2006, 2009 – based on Landsat-5; 2013 – based on Landsat-8; 2015, 2018 based on Sentinel-2. As a result of research, it was found that aeration wedges had been constantly built-up. In 1992 built-up areas covered 14% (767 ha) of aeration corridors, in 1998 – 17% (918 ha), in 2006 – 24% (1245 ha), in 2013 – 26% (1341 ha), in 2018 – 27% (1383 ha). The largest loss of green areas was noticed as: arable lands and meadows – from 42% to 29%. In addition, during the research it was observed that new buildings have been situated in unfavorable way. New buildings are the walls and barriers to the air masses coming to the downtown.

Keywords: aeration of cities, land cover changes, urban space, Sentinel-2, Landsat

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1. Introduction

The city is an extremely dynamically changing structure. Variety of forms of space and buildings is one of the characteristic of the city (Le Corbusier, 1943). Constant development and increase of city's population (Statistics Poland, 2009) forces changes in the urban space structure. Heavily urbanized areas provide a specifically urban environment, consisting densely built-up areas, limited green spaces and open spaces. The natural environment is degraded and replaced by environment created by people. Because of it, the climatic factors in the city transform (e.g. existence of phenomenon of urban heat island, changed directions of winds, slowing down incoming wind, shading) (Zielonko-Jung, 2014). To design comfortable living, sustainable and healthy environment, is a big challenge which politicians and urban planners participated in spatial planning process, must face. Climatic factors are worthy of inclusion and consideration in these process (Cleugh et al., 2009). Creation of this comfortable environment could be achieved in many ways. During the spatial planning process, designers and other involved groups should take into consideration geometrical characteristics of the buildings including height, width, shape and their relation to the open spaces and biologically active areas (Capeluto et al., 2003).

Aeration wedges are one of the tool of the sustainable urban planning. They are important for the following purposes:

– air pollution;
– urban thermal comfort;
– indoor ventilation of the city (Ng, 2010).

Due to proper urban ventilation, air pollution and thermal conditions could be reduced at source. Task for urban planner is to optimize appropriate building layouts and design of the city (Ng, 2010).

Authorities and planners in many cities take into consideration proper ventilation. Spatial management plans and others documents consist assumptions of aeration wedges. One of example is Stuttgart (Hebbert and Webb, 2012; Ren et al., 2012). Municipality of Stuttgart prepared principles also included in the Climate Booklet for Urban Development Online – Städtebauliche Klimafibel Online:

– Vegetation should be placed to surround developments and larger, connected green spaces should be created or maintained throughout developed areas to facilitate air exchange;
– Valleys serve as air delivery corridors and should not be developed;
– Hillsides should remain undeveloped, especially when development exists in valleys, since intensive cold- and fresh-air transport occurs here;
– Saddle-like topographies serve as air induction corridors and should not be developed;
– Urban sprawl is to be avoided;
– All trees growing in the urban core with a trunk circumference of more than 80 cm at height of 1m are protected with a tree preservation order. (Ministry of Economy, Labor and Housing of Baden-Württemberg, 2012).

Other cities where the problem of ventilation was noticed are: Tel Aviv – the authors present case study of a design of a new business district including wind and sun controlled planning (Capeluto et al., 2003), Sydney where fine ventilation could mitigate the urban heat island (He, 2017), Hong Kong – one of the most densely populated cities in the world (Ng, 2009), Taiwan – the authors prove that aeration corridors are reported to be one of the best strategies to mitigate the heat island effect (Hsieh and Huang, 2016), Wroclaw where the location of ventilation corridors for urban area have been already presented by scientist (Suder and Szymanowki, 2014) and Warsaw – analysis of land use were performed (Osinska-Skotak and Zawalich, 2016).

The meaning of proper urban planning and methods of evaluating physiographic and environmental conditions were noticed in 1971 (Rozycka, 1971). Unfortunately, in Polish law, there is still no regulation and even order to design aeration wedges. Despite of this, there are some act of laws which suggest planning wedges. According to the Act on Planning and Spatial Development (Act on Planning and Spatial Development, Dz.U. 2003/80/717, Parliament of the Republic of Poland, 2003), Study of Conditions and Directions of Spatial Development (SCDSD) should consists conditions of environment and rules of protection and creation of environment. The details about this conditions and rules should be included in Ecophysiographic Study (ES). Decree about Ecophysiographic Study says that ES has to consist diagnosis of conditions and functioning of environment. The most important for this paper is paragraph 6 point 6:

– determining the suitability of particular areas for the development of utility functions, in particular: residential, industrial, recreational and recreational, agricultural, forest, health resort, communication, including infrastructure necessary for the proper performance of these functions;
– determining the areas which usage and management should be subordinated to the needs of ensuring the proper functioning of the environment and preservation of biodiversity, due to the features of the environment and their role in the natural structure of the area;
– determining the limitations resulting from the need to protect environmental resources or the occurrence of nuisances and threats to the environment, and to define the areas where these limitations occur (Decree of 9th of 2002 about Ecophysiographic Study, Dz.U. 2002/155/1298, Minister of Environment, 2002).

The objective of this research is to verify changes in the built-up (which could cause all of the consequences mentioned in this introduction) at the areas of aeration wedges of City of Warsaw, using remote sensing data from different satellites, including Landsat-5, Landsat-8 and Sentinel-2. Furthermore, it will be verified what areas increased and decreased. The most threatened territories will be pointed. That is also pre-research, to farther studies about city's environment, including data about pollution from Sentinel-5P and land surface temperature from Sentinel-3.

2. Study area

The studies were performed for areas of Warsaw aeration wedges. The idea of Warsaw aeration wedges (corridors) had been arisen in 1916 (Osinska-Skotak and Zawalich, 2016). It assumes the existence of the open green areas, wide communication routes and other areas which are not built-up. The goal of these corridors was creation of air exchange between the open areas around the city (green areas) and downtown areas. The free movement of air masses has to improve the urban climate (to mitigate urban heat island effect) and to reduce air pollution (Blazejczyk et al., 2014). During the period of Polish People's Republic authorities did not back to these ideas (Osinska-Skotak and Zawalich, 2016). Some document established during this period contained arrangements about preservation from urbanization and protection open and green areas but there was no plan concerning system of air regeneration (Skorupski, 2000).

Ventilation and air regeneration system including aeration corridors was specified in 1992 in Local General Development Plan of Capital City of Warsaw. The Plan assumed prohibition for locating: any emitters of air pollution; any mechanistic and thermal barriers which could significantly hold down movement of air masses. Moreover, the Plan assumed adjuration to consider every investment as a potential threatens for environment (Local General Development Plan of Capital City of Warsaw, XXXV/199/92, Warsaw City Council, 1992). The system contained nine corridors: Brodnowski; Kolejowy Wschodni; Wilanowski; Podskarpowy; Mokotowski; Jerozolimski; Kolejowy Zachodni; Bemowski; Wisla (Fig. 1).

In 2001, the area and borders of several ventilation corridors were changed in the study "An Assessment of the Ventilation and Air Regeneration System in Warsaw" (Local management plan of Capital City of Warsaw including obligatory agreements about creating local management plans, XXXVIII/492/2001, Warsaw City Council, 2001). The next change was performed in 2006 in Ecophysiographic Study developed for Study of Conditions and Directions of Spatial Development of Capital City of Warsaw

Fig. 1. Warsaw aeration wedges in 1992 (1992 Local General Development Plan of Capital City of Warsaw, XXXV/199/92, Warsaw City Council, 1992); Landsat-5 Image 1992-08-29 RGB321

(Change of Study of Conditions and Directions of Spatial Development of Capital City of Warsaw – stage II, LXXXII/2746/2006, Warsaw City Council, 2006) (Fig. 2). These borders were in force to 2018 (Study of Conditions and Directions of Spatial Development of Capital City of Warsaw, LXII/1667/2018, Warsaw City Council, 2018). The biggest changes have taken place in Brodnowski corridor.

In that study, land use rules were established:

- prohibition for locating any emitters of air pollution;
- prohibition for location buildings which could significantly hold down flow movement of air masses;
- order to manage the area in a manner conducive to the exchange of air;
- land use has to be in accordance with rules defined in Study (Change of Study of Conditions and Directions of Spatial Development of

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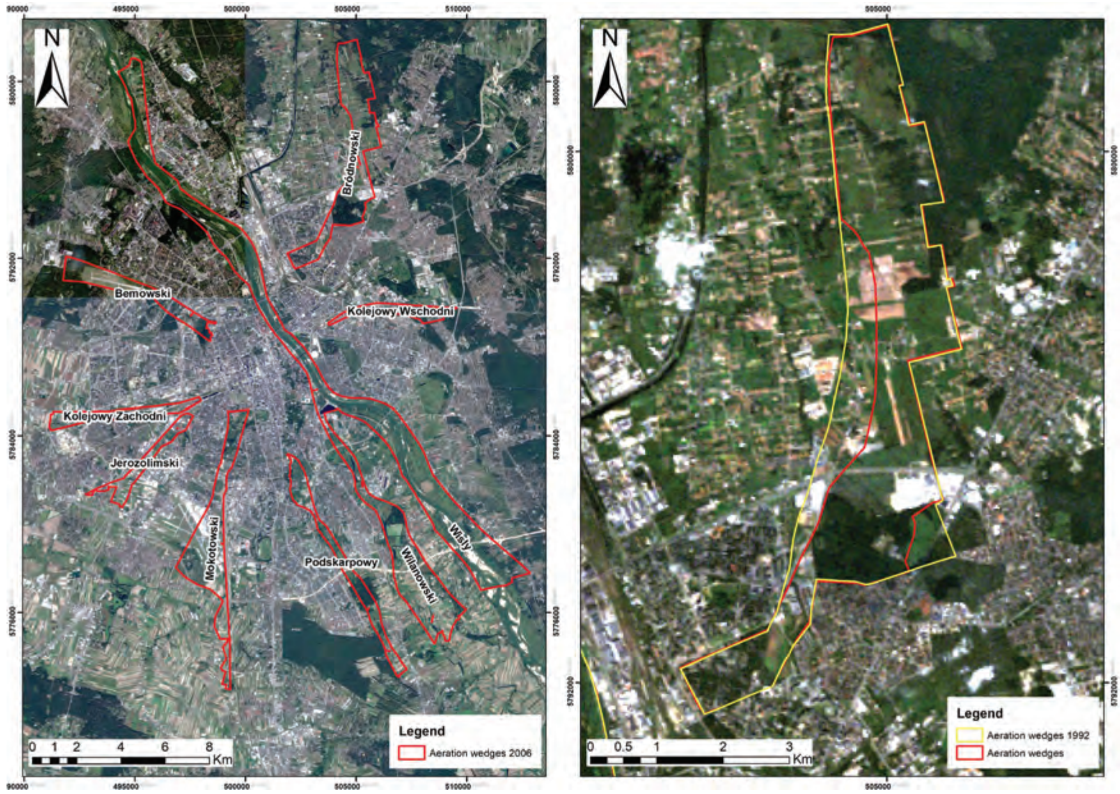

Fig. 2. Warsaw aeration wedges established in 2006 (L) and comparison borders of Bodnowski corridor in 1992 and 2006 (R) (Change of Study of Conditions and Directions of Spatial Development of Capital City of Warsaw – stage II, LXXXII/2746/2006, Warsaw City Council, 2006); Landsat-5 Image 2006-08-28 RGB321

Capital City of Warsaw – stage II, LXXXII/2746/2006, Warsaw City Council, 2006).

It was proved that there are rules about protection of aeration corridors. On the other hand, Study of Conditions and Directions of Spatial Development is not a local act of law – it does not cause legal effect. It is an internally act of law – document which describes space policy of the city in general. However, regulations concluded in the Study must be contained in Local Management's Plans which are the local act of law. In spite of this, it should be marked that predestination of land in Study is not the same what predestination of land in Local Management's Plan (Supreme Administrative Court, II OSK 1028/07). Moreover, Local Management's Plan is are not obligatory act of law – according to the Polish law, the commune has no obligation to enact it.

The corridor along the Vistula river was excluded from analysis, because it is mostly covered by water. This is a special case which land cover is absolutely different than others at wedges. Authors knows that there are some areas that could be built-up, but they wanted to focus on changes at similar areas more threatened by total coverage by buildings.

3. Materials and methods

Three types of satellite data have been used for the research works (Table 1).

The objective was to analyze changes in the built-up areas in the 3-year cycle. Exceptions were caused by lack of cloudless images. The Study of Conditions and Directions of Spatial Development of Capital City of Warsaw was adopted in 2006, so that year was included to research, too.

For each year classification was carried out (visual interpretation). To improve interpretation there were used maps of two indices: Normalized Difference

Table 1. Satellite data used for analysis

Landsat-5	Landsat-8	Sentinel-2
1992-08-29 1995-08-22 1998-05-10 2001-07-30 2004-08-30 2006-09-21 2009-08-28	2013-09-08	2015-10-10 2018-09-20

Vegetation Index – NDVI (Rousse et al., 1978) and Soil Adjusted Vegetation Index – SAVI (Huete, 1988). It was useful to identify green areas. The false color composition was used to easier classification of built-up. There was a purpose to set apart six classes: arable land/meadows, forests (area covered by trees including parks; not forest defined by a law), built-up areas, airports, railways areas and water. In spite, the railways areas and airports are partly covered by imperviousness, they are not classified as a built-up. The reason is they are open areas. Surface of areas was determined as follows:

1. Visual interpretation and creation of polygon with adequate attributes (assignment to the right class);
2. Compute surface of each polygon in ArcGis;
3. Convert shapefile to excel file (.xls);
4. Make calculation, statistics, graph and tables in MS Excel also finding differences.

Furthermore, data about height of the buildings was used – The Building Height 2012 layer – which is available by Copernicus Land Monitoring System within the Urban Atlas. First, the raster image had been used. Then, it was conversed to vector. Finally, attribute "height" was related with built-up areas. The average height was calculated for each built-up area polygon. It was used to verify height and calculate volume of the buildings.

Wind conditions in city's environment is changed by urban geometry (Oke, 1987) because buildings generate greater frictional drag than any other surface roughness elements in a natural environment (Taylor, 1988). Wind flow in space surrounded by built-up areas is not simple recirculation flow nor unidirectional flow windward to leeward side, but it is much more complicated (Kato and Huang, 2009). So, for one aeration wedge – Bemowski corridor – there was carried out the analysis of the situated of the buildings, based on its area, height, shape and location. In addition to literature about urban aerodynamic phenomenon (Zielonko-Jung, 2010), there was verified if new built-up areas are not an obstacle to the wind (Kolokotsa et al., 2009).

It was mentioned that since 2018, the Brodnowski corridor has not been an aeration wedge. In spite of this, authors wanted to keep continuity and they carried analysis for Brodnowski corridor in 2018, too. Moreover, new corridor was adopted – Kolejowy Polnocny. In earlier years, there was not such wedge, so it has not been included to analysis.

4. Results and discussion

4.1. Changes in the built-up areas at the aeration wedges of the City of Warsaw

Changes for four classes, over the years 1992–2018 are presented in Figure 3 and Table 2.

Table 2. Land cover changes at the aeartion wedges of the City of Warsaw 1992–2018 [%]

Year	Built-up area	Arable lands/meadows	Forests	Railway areas	Waters	Airports
1992	14.29	42.26	26.11	5.50	2.49	9.34
1995	16.89	40.10	26.48	5.35	1.83	9.34
1998	17.08	40.10	26.41	5.31	1.75	9.34
2001	18.20	35.32	27.49	5.88	3.36	9.75
2004	19.81	34.42	27.34	5.88	2.80	9.75
2006	23.97	31.02	27.19	5.29	2.86	9.67
2009	25.25	29.66	27.09	5.43	2.90	9.67
2013	25.81	29.17	27.02	5.43	2.90	9.67
2015	26.02	29.10	26.88	5.43	2.90	9.67
2018	26.62	28.96	26.42	4.99	3.34	9.67

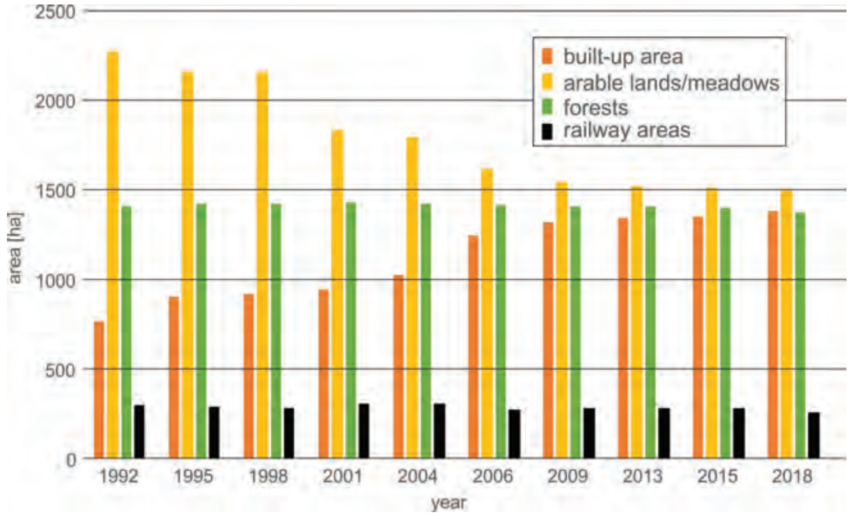

Fig. 3. Land cover changes at the aeartion wedges of the City of Warsaw 1992–2018

In comparison with 1992, it was found that aeration wedges were constantly built-up. In 1992 built-up areas covered 14% (768 ha) of aeration corridors, in 2001 (the borders of corridors were modified) – 18% (945 ha), in 2006 (the borders of corridors were modified) – 24% (1245 ha) and in 2018 – 27% (1383 ha). The largest loss of open areas was noted as: arable lands and meadows – from 42% (2271 ha) to 29% (1504 ha). There were not significantly changes of the forests, railway areas, water and airports. In 1992 forests had covered 26% of whole analyzed territory, in 2018 it was still 26% but it decreased from 1403 ha in 1992 to 1372 ha in 2018. Railway areas had covered 5.5% in 1992 (296 ha) and in 2018 it covered 5% (259 ha). Area of water was changing over the years. It was mainly caused by change of corridor's borders but also by differences in water's level in each year. Airports increased 0.4% (c.a. 1 ha). The biggest increase of built-up was noted between 2004 and 2006 – 216 ha, between 1992 and 1995 – 139 ha, between 2001 and 2004 83 ha.

It was noted that built-up areas accrued in every wedge (Fig. 4 and Table 3). The biggest changes have taken place in Brodnowski, Bemowski, Jerozolimski and Kolejowy Zachodni corridors. In Brodnowski corridor the built-up area increased by 130 ha (57%), in Bemowski corridor that increased by 71 ha (313%) in Jerozolimski corridor built-up area increased by 140 ha (262%) and in Kolejowy Zachodni corridor increased by 76 ha (408%). There was also a big growth in Wilanowski corridor (87 ha, 107%) but the share of built-up increased only by 7% (to 14%). It is the less built-up wedge.

Table 3. Changes in built-up areas at the aeration wedges of City of Warsaw 1992–2018

	1992 [ha]	2018 [ha]	Change [%]
Brodnowski	229.68	359.85	57
Kolejowy W.	45.49	71.56	57
Wilanowski	80.40	166.63	107
Podskarpowy	48.97	97.09	98
Mokotowski	230.19	312.28	35
Jerozolimski	53.51	193.67	262
Kolejowy Z.	18.79	95.38	408
Bemowski	22.84	94.44	313

In comparison with work Osinska-Skotak and Zawalich (2016) there are some differences, especially about agricultural areas (c.a. 10–15%). They could be caused by different classification. In this paper there is a class "arable lands/meadows" and in the referenced article there are separately classes "agricultural areas" and "open area". The second one class contains meadows and waters. Moreover, in this work Sentinel-2 images were used which are of higher resolution than Landsat 5 and Landsat 8 images, so the classification could be performed more accurate.

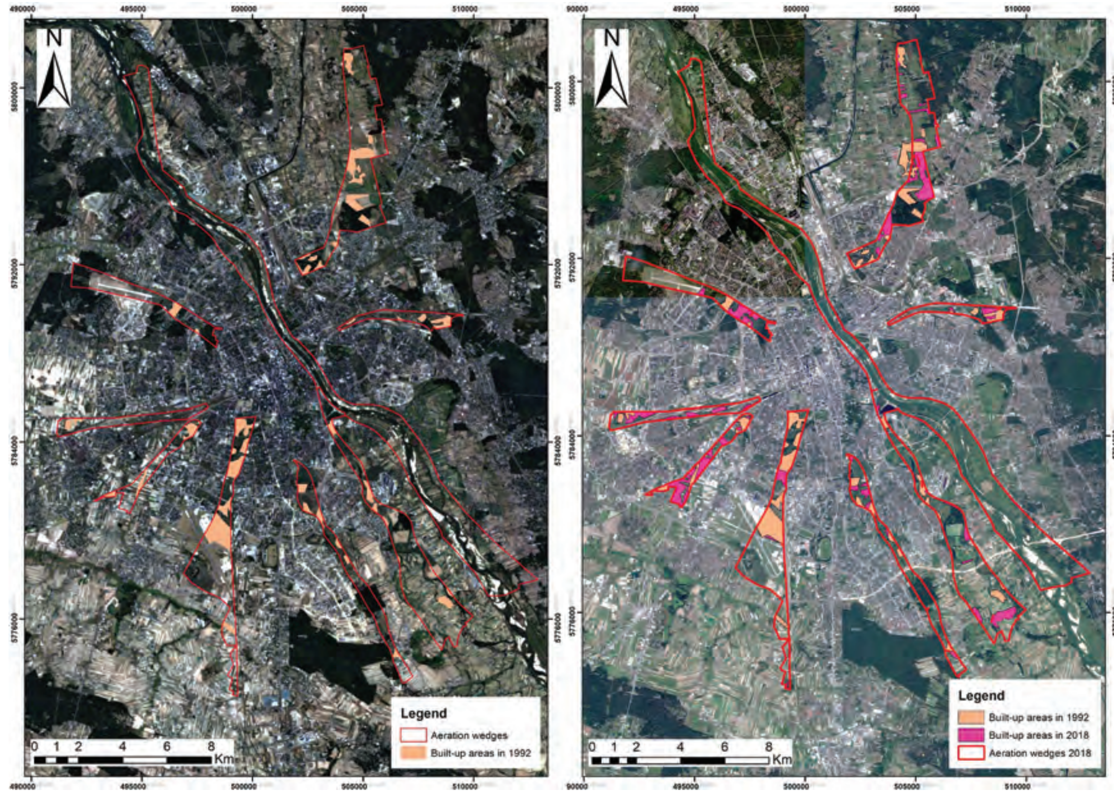

Fig. 4. Built-up areas at the aeration wedges of City of Warsaw in 1992 (L – Landsat-5 image 1992-08-29 RGB321) and 2018 (R – Sentinel-2 image 2018-09-20 RGB432)

4.2. Analyses of selected years

It was mentioned the biggest changes in built-up had been noticed between 1992 and 1995, between 2001 and 2004, between 2004 and 2006.

The 1992 was the year when aeration wedges were specified. In that year, built-up area covered 14% (768 ha) of corridors, arable land and meadows – 42% (2271 ha), forests – 26% (1403 ha), railways area – 6% (296 ha), water – 3% (172 ha) and airports 9% (502 ha). In 1995, corridors were covered in 17% by built-up (907 ha) and 40% (2212 ha) by arable land and meadows. Coverage of rest classes did not change (Fig. 5 and Table 4).

In 1992 the most built-up corridors were Mokotowski – 23% and Jerozolimski – 21%. Large area covered by built-up was located in Brodnowski corridor, too. It was 230 ha. In 1995, the same wedges were the most built-up: Mokotowski – 25% and Jerozolimski 21%. In view of acreage, Brodnowski almost became the most covered – 242 ha (Mokotowski 244 ha). In 1992 the least built-up corridor had been Bemowski – 5%, but in 1995 built-up area increased to 10%. Kolejowy Zachodni (1992 – 6%, 1995 – 9%) and Wilanowski (1992 – 7%, 1995 – 8%) also were insignificantly covered by buildings (Fig. 6).

Table 4. Land cover at aeration wedges of City of Warsaw in 1992 and 1995

Year	Built-up area [ha]	Built-up area [%]	Arable lands/ meadows [ha]	Arable lands/ meadows [%]	Forests [ha]	Railway areas [ha]
1995	907	17	2155	40	1423	288
1992	768	14	2271	42	1403	296

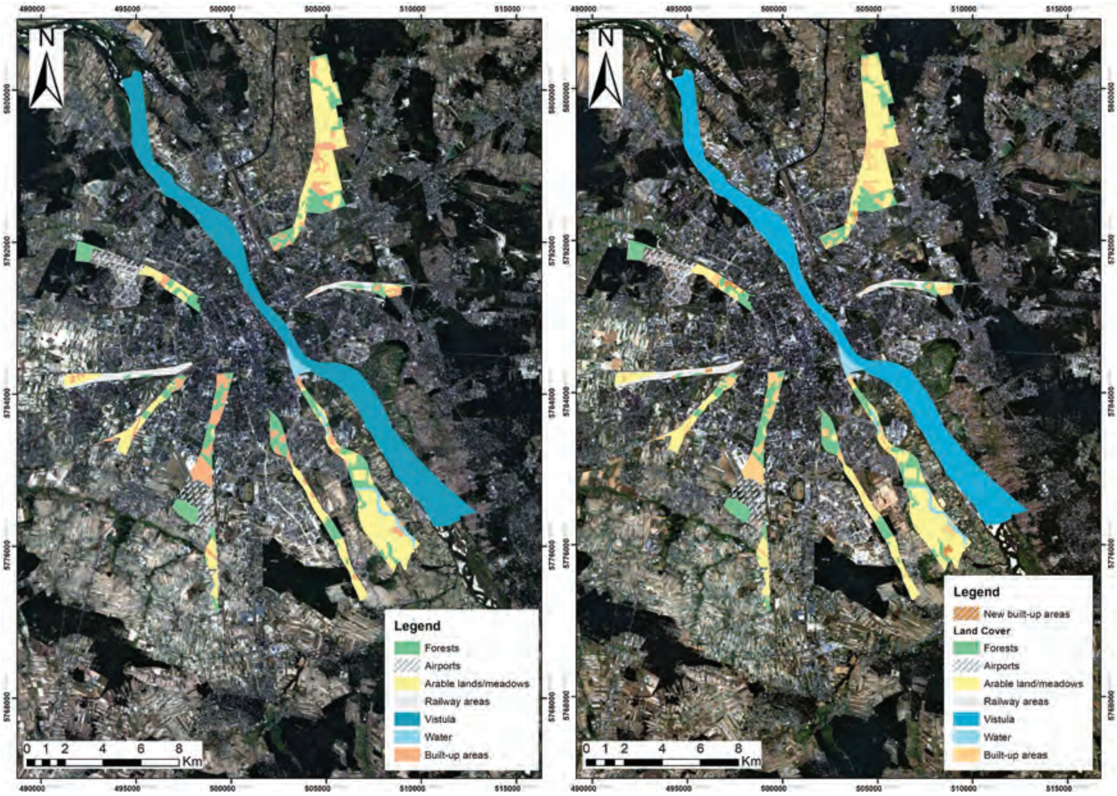

Fig. 5. Land cover at aeration wedges of City of Warsaw in 1992 (L – Landsat-5 image 1992-08-29 RGB321) and in 1995 (R - 1995-08-22 RGB 321)

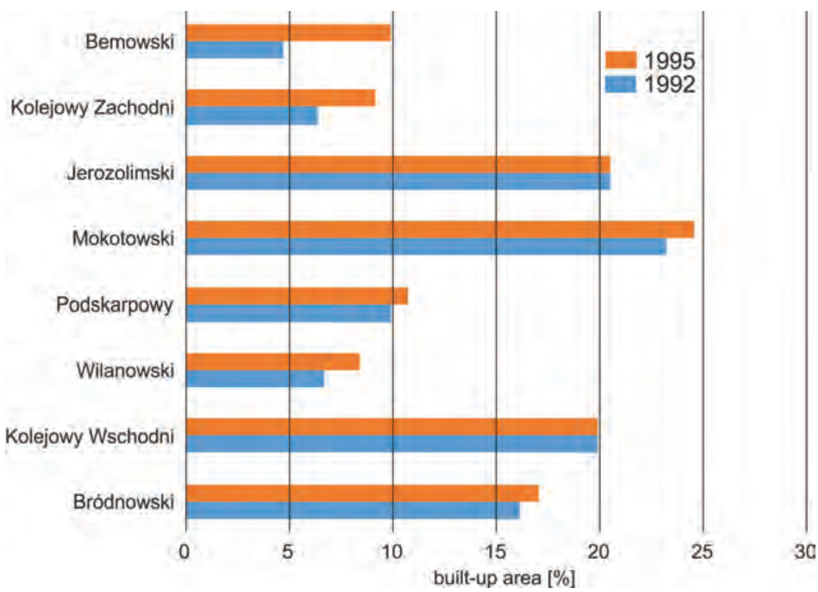

Fig. 6. Built-up areas at aeration wedges in 1992 and 1995

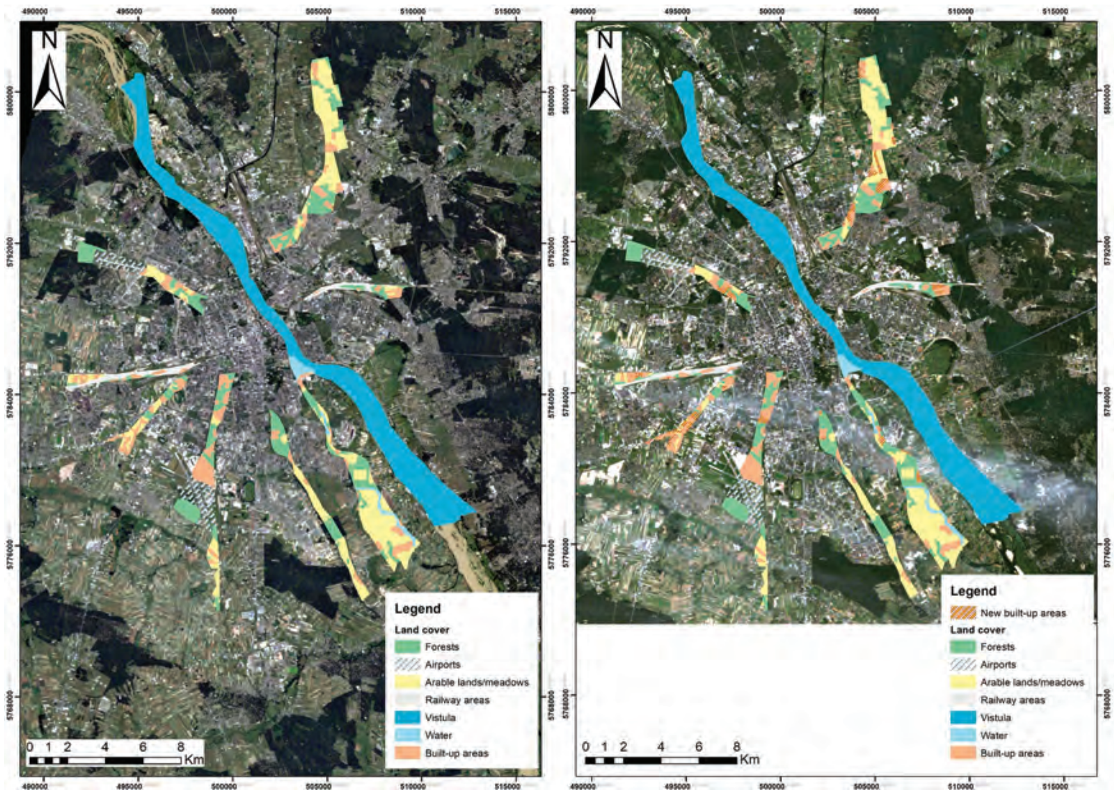

Fig. 7. Land cover at aeration wedges of City of Warsaw in 2001 (L – Landsat-5 image 2001-07-30 RGB321) and in 2006 (R – Landsat-5 image 2006-09-21 RGB 321)

Table 5. Land cover at aeration wedges of City of Warsaw in 2001 and 2006

Year	Built-up area		Arable lands/ meadows		Forests [ha]	Railway areas [ha]
	[ha]	[%]	[ha]	[%]		
2006	1245	24	1612	31	1413	275
2001	946	18	1835	35	1428	305

In 2001 built-up areas covered 18% of aeration wedges, arable land and meadows – 35%, forests – 27%, railways area – 6%, water – 3%, airports 10%. In 2006 built-up areas increased to 24% and arable land and meadows dicreased to 31%. Coverage of the rest classes did not change (Fig. 7 and Table 5).

In 2001, the most built-up channels were still Jerozolimski – 47%, and Mokotowski – 27% (272 ha – the biggest area). Five year later, built-up area in Jerozolimski corridor increased to 67% (more about 56 ha than in 2001). There were not many new buildings in Mokotowski corridor, so share of built-up increased to 29%. Moreover, big increases were noted in Kolejowy Zachodni corridor – from 16 to 30%, Kolejowy Wschodni corridor – from 18% to 27%, Brodnowski corridor – from 18% to 25% and in Bemowski corridor – from 12 to 17%. In 2001 and 2006, the least built-up corridors were Podskarpowy and Wilanowski. Furthermore, in 2001 every corridor was built-up at least by 10%. In 2006 only two wedges – Podskarpowy and Wilanowski – were covered by built-up in less than 15% (Fig. 8).

The 2018 was the last year when the analyses were carried out. Built-up area comprised 27% of wedges (1383 ha), arable land and meadows – 29%, forests – 27%, railways area 5%, water 3% and airports 10% (Fig. 9 and Table 6). The most built-up corridor was Jerozolimski – 68%. Three other corridors were built-up more than 30% – Brodnowski, Mokotowski and Kolejowy Zachodni. Only three wedges – Bemowski, Podskarpowy and Wilanowski – were covered by built-up in less than 20%.

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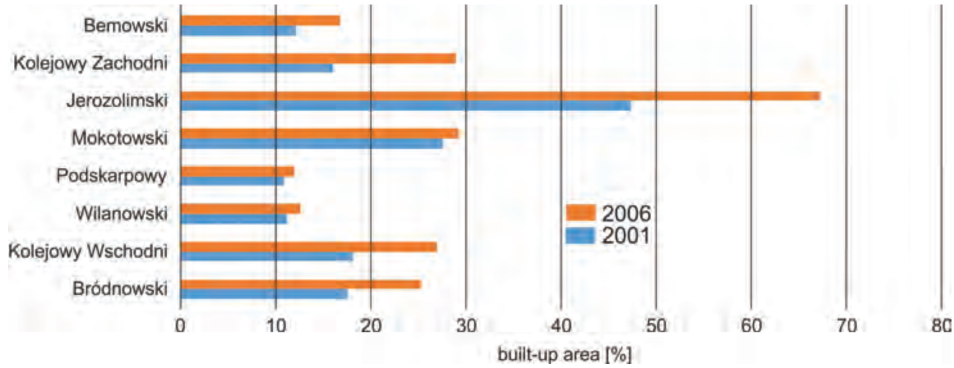

Fig. 8. Built-up areas at aeration wedges in 2001 and 2006

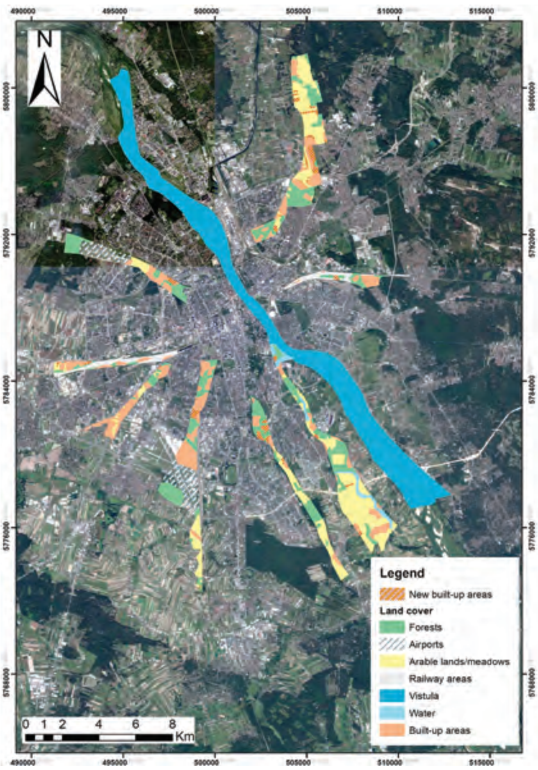

Fig. 9. Land cover at aeration wedges of City of Warsaw in 2018 (Sentinel-2 image 2018-09-20 RGB432)

Wilanowski corridor was the only channel where share of built-up areas was less than 15%. Very important issue is that Brodnowski corridor have been so built-up that it is not anymore an aeration wedge (Study of Conditions and Directions of Spatial Development of Capital City of Warsaw, LXII/1667/2018) (Table 7). It is wondering why

Table 6. Land cover at aeration wedges of City of Warsaw in 2018

Year	Built-up area		Arable lands/ meadows		Forests [ha]	Railway areas [ha]
	[ha]	[%]	[ha]	[%]		
2018	1383	27	1505	29	1373	259

other corridors (like Jerozolimski and Kolejowy Zachodni) where situation is more severe, are still aeration wedges. It should be noted that corridors are open spaces and also wide communication routes. In Jerozolimski there is Aleje Jerozolimskie street running over the corridor. In Kolejowy Zachodni there are railways running in west–east direction. They still provide air's movement which needs to be considered if the borders of these corridors should be changed.

Table 7. Built-up areas at aeration wedges in 2018

Aeration wedge	Built-up [%]	Aeration wedge	Built-up [%]
Brodnowski	31	Mokotowski	31
Kolejowy W.	29	Jerozolimski	68
Wilanowski	14	Kolejowy Z.	31
Podskarpowy	19	Bemowski	19

4.3. Height of the buildings

Particular obstacle to free air flow are high buildings, so it is important to analyze the height of them.

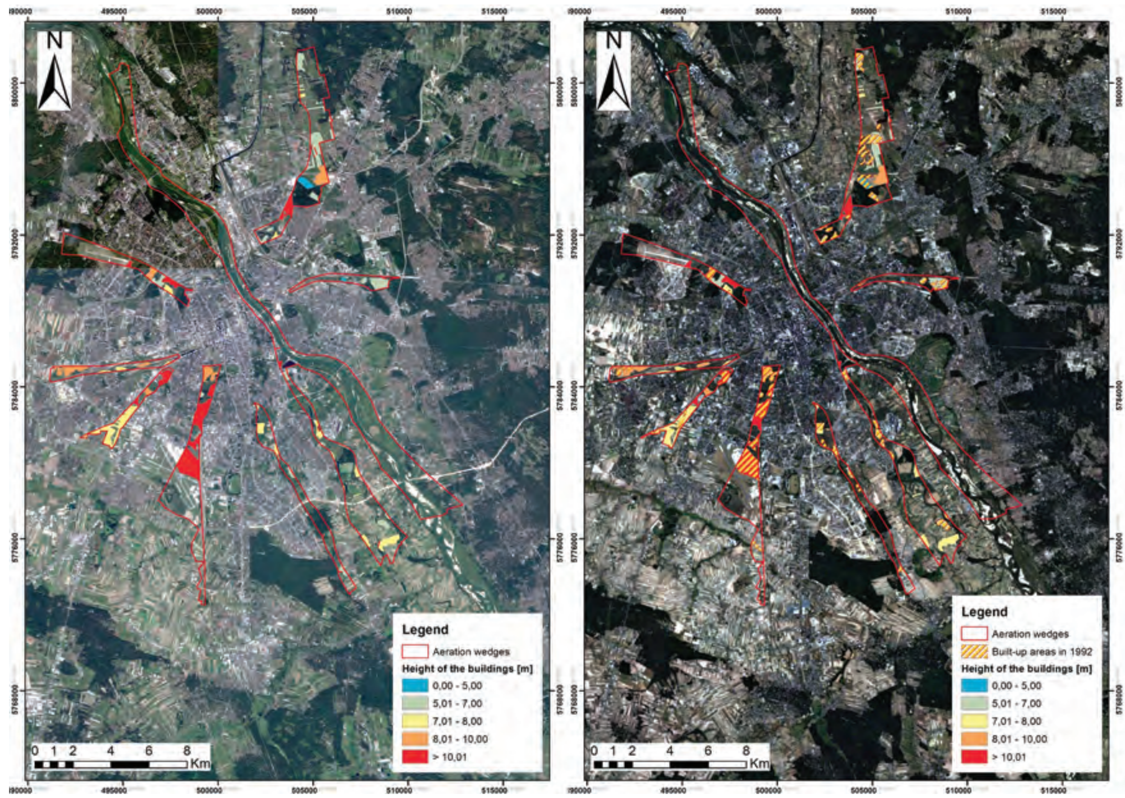

Fig. 10. Height of the buildings at aeration wedges of City of Warsaw (L) and height of the buildings built after 1992 (R)

The highest buildings have been built at wedges located at the west. In Bemowski corridor average height of the building is 9.45 m, in Jerozolimski 9.78 in Mokotowski 9.17 m. In Mokotowski corridor, 40% of all building located at the built-up areas, is higher than 10 m. Most of these building had existed before 1992 but some of them were built in the next years. In Jerozolimski most of the buildings are 7–8 m high but they are higher closer to the downtown (8–10 m and more than 10 m). In Bemowski, there is no class of building which dominates but there is a big area of buildings higher than 10 m (352 ha). What is important, most of buildings were built after 1992. The biggest variability of height is located in Brodnowski corridor where average height is 6.6 m (Fig. 10). Moreover, Mokotowski and Jerozolimski corridors count the most average volume of the buildings (Fig. 11). It is the area where are located multi-family housing, office building and warehouses. The least volume of building was noticed in Wilanowski, Podskarpowy and Kolejowy Wschodni corridors (Fig. 11). Taking into consideration this fact and height, it suggest that built-up in these areas is low single-family housing.

Problematical aspect of that analysis was accessibility of data. Data from only one year (2012) was available. Because of that, it was impossible to make a complex research and comparison as with built-up area's surface. On the other hand, this data provide information about direction in urban planning at these areas.

4.4. Situaitng the buildings

One of the most built-up wedge is the Bemowski. It was mentioned in previous chapters that the built-up area at the wedge increased by 72 ha (313%) over the years 1992–2018. In Figure 12, it is presented how buildings are situated. On the west, there have been built a large shopping center which is located across the wedge. Its height is more than

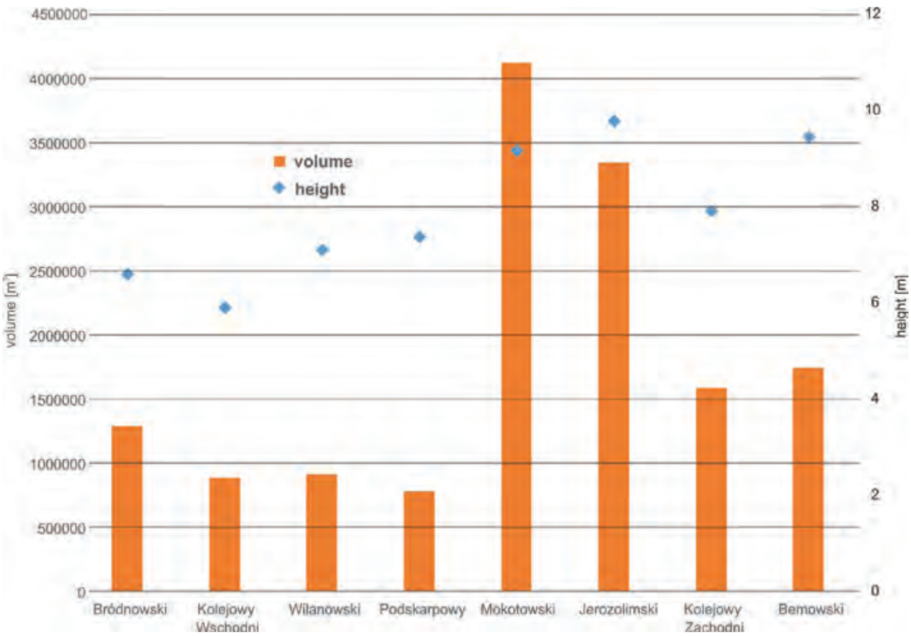

Fig. 11. Average height and volume of the buildings in 2012

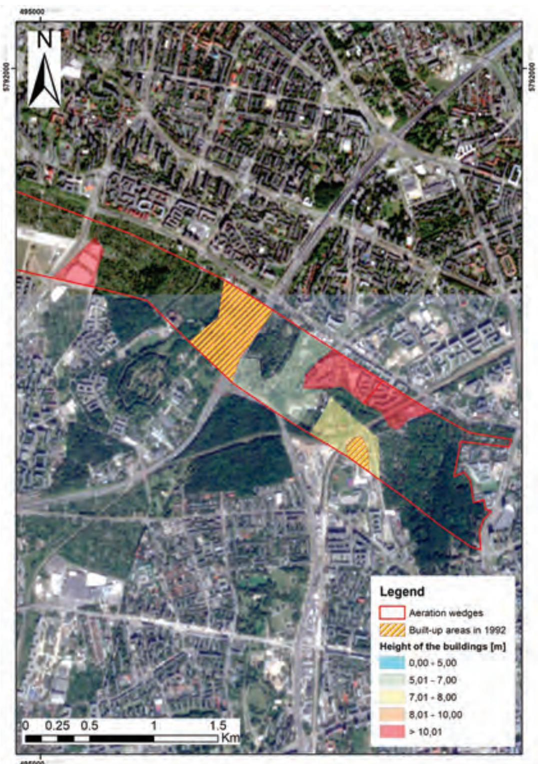

Fig. 12. Height of the buildings at Bemowski corridor in 2012 (The Building Height 2012 – Urban Atlas; Sentinel-2 image 2018-09-20 RGB432)

10 m. In the middle, there is a group of building, but they had been built before 1992. On the east, there have been built many lower building (5–7 m). At the end of the corridor, there have been built estate of multihousing-family. Their height exceeds 10 m (Fig. 10). What is more, their wider walls are situated across the corridor (Fig. 12). Because of that, prevailing wind is less useful (Kolokotsa et al., 2009; Yuan and Ng, 2012).

5. Conclusions

The results of the work point out that built-up areas increased during the years 1992–2018. Arable land and meadows are the territories which have been replaced by buildings mostly. The biggest changes have taken place between 1992 and 1995, 2001 and 2004, 2004 and 2006. If the current trend continues built-up will cover larger area than arable lands and meadows, in next years (Fig. 13).

The biggest increase of built-up have taken place in Brodnowski, Bemowski, Jerozolimski and Kolejowy Zachodni corridors. The open spaces in these areas should be especially protected. Otherwise, mentioned corridors could stop being an aeration wedges, like Brodnowski. Situation is dif-

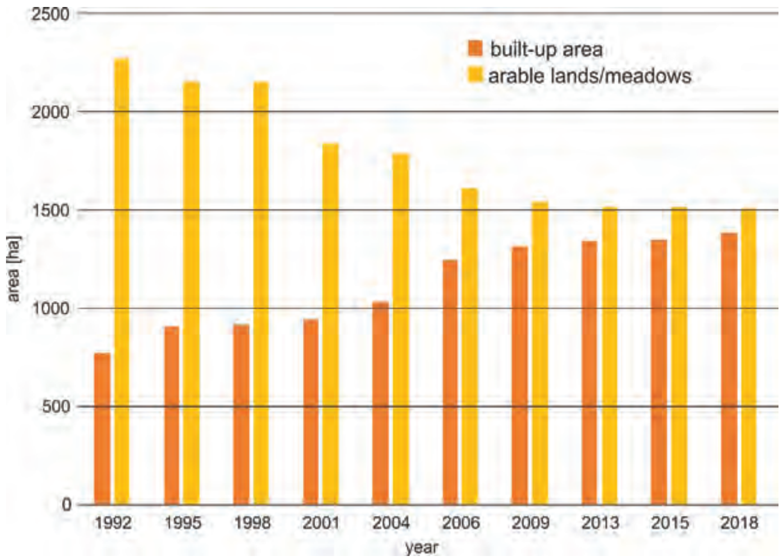

Fig. 13. Built-up areas and arable lands/meadows changes in 1992–2018

ferent than in 1992 in mentioned corridors, so the borders should be changed. Moreover, the altitude of buildings in Jerozolimski and Mokotowski corridors is high that impacts on neighboring open areas. Shadow of the buildings affects on vegetation – the light is limited. Considering two factors – increase of built-up area and height of the building – it seems that Jerozolimski corridor is the most threaten to be no longer active. There are still much open and green spaces at Wilanowski and Podskarpowy corridors. Authorities should pay a special attention to prevent building on these areas. The solution could be a design and adopt of Local Management's Plan which are in force to impose building standards and limits. Remote sensing and GIS tools could be useful for monitoring of changes in land cover and pointing the most threatened territories.

The case of Warsaw proves that the Polish legislation does not adequately protect areas of aeration wedges. The authorities make out plans about ventilation and air regeneration systems but there are no mandatory act of laws which could stop build-up of open spaces.

If the aeration wedges are still built-up, the issues like air pollution, thermal unconfort and not proper indoor ventilation of the city could be more and more serious to Warsaw and its citizens. On the other hand, Warsaw's population is constantly increasing so desire and need for new buildings will increase, too. The goal for authorities and planner is to reconcile needs of new dwellers and protection of environment.

Preliminary research was performed during poster session of Mapping Urban Areas from Space Conference – MUAS 2018 at Frascati (Grzybowski and Kałuski, 2018). Participants pointed out that building of open areas is alarming problem which could cause all of the consequences mentioned in the paper.

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Zmiany w zabudowie na terenach klinów napowietrzających miasta Warszawy

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Streszczenie: Głównym celem pracy było zaprezentowanie zmian w zabudowie na obszarach klinów napowietrzających miasta Warszawy. Idea korytarzy napowietrzających narodziła się w 1916, a następnie była zaadaptowana to potrzeb i warunków i obecnych czasów w latach 1992, 2006 i 2018. Opisana ona była w dokumentach dotyczących zagospodarowania przestrzennego Warszawy. Celem, dla którego wyznaczono kliny było zapewnienie wymiany powietrza pomiędzy centrum miasta a terenami podmiejskimi (szczególnie terenami zieleni). Analizy zostały przeprowadzone dla lat 1992, 1995, 1998, 2001, 2004, 2006, 2009 – wykorzystano zobrazowania Landsat 5; 2013 – wykorzystano zobrazowanie z Landsat 8, 2015 i 2018 – wykorzystano zobrazowanie z Sentinel-2. W wyniku badań, stwierdzono, że tereny korytarzy są stale zabudowywane. W roku 1992 obszary zabudowane wynosiły 14% całości powierzchni korytarzy (767 ha), w 1998 – 17% (918 ha), w 2006 – 24% (1245 ha), w 2013 – 26% (1341 ha), a w 2018 – 27% (1383 ha). Zmiany te w największym stopniu, spowodowały straty w obszarach rolniczych i łąkach. Ich powierzchnia w 1992 roku zajmowała 42%, w 2018 było to tylko 29%. Ponadto, podczas badań zaobserwowano, iż nowe budynki budowane są w niekorzystnym położeniu – są one przeszkodą dla swobodnych ruchów mas powietrza.

Słowa kluczowe: przewietrzanie miasta, zmiany pokrycia terenu, przestrzeń miejska, Sentinel-2, Landsat