city regions

Evaluation of green infrastructure for shaping climatic conditions (mesoclimate and topoclimate) in the Wrocław Metropolitan Area (Wrom) - summary

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1. Legal regulations concerning climate protection

The subject of law concerning climate change is the protection of climate system as a resource of natural environment. On a global scale, the most important documents regarding climate protection are the United Nations Framework Convention on Climate Change (UNFCCC) signed in 1992 and Kyoto Protocol (1997). The aim of the Convention was to undertake actions for stabilizing concentration of greenhouse gases in the atmosphere at the level preventing dangerous anthropogenic influence on the climate system. The Kyoto Protocol obliges developed countries to reduce greenhouse gases emission, establishes emission limits and points out possibilities of trade in emission in case of exceeding or not reaching the established limits.

The problem of climate change is a priority over the policy concerning protection of the environment in the European Union. The European Union is obliged within the international law to prevent climate change, it also constitutes regulations which are obligatory for its member states. One of the latest and the most important regulations concerning climate issues is the Climate and Energy Package, signed in 2008 during the European Council meeting. The Package obliges the states of the Commonwealth to a reduction in greenhouse gases emission (20%), increase in energy efficiency (20%) and increase in renewable energy (20%; 15% for Poland).

In Poland, the issues concerning environmental protection are considered in Art. 5 of the Constitution of the Republic of Poland. The main aim of the national ecological policy is to provide ecological security and create a basis for development and accomplishment of the strategy concerning sustainable development of the state. The climate policy of Poland is an integral element of the national ecological policy. In November 2003, the Cabinet of Poland introduced “Poland’s climate policy. The strategy for greenhouse gases emission reductions in Poland until 2020” document. The priority of Poland in this case is to participate in the international activities concerning global climate protection.

The regulations connected with activities focused on climate protection are included in the Act on Energy Law (1997), Act on Environmental Law (2001), Act on Environmental Protection (2004). In the context of the adaptation to climate protection, the regulations connected with threats regarding natural disasters can be specified, i.e. Act on Water Law (2001), Act on Natural Disasters (2002) and Act on Emergency Management (2009).

2. **Characteristics of climate elements in the WROM modified by open and green areas and the modification of their land use**

The region of WROM, similarly to the entire Lower Silesia area, is located in the maritime temperate climate zone (Cfb, according to W. Köppen's classification).

The climate conditions of the WROM are shaped by astronomical (latitude, sun angle, day length), geographical (location in the relation to the sea and ocean, hypsometric variability, terrain relief, land use), circulation and anthropogenic (changes in land use, modification of chemical composition of the atmosphere) factors.

Astronomical factors are crucial in the context of the amounts of solar radiation. Mean annual total radiation in Wrocław is equal to 3685 $MJ \cdot m^{-2}$ (Dubicka 1994).

The climate conditions of the WROM are shaped by western circulation and advections of maritime polar air masses connected with this direction. They occur during 46% of days per year, while continental polar air masses are observed with a 38% frequency (Dubicka 2000). The domination of the maritime polar air masses is characteristic for whole seasons, with its maximum noticed in summer. Cyclonic types of atmospheric circulation prevail in the Lower Silesia. Their occur during 56% of days per year (Sobik 2005).

The location of the WROM in the background of the areas characterized by varied terrain relief (Trzebnica Hills in the north and Sudety Mts. with their foreland in the south) is a very important climatic factor. The location in the Odra river valley and in the foreland of the Sudety Mts. determines the features of thermal conditions, affected by foehn winds and dynamic heating of air masses at the leeward side of the mountain massif (Dubicki et al. 2002).

The most of WROM region is characterized by low hypsometric variability, but for two regions: Trzebnica Hills and Ślęża Massif. Both of these regions are located within convex terrain forms and are characterized by more significant hypsometric variability. In the case of Trzebnica Hills, the highest peaks are located at an altitude of over 250 m a.s.l. Ślęża Massif rises over 500 m above surrounding lowlands, with its culmination at an altitude of 718 m a.s.l. The influence of altitude on climate in the WROM is significant especially in the case of Ślęża Massif.

Land use and its changes, that are crucial in the context of variability of climatic conditions on the microclimatic scale, are also a very important climatic factor. In the region of WROM, arable lands prevail and cover ca. 60% of whole area. Forests are observed in the case of 19%, while built area covers ca. 8% of the region. Within the built-up areas, the most important factors, affecting climatic conditions on a local scale, are: changes in land use, buildings and emission of pollution and anthropogenic heat.

Wind conditions in the region of WROM are determined by regional atmospheric circulation and are modified by valleys' and hills' directions and land use as well. The results of the measurement from Wrocław-Strachowice meteorological station indicate the domination of NW wind (21%) with significant frequency of W (18,3%) and SE (17,4%) directions. The wind from NE (4,9%) is the most rarely observed direction. Calms are noticed with ca. 9% frequency. Variability of air pressure in an annual cycle determines the changes in the frequency of dominating wind directions. During winter and autumn the frequency of SE winds increases, while in spring and summer winds form NW dominate.

Mean annual air temperature in the region of WROM is amounted to ca. 8,5°C, with the maximum observed in July (ca. 18°C) and the minimum in January, which varies from -0,5°C in most of the area to -1,2°C in the eastern and the north-eastern part of the region. In Ślęża Massif the decrease in mean annual air temperature with the altitude is equal to ca. 0,54°C/100 m (Błaś & Sobik 1998).

Frosty days (T_{max}<0°C) occur in the period from November to April with the maximum frequency observed in January (8-9 days), while icy days (T_{max}<-10 °C) are sporadically noticed from December to March. Warm days (T_{max}>25°C) occur from April to October and the largest number of warm days is observed in July and August (ca. 23-25 days). Hot days (T_{max}>30°C) are characterized by significantly lower frequency and similarly to warm days are the most frequently noticed in July (ca. 2 days) and August (2-3 days).

Mean annual precipitation totals in the region of WROM are 540-580 mm, excluding higher located areas (Trzebnica Hills, Ślęża Massif) where they amount to over 600 mm. Precipitations are meanly noticed during 155-165 days a year. Snow cover in the region is observed during 32-43 days a year with its highest frequency in January.

Sensible climate conditions (bioclimate) in the WROM, assessed on the basis of the UTCI (*Universal Thermal Climate Index*), are characterized by no thermal loads in the warm season. The highest frequency of such conditions is observed in June and September. June and August are characterized by lower frequency due to intensity of heat stress which occurs during 30% of days. The occurrence of days characterized by heat discomfort is mainly caused by high values of air temperature, high frequency of sultry conditions and lower wind speed if compared to the rest of the year.

Cold season, especially its winter months, is characterized by low number of days with comfortable weather conditions that do not cause thermal loads for the human organism. The highest frequency of cold stress is observed in January when it occurs during over 50% of days. It is mainly due to uncomfortable thermal-humidity conditions (low air temperature, high relative humidity), relatively high wind speed and less comfortable cloudiness and radiation conditions when compared to the warm season.

3. **Evaluation of threats for local climate in the context of proceeding process of urbanization in the open areas**

Climatic conditions in urban areas are modified by the influence of anthropogenic factors, including: increase in synthetic surface area, emission of pollution and anthropogenic heat, buildings (fig. 1). These factors determine the development of specific urban climate which is different from climatic conditions observed outside the city. The range of the influence of these factors is determined by i.e. city size, number of inhabitants, urban system and topographic conditions. Modification of local climate in urban areas mainly concerns solar radiation balance and heat balance of active surface. As a result of the processes occurring in the atmosphere, scattered radiation increases due to increased amount of aerosols. Furthermore, lower values of deflected radiation (albedo) are observed from various types of active surface, characterized by different physical features. Different values of heat balance of active surface in the comparison to the area located outside the city are due to different conductive, turbulent and latent heat exchange as well as to heat emission connected with fuel combustion (Lewińska 2006).

The observed variability contributes to specification of an urban area climate with its characteristic features different from the area located outside the city. Climatic conditions of Wrocław are characterized by typical features for urban areas.

Modification of meteorological conditions in urban area is the most characteristic in case of air temperature. Higher values of air temperature, especially in the city centre characterized by vast area of synthetic surface, are typical effect of climate modification in the urban areas. The increase in air temperature is called an urban heat island. The research conducted by the University of Wrocław (Dubicka 1994, Dubicka & Szymanowski 2001, Szymanowski 2004) implies that the urban heat island in Wrocław is observed throughout the year, however it is characterized by various intensity on a diurnal and an annual scale as well. The intensity of this phenomenon is assessed by the difference in air temperature between the urban area and the terrains located outside the city.

Mean annual intensity of the urban heat island in Wrocław equals 1^{o}C and it ranges from 0,5^{o}C during daytime to 1,6^{o}C at night (Dubicki et al., 2002). In case of high buildings (5-11 floors) it is equal to 0,7^{o}C, while in the area of low buildings characterized by large green areas it amounts to 0,3^{o}C.

The urban heat island in Wrocław is characterized by the greatest intensity during nighttime in summer months, 2,3^{o}C in the centre, 1,6^{o}C in the high buildings area and 0,6^{o}C in the zone built with low types of buildings (Dubicka 1994; Dubicki et al., 2002). It is mainly conditioned by lower cloudiness if compared to the winter season and lower wind speed as well, which causes strong heating of the areas with synthetic surface and limited ventilation conditions. The increase in wind speed over 4 m/s at night and 1 m/s during daytime, regardless cloudiness, causes declining or vanishing of the urban heat island (Szymanowski 2004).

The influence of the city on local weather conditions is also observed in the case of air humidity. In the densely built centre of Wrocław, a significant shortage of vapor pressure is noticed during daytime. The intensity of the shortage in July amounts to -1,9 hPa, while in winter it reaches about -0,5h Pa (Rosiński 2005).

One of the most characteristic features of the city's climate is a phenomenon of 'town breeze', caused by various heating of different types of surface. Local circulation within the urban area can lead to positive as well as negative effects on the city's ecosystem. Air advection from the areas surrounding the city, improvement in ventilation conditions and cleaning of the atmosphere can be regarded as positive effects. The negative influence of local circulation can be connected with i.e. advection of polluted air from industrial zones, occurrence of tunnel effect, causing significant increase in wind speed in narrow routes and an increase in heat losses during cool days (Tamulewicz 1997).

In the context of precipitation, the city of Wrocław affects the terrain up to 10-15 km around the city (Schmuck 1967). In the city area precipitation totals and number of days with precipitation are higher in comparison to the area located outside the city. The increase in precipitation in urban areas can be regarded as advantages and disadvantages for the city ecosystem. Higher precipitation totals contribute to an efficient ventilation concerning air pollution, while pollution of ground waters and difficulties in communication due to rainfall can be considered as negative effects (Tamulewicz 1997).

Modification of city local climate, concerning changes in thermal, humidity, wind and solar conditions, is mainly characterized by unfavorable influence on human organism. Meteorological elements affect human organism by mutual acts. Complex influence of weather conditions on human organism and its heat balance can be assessed with the use of biometeorological indices, e.g. subjective temperature (STI). In Wrocław, the most frequent types of weather, characterized by high occurrence of "cold" thermal senses, are observed during ca. 50% days a year. The weather characterized by "warm" thermal senses and unfavorable for human organism heat stress occurrence is noticed in case of 29% days a year. During the period from May to October its frequency exceeds 50%. Weather types causing cold stress are observed with the frequency of 7%. Their maximum is noticed in December when this type of weather occurs during 10 days (Sikora 2005).

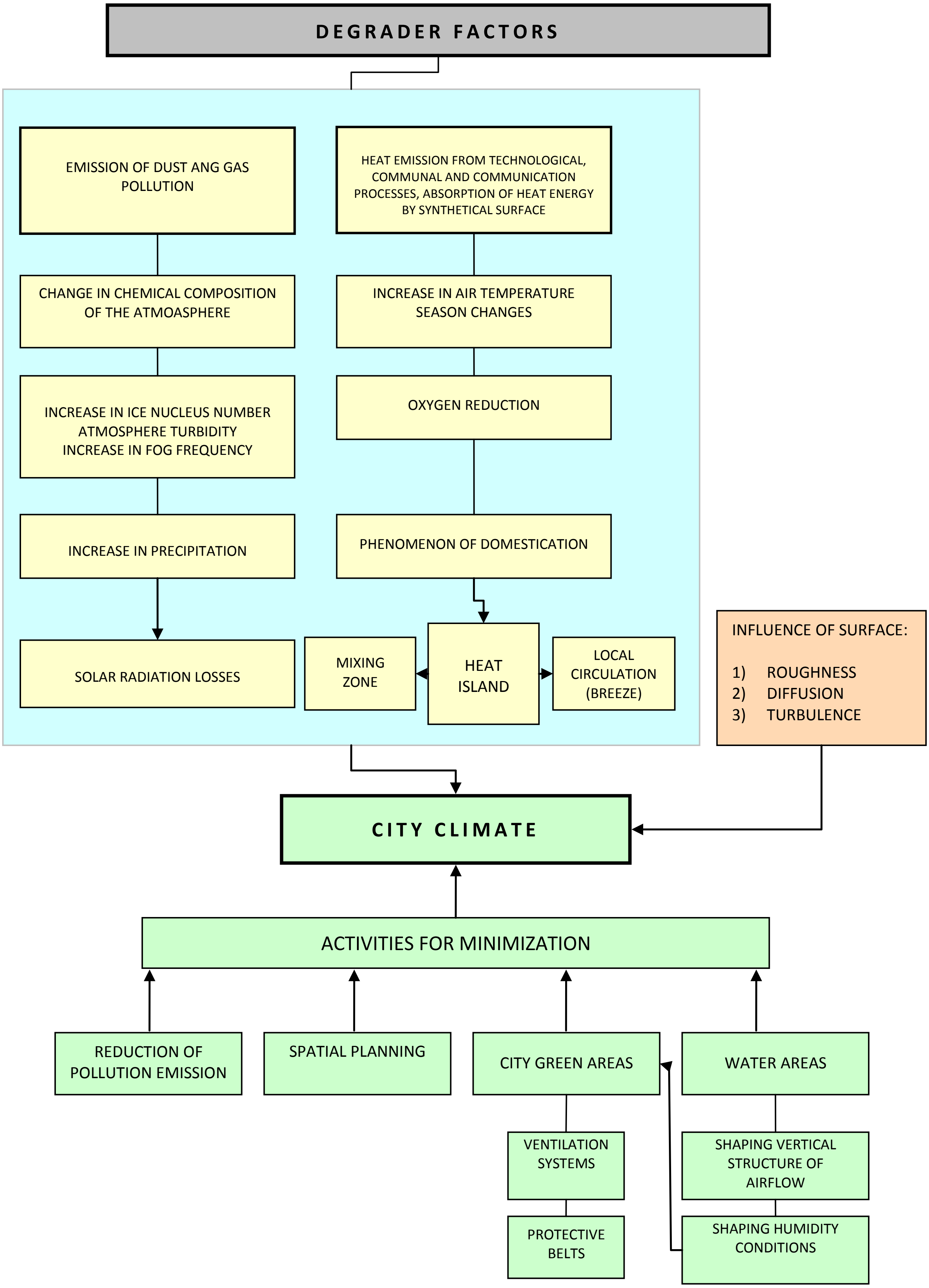

DEGRADER FACTORS
EMISSION OF DUST ANG GAS POLLUTION
HEAT EMISSION FROM TECHNOLOGICAL, COMMUNAL AND COMMUNICATION PROCESSES, ABSORPTION OF HEAT ENERGY BY SYNTHETICAL SURFACE
CHANGE IN CHEMICAL COMPOSITION OF THE ATMOASPHERE
INCREASE IN AIR TEMPERATURE SEASON CHANGES
INCREASE IN ICE NUCLEUS NUMBER ATMOSPHERE TURBIDITY INCREASE IN FOG FREQUENCY
OXYGEN REDUCTION
INCREASE IN PRECIPITATION
PHENOMENON OF DOMESTICATION
SOLAR RADIATION LOSSES
MIXING ZONE
HEAT ISLAND
LOCAL CIRCULATION (BREEZE)
INFLUENCE OF SURFACE:
1) ROUGHNESS
2) DIFFUSION
3) TURBULENCE
CITY CLIMATE
ACTIVITIES FOR MINIMIZATION
REDUCTION OF POLLUTION EMISSION
SPATIAL PLANNING
CITY GREEN AREAS
WATER AREAS
VENTILATION SYSTEMS
SHAPING VERTICAL STRUCTURE OF AIRFLOW
PROTECTIVE BELTS
SHAPING HUMIDITY CONDITIONS

Fig. 1. Scheme on anthropogenic factors and processes affecting climate of urbanized areas (Lewińska 2000; modified)

4. Importance and functions of open ground and current green infrastructure of the Wrocław Metropolitan Area in the context of shaping climatic conditions

Green area plays a very important ecological, usable, acoustic, protective, climatic and aesthetic role in urban areas. In the region of WROM, it covers over 30% of its surface. Modification of thermal conditions on green area is mainly connected with the characteristics of heat absorption and accumulation during daytime and its losses at night. Green area is cooler and more humid if compared to built-up areas, however the variability depends on a season and the characteristics of the green area. The research shows that parks are characterized by air temperature lower by about 2-3^{o}C in summer and about 1^{o}C in winter if compared with open areas (Kopacz-Lembowicz i in. 1984). The highest thermal and humidity contrasts between green and built-up areas are usually observed in summertime during radiative weather.

Green area, especially high greenery, has a significant influence on shaping wind speed. It is also a good protection against strong wind. In case of high greenery belts, wind speed is modified in the distance of 8- to 60-tuple trees height at a leeward side, while at a winward side the modification equals to about 2- to 10-tuple trees height. Wind speed significantly decreases in parks and forests. In the distance of about 50 m from the forest/park edge, the wind speed is only equal to about 55-75% of the speed observed in open areas. In the distance of 200 m from the edge this value decreases to only 2% (Yoshino 1975).

Green area due to differences in heat absorption and losses in the comparison to built areas, also contributes to local circulation which occurs especially during calm and radiative weather.

Green area contributes to noise suppression as well. Green belts with tree and bush rows along streets can decrease the intensity of noise by their absorption or deflection by 2-3 times (Łukaszewicz i Łukaszewicz 2006).

Green area also makes a contribution to absorption of gas and dust particles. It acts like a filter that is cleaned by precipitations. Favorable conditions for filtering role played by greenery occur during weather characterized by calm or low wind speed. Optimal condition in this case are observed for the trees characterized by low coherency (to 50%) which enables airflow into the internal parts of park/forest (Czerwieniec i Lewińska 2000). On the other hand, low greenery (areas covered with grass) play a role of a pollution filter in the ground zone. It protects against secondary pollination from the surface which is a very inconvenient phenomenon in the urban areas. Plants also have a significant influence on an increase in oxygen concentration in the air.

The following terrains in the environmental system of WROM can be specified (fig. 2):

Nod areas - large forest areas (over 70 ha) characterized by environmental and climatic functions. They are mainly represented by forest area located in Ślęża Massif, Trzebnica Hills and the western parts of the region situated between Odra and Widawa valleys.

Auxiliary areas – forests (below 70 ha), parks, gardens, orchards that are a very important link supporting environmental system. The following areas can be included here: city parks (Niskie Łąki, Szczytnicki, Wschodni and Zachodni) and city forests (Osobowicki, Pilczycki, Starachowicki, Rędziński, Mokrzański).

Open areas used for agriculture – support the ventilation system of the WROM by free airflow through the urban areas. The valleys of the Odra river, its tributaries as well as surrounding areas shape environmental conditions in the city. They introduce the air into the urban environment characterized by higher concentration of oxygen and higher humidity, they also play a recreational function for the inhabitants. Their environmental advantages contribute to the reclamation of the urban environment, cleaning the air from dust and other pollutions. The river valleys enable natural connections between the agglomeration of Wrocław with natural areas located outside the city, especially with the nod areas of WROM

Open areas of river valleys – are environmental systems used as ventilation corridors of WROM. They enable free airflow to the urban areas.

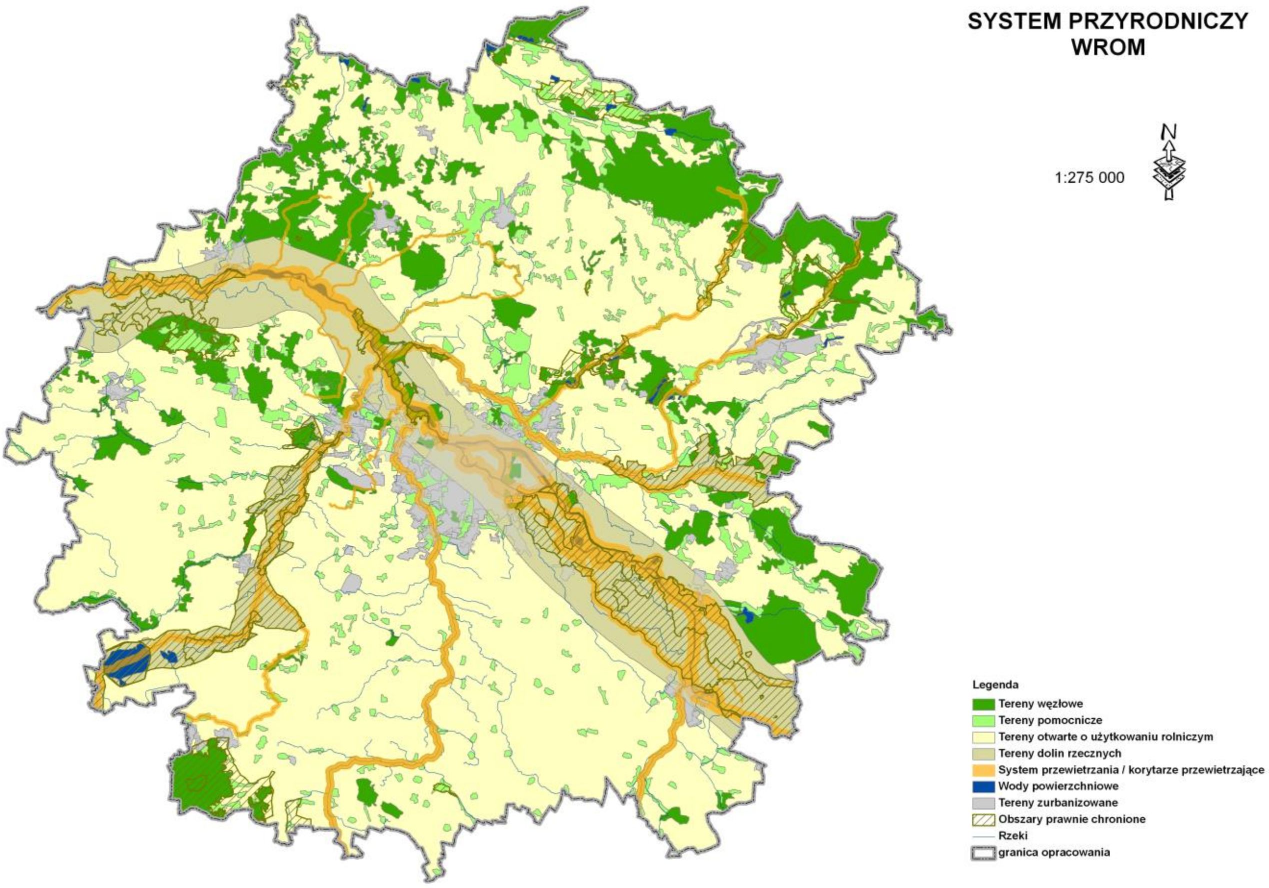


Fig. 2. Environmental system of WROM [own elaboration]

5. **Analysis and evaluation of trends concerning topoclimate in the region of WROM**

Climate change is mostly noticeable in case of thermal conditions. In 1971-2010, at Wrocław-Strachowice and other meteorological stations located in the WROM region and its surroundings, increase in air temperature is observed. Increasing trends occur in case of mean annual air temperature as well as for mean maximum and minimum temperature. The most noticeable changes in mean air temperature are observed during spring, summer and autumn, when they are characterized by statistically significant trend.

Increasing trend is also observed in case of mean annual sunshine duration. During the last decade, the longest periods of sunshine duration were observed in the years characterized by severe drought occurrence in 2003 and 2006. In these periods, the highest values of sunshine duration for the last 40 years were noticed.

In case of precipitations, mean values of bioclimatic indices and frequency of days with particular thermal loads for human organism, no statistically significant trends were noticed.

In the context of climate change scenarios, especially for an increase in air temperature values, an intensification of the urban heat island of Wrocław can take place. In case of densely built areas, an increase in thermal loads for human organism and related to them thermal discomfort can occur.

6. Climatic valorization of WROM

The aim of valorization is to evaluate and indicate the regions characterized by various topoclimatic values in the WROM area. The method used in the valorization is based on the Paszyński's method (1980) concerning an estimated classification of topoclimate types. Heat balance of active surface is the basis for this method. For the purpose of valorization of urban terrains, the method was modified by Lewińska (2000). According to the terminology proposed by Lewińska (2000), the following types of topoclimate can be distinguished:

- anthropogenic topoclimate – for urban areas,
- natural topoclimate - for none-urban areas, characterized by prevailing green and agriculture terrains

Next, 6 classes were distinguished concerning topoclimatic conditions, ranging from very favorable to unfavorable conditions (fig. 3).

Very favorable natural environmental topoclimate concerns: slopes exposed to SE-S-SW and inclined >5^{o}; flat and exalted areas used for agriculture. Regarding the important role of forests in the context of shaping climatic conditions, as well as their different climatic conditions on a local scale, forests topoclimatic types were distinguished according to the Paszyński's method (1980). Additionally, very favorable subtype of natural topoclimate ('forest') was distinguished.

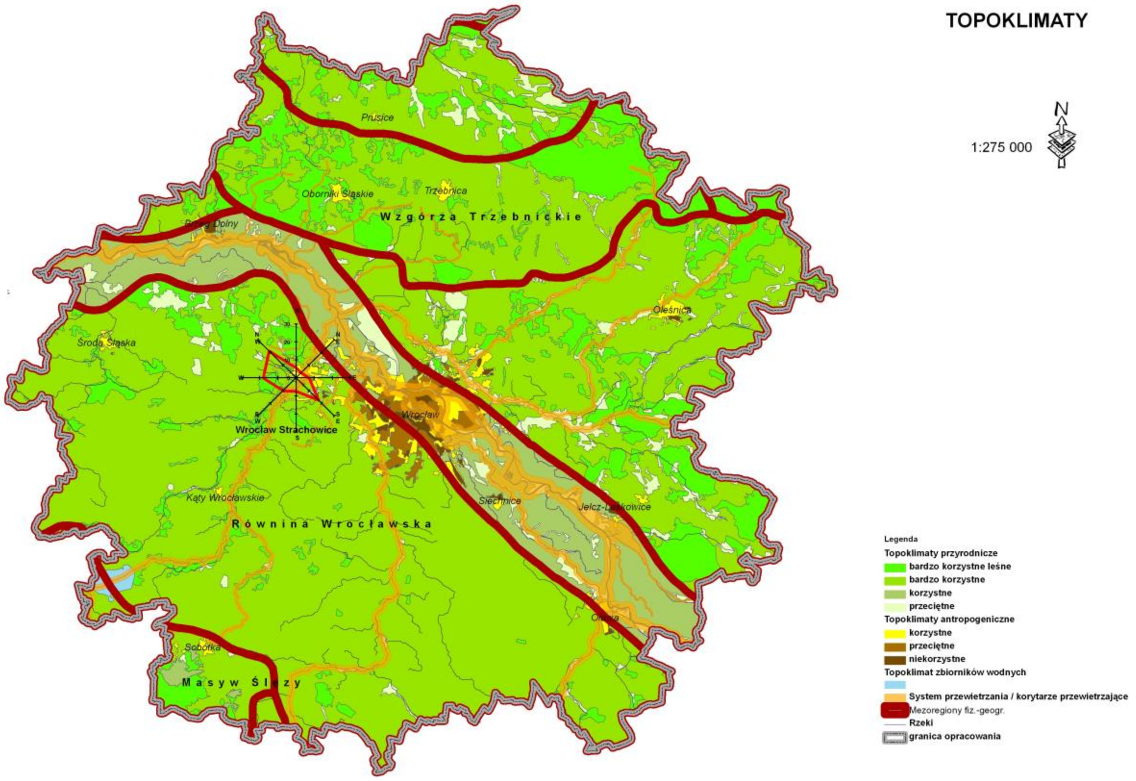
Favourable type of natural topoclimate – slopes exposed to W-NW-N-E-NE and inclined >5^{o}, areas of valleys (Wrocław valley).

Average type of natural topoclimate – meadows, swamp areas.

Unfavourable type of anthropogenic topoclimate – area of cohesive buildings, areas of industry and communication.

Average type of anthropogenic topoclimate – community houses characterized by a low cohesion.

Favourable type of anthropogenic topoclimate – prevailing single-family houses, city green terrains.



Ryc. 3. Climatic valorization for WROM [own elaboration]

7. **Recommendations for harmonious shaping of natural environmental system of WROM for the purpose of climate improvement and protection, with the use of available legal and planning methods.**

- The basic elements of environmental system of the WROM are as follows: Odra river valley and the valleys of its tributaries that play a role of ventilation corridors, as well as forests and open areas used for agriculture. The river valleys (Odra, Bystrzyca, Ślęza, Oława, Widawa) provide a natural connection between Wrocław agglomeration and nod areas characterized by high environmental significance, including large forest complex in Ślęża Massif, Trzebnica Hills and in the western part of the region.
- The Odra river valley is a central ecological axis of the whole WROM region. It crosses Wrocław in its central part, from the west to the east and therefore significantly enables the ventilation of the city. The direction of the Odra river is in accordance with the prevailing

wind direction from the NW. Thus, it is a basic ventilation corridor for Wrocław and for the region of WROM as well.

- Trzebnica Hills and Ślęża Massif are the nod regions for the ventilation corridors of the WROM. Therefore, in spite of investment pressure, the existing forest area should be retained because of its important role in the context of climate.
- The environmental system should be characterized by a spatial continuity so that the green terrains can be connected with their nod areas, supporting the system with: air exchange, water cycle and climate drainage, including oxygen production and heat balance modification (Lewińska 2006).
- Using the hydrographic system, the development of environmental system is recommended (Łukaszewicz & Łukaszewicz 2006). Such a system covers the area of at least 300-400 m from a river's or reservoir's banks. In case of minor rivers, depending on local conditions, maintenance of green belt is recommended. Its width should be equal to 20-350 m along both sides of the rivers.
- Properly planned arrangement of buildings and green areas can be support for the city ventilation (Lewińska 2000). Climate drainage with the use of green areas and buliding's structure can intensify vertical and horizontal air exchange.
- The basis of the environmental system should consist of relatively large parks or forests (nod areas), covering at least 75-100 ha. They are a basis for minor units that cover 40-50 ha and that play a role of a basic unit in a single city district. The supportive role is also played by minor parks and gardens (15-20 ha), squares and gardens (3-5 ha), flat areas and green belts (covering at least 3000 m^2 and minimum 9-12 m wide).
- In case of planning high and cohesive buildings, because of the direction of the Odra river valley (north-east to south-west) and prevailing wind direction (western sector), the ventilation corridors that enable ventilation in the direction west-east should be maintained. Such a role can be also played by communication arteries with green belts.
- In areas characterized by dense and cohesive buildings there is often no possibility to increase the area of green areas. Therefore, using bright colors on the building's elevation could decrease the amount of absorbed radiation and consequently soften the local climatic conditions.
- Green areas can be a supportive factor for technical sources of noise suppression. In case of the tree belts 70-100 m wide the noise is suppressed by 50%. Such belts, in the regions characterized by scattered buildings and located close to the highways (i.e. Kąty

Wrocławskie, Długołęka), play a very important role also in the context of dust and gas pollution filtration.

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