The influence of spatial organization on bio-thermal conditions of urban areas

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Abstract The aim of the paper is to present three spatial perspectives for assessing microclimate and bio-thermal conditions of various types of urban spaces. The attention will be paid for evaluation how particular urban spaces influence people's physiology and well being. The results of several bioclimatic studies will be discussed. The studies have been performed at various scales. We start from regional scale of Polish Lowland through urban scale of entire large cities up to individual residential. Depending of research scale the role of various urban components in creating bio-thermal conditions will be discussed.

Introduction

The majority of Polish population lives in urbanized areas. Polish cities are under great pressure of planning new residential districts. Developers, architects and landscape architects propose not only new technical solutions but also **a** new philosophy of organization of space. The general idea of urban planners is to make cities more friendly and less stressed. Residential areas should also create optimal conditions for daily outdoor recreation for elderly people and children.

Planning of ideal city and housing estate is very complicated and multi-level process. Planners and architects should take into consideration different factors: economical, organizational, historical, social, environmental and others. Very specific is creation of optimal microclimatic and bio-thermal conditions. It can be obtained by rational use of existing environmental conditions (e.g. relief, natural vegetation, hydrology, city surroundings). In very local scale the attention should be paid for building size and orientation, the structure of trees and green carpets as well as small forms of architecture.

The aim of the paper is to present the results of several bioclimatic studies performed in urban areas are discuss. They represent three spatial perspectives for assessing microclimate and bio-thermal conditions of various types of urban spaces. The attention is paid for evaluation how particular urban spaces influence people's physiology and well being.

Materials and methods

The research were performed at various spatial scales: regional (essential part of **Mazowiecka** Lowland), urban (the whole area of Warsaw) and micro (two small housing estates in Warsaw: Kaminskiego and Wlodarzewska) (Fig. 1).

Fig. 1. Location of studied areas on the territory of Poland

Depending on spatial scale the reported research have based on various groups of data and methods. For regional and urban scales the special GIS data base was established. In regional scale the basic raster area was 1x1 km. For each raster the information of particular geographical components were digitized. We have taken into consideration the following components: relief forms, land cover types and ground moisture. In urban scale the raster area was 250x250 m. We have established the following environmental layers: land use, types of relief, ground moisture as well as surface temperature. The surface temperature was taken from LANDSAT 5TM thermal image. Values of particular meteorological components (air temperature, global solar radiation, wind speed) were calculated by reclassification of environmental layers due to method proposed by Blazejczyk (2002) and modified by Kunert (2010). As bioclimatic variable we have calculated the Universal Thermal Climate Index (*UTCI*) for various weather scenarios for summer season:

- Cloudy (or sunny), air temperature of 10°C, air humidity of 50%, wind speed of 8 m/s,
- Cloudy (or sunny), air temperature of 30°C, air humidity of 80%, wind speed of 2 m/s.

For the calculations of Universal Thermal Climate Index the following simplified equation (*UTCI**) was applied (Blazejczyk 2011):

$$UTCI^{*}\cdot = 3.21 + 0.872 \cdot t + 0.2459 \cdot Mrt - 2.5078 \cdot v - 0.0176 \cdot RH$$

where: t is air temperature (°C), Mrt is mean radiant temperature (°C), v is wind speed at 10 m above ground (m/s), RH is relative humidity of air (%)

All the reclassifications and calculations were made as a part of Geographical Information System created for Polish Lowland and Warsaw with the use of IDRISI Tajga software package.

In micro scale the research consists of several steps. The first one was detailed inventory of vegetation (type, height), buildings and roads. Created data base has been used for statistical calculations and spatial analyses relevant for RBVA and GPR interpretation for each housing estate. RBVA is a ratio of biologically vital areas, the index comprises the area of lawns, flowerbeds, hedgerows, tops of the trees as well as ground surfaces. However green plot ratio (GPR) is based on leaf area index (LAI), which is defined as the single-side leaf area per unit ground area. The second step was long-term climatological studies. In this purpose in each studied estates the HOBO Pro data loggers were installed (called base data). Air temperature and humidity were collected every 10-minutes 1.5 m above ground, over the grass. In the third step special route measurements inside the quarters were made on chosen days of summer 2009. Measurements were carried with HOBO loggers in 6-12 posts over different surfaces and in different urban structures in each estate. The observers measured also wind speed and they noted their thermal sensation and cloud cover.

In the present paper data regarded two housing estates: Kaminskiego and Wlodarzewska are discussed. Kaminskiego estate is located on NE suburbs of Warsaw (Fig. 1) next to the open, green area. The C-shaped, mostly 4-floors blocks of flats form some kind of courtyards of different seizes. It is fenced with openwork, metallic fencing. The RBVA is 44.5% only and GPR is very high (2.25). Parking places are organized along the fences and big parking lot next to the estate. Włodarzewska estate is located SW from the city centre. It is surrounded by many open spaces and park, but fenced in with the wall and only open to the big, fertile meadow on SE. It is characterized by compact development, many small flowerbeds and lawns between buildings, partly organized on the top of the underground parking lot. RBVA is 40.7% and GPR is 1.28 only. The base station stays in the shadow most of the day.

Results

One of the most important feature of urban climate is urban heat island (UHI). It is demonstrated both, by increased air and sensible temperatures. One of the measure of UHI is deviation of city temperature from rural area temperature. The quantity of such deviation is a function of the city size (Fig. 2).

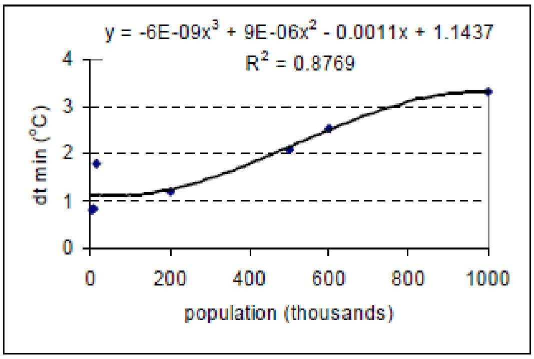

Fig. 2. Deviation of minimum air temperature in the city in relation to rural area (dt min) as a function of population of the city
Source: Blazejczyk et al. 2006

Inside the city deviations of air and sensible temperatures differentiate depending on the type of land use. The highest, positive deviations are observed in downtown and industrial districts. However, at suburban areas and in forests sensible temperatures are lower then at rural areas (Fig. 3).

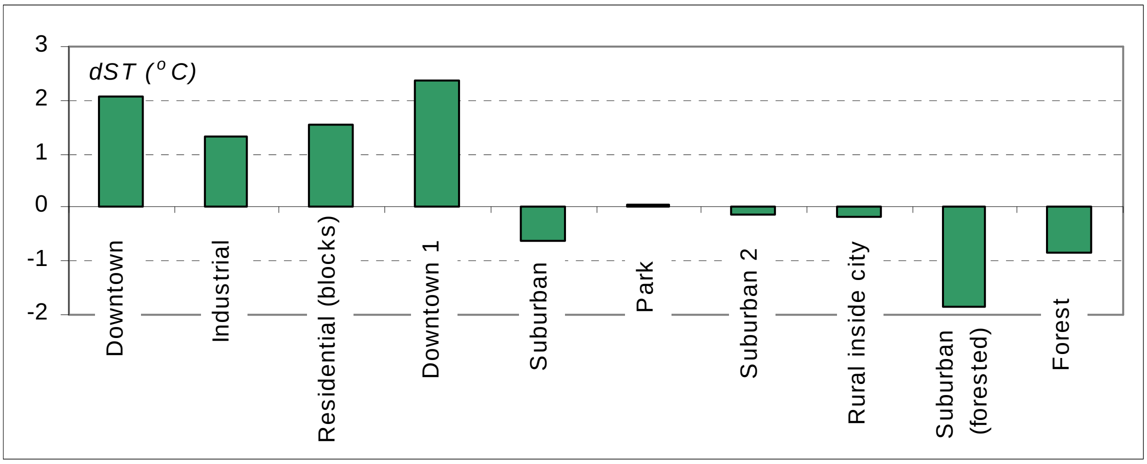

Fig. 3. Deviation of sensible temperature (*dST*) at various sites of Warsaw agglomeration from rural area
Source: Blazejczyk, Kunert 2006

Regional scale

At the flat areas local climate features are mainly formed by various forms of land use (Blazejczyk 2002, Kunert 2011). Thermal properties of urbanized areas, both, cities and villages, are seen in regional scale as warm spots. On the other hand, in large cities we can also mark out thermal and bio-thermal features of different urban structures as parks, forests and river channels (Fig. 4).

Względne wartości temperatury powietrza

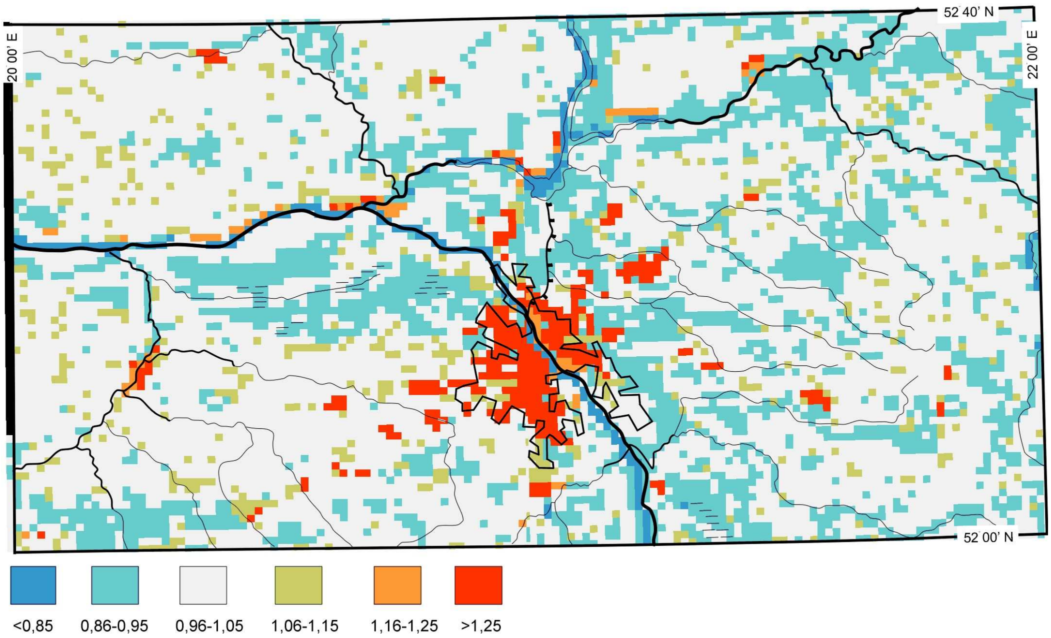

Fig. 4. Distribution of relative values of air temperature in the central part of Polish Lowland
Source: Blazejczyk, Kunert, 2002

Deviations of *UTCI* (*dUTCI*) from standard conditions (represented by meteorological stations) in different types of land use, depending on weather conditions ranged in warm season from -11.5^{o}C to +35.5^{o}C. *dUTCI* between the warmest and the coldest areas can reach 45^{o}C. The biggest negative deviations are noted on water bodies and in forests, however the biggest positive deviations are observed at urbanized areas: downtown and industrial zones. In the forests *dUTCI* can have negative or positive values, from -8.3^{o}C to 11.7^{o}C. Bio-thermal conditions in forests are modified by wind, air temperature and also by solar radiation. Positive deviations are observed during cold days with low solar radiation. Increase of wind speed is noted in cold days and *dUTCI* can rise even of 10^{o}C. Negative deviations are noted at soft winds, irrespective of air temperature, except of cloudy and cool weather conditions. The biggest negative *dUTCI* occurs in hot days with low wind speed and high solar radiation.

At open areas, with free air flow and also at areas with increased humidity the negative *dUTCI* always occurs. At these areas, *UTCI* values are determined especially by air temperature and wind speed. The highest deviations are noted in hot windy days with high humidity of air. Positive *dUTCI* occurs at ground transportation belts and at built-up areas; the highest values are noted at industrial areas. In built-up areas value of *UTCI* deviations is modified by solar radiation (at weak solar radiation they are higher of about 2^{o}C then at intensive radiation) and also by wind speed, especially in low air temperature (Fig. 5).

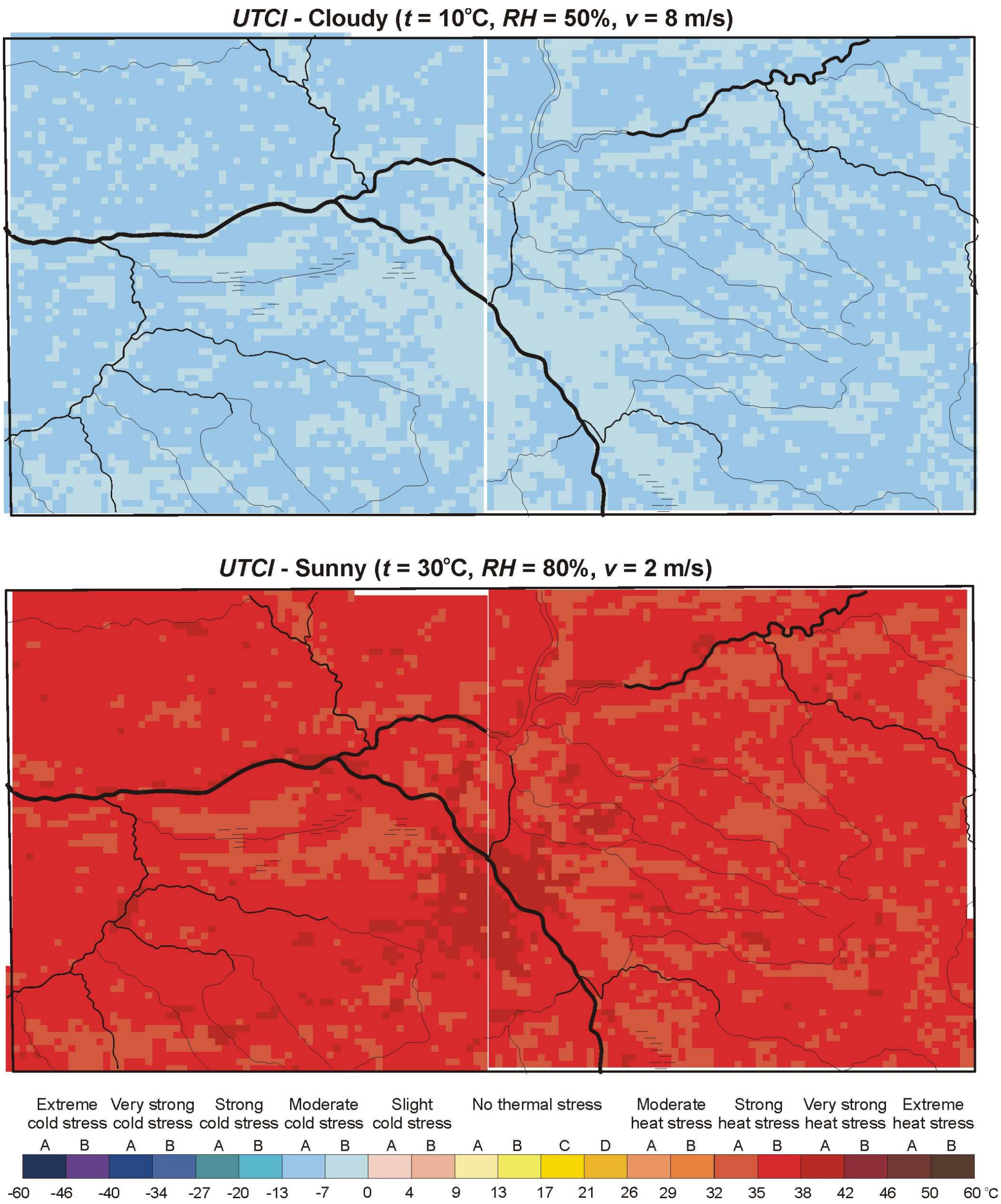

Fig. 5. Distribution of Universal Thermal Climate Index (*UTCI*) in the central part of Polish Lowland during selected weather scenarios
Source: A. Kunert own data

Urban scale

Warsaw is a city with an area of about 500 km^2 and with significant differentiation of land use. About 243 km^2 is a built-up area (28% no-dense and 22% dense settlements). Forests cover about 13% of city area. 85 km^2 is still used for agriculture as meadows and fields. Relatively great area (about 60 km^2, i.e. 12%) is used for transport system (roads and railways). When analysing thermal LANDSAT image we have found coefficients reducing air temperature (*TR*) for various types of land use in Warsaw. They changed from 0.85 for water bodies (river, lakes, ponds) up to 1.2 in dense settlements and industrial areas (Table 1, Fig. 6).

Table 1. Coefficient reducing air temperature (*TR*) for various types of land use in Warsaw.

Land use	Settlements			Forests			Open areas					
	dense	no-dense	villa's	conife-rous	decide-uous	mixes	gardens	rural areas	mead-ows	sands	earth works	water
TR	1.2	1.13	1.12	0.95	0.95	0.90	1.05	1.07	1.0	1.16	1.15	0.85

Source: Blazejczyk and Blazejczyk, 1999

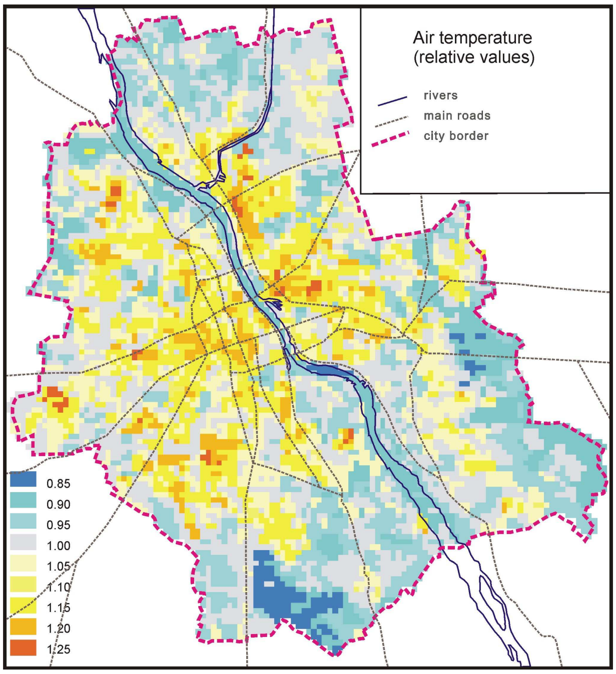

Fig. 6. Distribution of relative values of air temperature in Warsaw
Source: Kozlowska-Szczesna et al., 1996

When comparing bio-thermal conditions in selected types of land use in various weather scenarios we can notice that the greatest spatial differentiation of *UTCI** is observed during low air temperature and strong winds. The mean *UTCI** value for whole city area is about 2°C in cloudy and 4°C in sunny weather. In particular recreationally used types of landscape *UTCI** is significantly higher, especially inside forests. On the other hand during high air temperature forests reduce sensible temperature of about 5-6°C in comparison to city centre. Hot, sunny and humid weather is mostly stressed for tourists in the city centre. During weather with moderate temperature, humidity and wind speed there are not significant differences between tourist and recreation areas in Warsaw.

The spatial distribution of *UTCI** categories are presented on figure 7. The smallest differentiation of heat stress is observed at moderate temperature (20ºC), humidity (50%) and wind speed (4 m/s). Independent on cloudiness *UTCI** values are at majority of city area within the range of “no thermal stress” (9-26ºC). In sunny summer days moderate heat stress (26-32ºC) can be found only inside industrial and very dense settlement areas. During extreme weather conditions complicated city structure create great spatial differentiation of bio-thermal conditions. At cloudy, cool and windy weather *UTCI** in the city downtown can fall down to moderate cold stress range. On the other hand during sunny, hot, humid and calm weather several hot spells with extreme heat stress are found in the city centre.

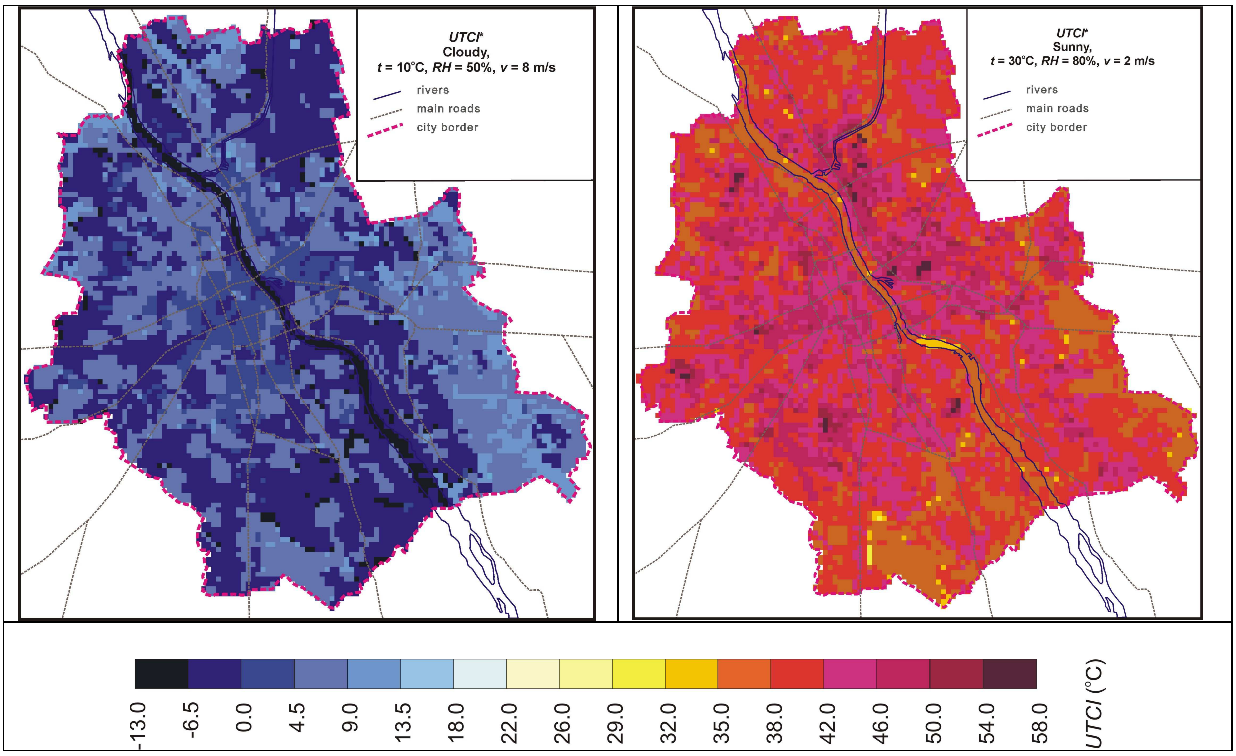

Fig. 7. Distribution of Universal Thermal Climate Index (*UTCI**) in Warsaw during selected weather scenarios
Source: Blazejczyk, 2011

Micro scale
Kaminskiego estate

The housing estate’ structure, the mosaic of different kind of areas evenly distributed (artificial surfaces, lawns, well arranged small gardens, flowerbeds, high trees, sandy playgrounds) cause that location of the warmest or the coldest places depend mainly on insolation and its changes during the day and under different weather. The north part of the estate is under the influence of both: the outside open green and high leafy trees which are grouped mostly in that part of the estate. It chills down easily in the evening and stays cool in the morning and warm up fast in the afternoon (measure posts 8-11). In the south part of the estate little warmer than others is the lawn of south exposure (post 6). The air move inside the estate is compatible with the buildings’ lay out. Due to the tunnel effect slightly higher wind speed is noted on the post 4. The highest wind velocities are noted outside the estate (measure posts 1, 2) or on its edge (11). Despite of low RBVA the estate is characterized by high participation of leafy species and quite favourable sensible climate (Fig. 8).

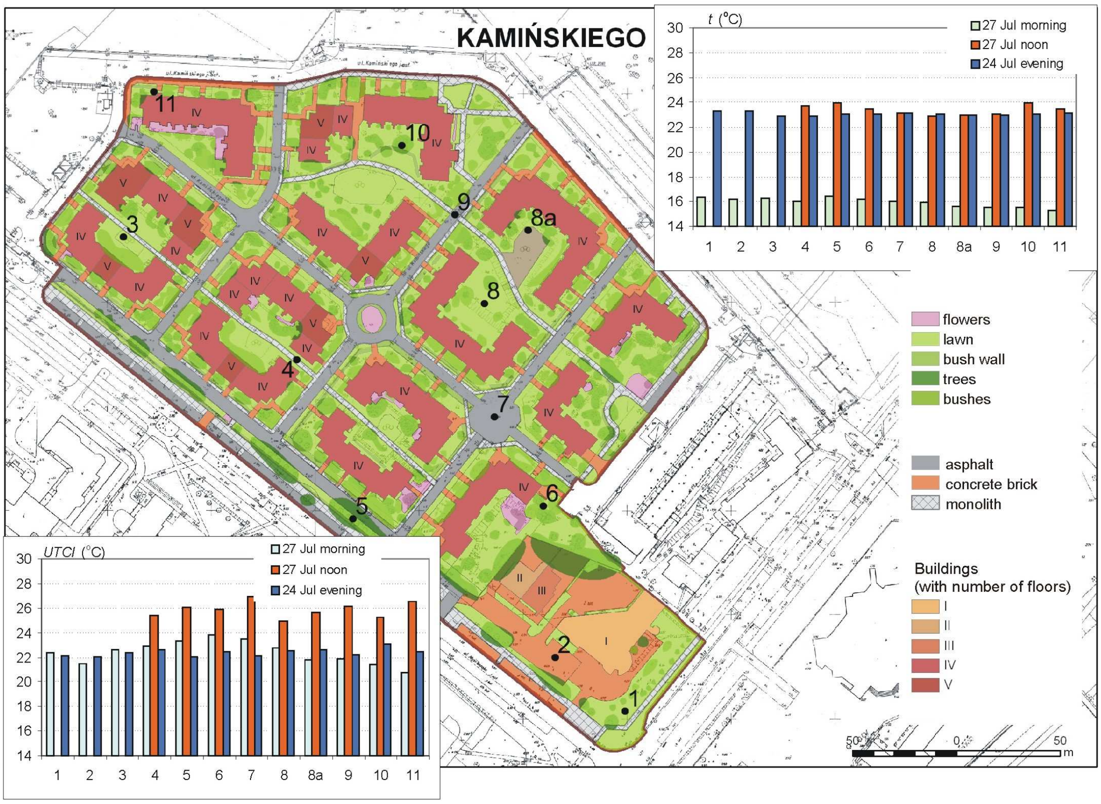

Fig. 8. Schematic map of Kaminskiego housing estate in Warsaw with values of air temperature (*t*) and Universal Thermal Climate Index (*UTCI*) in particular sites inside quarter
Source: M. Kuchcik own data

Włodarzewska estate

In the dense built area there is no evidence for the cooling effect of small green areas, especially during midday hours. Even more, the air above the small flowerbed adjacent to the building could be hotter (measure post 6) then above the concrete square (5, 6a). Because of the high brick wall fencing the estate – there is also no evidence for the cooling effect of neighboring big park. In the whole area very weak and chaotic air movement is noted. The south-east part of estate is under the influence of the fertile lawn and residuals of meadow, which is exposed to the sun and getting warm quickly during the day and getting cold rapidly in the evening. This produces stressful bio-thermal conditions because of great heat load in the day and cold stress in the evenings (Fig. 9).

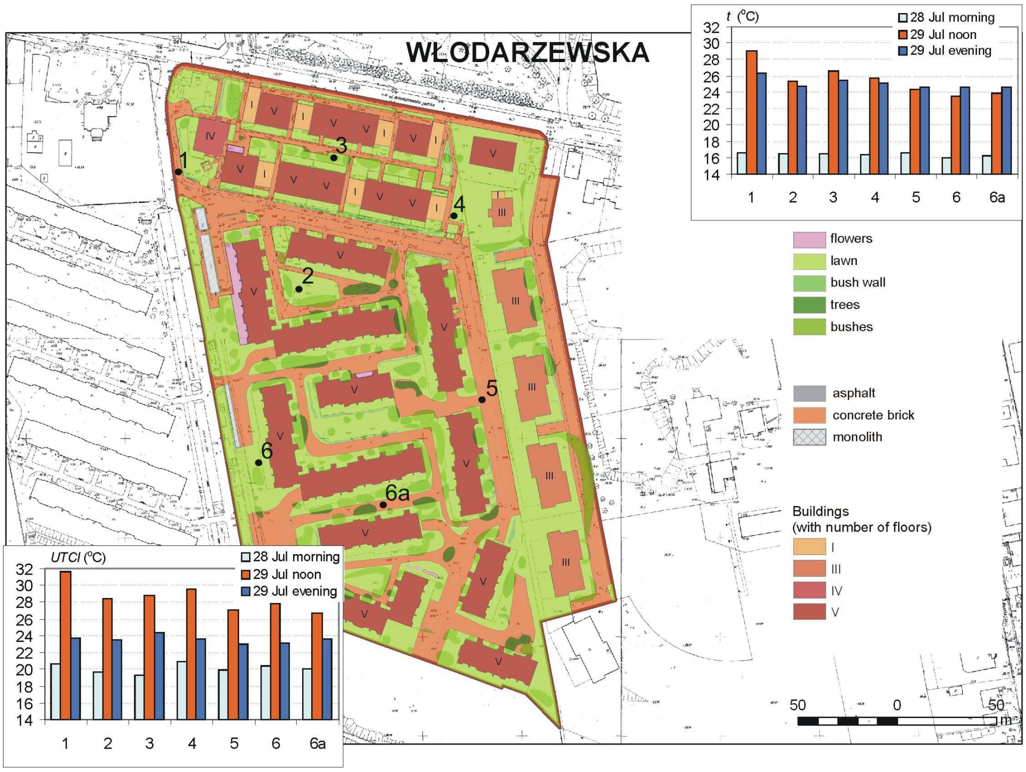

Fig. 9. Schematic map of Wlodarzewska housing estate in Warsaw with values of air temperature (*t*) and Universal Thermal Climate Index (*UTCI*) in particular sites inside quarter
Source: M. Kuchcik own data

Conclusions

Cities are life's environment for majority of Polish population. Living in the cities brings a lot of advantages (e.g. wide job market, easy access to education and culture). However, urban environment makes many charges. One of them is specific climate conditions. Important feature of urban climate are stressful bio-thermal conditions. They can be represented by sensible temperature indices. One of them is new developed Universal Thermal Climate Index (*UTCI*).

The mostly known feature of climate and bioclimate of cities is urban heat island (UHI). It is demonstrated both, by increased air and sensible temperatures. This mark of urban climate is well seen in various spatial scales. In regional scale only very schematic picture of UHI can be considered. However, not only large cities but also small towns and even big villages can be identify on temperature maps. In urban scale the picture of air and sensible temperature differentiation shows specificity of various city structures. We can watch what air temperature and *UTCI* is typical for downtown and industrial areas, forest, parks, various types of settled areas etc.

The most detail level of spatial analysis refers to individual housing estates. When comparing two studied estates we can conclude that: - the array of buildings enabled the advection of air from outside and in effect improve sensible climate; - very important is the proper maintenance of green areas: abandoned, dried lawns or only recumbent coniferous plants do not positively meliorate climate and bioclimate; - gardens next to the buildings should be sufficiently large and composed of different height leafy trees, bushes and perennials; - small flowerbeds adjacent to the buildings do not play any positive role for bio-thermal conditions; - when fencing the estates people should prefer rather openwork, metallic fencing than high brick walls which unable infiltration of the air from outside.

The results of research discussed in the paper allow to propose the following, general model of bio-thermal conditions within urbanized areas (Fig. 10). Spatial differentiation of sensible temperature is indicated for midday as well as for night hours.

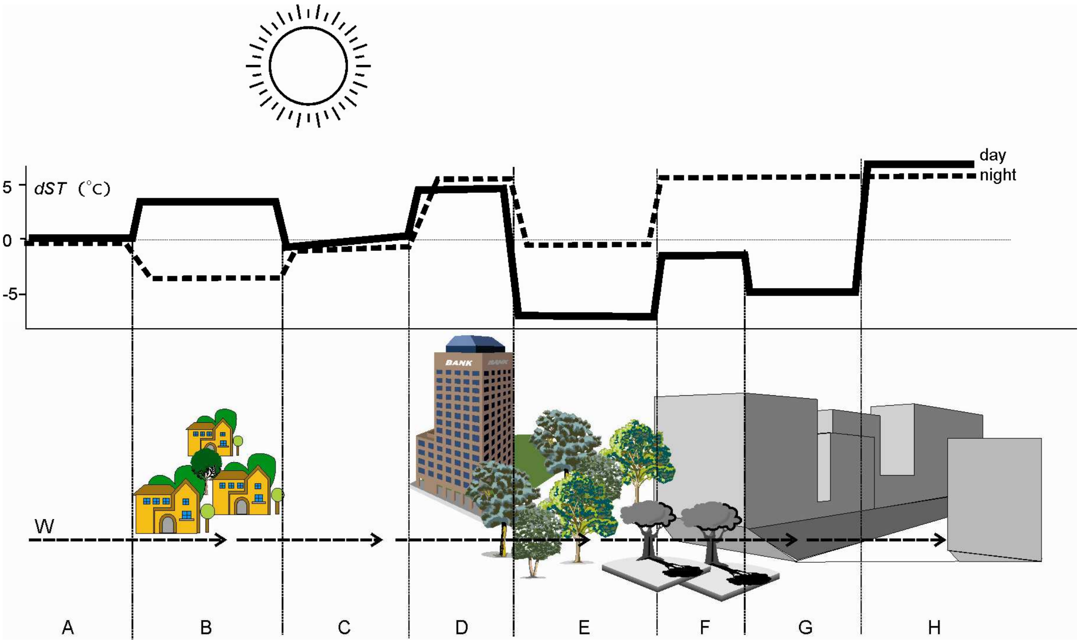

Fig. 10. The general model of bio-thermal conditions of urbanised areas; *dST* – shows relative values of sensible temperature (in comparison to rural area) during day and night hours along the profile W; A – rural area, B – suburban residential district, C – open areas inside the city, D – „block" settlements, E – park, F – trees-shaded streets, G – shaded street canyon, H – insolated street canyon
Source: Blazejczyk, Kunert, 2006

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