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Complex evaluation of the human-bioclimatological conditions of urban public spaces in Szeged and the potentials of such assessments in the urban area design

Summary of the PhD thesis

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1. OBJECTIVES

Due to the rapid urbanization, more than half of the world's population lives and works in urban areas nowadays. The expansion of cities involves the fact that an increasing proportion of the population is exposed to the loads of the urban environment, and especially to the impacts of urban atmosphere. This latter mainly can be attributed to the use of artificial materials with large heat capacity, the air pollution and heat emission in association with anthropogenic activities (such as traffic, industry or overuse of heating and air-conditioning devices), as well as the limited ventilation of urban areas. The heat stress caused by the altered physical properties of the urban environment, the air pollution, the noise, the accelerated life style and the stress may develop health problems on a long-term basis. However, the short-term exposure also influences the way of living by impairing our performance and the everyday comfort. The present tendencies in global climate change predict further increase in the surface temperature and in the frequency of extreme meteorological events. These trends may also worsen the present urban and microclimatological issues.

Paying attention to the health and general conditions of people living or working in cities and reducing the stress should be an especially important task for the urban area design and development. This requires the physiological assessment of the effects of the urban environment on the inhabitants. Both in Hungary and in other countries, urban planners usually prefer aesthetical design to the practical urban structure or the well-balanced human comfort conditions. However, during the urban area development, an emphasised consideration of the factors related to the human thermal sensation and the so-called thermal comfort could have a more pronounced impact on the quality of inhabitants than the spectacular design. In this intention, valuable support is expected from the human-bioclimatological studies focusing on the meteorological, climatological and air quality conditions of the urban atmosphere. The main objective of these investigations is to estimate the effects of the altered climatic conditions of urban areas on the inhabitants and to define the optimal climatic parameters for them. These studies should also provide guidelines to the urban planners as well as to the decision makers how they can establish a more sustainable and comfortable urban environment by using sensible strategies, choosing appropriate materials, and extending the planted urban areas.

The major motivation during my PhD work was to contribute to a clear human-bioclimatological methodology which can be used in the practice of public area design and pays special attention to the comfort and life quality of the inhabitants, contrary to the 'aesthetics-based' design. Further expectations toward such an approach are to provide relevant predictions for the upcoming climatic trends and to offer solutions to the present and future issues, instead of only calling the attention to them. Another important aim of my work was to join to the wide-spread international heat stress and thermal comfort studies related to open-air spaces.

Accordingly, the following objectives were set in the present dissertation:

- to present a brief outline on the human bioclimatology and to review the results of the most relevant Hungarian and international studies,
- to give a extensive overview about our human-bioclimatological project in Szeged, in the frame of which local public areas and their thermal conditions have been evaluated comprehensively for several years, and into which my personal research have been integrated,
- to characterise the thermal load in local public areas quantitatively, and to reveal the extend of the micro-bioclimatological altering effects due to the design of the areas,
- to demonstrate the spatial and temporal changes of the thermal conditions in details by means of two internationally acknowledged micro-bioclimatological models,
- to assess the reliability of the models, to evaluate their advantages, disadvantages and potential in the urban design,
- to investigate how the thermal conditions of an exemplary public area influence the temporal and spatial patterns of the area usage and the behavioural reactions of the visitors,
- to evaluate the subjective opinions of the visitors about the area design,
- to provide environmentally and climatologically conscious suggestions in order to reduce the thermal load occurring in urban areas,
- to promote a new approach for urban planning and to provide a planning guide which could optimise the open-air comfort conditions based on a comprehensive study on public areas.

2. METHODS

In the frame of a long-term project initiated by the urban climate workgroup of the Department of Climatology and Landscape Ecology (University of Szeged), local public areas with different surface morphology and function have been investigated since the spring of 2008. I joined to this complex human-bioclimatological research and performed a detailed evaluation of the investigated areas. The study involved two phases, each based on distinct methodologies. The present thesis will however discuss only the results based on the second phase. In the second phase (2011 to 2012), six areas of the city centre were evaluated: one with tree vegetation (‘Széchenyi tér’), two with overwhelmingly artificial coverage (‘Dugonics tér’ and ‘Szt. István tér’), one playground with significant vegetation (‘Honvéd tér’), another playground with less vegetation (‘Retek utca’), and a walking street covered by red pavement (‘Kárász utca’). The mapping of the investigated areas from the aspects of the natural and artificial objects as well as the surface coverage was followed by on-site human-bioclimatological measurements.

The on-site data collection was carried out in 5 to 7 weeks long phases in the spring, summer and autumn of the project years 2011 and 2012. These measurements followed two main methodologies. During the *environmental monitoring*, **micro-meteorological parameters** determining the thermal comfort (such as air temperature, T_a, relative humidity, RH, wind speed, v, and short- and long-wave radiation fluxes from the 3D environment, K_i and L_i) were **measured on-site**. Climatological data were registered by two mobile urban meteorological stations (UMS) at a height of 1.1 m, as set by the human-bioclimatological guidelines. One of the stations was located in the shade (UMS1), while the other station was exposed to the sun (UMS2). Due to the lack of shading, this concept could not be followed in case of one square (‘Szt. István tér’), where the two stations were placed at two positions with different surface coverage (grass and pavement). During the data processing, the mean radiation temperature, T_{mrt}, characterising the complex thermal effects of the radiation conditions, and the physiologically equivalent temperature, PET, describing the thermal load on the human body were calculated.

Simultaneously with the on-site measurement of the thermal parameters, a *human monitoring* was carried out, in the frame of which the characteristics of the area usage of the visitors, their subjective reactions and opinions were collected. During the **hidden observations**, the total attendances of the investigated areas as well as the sun exposure of the visitors were registered, and their positions were mapped. This part was complemented by **questionnaire surveys** in order to understand the human reactions to the thermal conditions and to the structures of the areas better. Beside the subjective evaluation of the thermal environment, the guided conversations with the visitors also had the aim to assess, how comfortable the visitors find the public area, how the design of the area satisfies them, and what structural changes they would welcome.

To introduce another objective methodology, the on-site measurements were later accompanied by the **simulation of the micro-bioclimatological parameters** by means of the open-access models *RayMan* and *ENVI-met*. This allowed the micro-bioclimatological characterisation of the entire investigated areas instead of evaluating them at single positions where the measurements were carried out. Due to the limited scope of the dissertation, the simulation-related findings will be discussed in the frame of a case study (one of the two investigated playgrounds, 'Retek utca'). The input meteorological data required for the modelling were obtained from the database of the meteorological station of the Hungarian Meteorological Service (HMS), located in the suburb of Szeged. The 3D model environment of the investigated area was built up based on the data obtained by the preliminary mapping of the objects (buildings and vegetation), and the parameters of the different types of surface coverage were also used in case of the ENVI-met model. From the output of the model, micro-scale maps were constructed, which demonstrate the area-specific spatial patterns of the microclimatological parameters (T_a, RH, v, T_{mrt}) and the derived PET values (thermal stress) for different times. To evaluate the reliability of the simulations, the time courses of the modelled and on-site measured T_{mrt} and PET values were compared.

10-minute averages of the **meteorological background parameters** during the on-site measurements (such as air temperature, relative humidity, wind speed, and global radiation) were also used as obtained from the database of the meteorological station of the HMS, Szeged. T_{mrt} was in this latter case calculated by RayMan using the data of the global radiation to substitute the lacking parameters from the 3D radiation environment (K_i, L_i). Before calculating the PET values by means of RayMan, the wind speed referenced to a height of 10 m was reduced to 1.1 m.

The following software products were used for the evaluation of the data, for the statistical analyses and for the representation of the results: *Microsoft Excel*, *SPSS Statistics 20*, *Surfer 8.0*, *ESRI ArcView GIS 3.3*, and *CorelDRAW X3*.

3. RESULTS AND CONCLUSIONS

New scientific results

1. Based on the observations of the objective evaluations, it was shown that the **characteristics of the surface design** (such as shading, surface coverage, ventilation) **have more significant influence on the course of the physiologically equivalent temperature (PET) than the air temperature (T_a)**. The more pronounced temporal and spatial variance of the PET values was also confirmed by the on-site measurements and the results of the micro-bioclimatological simulations.

1.a Based on the difference between the *micro-bioclimatological parameters measured* at various positions and the corresponding (suburban) meteorological background parameters provided by the HMS, it was shown that the differences between the T_a values and the corresponding background air temperature values only rarely exceeded 3 °C (in absolute value) over the different seasons for each investigational area. The similar differences in PET values however frequently went beyond the range of ±10 °C.

1.b *Micro-bioclimatological simulations* by ENVI-met (playground 'Retek utca') revealed that the PET differences between the variously shaded and covered positions of the investigated area on a sunny day exceeded 15 °C (independently of the season), meanwhile the corresponding differences in the T_a values for the same times remained below 1 °C (*Égerházi és Gál* 2012, *Égerházi et al.* 2013a).

1.c Similar results were found by comparing the time courses of the *data measured* on cloudless days: the PET differences between the sun-exposed and shaded positions often exceeded 15 °C, whilst the average difference in the corresponding T_a values was up to 1.5 °C (*Kántor et al*. 2012).

2. Based on the data measured in the investigated public areas and the results of the simulations, it was shown that **certain area designs can modify the bioclimate systematically**.

2.a *Measurements* proved a human-bioclimatological loading effect in summer for the red **pavement**, compared to that of the near natural grassy surface coverage. This was confirmed by the fact that PET values belonging to the category of extreme heat stress occurred by 9.5% greater frequency for the red-paved area, meanwhile slight thermal load was registered there by 2.1% less frequency. The *model results by ENVI-met* (as run on the investigated playground 'Retek utca') also supported the unfavourable effects of the artificial coverage, since PET values belonging to the extreme heat stress dominated for the cobblestone concrete covered (paved) area in summer (*Égerházi et al*. 2013c, 2014).

2.b *Measurements* revealed that **shading** may play a more significant role in reducing the summer heat load than the near-natural surface coverage. It was shown that the shading by buildings and/or vegetation may result in by up to 9 °C less warm thermal conditions on average, as compared to the reference data. Beside this observation, measurement results (for the playground 'Retek utca') confirmed that the thermal conditions expressed in the levels of physiological loading were often by 2 to 3 categories less warm in the shaded areas, than at the sun-exposed locations (*Kántor et al*. 2012).

2.c *Measurements* revealed that in all the three investigated seasons, the **closed surface design** surrounded by buildings and/or vegetation and the **surface coverage by light gravel with high-albedo** together lead to average PET values in the directly sun-exposed areas by 6 to 8 °C greater than the suburban background data provided by the HMS.

3. It was proven that **the meteorological background influences the extend of the spatial micro-bioclimatological differences significantly**.

3.a *Measurements* and *model results* for early spring days revealed that an intensive airflow not only has a cooling effect on the thermal conditions, but also acts as a micro-climate balancing factor. This observation was mainly reflected by the relatively small differences between the (measured or modelled) air temperature values for different positions of the site.

3.b The greatest spatial variability in both the *measured* and the *modelled* thermal conditions occurred on sunny (and windless) days.

4. The radiation parameter was found to be that determining factor out of the thermal parameters, whose variation is obviously responsible for the most pronounced (temporal and spatial) **differences in the PET values**.

4.a Simultaneous investigations on the PET values obtained from the *on-site measurements* and on the diurnal course of the global radiation proved that the diurnal pattern of the PET values on days with unsteady cloud coverage markedly followed the change of the global radiation above the sunny measurement point (*Kántor et al.* 2012).

4.b At the same time the output maps of the *ENVI-met model* suggested that the thermal conditions on the investigated site had a significant spatial variability throughout the three investigated seasons, mostly in connection with the spatial pattern of the T_{mrt} values. The spatial distribution of the T_{mrt} values was in accordance with the locations and the shapes of the areas with various shading conditions or different surface coverage. In addition, the T_{mrt} values on the sites exposed to direct sunlight significantly exceeded the corresponding values in the shade (*Égerházi és Gál* 2012, *Égerházi et al.* 2013a).

5. On-site measurements and simulation results both supported that **the modifying effects of the area design on the micro-bioclimatic conditions may be considered to be pleasant or unpleasant depending on the season and the meteorological background conditions**.

5.a The *on-site measurement* based evaluations of the investigated areas revealed that the **shading**, which aims the reduction of the T_{mrt} values and thereby the PET values on warm and hot summer (or autumn) days, has an unquestionably positive effect by significantly reducing the heat load by direct sunlight. In the cooler transitional seasons however it may have an unfavourable effect, since in these periods it may enhance the level of cold stress. The analysis of the frequency distribution of the PET categories for different positions supported that in spring, the frequency of cold stress occasionally exceeded 80% in the shaded areas, while in summer (or in autumn) neutral and nearly neutral categories prevailed under such shading conditions.

5.b. *ENVI-met model results* revealed that the enhanced warming and heat emission of the **cobblestone concrete covered** (paved) **areas** under warm or hot summer conditions cause strong or extreme thermal stress on the visitors (*Égerházi et al*. 2013c, 2014). The thermal stress under cooler meteorological conditions (in spring) is here however practically negligible.

6. The *observations* on the attendance of the playground 'Retek utca' suggested that **beside the thermal conditions, other subjective factors also affect the temporal and spatial patterns of the public area usage**.

6.a. **Beside the thermal conditions, the diurnal cycle** (such as lunch break or the end of business hours) **of the visitors' activity had a significant effect on the temporal visitation pattern.** On days with strong heat load (such as on cloudless 'heat days'), a drastic reduction characterised the diurnal course of attendance around midday, and the usage of the shaded areas was more pronounced at these times. The increase in attendance after 4 p.m. could mainly be attributed to the end of the working time of the parents, who brought their children to the playground (*Kántor et al.* 2012). On days with calmer meteorological conditions (such as on summer days with changing cloud coverage), both the number of visitors and the attendance of the sun-exposed areas were significantly greater. On cooler spring days, the visitors again rather preferred the sun-exposed parts of the area.

6.b. The comparison of the area usage maps with the thermal stress maps obtained by RayMan revealed that beside the spatial variety of the thermal conditions, the **different preference of the various items of the playground equipment also significantly affected the spatial pattern of the area usage**. Thereby the children at the playground utilised the investigated area not necessarily according to the logical human reactions, i.e. they often stayed in such parts of the area, where their body was exposed to an extreme thermal load (*Égerházi et al*. 2013b, *Égerházi et al.* 2013c).

7. Based on the *survey results*, more than 70% of the visitors considered the playground 'Retek utca' definitely pleasant. The visitors **mostly acknowledged the quality of the playground equipment and the safety of the playground due to the fences**. Around 60% of the people asked mentioned no negative experience in connection with the playground. 17% of the interviewees considered it as a **general problem that the shading is not satisfactory**, and some of them emphasised their negative experiences regarding the surface coverage. As a suggested change, most of the interviewees mentioned that trees should be planted and artificial sun shields should be installed. These suggestions were in harmony with the facts they mentioned among the shortcomings of the playground (*Égerházi et al*. 2013c, 2014)

Results in connection with the practical applications of the human-bioclimatological investigations

8. A methodology was elaborated through which the human-bioclimatological investigations (including the environmental monitoring and the human monitoring) **could be integrated into the sub processes of the urban area development.** The steps of the provided guide will hopefully help fulfilling the needs of the inhabitants during the public area design in the future.

9. In order to help the practical application of the micro-bioclimatic modelling software products, a new utilization was elaborated for **the RayMan model, which normally provides point-like output.** Running the model on the grid points of a grid of arbitrary resolution allowed simulating the T_{mrt} and PET values over a whole area (*Égerházi et al*. 2012, *Égerházi et al.* 2014).

10. In order to promote the integration of the models in the practice of the urban area development, **the outputs of the RayMan and ENVI-met simulations were compared, their reliability was evaluated, and the main advantages and disadvantages of the two models were summarised in form of a practical guide**, which highlights the potentials of the individual software products for the practical applications (*Égerházi et al*. 2014).

10.a The comparison of the *heat stress maps by ENVI-met and RayMan* supported that both models are capable to illustrate the diurnal changes in the spatial pattern of the thermal conditions, as well as the modifying effect of the buildings and the vegetation on the PET values. It was however observed that while RayMan predicted differences of 2 stress category levels between the differently shaded or covered points of the area, this difference was 3 to 5 levels in case of ENVI-met. Thereby the heat stress maps by ENVI-met were relatively uneven, as compared to the more homogeneous maps by RayMan. This could be explained by the facts that different spatial resolutions were used for the two types of simulations, and the same input meteorological data were applied to all the model points of the RayMan simulations, while the input data for ENVI-met simulations were position dependent. Beside these two reasons, out of the two models only ENVI-met is capable to take into account the thermal effect of the surface coverage (*Égerházi et al*. 2014).

10.b The analysis of the *reliability of the models* proved a statistically significant difference between the pairs of measured and modelled PET values for both simulation software products. ENVI-met was found to significantly underestimate the T_{mrt} and thereby the PET values both for the shaded and the sun-exposed areas. The average underestimation for the positions in the shade and exposed to the sun was 9 °C and 11 °C (in PET), respectively. This pronounced deviation can be attributed to the fact that ENVI-met simulates all the fundamental parameters used for calculating the PET values. Contrary to the ENVI-met simulation results, RayMan predicted PET values for the positions in the shade and exposed to the sun only by 1.5 °C and 9 °C less than the corresponding measured values, respectively. The significant difference between the accuracy of the RayMan based estimations for the shaded and sun-exposed positions can be reasoned by the following. Due to the lack of the direct sunshine, the reflected short-wave radiation and the warming up of the surface is not enough to notably affect the T_{mrt} and PET values in the shade. However in the areas exposed to the sun, the effect of the surface coverage is much more pronounced, and since RayMan is not able to take this factor into account, the difference between the measured and the modelled values will be greater here. As a conclusion, if RayMan could provide a satisfying estimation for the thermal behavior of not only the field objects but also of the surface coverage, then probably acceptable results could be obtained by this model for the whole investigated area (*Égerházi et al.* 2014).

11. Based on the investigation results and experiences, the most urgent task in connection with public area design proved to be the reduction of the summer heat stress by such solutions, which do not impair the thermal comfort of the visitors even on the cooler days of the transitional seasons. Based on the practice of the urban climatology and urban human-bioclimatology, **a summary of the most relevant actions for heat stress reduction was provided** with the emphasis on the favourable effect of natural and artificial shading and the importance of the reasonable choice of the surface coverage and the street equipment (*Kántor et al*. 2012).

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