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Heat vulnerability digital mapping at neighbourhood level in the compact city

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Heat vulnerability digital mapping at neighbourhood level in the compact city

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Abstract. This paper analyses the impact of urban form and vegetation on one of the most significant parameters that affect people's thermal comfort and an indicator of urban heat vulnerability: the mean radiant temperature (MRT). To obtain spatialized results and understand in detail the current thermal situation of different public spaces that are part of the city, we combined the SOLWEIG calculation model included in the *UMEP* tool for *QGIS* with *Urban Weather Generator* for Rhino. Six neighbourhoods of Rome (IT) and the associated areas with typical compact urban forms, ranging from historical centre to modern suburbs, have been analysed in the warmest week of the year (August 03-09) during the most critical hours of the day (10 a.m. - 4 p.m.). Georeferenced maps with the mean values of MRT for the studied period allow us to analyse the thermal behaviour of each public square and neighbourhood and locate possible urban havens during heatwaves. This study is part of a larger work that seeks to define a more accurate approach to quantify heat vulnerability within the urban vulnerability indexes, in light of the climate crisis facing cities.

1. Introduction

Urban Heat Vulnerability (HV) has been widely investigated in light of the urgency to adapt and mitigate climate change impacts on inhabitants and the built environment. An increasing number of methods - and associated indicators – based mostly on statistical data have been developed in recent years [1-6]. For these reasons, a relevant number of studies use the census-tract level for HV assessment, due to the need to find accessible data and calculate the demographic, socioeconomic and environmental indicators constraining the modelling [7]. Nonetheless, the selection of heat-related environmental indicators is mostly statistical, geographical or climate-based and cannot describe the HV with the expected accuracy.

This paper is the first-step of a broader study that aims at proposing and testing a novel approach in the evaluation of HV, including a combination of environmental indicators for a more precise assessment of thermal and environmental conditions in urban spaces of the compact city. Here, we discuss and analyse the possibility of using Mean Radiant Temperature (MRT) of urban spaces at neighbourhood level in the compact city as one of these indicators. Among the microclimate variables affecting human comfort in urban spaces, MRT is suitable for multi-scale analyses of neighbourhoods and urban spaces: it offers an overview of the neighbourhoods' thermal environment and a high-resolution spatial variation in urban spaces [8]. A practical digital workflow is presented and tested. The aim is twofold: to integrate HV in the urban vulnerability definition and to map it both at neighbourhood and local levels; to identify spatial key performance indicators able to describe the environmental performances. Incorporating MRT into these analyses permits a more nuanced and spatial understanding of the complex interactions between physical and social factors that contribute to HV in urban areas.

2. Method

The study focuses on six neighbourhoods of Rome (IT), taken as a reference model of typical urban geometries of compact cities, ranging from historical city centre to the late XX Century peripheral areas (Figure 1). The Municipal area has been divided into cells and morphologically-uniform urban textures have been highlighted. Within the textures, one urban square per each has been identified for a detailed analysis of environmental simulations. Figure 2 shows the digital workflow used in the study.

The physical models of the case studies have been developed with QGIS by combining shapefiles and raster files from different sources: buildings, topography, land use, trees, etc. [9–11]. Next, the model has been imported into a 3D Rhino environment, by means of an automatic importation of shapefiles of buildings, trees and green areas with the Grasshopper (GH) plugin Urbano [12]. This phase has been conducted for the spatial metrics calculation and urban heat island (UHI) assessment for each area, using the Urban Weather Generator in GH, starting from the closest rural EPW file containing hourly climate data related to *Rome Ciampino* Airport weather station (EnergyPlus weather data repository, 162390 IGDG). To create the climate models and new EPW files influenced by the impact of UHI, in addition to geometry parameters, specific input parameters for each area have been inserted: building construction, window to wall ratio, vegetation, anthropogenic heat [13,14].

Afterwards, we proceeded to the climate analysis mapping of each case at the neighbourhood scale and focusing on pedestrian thermal comfort in public squares through MRT and UTCI. The SOLWEIG calculation model, included in the QGIS open-source plugin UMEP tool has been used for this purpose [15, 16].

Q	GSI[1]	FSI[2]	Green space index[3]	Tree coverage index[4]
1	0.57	3.32	0.003	0.009
2	0.31	2.01	0.035	0.028
3	0.24	0.97	0.165	0.191
4	0.22	0.98	0.065	0.136
5	0.26	1.18	0.024	0.075
6	0.12	0.42	0.237	0.056

The four metrics are expressed as the ratio between four different areas and the neighbourhood area: 1 – footprint; 2 – gross floor area; 3 – green area; 4 – tree coverage.

Figure 1. Location and associated urban metrics of the analysed neighbourhoods in Rome.

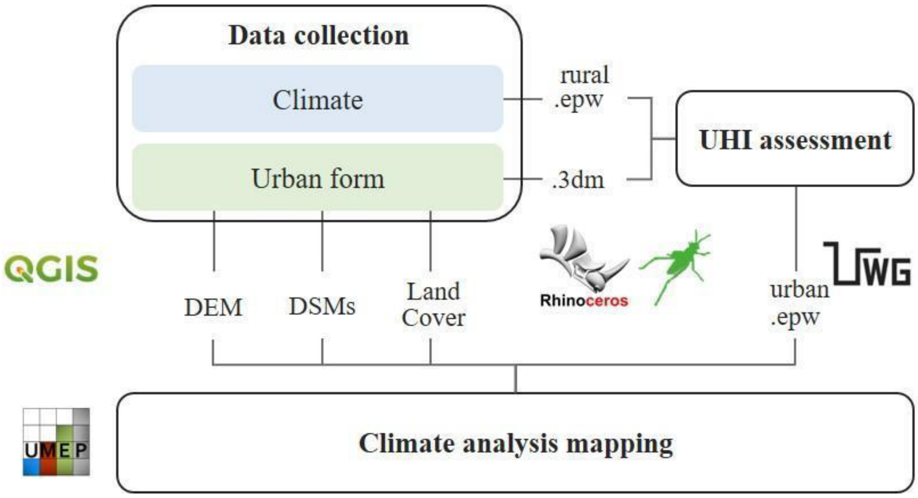

Figure 2. Digital workflow chart.

Firstly, we created a DEM (Digital Elevation Model) of the terrain from the contour elevation data. The DEM is made using the QGIS GRASS tool, resulting in a raster with a resolution of 1 pixel = 1 m and dimensions of 750 m x 750 m. After creating the DEM, other rasters necessary for UMEP simulation have been produced: DSM (Digital Surface Model): Terrain elevation, buildings footprint and height; CDSM and TDSM (Canopy Digital Surface Model and Trunk Digital Surface Model): vegetation data (trees); Land Cover: urban land covers data (paved surfaces, buildings, lawn, water, etc.). In the next step, we calculated the Sky View Factor (SVF) with the UMEP SVF calculator tool by utilising the DSM together with the vegetation rasters (CDSM, TDSM). This process produced a SVF raster with a 1m resolution. Then, we processed the different raster data in the SOLWEIG tool to generate a new set of rasters with MRT data, and to calculate the mean values of the UTCI thermal comfort index [17] of the different public squares (using a grid of points). Finally, to obtain and analyse the different values of MRT, we used an analysis through the Zonal Statistics and Raster layer histogram tool of QGIS.

3. Results and discussion

The results of this study are twofold. On the one hand, analysing the thermal environment of neighbourhoods and, in particular, their typical urban squares. On the other hand, understanding potentialities and constraints of the proposed calculation model for the description of neighbourhoods' microclimates against the statistical model. Table 1 shows the average UTCI values of the analysed public squares. These values correspond to the week of August 3 to 9 and a schedule from 10 a.m. to 4 p.m. The mean value (*mean*) of all the public squares surface is within the UTCI range of strong heat stress (between +32.7 and +34.8). However, when looking at the mean maximum values (*m_max*), they fall within the very strong heat stress range (between +39.7 and +41.3). Even though the public squares have similar UTCI values, we can see the differences if they are spatially analysed (MRT maps, Figure 3). The squares present different thermal performance due to the urban fabrics in which they are found, and the presence or absence of vegetation or fountains.

Table 1. Public squares UTCI mean values (week 03-09/August 10 a.m. - 4 p.m.)

Public square	m_min	mean	m_max
Navona (Q1)	22.69	34.20	41.31
S. Giovanni Bosco (Q2)	22.58	33.53	40.13
Testaccio (Q3)	22.08	32.73	39.79
Damiano Sauli (Q4)	23.27	33.95	40.32
Teofrasto (Q5)	23.74	34.75	40.76
Arquata del Tronto (Q6)	23.37	34.21	40.68

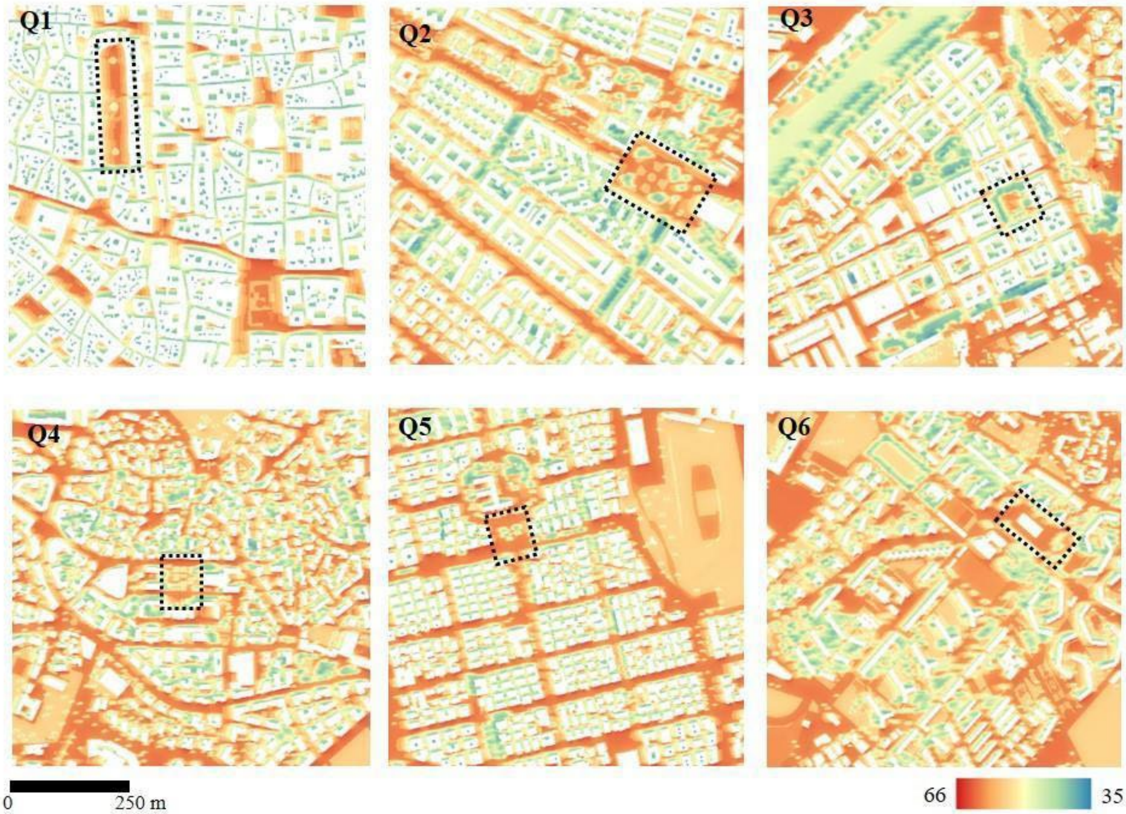

Figure 3. Maps with the mean values of daily MRT (week 03-09/August 10 a.m. - 4 p.m.)

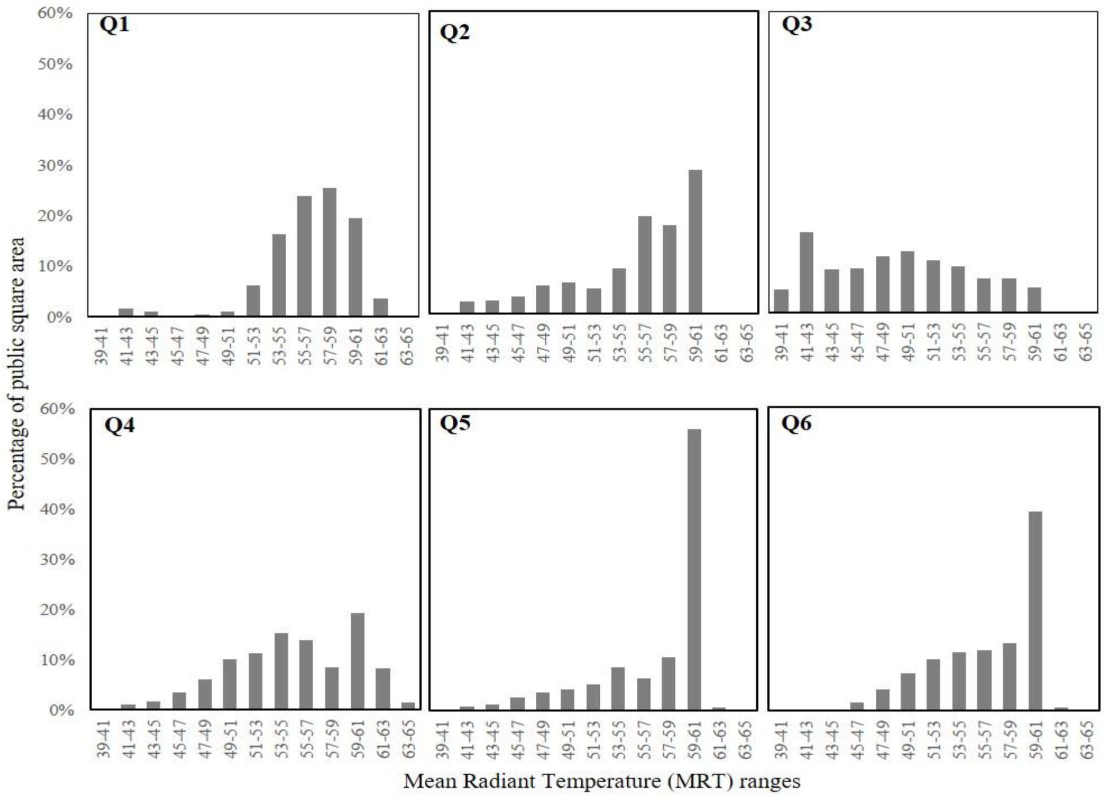

Figure 4. Histograms of the mean values of daily MRT (03-09/August 10 a.m. - 4 p.m.)

Figures 3 and 4 show the results of the UMEP-SOLWEIG MRT simulation for the cases analysed. The maps in Figure 3 allow us to quickly see the areas with the lowest and highest temperatures in each public square, and therefore, the coolest places in summer conditions. In addition, even though a deep analysis of the thermal environment of the selected neighbourhoods lies outside the scope of this study, it is worth emphasizing that the proposed approach can lead to understand the relationship between urban characteristics and neighbourhood HV. By analysing the digital maps in relation to the census-tracts it is possible to enrich the spatial definition of urban vulnerability at high resolution. Moreover, in Figure 4, we analyse the MRT values of each public square by dividing them into two-degrees temperature ranges (from 39 to 65°C). In turn, each of these ranges corresponds to a percentage of the area of the square.

Considering the range 51-53°C as a midpoint, Piazza Testaccio (Q3) has the highest percentage of surface area with a lower MRT (61.7%). Piazza Testaccio is followed by the plazas Damiano Sauli (Q4, 22.2%), San Giovanni Bosco (Q2, 20.4%), Arquata del Tronto (Q6, 13%), Teofrasto (Q5, 12.2%) and Navona (Q1, 4.8%). The public squares located in neighbourhoods with porous urban form (lower *Compactness* also known as *Ground Space Index*, i.e. *footprint/urban area* ratio) present large percentages of area with a high MRT. Plazas Q5 and Q6 with 56.7% and 40% of their surface with a MRT higher than 59°C are an example of this type of urban morphology, and are followed by Q4 (28.9%) and Q2 (28.7%). However, the squares located in more compact urban fabrics i.e., Q1 and Q3, have cooler thermal environments thanks to shading produced by urban forms. In Q1, 23.2% of its surface exceeds 59°C of MRT, and in Q3 only 4.9% of its surface exceeds it. This difference is mainly due to two formal aspects: the configuration of Piazza Navona (elongated from North to South), and the trees presence in Piazza Testaccio.

This method allows for obtaining qualitative (spatialized MRT values) and quantitative (numerical MRT values) results of large urban areas (1 km^2) using computers with regular processing power. Therefore, it is possible to analyse one of the most significant environmental parameters for the thermal comfort of people [18] and one of the necessary indicators to evaluate neighbourhood HV.

The proposed modelling approach requires a large amount of georeferenced data (DEM, DSM, CDSM, landcovers). A large number of cities lack this type of information, or it is not open data. Therefore, collecting and processing this type of data takes a significant amount of time. However, the method allows analysing large models (1000 x 1000 pixels / 1000 x 1000 m) with high resolution MRT maps in a shorter time than other calculation methods, thus allowing the analysis of large urban areas. Though, some limitations when compared to similar tools appear. To name a few, the urban model uses an average albedo or emissivity value, the minimum calculation time resolution is one hour, and global radiation is a necessary input for the calculations. Nevertheless, UMEP is an open-source tool constantly updated that works with georeferenced open data (an advantage over others). This work will allow us to establish guidelines for evaluating heat vulnerability in public spaces. In this study, we only considered formal urban aspects and climate data. However, in the work that we are developing, it is necessary to take into account other elements such as population data, economics, construction, etc.

4. Conclusions

In this paper we described and tested a digital workflow to integrate HV in the urban vulnerability definition and to map it both at neighbourhood and local levels. Indeed, we spatially situated a crucial heat-vulnerability indicator (MRT) at neighbourhood and urban space level, considering six neighbourhoods of Rome (IT), taken as a reference model of typical urban geometries of compact cities. Moreover, the proposed workflow is a substantial first step to identify potential areas for further research and intervention, defining local-oriented policies and transformation actions with the aim to counteract HV within the neighbourhoods and to improve thermal comfort, urban health, inhabitants' well-being, and resilience to global warming, heat waves, and UHI increase.

The analysis of the urban spaces at the local level identifies a network of urban havens in support of densely-populated neighbourhoods, the most exposed to climate change. These results demonstrate the potential to include HV assessment in the spatial-based urban vulnerability analysis and increase the results' resolution. The environmental and thermal quality of neighbourhoods and urban spaces have received little attention in this kind of analysis but are crucial for urban quality and climate resilience, together with demographic, social, and economic aspects.

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