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Assessment of Different Methodologies for Mapping Urban Heat Vulnerability for Milan, Italy

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Abstract. *Aims:* To compare methodologies for calculating vulnerability index of Milan city and find correlation between the main components influencing vulnerability.
Methodology: At-satellite brightness temperatures were used to study exposure of city districts to Urban Heat Island. The distribution of vulnerable population (people younger than 14 and older than 65) was also taken into account by producing a map, which showed sensitivity indices for each city district. Adaptive capacity was represented as a complex set of sub-indicators such as health care accessibility, level of living conditions and vegetation cover. Exposure, sensitivity and adaptive capacity – main indicators of vulnerability – were used to obtain five different maps, which could identify districts more vulnerable to the Urban Heat Island. Collected data showed correlations between factors influencing vulnerability.
Results: All formulas except one show similar vulnerability index distributions. Correlation graphs showed direct proportionality with exposure, very low correlation with sensitivity and indirect proportionality with adaptive capacity (except one formula which is discussed in paper).

1. Introduction

One of the impacts of climate change is the likeliness of the global occurrence of heat waves with more severity, higher frequency and for longer duration in the next decade [1]. Heat waves have adverse impacts on human health and increases the likelihood of heat-related mortality [2]. Europe has already experienced several heat wave events since 2000 (2003, 2006, 2007, 2010, 2014, 2015 and 2018). In 2003, the heat wave event resulted in up to 70,000 deaths in Europe [3].

The impacts of heat waves upon human beings are first experienced in cities [4] because around 73 percent of people in Europe are living in urban areas [5]. Over the past, increasing urbanization have increased the vulnerability of European cities to heat waves. In the future, growth and concentration of population in cities, and an ageing population contribute to further increasing the vulnerability of cities to climate change. The formation of Urban Heat Islands which is the relative warmth of a city compared to the surrounding rural areas, associated with changes in runoff, effects on heat retention, and changes in surface albedo [1] further exacerbates the vulnerable of cities to extreme heat. Several studies have provided evidence that Urban Heat Islands can lead to increased mortality risk [6]. The synergistic interaction of Urban Heat Island and climatological heat waves will lead to increase in heat stresses for urban residents [6]. The Urban Heat Island effect is increasingly affecting

cities especially in central and north-western Europe. Therefore, it is important to explore possible solutions for facing the challenge of extreme heat vulnerability in cities. European cities are generally known to have high response capacity which makes them less vulnerable to climate change impacts when compared to cities in other regions of the world but further actions may still be essential to maintain this high degree of preparedness to climate change [7]. For effectively implementing these mitigation strategies, it is important to identify which areas within the city are most vulnerable to extreme heat events. The objective of this paper is to identify and compare available formulas for urban heat vulnerability assessment.

2. Research design, materials and methodology
This paper presents an investigation on the identification of extreme heat events which includes Urban Heat Island and heat waves in cities. From a general literature review [8, 9, 10, 11, 12], it became clear that it is possible to quantitatively calculate and map the vulnerability to extreme heat events in cities using inductive methodology [8]. This study is aimed at developing heat vulnerability maps with a similar methodology.

2.1. Study Area: City of Milan, Italy
Milan (Italy) was selected as the study area as it boasts one of the highest economic outputs in Europe, promoted by rapid urban expansion which enhances the effects of extreme heat [13]. In Milan, at planning level, there are three main documents considered as points of reference in defining key objectives and strategies against climate change: the city plan *Piano di Governo del Terriotrio* (PGT), the energy city plan *Piano di Azione per l'Energia Sostenibile* (PAES) and the sustainable mobility plan *Piano Urbano della Mobilità Sostenibile* (PUMS). According to these documents, Milan has problems related to climate change for many years. As a consequence, the city suffers some environmental changes that impact daily life of people. According to PAES, heat waves in summer are a problem. With the aim of facing these issues the city of Milan has joined international projects at the bigger scale, such as 100 resilient cities (Rockefeller Foundation), C40 Megacities vs Climate Change, CLEVER Cities H2020 Nature Based Solution for social challenges, and developed specific interventions at the local scale, such as the campaign "Foresting Milan", the reconversion of rail yards into new city parks and the Human Technopole at the former expo site. For Milan, the possibility to identify critical areas and estimate the potential of nature based solutions (NBSs) or other possible actions contrasting environmental negative effects is interesting.

2.2. Calculation of Indices and Mapping of Sensitivity (S), Exposure (E) and Adaptive Capacity (AC)
Vulnerability is a complex concept. The IPCC has defined it as the propensity or predisposition to be adversely affected [14]. In terms of climate change impacts, previous studies have agreed that it is a function of three components: exposure, sensitivity and adaptive capacity [1]. This characterisation is particularly useful for designing specific mitigation and adaptation strategies with respect to specific areas within the city. Following are the representations of the three components of vulnerability [14]:

- *Exposure:* The nature and degree to which a system is exposed to significant climatic variations.
- *Sensitivity:* The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli.
- *Adaptive capacity:* The ability of a system to adjust to climate change, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

For calculating heat vulnerability, the above components were quantified using indices. These components and their representative indices are shown in Table 1 along with their descriptions. The indices are normalised and averaged to quantify each component of heat vulnerability. The selection and representation of indices for the components of heat vulnerability have been inspired by similar previous studies [15; 16].

Table 1. List of indicators for each component of urban extreme heat vulnerability.

	Indices	Descriptions
Exposure	*Urban temperature index (I_{ut})*	This index represents the normalised average temperature prevailing in a given district obtained from at-brightness temperature (Landsat 8) *Source of Data:* https://earthexplorer.usgs.gov/ *Year of Data:* 2011
Sensitivity	*Vulnerable population index (I_{vp})*	This index represents the percentage of highly vulnerable population residing in a given district. Two age groups were considered as vulnerable to urban heat: below the age of 14 and above the age of 65 *Source of Data:* http://dati.comune.milano.it/ *Year of Data:* 2011
Adaptive Capacity	*Healthcare accessibility index (I_{hca})*	This index represents the ratio of area within a given district which is within the buffer of 1 km radius around a public hospital to the total area of the given district. *Source of Data:* http://www.mi-lorenteggio.com/archivio-storico/ *Year of Data:* 2017
	Housing quality index (I_{hq})	This index represents the ratio of badly maintained houses to the total number of houses in a given district. *Source of Data:* http://dati.comune.milano.it/ *Year of Data:* 2011
	Normalised difference vegetation index (I_{NDVI})	This index quantifies the average density of plant growth on Earth in a given district. *Source of Data:* https://earthexplorer.usgs.gov/ *Year of Data:* 2011

2.3. Calculating urban heat vulnerability indices (UHVI) with five formulas
Four formulas (represented as V1, V2, V3 and V5) were obtained from literature. Table 2 enlists these formulas and their references respectively. The formula represented as V4 is a modified version of V2.

Table 2. List of formulas and their references.

	Formulas	References
V1 =	(E-AC)*S	[16]
V2 =	E*AC*S	[17]
V3 =	E-AC+S	[15]
V4 =	E*(1-AC)*S	Modified from [17]
V5 =	E*(1-AC+S)/n	[18]

3. Results

3.1. Urban heat vulnerability maps from five formulas
For each of the 87 districts in the city of Milan, the heat vulnerabilities were represented by an index (UHVI) where 0 and 1 represent closeness to low and high vulnerability respectively. The variations in the results obtained from all the five formulas can be observed from these maps.
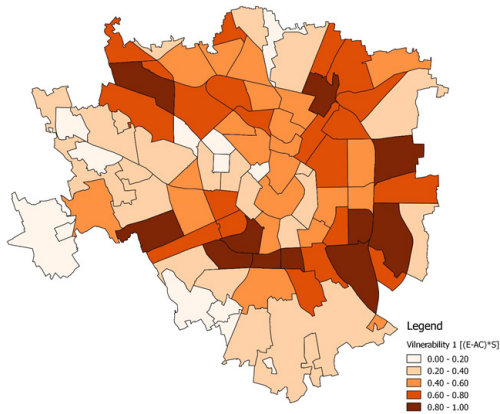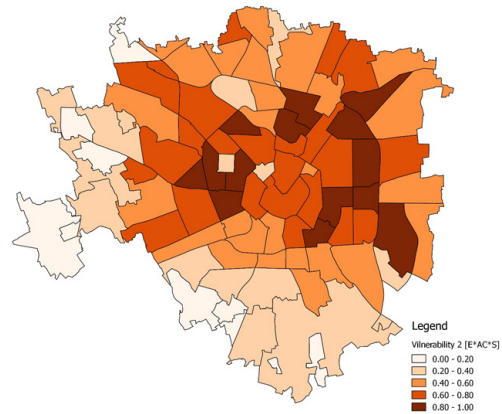
Figure 1. UHVIs obtained from V1.
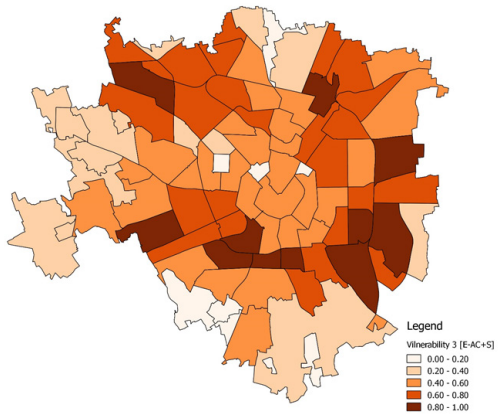

Figure 2. UHVIs obtained from V2.
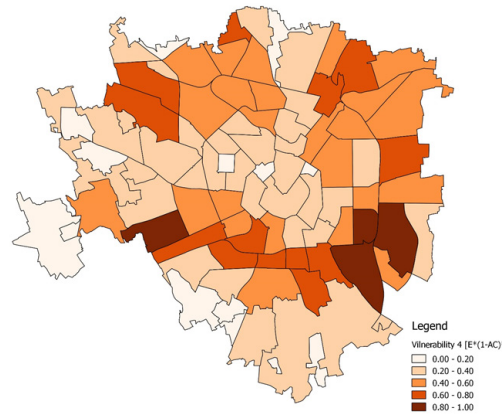

Figure 3. UHVIs obtained from V3.
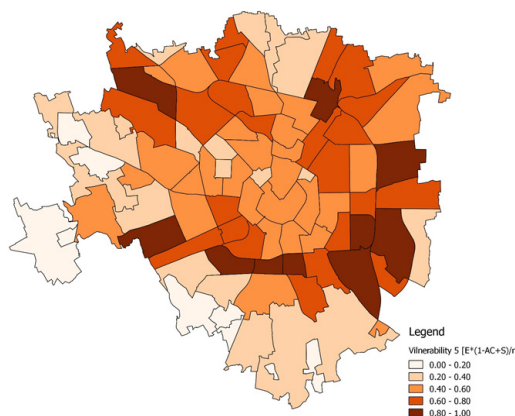

Figure 4. UHVIs obtained from V4.

Figure 5. UHVIs obtained from V5.

3.2. Correlations between heat vulnerability and its components

In order to study the relationship among sensitivity, exposure and adaptive capacity and heat vulnerability for each formula listed in Table 2, their respective correlations were calculated and plotted as shown in Figure 6–10 followed by Table 3 which presents their respective statistical correlations.
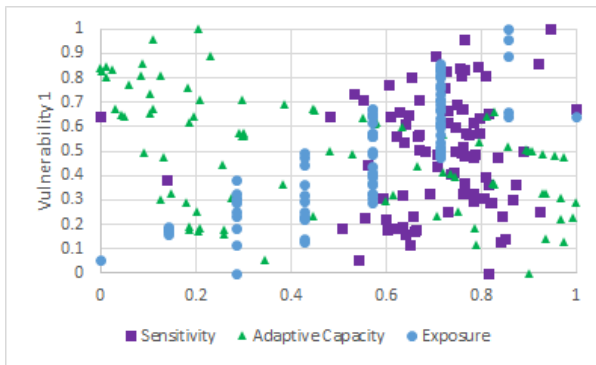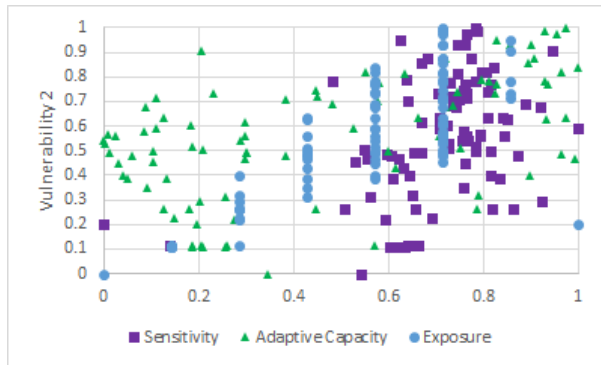
Figure 6. Correlations obtained from V1.

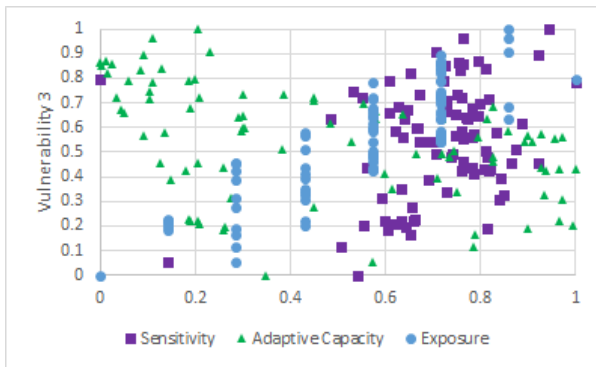**Figure 7.** Correlations obtained from V2.

Figure 8. Correlations obtained from V3.

Figure 9. Correlations obtained from V4.

Figure 10. Correlations obtained from V5.

Table 3. Statistical correlation between heat vulnerability and its components

	Sensitivity	Exposure	Adaptive Capacity
UHVI from V1	0.074968	0.827037	-0.47615
UHVI from V2	0.416999	0.764731	0.523765
UHVI from V3	0.854084	0.854084	-0.43164
UHVI from V4	0.381951	0.709084	-0.51476
UHVI from V5	0.214918	0.903174	-0.32478

3.3. Comparison of heat vulnerabilities obtained from five formulas
In order to compare the values of heat vulnerability obtained from the five formulas, a graph was plotted which contained these values for all 87 districts as shown in Figure 6–10 to compare which districts of Milan are shown to have highest or lowest heat vulnerability according to the different formulas.
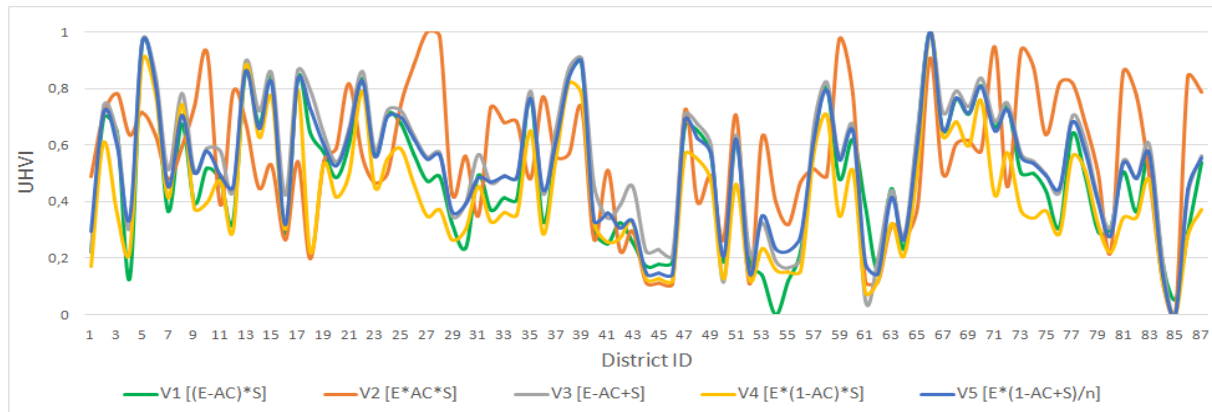

Figure 11. Graphs showing the UHVIs for all 87 districts of Milan (Italy).

4. Analysis and discussion of results and scope for future work

4.1. Expectations from the results
The five formulas were compared to understand the functioning of the framework used to quantify heat vulnerability of the districts of Milan (Italy) and also to understand the relationship between the components of heat vulnerability and the heat vulnerability itself. One expectation, was that the adaptive capacity component should be inversely proportional to the heat vulnerability which would indicate that if the adaptive capacity of a district to heat waves is high, then the vulnerable populations residing within that district would be relatively less vulnerable to extreme heat. It is well known that climate policies such as development of blue and green infrastructure [19], improvement in availability of health care facilities [20] and improvement of the quality of housing [21] contribute positively towards the reduction of heat vulnerability of the residents of a given district. Such policies are measurable using the indices representing adaptive capacity in this study. Another expectation was that the heat vulnerability index obtained for a district would vary for each formula but if a district is indicated to be vulnerable to extreme heat, then all formulas should produce a relatively higher value of heat vulnerability index for that district. As a nutshell, all formulas should produce relatively similar heat vulnerability for a given district with respect to other districts i.e. heat vulnerability for districts should be consistent with one another even though they may not have the same exact value for heat vulnerability.

4.2. Analysis of heat vulnerability obtained from the five formulas
Figures 1−5 presents the spatial distribution of heat vulnerability across the districts of Milan and Figure 11 presents the graphical presentation of the same. The following points were noted from these figures:

- V1, V3 and V5 showed relatively similar trends in Figures 1−5 for heat vulnerability across the districts of Milan. These trends are also supported by the positions of the peak and valleys in their respective graphs in Figure 11.
- A relative disagreement between results obtained for V2 and V4 was observed.
- V4 results were slightly closer to V1, V3 and V5 only when it is compared to V2.

4.3. Analysis of correlations between heat vulnerability and its components for the five formulas
The following points were noted from these Figures 6–10 and Table 3:

- All formulas showed positive correlation between heat vulnerability and exposure component.
- All formulas showed no correlation between heat vulnerability and sensitivity component.
- V1, V3, V4 and V5 showed negative correlation between heat vulnerability and adaptive capacity component and V2 showed positive correlations for the same.

4.4. Implications and recommendation of analysis
The above study showed that the V1, V3 and V5 formulas were most consistent with each other in terms of heat vulnerability distribution across the districts of Milan (Italy) and they have also shown inverse proportionality of adaptive capacity with heat vulnerability. Both these outcomes were in accordance with the expectations mentioned in Section 4.1. Therefore, these formulas are most recommended for assessing which districts of the city are most vulnerable to extreme heat events. The results obtained from V2 formula were mostly inconsistent with V1, V3 and V5. Moreover, the direct relationship between adaptive capacity and heat vulnerability which was shown by the results obtained from V2 formula is also another contrast with respect to the other formulas. Here, it was interesting to note that unlike V1, V3 and V5, V2 was originally to assess the vulnerability to flooding [17]. However, this does not indicate a justification for the direct proportionality of adaptive capacity with heat vulnerability or vulnerability to any hazard. Moreover, the framework adapted in this study was given by the IPCC [1; 14] for assessing vulnerability to hazard was indicated to all the possible climate change impacts which includes both flooding and extreme heat events. Therefore, based on this study, V2 methodology is the least recommended for measuring UHVI, at least for the framework used in this study. The V4 formula was seen as an improvement over V2 as it was a modification of V2. It has shown better results compared to V2 in terms of consistency with V1, V3 and V5 and also has shown negative correlation between adaptive capacity and heat vulnerability.

4.5. Limitations and scope for future work
The obtained results have shown to be quite consistent with the expectations. However, there are a few noted limitations of the above study. First, for practical purposes the district scale of assessment can be quite big as each district consists of many neighbourhoods. With this type of study, it can be difficult to identify which neighbourhoods are more vulnerable. Second, the method used for assessing health care accessibility index was not the optimal method because it did not consider the transport network in that area for calculating the distance from the public hospitals. Lastly, urban population data can be a tricky indicator as it is very dynamic with respect to time. There is a need to consider this dynamic aspect while analysing heat vulnerability and this can also vary greatly from city to city. Nevertheless, these issues does not dilute the significance of this study as the components of heat vulnerability are kept constant for all the formulas. This study serves as a preliminary study which was aimed at forming a foundation for the development of usable urban heat vulnerability maps for the benefit of urban development stakeholders based on sensitivity, exposure and adaptive capacity. Several other data, such as income and employment distribution, energy consumption etc. can also be included in the framework. Another interesting development for making these maps is the possibility to predict urban heat vulnerability for the future. The practical application of this type of assessment of urban heat vulnerability for cities as well as other urban stakeholders is to support strategic urban developmental planning, improved urban public health care, promotion of outdoor comfort, green spaces, green infrastructures and sustainable development in cities. Future studies should focus on developing more complex maps so that they can be reliable instruments for city councils and urban development stakeholders. A comparison of urban heat vulnerability for different cities is also interesting.

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