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Linkages between Typologies of Existing Urban Development Patterns and Human Vulnerability to Heat Stress in Lahore

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Abstract: The combined effects of global warming, urbanization, and demographic change influence climate risk for urban populations, particularly in metropolitan areas with developing economies. To inform climate change adaptation and spatial planning, it is important to study urban climatic hazards and populations at risk in relation to urban growth trends and development patterns. However, this relationship has not been adequately investigated in studies dedicated to climate vulnerability. This study identifies the typologies of development patterns within Lahore, Pakistan, investigates the heat vulnerability of residents at a neighborhood scale, and establishes a relationship between both of these factors. We identified urban clusters with diverse development patterns. Fourteen context- and site-specific indicators were selected to construct a human heat vulnerability index. Weighted sum, cluster analysis, and ANOVA test of variance were conducted to analyze the data. Our results demonstrate that development patterns significantly influence human vulnerability to heat stress, e.g., vulnerability is higher in older cities and undeveloped neighborhoods with less diverse land uses. These findings are essential for informing policy-makers, decision-makers and spatial planners about proactive adaptation planning in dynamic urban environments.

Keywords: climate change adaptation; heat stress; human vulnerability; urban development patterns; spatial analysis

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1. Introduction

Urbanization has become a ubiquitous process in recent decades and is recognized as the most defining feature of climate change [1–3]. On average, the size of cities has doubled in comparison to urban population growth, which resulted in a rapid transformation of global land cover and land-use patterns [4,5]. Urban areas cover 2% of the surface of the globe; however, they are responsible for 70% of climate changes [3]. Moreover, the concentration of economic activities, enormous traffic volumes, and disregard for urban green planning are pressing issues faced by many cities in the developing world [6]. Consequently, these anthropogenic changes have made cities increasingly vulnerable to climate change impacts [3]. Among all the effects caused by the substitution of natural ecosystems for urban land use, the most pronounced is the increase in the amount of energy stored in the urban canopy, which causes the urban heat island (UHI) effect [7]. Extreme events in the form of heatwaves have created enormous sustainability challenges in rapidly urbanizing cities.

Cities are recognized as centers of global climate action [3]. In the IPCC's sixth assessment report, urban areas are recognized as the main driver of greenhouse gas emissions [5,8]. Several studies have shown how urban texture and density as well as the geometrical structure shaped by the spatial distribution of urban elements, for example, buildings, roads, green areas, and open spaces, can significantly alter local urban climates [9]. Hence, it is established that urban development pattern typology has a significant impact on local, regional, and global climate [3,9]. It can also be concluded from the literature that the relevance between development patterns and urban climate is studied mainly in terms of how exposed different settlement types are to the impacts of climate change [5,10–12]. However, this climate–development nexus is even more advanced than the state of the art, and thus requires a greater understanding beyond the exposure dimension [12–14]. For instance, it is also important to explore how people living in different area types (such as developed and undeveloped neighborhoods) are vulnerable to the impacts of climate change [15,16]. It is crucial to study this climate vulnerability and development nexus at different scales because adaptation needs for different typologies of development patterns vary between and within urban areas [15–18].

Moreover, the wide diversity of physical, environmental, demographic, and socioeconomic aspects within cities highlights the need for understanding the spatial planning contexts, in which these variations emerged [19]. Vulnerability assessment at the neighborhood scale is an entry point for exploring intra-city disparities regarding these various aspects [20,21]. In most cases, the index-based vulnerability assessment approach provides the first overview of hotspots in a particular location [22–24]. However, it is difficult to derive specific adaptation needs from these hotspots in the absence of environmental/physical information about the urban fabric and functions within a neighborhood [25,26]. Therefore, for context- and site-specific climate change adaptation planning, it is important to identify distinct neighborhood types based on the clustering of zones within urban areas considering various aspects [17,27]. The first step for identifying typologies is to explore urban development patterns considering disparities within cities [9,28]. The study of the interaction between these typologies is crucial in understanding how cities can contribute to climate change adaptation, and which mix of economic, social, and environmental policies can be implemented to better adapt to climate change impacts.

A rapidly growing canon of scientific literature exists on vulnerability assessment frameworks and methods, as well as typologies of urban development pattern and their clustering [15,29–33]. Missing from the current understanding is the interrelation of how metrics of vulnerability encompass the development pattern typologies of cities [16,27,34]. Because every single neighborhood within a city has its own distinct development characteristics, it is important to identify different neighborhoods based on the clustering of their relevant characteristics. To formulate and implement specific adaptation strategies, policies and measures, there is a need to establish the relevance between urban development patterns and human vulnerability. Following this discussion, this paper focuses on the use case of the metropolitan city of Lahore, Pakistan and answers the following three research questions:

1. What are the typologies of existing development patterns for Lahore based on urban configuration (settlement types, density) and urban composition (land-use pattern)?
2. What is the spatial variability of human vulnerability to heat in Lahore?
3. What are the linkages between urban development patterns/structures and human vulnerability to heat stress in different urban settings?

2. Theoretical and Conceptual Perspectives on Typologies of Urban Development Pattern and Human Vulnerability

With a focus on understanding the relevance of urban development pattern typology for human heat vulnerability, a growing number of scientific reports and journal articles have been studied. In this section, key terms used in the study relating to typologies of urban development patterns and heat vulnerability are discussed. Moreover, a conceptual framework for understanding the relevance of typologies of development patterns for human vulnerability is developed, which forms the basis of this study.

2.1. Typologies of Urban Development Pattern, Human Vulnerability, and Their Interdependence

An urban development pattern refers to the extent of both types of spatial/physical growth and is defined as: ‘‘the spatial pattern of human activity at a certain point in time" [35]. Thus, spatial and temporal aspects are important in terms of defining urban development patterns [35,36]. In the literature, two dimensions of urban typologies are used to distinguish patterns of urban development, the first dimension is configuration, and the second dimension is composition [34–36]. Urban configuration is a spatial description [37] that refers to the distribution and arrangement of land cover, built-up areas and other urban elements [18]. In other words, urban configuration represents the spatial reality of an urban area. Various factors related to structure, density, and geometry are included in this category [35,38]. On the other hand, urban composition describes the distribution of land-use features in specific relation [39,40]. Therefore, composition relates to the proportion of various land-use features in relation to each other. There are various other dimensions of urban development, for instance, related to demography, economy, society, etc. However, this study focuses on a pattern of urban development, which is manifested by the spatial and physical growth of an urban area because of human activities.

Typologies of urban development patterns can directly influence the exposure to climate hazards within an area [10,27,41]. However, people living in identical neighborhoods and buildings are not equally exposed to climate hazards due to different socio-cultural backgrounds and economic conditions [42]. In this respect, there is an additional layer of information required, which can highlight the characteristics of a population. Therefore, in addition to information about climate hazards, there is a growing consensus on assessing human vulnerability to proactively manage hazard risks and address climate change adaptation [4,42–44]. This review of the literature confirms that vulnerability assessment is a key step toward enhancing the resilience of a system [22,45,46]. In this context, there are many different approaches to vulnerability assessments based on conceptualization, dimensions, factors, quantification methods, and spatial and temporal scales due to the strong crossover in several disciplines (e.g., climate change research and disaster risk reduction). In this study, an approach based on IPCC 2014 and 2022 was used for the vulnerability assessment [4,5]. It caters to the researchers from both climate change and disaster risk reduction disciplines, and the assessment reports of the IPCC emerge from a large body of assessed literature [4,5,12].

In the IPCC, vulnerability refers to "the propensity or predisposition to be adversely affected" [47]. In this paper, social vulnerability can be defined in the context of "an inherent property of a system arising from its internal characteristics" which may encompass "the characteristics of a person or group and their situation that influences their capacity to anticipate, cope with, resist, and recover from the adverse effects of physical events" [48]. A vulnerability assessment has three components: (a) sensitivity or susceptibility of a system to be harmed and its response capacities, including the lack of capacity to (b) cope and (c) adapt [4,42,49]. Thus, not only is the fragility or susceptibility of a population group, community or infrastructure important, but also their capacity for dealing with and adapting to climate hazards for a vulnerability assessment [5,12]. There are both qualitative and quantitative approaches and methodologies for evaluating human vulnerability [49–54]. The indicator-based approach has been widely used in the literature and is highly acceptable despite criticism regarding data limitations and uncertainty [55]. Social and economic vulnerability encompasses these intangible factors, which are difficult to quantify and validate. In this case, proxy variables are used, which affect the significance of the assessment [56]. However, this indicator-based quantitative approach is widely used because it allows for a multi-dimensional perspective of urban development and captures different facets of human vulnerability [57,58]. Hence, it allows the operationalization of various aspects, related to the social, environmental, economic, and political system through time and space; therefore, it significantly systemizes the monitoring process and reduces complexity [42]. There are multiple dimensions to the vulnerability assessment of a system, but in this study, we focus on human vulnerability and how it varies among different typologies of development patterns.

The study of urban development patterns and their interrelationship with climate hazards has a long history, with various disciplines emphasizing the importance of urban form and its role in altering local climate [59,60]. Some studies have established this interdependence to comprehend key aspects of urban structure, which are strongly associated with climate risk [61]. However, despite numerous studies, there is a lack of consensus on the most critical aspects of climate risk relative to urban development patterns. Moreover, this interdependence between urban climate hazards and typologies of development patterns is mainly studied in terms of hazard exposure, thus ignoring the susceptibility and capacities of people to address these hazards, which are crucial for climate risk [11,14,62,63]. Thus, there is a need for new urban typologies related to urban climate to emerge, characterizing the trajectories and dynamics of land expansion and urban densification, as well as the human vulnerability to climate change [17].

2.2. Conceptual Framework

In this study, the framing of the typologies of urban development patterns is based on urban configuration covering settlement forms (i.e., developed or undeveloped areas) and settlement density, as well as urban composition catering to land-use distribution. On the other hand, a human vulnerability assessment is outlined by incorporating its three components, i.e., susceptibility, as well as coping and adaptive capacity. For both identifying urban development pattern typologies and estimating human vulnerability components, satellite imageries are processed. Finally, the interrelation between these two variables is examined by computing the variance of human vulnerability in different typologies of urban development patterns (see Figure 1).

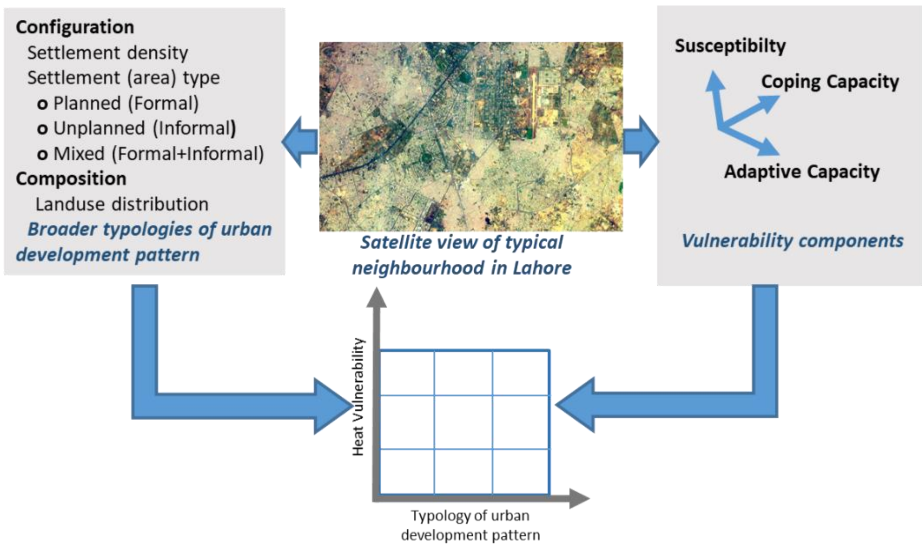

Figure 1. Conceptual framework for schematic analyses of heat vulnerability and urban development typology. Source: Own figure.

In this study, various dimensions of current urban development patterns related to human vulnerability are explored. The first dimension encompasses formal and informal settlement areas. Weak urban planning regulation implementation, for example, a lack of enforcement of land-use regulations, as well as building codes and permissions, intensifies the risk for those who live and work in urban areas. Most vulnerable groups, typically living under the poverty line, tend to settle and construct homes in informal settlement areas, which are unsafe and do not have an adequate supply of utilities, provision of infrastructures, and availability of green areas [64,65]. Those living in urban poverty are predominantly vulnerable to climate hazards because of their location within cities [5]. The other dimension is building density, another important defining feature of development patterns. Settlement density has a direct positive relation with climate hazard exposure [65], and it is vital to establish its relationship with human vulnerability, which remains unclear. The third dimension is related to the composition of development patterns, and thus land-use distribution. Land use is even more diverse since social and natural infrastructures tend to be more accessible [66]. However, its link with human vulnerability remains unclear [15,34,43]. Therefore, this study attempts to explore the interrelations between these different aspects of urban development patterns and human vulnerability.

3. Contextual Analysis of Lahore

Lahore is a rapidly growing metropolis and the second-largest city in Pakistan, with more than 11 billion inhabitants [67]. With a remarkable heterogeneity in terms of development patterns and socio-economic conditions across its nine administrative districts, the city covers an area of 1772 km^2 [67]. Lahore has exponentially expanded upon its rich cultural heritage, creating a thriving base for economic activities, driven by business, industry, trade, and education [6].

Massive urbanization, driven by the rapid expansion of the city, is one of the most dominant transformations and has characterized the growth of Lahore in recent years [68,69]. With the mix of urbanized and peri-urban areas, this metropolitan region presents a spatial variation in the dynamics of urbanization [6,69]. Figure 2 presents the built-up area of Lahore City in the years 1995, 2005, and 2017. It is evident from Figure 2 that several areas, first identified as peri-urban or even rural in 1995 and 2005, have become part of a continuous urban expansion over the years. From the graph in Figure 2, it is evident that the built-up area of Lahore increased by nearly one-third, i.e., from 220 km^2 to 336 km^2 between 1995 and 2005 [70]. However, this expansion doubled in the next 12 years, as an increase in built-up land was witnessed: up to 665 km^2 in 2017 [70]. While the annual area growth rate in the first decade was 4.3%, it increased to 7.1% in the second period of this time frame [70].

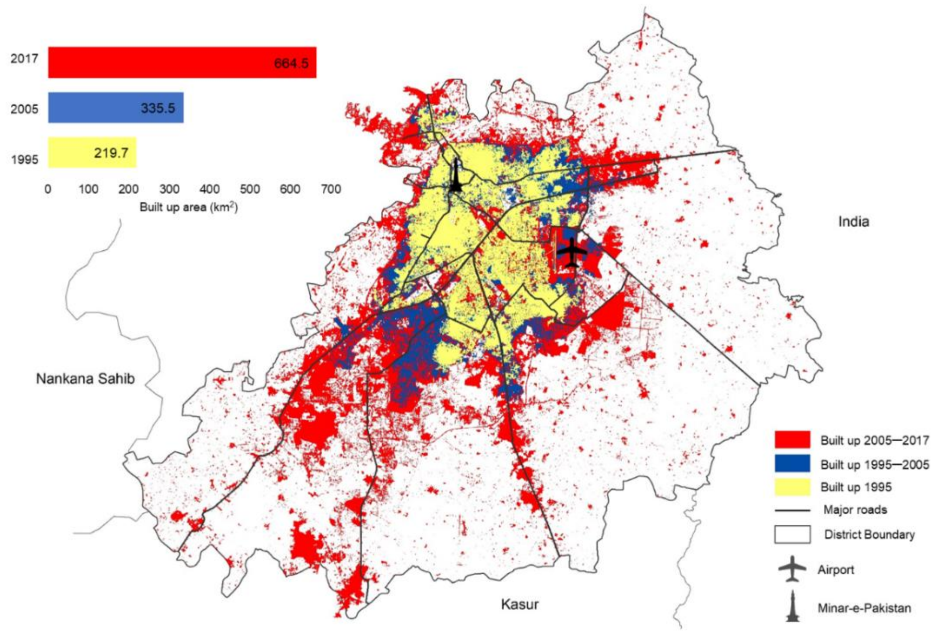

Figure 2. Built-up areas in Lahore between 1995 and 2017. Source: Own figure based on data from The Urban Unit, 2018.

Lahore is situated in a semi-arid climate zone. The summer season starts in April and ends in September when the mean maximum temperature in June, July, and August exceeds 40 °C and is even higher in dense inner-city areas [67,71]. May, and especially June, are observed as the hottest months of the year when the maximum temperature reaches up to 48 °C. December and January are the coldest months; the mean temperature recorded during these months is approximately 5 °C [71]. Moreover, strong monsoon conditions in this region make the weather extremely unstable. Currently, record-breaking heatwaves are hitting the region and influencing the daily lives of residents [72,73]. Overall, the environmental features of the region are greatly affected by these weather conditions, thus making the climate change impacts in the city quite pronounced [74,75].

4. Data and Methods

This study firmly coincides with the space-specific vulnerability assessment paradigm and used a method in conjunction with vulnerability assessment approaches employed by other researchers. In addition, three dimensions of urban development pattern typology are coupled with human vulnerability. Briefly, our approach to analyzing the pattern of urban development and its linkages with human heat vulnerability can be distinguished into three steps. The first part relates to the systemization of different urban development pattern typologies at the union council level in Lahore. The union council is the lowest administrative scale in Lahore. The second step relates to the assessment of human heat vulnerability and the identification of vulnerability hotspots within the city. Finally, the level of vulnerability in different urban settings is explored and the relationship between human heat vulnerability and urban development pattern typologies is statistically tested. The following subsections provide a detailed view of these steps.

4.1. Typologies of Urban Development Pattern in the Case Study

As mentioned in the conceptual framework, patterns of urban development are analyzed based on urban configuration and composition. Broadly, urban configuration at the city scale is studied by settlement area type and density. Data regarding settlement area typology were acquired from the Urban Unit, Lahore [70]. Based on these data, three categories of settlement areas: planned, undeveloped and mixed development (partially developed and partially undeveloped), are proposed. These areas are demarcated based on different structural characteristics such as the pattern of houses, building lines, layout and width of streets, extent of open spaces, as well as plot size [70]. See 'Appendix A' for details about the criteria and characteristics distinguishing these areas. Even though urban morphology could be similar between these categories at times, the perspective of settlement area typology is important to stress how informal settlement areas affect the overall urban development. It is important to mention that for clustering and statistical analysis, the settlement area type of each union council is interpreted from these vector data, thus, the predominant settlement area type is assigned to each union council. The second indicator of urban configuration is building density. Data regarding building density are gathered from the Lahore development authority. For clustering and systematization, building density was differentiated into three quantiles, i.e., high, medium, and low.

On the other hand, the urban composition is attributed to land-use distribution. In this respect, the land-use mix index was calculated to quantify the diversity in land-use patterns, ensuring urban sustainability [76]. There is a wide range of conceptual underpinnings and mathematical formulas to quantify the land-use mix index [76–78]. Comparing the advantages and limitations of various indices, the entropy index (*ENT*) is selected to measure the land-use diversity in the study area. The *ENT* measures the relative percentage of the types of land use within an area [79]. The following mathematical expression is used to calculate the *ENT* for union councils in Lahore:

$$ENT = -\sum_{j=1}^{k}\left(P^j \ln(P^j)\right) / \ln(k)$$

P^j is the percentage of land-use type j in an area;
$k \geq 2$ is the total number of land-use types.
ENT ranges from 0 to 1, where 1 represents the maximum diversity of land uses in an area. Finally, a k-mean cluster analysis was performed in SPSS to group the census tracks based on their development typology: settlement area type, building density and land-use distribution. To choose the appropriate value of k, i.e., the number of clusters to build, a

hierarchical cluster analysis was conducted. In this case, Ward's method was applied to group the data into uniform-size clusters (see Appendix B) [80]. Finally, the typologies of the development patterns are grouped into three heterogeneous and robust clusters depending on their z-score.

4.2. Human Heat Vulnerability Assessment

The assessment of the human heat vulnerability index for the case study is an important aspect of this research. Overall, Figure 3 summarizes the steps required for index computation. These steps range from data collection and data transformation to the weight assignment, computation, and categorization of the urban human vulnerability index in relation to heat stress.

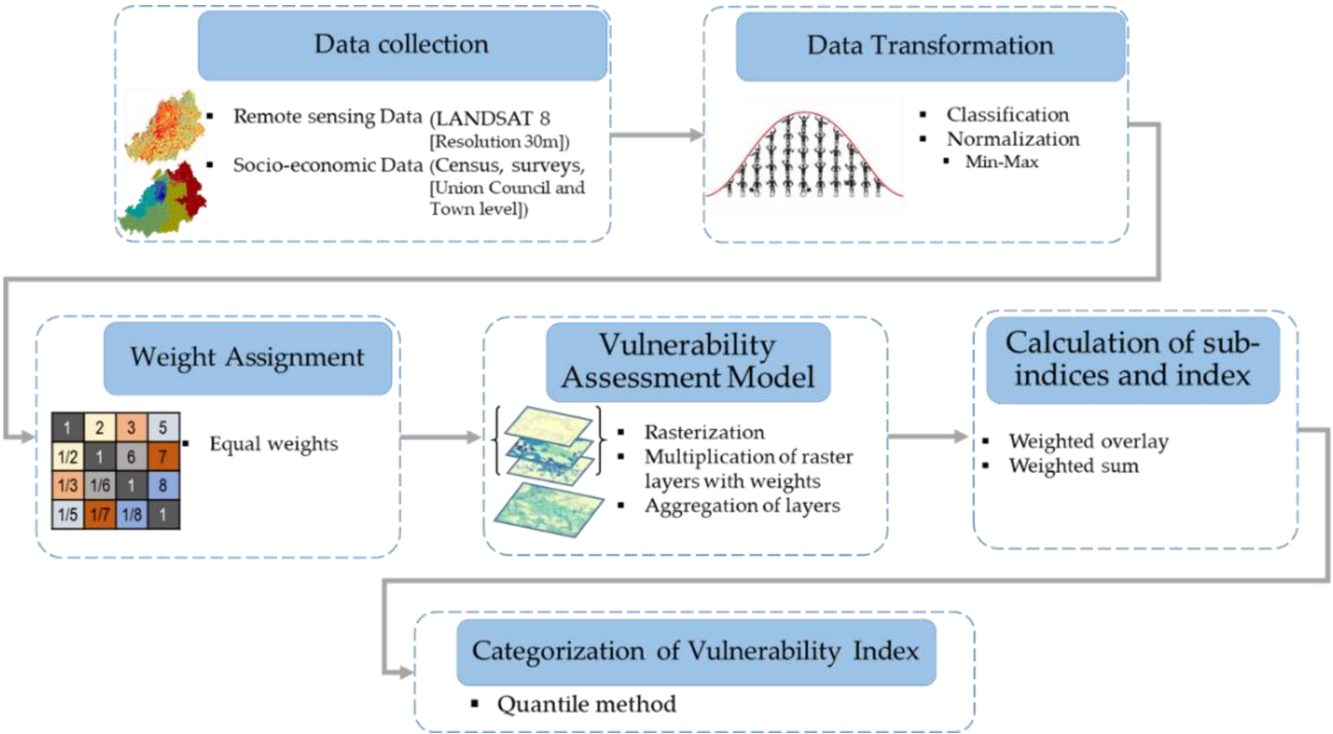

Figure 3. Overview of the methodology for the calculation of urban human vulnerability. Source: Own figure.

4.2.1. Data Collection and Normalization

An extensive range of data regarding the environmental and socio-economic state and dynamics in the city is required for a human heat vulnerability assessment. Fourteen indicators were selected to compute the index based on previous research [20,21,27,29,74,81–84]. From our literature review, a list of indicators was derived from different sources and grouped into the categories of susceptibility, as well as coping and adaptive capacity, as shown in Table 1. For aggregation, all indicators are normalized based on the data unit of the source (see Table 1) and transformed into a dimensionless rank level between 0 and 1. Table 1 presents the indicators, their justification, data source as well as the transformation methods used for the 15 indicators characterizing human heat vulnerability.

Table 1. Indicators used to assess human vulnerability in urban areas, data sources, justification of the indicators, and the transformation method used.

Indicator	Source	Explanation and Relevant Studies	Unit	Transformation Method
Susceptibility				
Age group < 5 and >65	Population census	People aged between 0 to 4 years and above 65 years is an important vulnerability determinant concerning weather-related stresses [20,29,81].	Inhabitants	Min–max normalization
Pre-existing illness	Rolling plan of the health department	Populations with existing health issues are more susceptible to heat stress [74,82,84].	Percentage	Scaled 0 to 1
Household Income	Lahore Urban Transport Master Plan	Relative poverty causes social exclusion and increases an individual's susceptibility [85]	Average	Min–max normalization
Education level	Multiple indicators cluster survey (MICS)	A lower education level closely correlates with the individual's ability to comprehend climate hazards [20,74,86].	Percentage	Scaled 0 to 1
Household size	MICS	The larger the family size, the more people are vulnerable to heat stress [20,74].	Percentage	Scaled 0 to 1
Coping and adaptive capacity				
Ownership status	MICS	People who own a house and other assets have more ability to adapt [87,88].	Percentage	Scaled 0 to 1
Access to hospitals	MICS	Access to healthcare is another factor that determines the copying capacity of individuals to heat events [20].	Percentage	Scaled 0 to 1
Access to green	Landsat 8	The density of green spaces on a patch of land is important to describe the capacity of people that can withstand extreme heating events [29,74]	−1 to +1	Min–max normalization
Access to water	Landsat 8	A water body tends to have low radiation and strong absorption; therefore, it significantly reduces the heat stress [20,29].	−1 to +1	Min–max normalization
Access to electricity	MICS	The access to electricity can increase an individual's capacity to cope with heat stress [20,86].	Percentage	Scaled 0 to 1
Access to an improved water source	MICS	The access to improved water supply can be helpful to minimize the effects of heat-related events [20,29,86].	Percentage	Scaled 0 to 1
Access to information	MICS	The access of households to electronic or print media is an important determinant while quantifying heat-relevant coping capacity [34,81].	Percentage	Scaled 0 to 1
Use of air conditioning	MICS	Air conditioning is a spontaneous coping-related measure for rising temperatures [27,38].	Percentage	Scaled 0 to 1
Insurance coverage	MICS	By dealing with the effects of heat stress, insurance coverages can provide financial security [86,89].	Percentage	Scaled 0 to 1

4.2.2. Data Aggregation and Index Development

Considering the equal relative importance of the indicators, all the indicators are equally weighted [20,27,29]. Equal weighting implies a recognition of the equal status of all the indicators [74]. Weighted sum [90] is used to quantify the spatial indexes related to susceptibility, coping and adaptive capacity, and, finally, human vulnerability. Different areas of the city have been categorized based on their respective vulnerability score using five quantiles ranging from high to low. It is important to mention that this spatial analysis is based on the administrative boundary of the city, providing an opportunity to develop policy recommendations that can be implemented by specific administrative units.

4.3. Interrelation between Typologies of Urban Development Patterns and Human Heat Vulnerability

The typologies based on developed and undeveloped neighborhoods, building densities, and diversity of land uses were plotted against their mean vulnerability scores to confirm if there is a link between vulnerability scores and urban development pattern typologies. A general linear model ANOVA test of variance was performed to compare the marginal means of vulnerability scores for different typologies of development patterns.

5. Results

This section presents the findings of the study based on the case study of the city of Lahore. The clustering of census tracks based on their typologies of urban development pattern is presented in Section 5.1 followed by their heat vulnerability score presented in Section 5.2. Finally, the results of the ANOVA test of variance are presented in Section 5.3 to establish the interrelation between human heat vulnerability and typologies of development patterns.

5.1. Clustering of the Typologies of Urban Development Pattern

Figure 4 presents the clustering of typologies of development patterns for the case of Lahore at the spatial scale of union councils. There is a huge heterogeneity of development across the administrative units of Lahore. Based on the conceptual framework (see Section 2.2), the differentiation shown is based on settlement area types, building density, and land-use mix index. Settlement areas are grouped into developed, undeveloped, and mixed development types. Building index and ENT are categorized into three quantiles: low, medium, and high. Nearly half of the built-up areas in Lahore are undeveloped [70], where building density is quite high and land use is less diverse. Importantly, the land-use mix index is higher, and the building density ranges from low to medium in the developed areas because of the high adherence to planning regulations in these areas. Moreover, more than half of the union councils have both developed and undeveloped zones, where building density values, as well as land-use diversity, are relatively higher in these areas. According to k-mean clustering analysis, a large number of union councils in Lahore have high building density and their ENT is medium to high, which means that land use is more diverse.

5.2. Hotpots of Human Heat Vulnerability

The sum of susceptibility and lack of coping and adaptive capacity calculates heat vulnerability [52]. Thus, it incorporates both the conditions, as well as the processes of societies that determine, whether a disaster may ensue when a climate hazard occurs. In the case study area, there exists a diverse pattern of susceptibility and coping and adaptive capacity. While there is less variation in terms of economic and educational disparities, a clear differentiation can be observed in terms of access to natural and social infrastructures (see Appendix C). Overall, central areas of the city are less susceptible, and this susceptibility dramatically increases when moving towards peri-urban areas. On the other hand, central and northern areas are more robust in terms of capacities, while old urban areas in the Ravi, Data Gunj Buksh and Shalimar towns, as well as southern locations, lack coping and adaptive capacity. Ravi town has a significantly higher susceptibility and less coping and adaptive capacity (see Appendix C). Moreover, the Aziz Bhatti and Iqbal towns have a high coping capacity. Since the urban growth of Lahore mainly extends southward, it is important to note that this location already lacks coping and adaptive capacity, so there is a need for prerequisite measures to promote climate change adaptation in these areas.

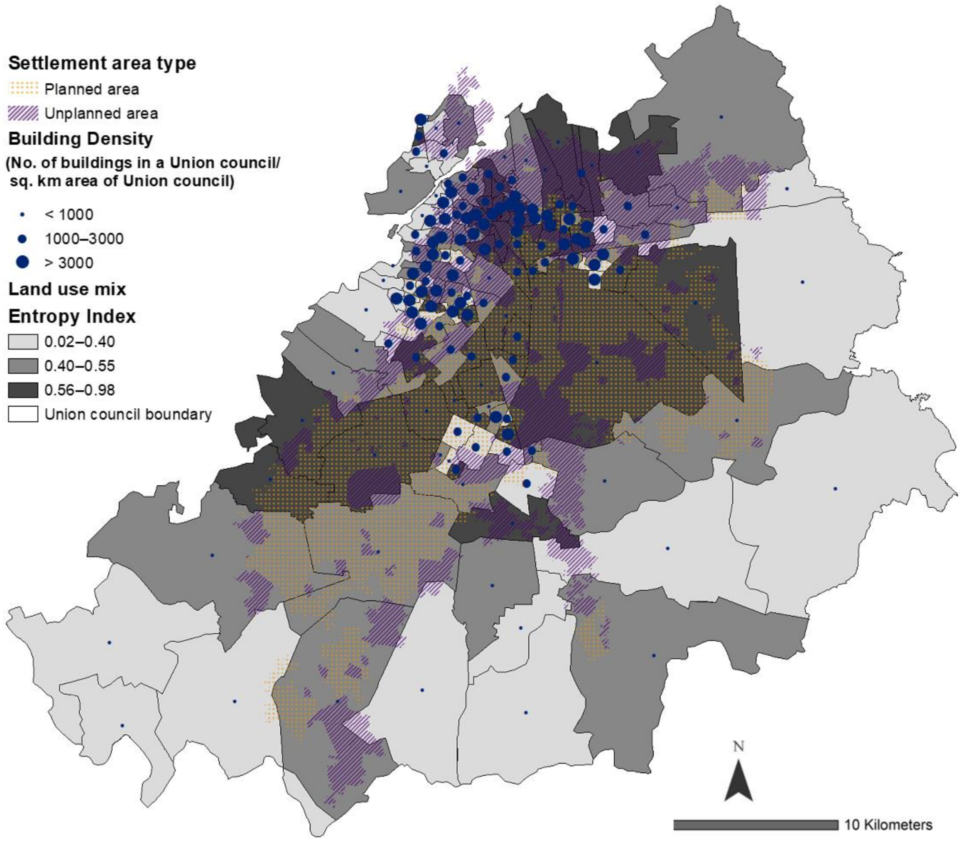

Figure 4. Typologies of urban development patterns in Lahore. Source: Own Figure based on data from The Urban Unit and Lahore Development Authority.

Finally, Figure 5 presents the relative heat vulnerability scores of the union councils of Lahore city. It is clear that the heat vulnerability of Lahore city is higher towards the northwest, particularly in Ravi town. Moreover, some parts of the Shalimar and Aziz Bhatti towns also fall into the category of highly vulnerable areas due to the socio-economic and demographic profile of those, who are living in these areas. Generally, the vulnerability values of the southern part of the city are higher than in the northern areas, especially the northeastern part. Towards the south, the Allama Iqbal and Nishtar towns are in the category of medium vulnerability. However, central areas of the city, including Gulberg and Cantonment, have a lower heat vulnerability score due to the socio-economic profiles (e.g., income levels) of people and their access to green spaces. In Figure 5, three hotspots are circled with dash lines. A full overview of the results of all indices, including individual ranks of the union councils is shown in Appendix C. However, the analysis revealed the following hotspots of human heat vulnerability in Lahore:

- Vulnerability hotspot A: Areas around the Ravi river course, formerly an industrial district and nowadays predominantly inhabited by a working-class population. In these locations, the susceptibility index is relatively high and coping and adaptive capacities are quite low.
- Vulnerability hotspot B: Undeveloped old parts of the city that lack green places. Moreover, the population and building densities are significantly higher in these areas.
- Vulnerability hotspot C: Recently and rapidly urbanizing areas of the city performing poorly in terms of coping capacities. The access to natural and social infrastructures is also quite low in these locations.

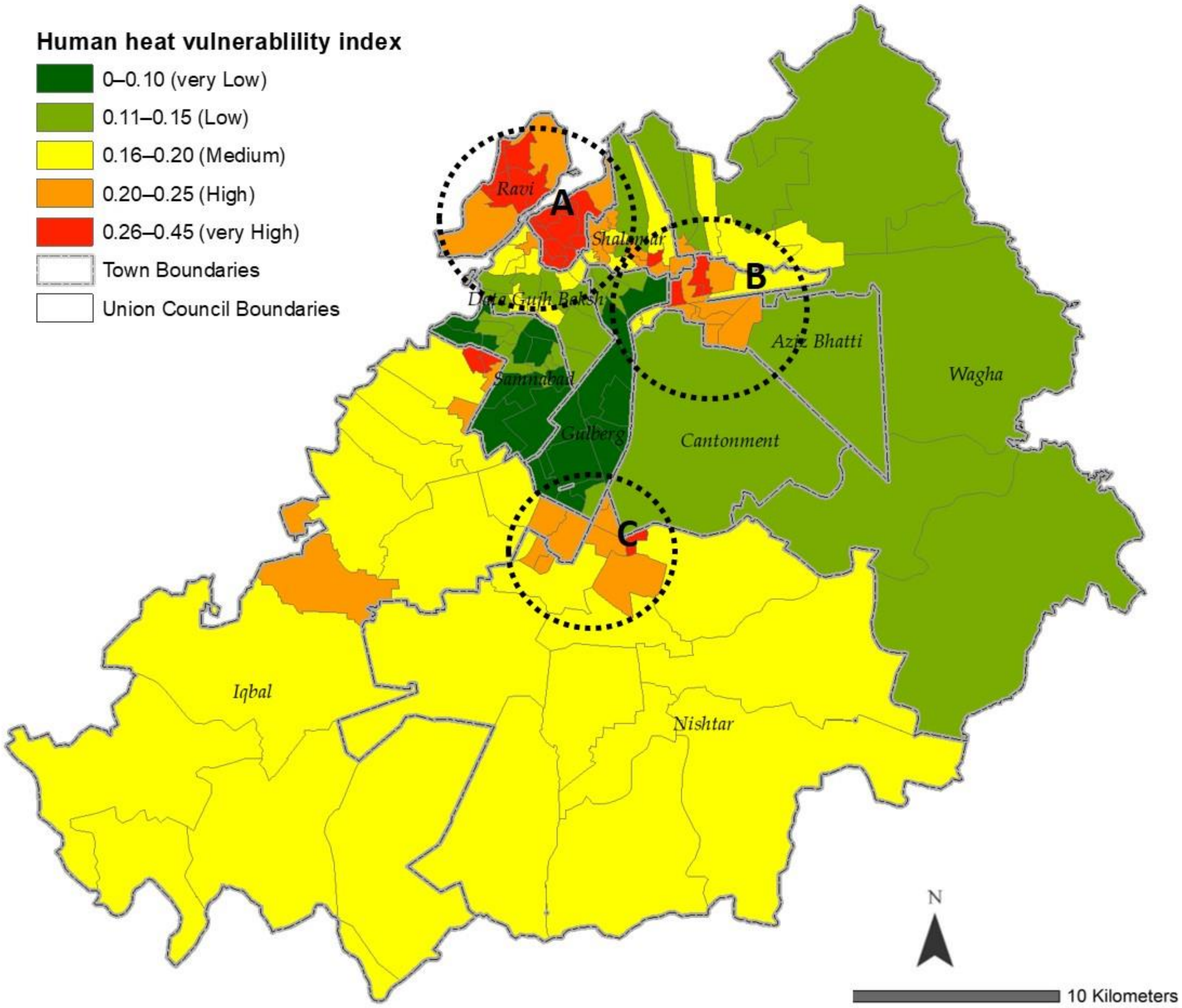

Figure 5. Map presenting relative human heat vulnerability at union council scale in Lahore (the dotted circles marked with **A**, **B**, and **C** are showing vulnerability hotspots in the city). Source: Own figure.

5.3. Links between Human Heat Vulnerability and Typologies of Urban Development Pattern

The analysis of human heat vulnerability considering the typologies of development patterns yielded interesting results. Figure 6 presents box plots that illustrate the vulnerability index (VI) and three typologies of development patterns: settlement area type, ENT index, and building density. Vulnerability is attributed depending on developed, undeveloped, and mixed development, and low-to-high scores of ENT and building density. Between settlement area type and vulnerability, there is a positive significant correlation (r = 0.425, p = 0.01). In terms of settlement area types, VI is 0.43 in developed areas, compared to 0.46 in mixed areas (partially developed and partially undeveloped). However, VI is 0.68 in the undeveloped areas, which is very high compared to the mean VI. The variance in VI is also plotted, which is quite high in the undeveloped areas. An unbalanced development trend is a major reason behind this high variance. In the case of ENT, a negative relation (r = −0.19, p = 0.01) is explored with the VI. For areas with a low ENT, VI is 0.64 compared to VI = 0.55, when the ENT is low. This means that land-use diversity reduces human vulnerability to heat stress. In this category, the variance within VI is relatively constant for the high, medium, and low ENT. Finally, plot B presents the VI for low-to-high building densities. From the results, it is evident that there is no significant correspondence between these variables.

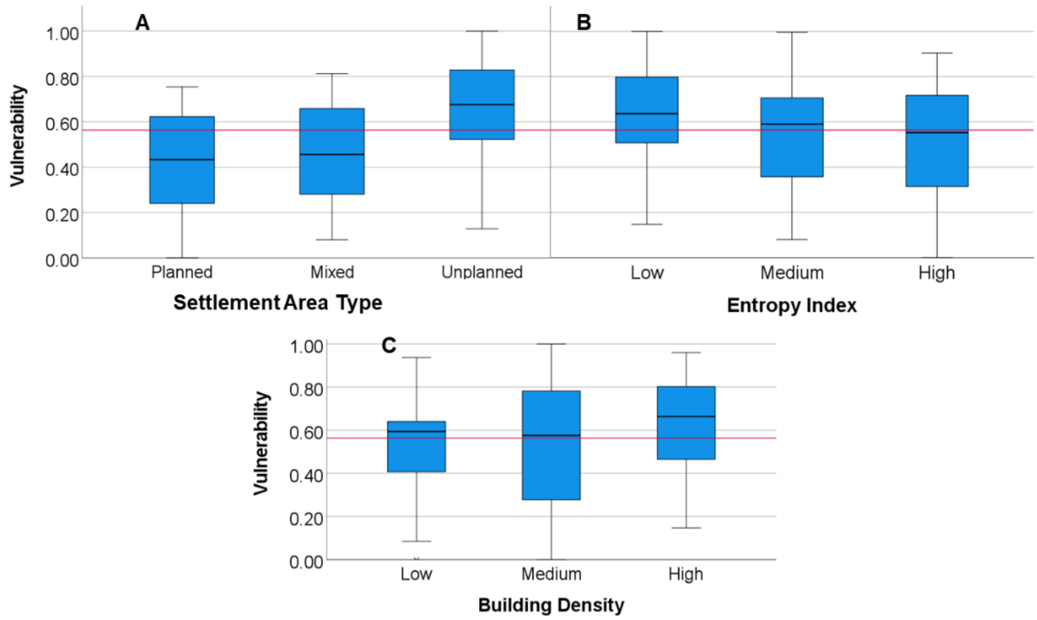

Figure 6. Box plots between human heat vulnerability and typologies of development pattern (settlement area type (**A**), entropy index (**B**) and building density (**C**)). Redline indicates the mean value of the overall vulnerability. Source: Own figure.

Table 2 presents the results from the general linear model two-way ANOVA analysis of variance. It is clearly seen that some typologies of development patterns strongly influence human heat vulnerability. Between the types of settlement areas (planned, undeveloped, and mixed) and human vulnerability, there is a strong relationship, whereby, the statistical significance is less than 0.001. Likewise, the significance between the ENT and human heat vulnerability is 0.004, so there is a considerable relationship between human vulnerability and land-use diversity. On the other hand, the significance is 0.277 in the case of building density, meaning that there is a less substantial influence of the building density on the human vulnerability to heat waves/stress. It is also evident from the analysis that the interactions of the settlement type with the building density and the settlement type with the ENT significantly contribute ($p = 0.004$ and $p = 0.012$, respectively) to influencing overall human vulnerability.

Table 2. The influence of typologies of development patterns on the human heat vulnerability in Lahore.

Dependent Variable: Human Heat Vulnerability					
Source	**Sum of Squares**	**Degree of Freedom (df)**	**Mean Square**	**F**	**Significance (*p*)**
Corrected model	3.375 [a.]	22	0.153	3.565	<0.001
Intercept	23.676	1	23.676	550.196	<0.001
Settlement area type	1.535	2	0.768	17.841	<0.001
Building density	0.112	2	0.056	1.296	0.277
ENT	0.492	2	0.246	5.721	0.004
Settlement area type * Building density	0.487	3	0.162	3.771	0.012
Settlement type * ENT	0.275	4	0.069	1.596	0.179
Building density * ENT	0.120	4	0.030	0.696	0.596
Settlement area type * Building density * ENT	0.260	5	0.052	1.209	0.309
Error	5.508	128	0.043		
Total	56.870	152			
Corrected total	8.883	150			

[a]. R squared = 0.380 (adjusted R squared = 0.273). * sign is presenting the interaction effect of different typologies of urban development pattern.

Lastly, the adjusted r-squared value shows that 27.3% of the variance in vulnerability is attributed to the settlement type, building density, and ENT. This value indicates the strength of the model, i.e., the strength of the relationship between typologies of development patterns and human vulnerability. Thus, the study statistically proves that there is a strong influence of settlement area type and land-use diversity on human heat vulnerability. In Figure 7, estimated marginal mean vulnerability (EMMV) is plotted against settlement area types and ENT. It is also important to note that within the same settlement area type, vulnerability dramatically increases depending on the ENT. When land-use diversity is high, the EMMV in the developed areas is 0.32; however, when the ENT is low in the same settlement area type, EMMV = 0.49. In the other two settlement area types (i.e., mixed and undeveloped areas), the same trends apply.

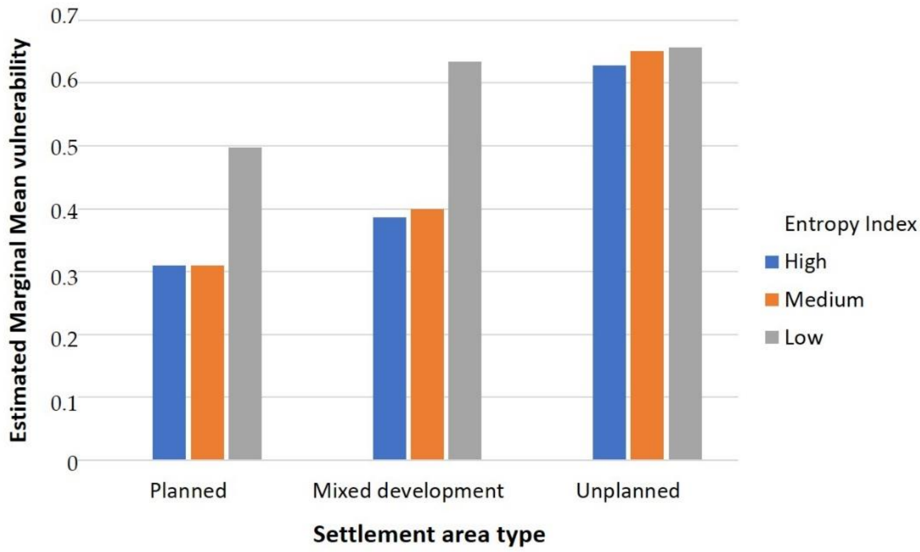

Figure 7. The estimated marginal means of vulnerability (*y*-axis) for the different development pattern typologies (*x*-axis) and entropy index (*x*-axis). Source: Own figure based on categories explained in Section 2.2.

6. Discussion, Conclusions, and Outlook

This paper identified and explored key links between typologies of urban development patterns and human heat vulnerability at a union council scale. The most important aspects of this research are as follows.

6.1. Relevance of Development Patterns for Human Heat Vulnerability

Several previous studies stressed the need for a local-scale assessment of vulnerability to identify risk hotspots within cities [15,16,91–93]. Human vulnerability assessment in a localized context with a spatial focus on development pattern typologies facilitates the identification of specific adaptation needs in the context of heat stress [16,41]. However, few pieces of evidence from the literature interlink these vulnerable hotspots with urban development patterns. For instance, Kim and Ryu have captured the spatial patterns of heat-related vulnerability from the perspective of urban design typologies in the Korean city of Suwon [94]. This study examined the heat vulnerability of different urban districts based on their geometry [94]. With a particular focus on settlement density and related indicators such as elevation, building footprint, urban geometry, and road density, various other aspects of urban development typologies, for instance, land-use patterns, settlement types, etc., are not adequately incorporated. Therefore, particular attention is given to exploring the linkage between typologies of development patterns and human vulnerability to heat stress in different urban settings, which have undergone distinct development processes. Despite their proximity, there is a marked variation regarding the heat vulnerability amongst the households living in different settlement areas (see

Figure 6). From the analysis, it is evident that the developed areas generally have lower levels of human vulnerability to heat stress as compared to undeveloped areas. This can be explained by various factors, for example, households living in developed areas have improved socio-economic conditions and access to important facilities and infrastructures [95]. Moreover, the ENT is higher, which means that land use is more diverse (see Appendix D). Furthermore, people have good access to green areas and social infrastructures, such as medical services [42,78,95,96].

On the other hand, undeveloped areas generally contain more people with a higher level of human vulnerability (see Appendix C) to heat stress due to the socio-economic characteristics of households and limited access to social and natural infrastructures [88,97]. This can increase the adaptive capacity of people to heat stress [30,36,95]. For example, residents of two settlements (in a case study by Makhan Pura and Wassan Pura) that underwent informal urban development processes had a higher susceptibility index (see Appendix B). At the same time, land-use types are less diverse in these locations, which may have hindered the capacity of households to access green areas and other social services, such as medical services (see Appendix C). All the above conditions influence the overall vulnerability of residents to heat stress. It can therefore be understood that whereas the spatial patterns shaped through informal development are highly vulnerable to heat stress, those formed by pre-planned development processes reduce the heat stress [88,97]. The analysis and discussion reveal that the capacity of the residents can be increased by effective land-use planning, which enhances land-use diversity. However, the challenges remain for undeveloped areas, which are often characterized by a lack of institutional capacities. These areas need to be strengthened through integrated urban planning strategies and programs to enable cities to strategically reduce vulnerability. Therefore, the clustering of vulnerability based on the settlement area types is important for understanding the importance of spatial planning paradigms and the climate change adaptation needs of specific households located in different urban settings.

6.2. Study Limitations

Generally, one of the most important aspects of the calculation of the spatially explicit index is the robustness of spatial data and trade-offs between data and indicators [98]. In this research, the spatial unit used for quantification purposes is the union council. The data emerging from satellite imagery with remote sensing techniques are always well-distributed in space because of the fixed spatial mapping unit—the pixel. However, the socio-economic data collected from various sources for some indicators are less spatially explicit in most cases, including the case of Lahore. For instance, the data related to household insurance coverages and access to services are available at a town scale and are downscaled to a union council scale for the assessment. The improvement of the scale of socio-economic data can highly influence the assessment of the heat VI. Another important aspect is the use of proxy indicators in the assessment. In this regard, some complementary variables related to household characteristics, such as knowledge and preparation regarding heat events that can support the warning or recovery system, are difficult to quantify. Therefore, education level and access to information are used as proxy variables. Finally, the selection of indicators largely represents the dimension of susceptibility. Coping and especially adaptive capacity dimensions are underrepresented. These issues can be addressed via primary data collection for a vulnerability assessment. On the other hand, some other aspects associated with urban configuration, i.e., floor space ratio and building structure, require further studies.

6.3. Transferability of the Methodology and Future Research Potentials

Overall, this methodology is transferable to other cases with the context-specific adjustments of some indicators. For instance, development nomenclature is quite diverse among different regions around the world and can be adapted for each specific case study. Moreover, adding context-specific variables for a vulnerability assessment based on the hazard type and locational characteristics are essential. Moreover, the lessons learned from our analysis can generally be applied to other case studies. However, in some cases, our results are specific, for instance in cities with similar types of urban development patterns in emerging economies with formal and informal development patterns.

Overall, a methodology for this study is established to explore the relationship between heat-related human vulnerability and typologies of development patterns. The key objective is to strengthen the knowledge about the climate change adaptation needs of residents living in different urban areas at different stages of development. However, there is an urgent need to dynamically understand cities, their transformation processes, and their exposure and vulnerability to overall climate hazards in order to devise policy recommendations. Therefore, more research is required on how to develop an integrative assessment framework that can capture the dynamics of urban development (densification vs. expansion, demographic change, and economic development), dynamics of behavior (travel pattern and activities profiles), dynamics of exposure (day and nighttime temperature) and dynamics of vulnerability.

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Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Criteria of developed and undeveloped areas.

Characteristics	Undeveloped Areas/Informal Areas	Planned Areas/Formal Areas
Density	High	Low–medium
Pattern of houses	Irregular	Uniform
Building line **	Less than 5 ft.	5 ft. to 20 ft. or more *
Layout of roads	Irregular layout pattern	Uniform layout pattern
Width of streets	Less than 30 ft.	30 ft. to 220 ft. or more *
Number of green spaces	Fewer	More
Plot size	Max. 5 marla 1 marla = 225 sq. feet (Lahore City) 1 marla = 272.5 sq. feet (other cities)	5 Marla to 4 Kanal or more *

Source: The Urban Unit, 2018. * If the value exceeds from the maximum value, it will be considered an anomaly. ** Building line means a line beyond which the outer face of any building except compound wall, may not project in the direction of any street existing or proposed.

Appendix B

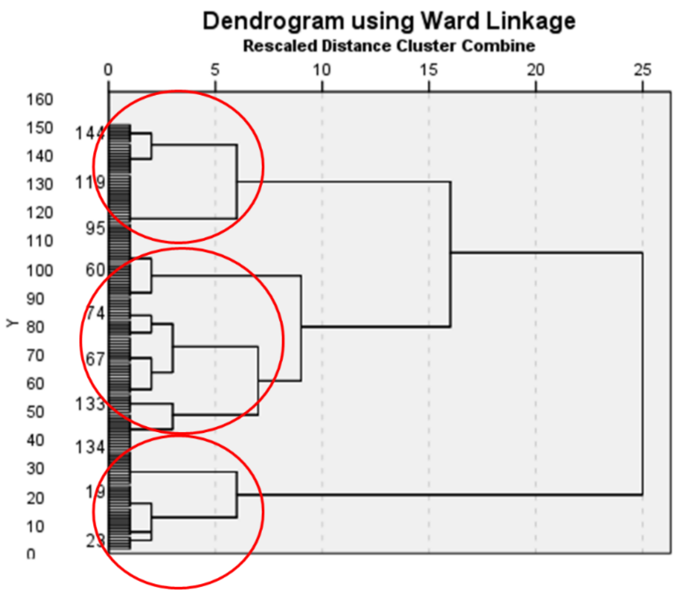

Figure A1. Dendrogram from hierarchical cluster analysis (red circles present optimal clusters, i.e., the value of k). Source: Own figure.

Appendix C

Table A2. Exposure, susceptibility, capacity, and vulnerability index at UC level in Lahore.

NO.	UC	Exposure Index	Susceptibility Index	Capacity Index	Vulnerability Index	Vulnerability Rank
1	Cantonment	0.59	0.45	0.45	0.00	Lower
2	Bhangali	0.31	0.44	0.44	0.00	Lower
3	Anarkali	0.68	0.35	0.35	0.01	Lower
4	Sanda Kalan	0.82	0.33	0.32	0.01	Lower
5	Chohan Park	0.44	0.35	0.34	0.01	Lower
6	Darogha Wala	0.46	0.52	0.50	0.01	Lower
7	Qila Gujjar Singh	0.74	0.36	0.34	0.02	Lower
8	Bilal Park	0.82	0.45	0.44	0.02	Lower
9	Jinnah Hall	0.72	0.35	0.34	0.02	Lower
10	Gujjar Pura	0.41	0.34	0.32	0.02	Lower
11	Railway Colony	0.74	0.43	0.45	0.03	Lower
12	Muslim Abad	0.42	0.54	0.51	0.04	Lower
13	Barki	0.38	0.51	0.55	0.04	Lower
14	Riwaz Garden	0.58	0.41	0.37	0.04	Lower
15	Muhammad	0.31	0.52	0.56	0.04	Lower

Table A2. *Cont.*

NO.	UC	Exposure Index	Susceptibility Index	Capacity Index	Vulnerability Index	Vulnerability Rank
16	Dograi Kalan	0.25	0.51	0.56	0.05	Lower
17	Kareem Park	0.55	0.43	0.38	0.05	Lower
18	Minhala	0.17	0.51	0.57	0.05	Lower
19	Mian Meer	0.27	0.48	0.43	0.06	Lower
20	Hadiara	0.34	0.49	0.55	0.06	Lower
21	Shadman	0.51	0.33	0.40	0.07	Lower
22	Muhamad Colony	0.62	0.39	0.33	0.07	Lower
23	Mustafa Abad	0.45	0.48	0.41	0.07	Lower
24	Hanjarwal	0.32	0.42	0.34	0.08	Lower
25	Lakhodher	0.27	0.49	0.57	0.08	Lower
26	Chah Miran	0.81	0.31	0.24	0.08	Lower
27	Sodiwal	0.84	0.38	0.46	0.08	Lower
28	Maraka	0.39	0.45	0.36	0.08	Lower
29	Mozang	0.75	0.44	0.36	0.09	Lower
30	Salamat Pura	0.90	0.54	0.45	0.09	Lower
31	Sare Sultan	0.83	0.41	0.32	0.09	Lower
32	Gulgasht Colony	0.83	0.38	0.47	0.09	Lower
33	Sanda Khurd	0.80	0.41	0.32	0.10	Lower
34	Garhi Shahu	0.52	0.40	0.50	0.10	Lower
35	Shahpur	0.38	0.45	0.35	0.10	Lower
36	New Samanabad	0.83	0.35	0.46	0.11	Lower
37	Harbanspura	0.64	0.47	0.36	0.11	Lower
38	Shamke Bhattian	0.01	0.50	0.39	0.11	Lower
39	Bhaseen	0.00	0.49	0.60	0.11	Lower
40	Haloke	0.78	0.44	0.33	0.11	Lower
41	Jia Bagga	0.38	0.46	0.35	0.11	Lower
42	Bhaseen	0.56	0.62	0.51	0.11	Lower
43	Shah Kamal	0.77	0.35	0.47	0.11	Lower
44	Bilal Ganj	0.76	0.43	0.32	0.11	Lower
45	Ali Raza Abad	0.75	0.45	0.33	0.12	Low
46	Pandoki	0.18	0.49	0.37	0.12	Low
47	Kot Khawaja	0.83	0.34	0.22	0.12	Low

Table A2. *Cont.*

NO.	UC	Exposure Index	Susceptibility Index	Capacity Index	Vulnerability Index	Vulnerability Rank
48	Chandrai	0.68	0.44	0.32	0.12	Low
49	Kot Lakhpat	0.70	0.33	0.45	0.12	Low
50	Hair	0.26	0.49	0.36	0.13	Low
51	Faiz Bagh	0.84	0.34	0.21	0.13	Low
52	Ganj Kalan	0.83	0.43	0.30	0.13	Low
53	Dhaloke	0.25	0.49	0.35	0.13	Low
54	Pakki Thatti	0.81	0.32	0.46	0.14	Low
55	Sabzazar	0.46	0.48	0.34	0.14	Low
56	Gajju Matta	0.47	0.46	0.33	0.14	Low
57	Khawaja Saeed	0.47	0.50	0.36	0.14	Low
58	Kasur Pura	0.26	0.54	0.40	0.14	Low
59	Sham Nagar	0.81	0.32	0.46	0.14	Low
60	Gulshan-e-ravi	0.82	0.32	0.46	0.14	Low
61	Race Course	0.30	0.30	0.44	0.14	Low
62	Manga	0.19	0.53	0.38	0.14	Low
63	Bibi Pak Daman	0.65	0.32	0.47	0.15	Low
64	Ichhra	0.73	0.35	0.50	0.15	Low
65	Islam Pura	0.82	0.46	0.32	0.15	Low
66	Kahna Nau	0.31	0.49	0.34	0.15	Low
67	Gawalmandi	0.80	0.46	0.31	0.15	Low
68	Niaz Beg	0.34	0.50	0.35	0.15	Low
69	Paji	0.59	0.50	0.35	0.15	Low
70	Johar Town	0.63	0.48	0.33	0.15	Low
71	Daras Baray Mian	0.59	0.34	0.50	0.16	Medium
72	Baghbanpura	0.82	0.39	0.23	0.16	Medium
73	Green Town	0.73	0.47	0.30	0.16	Medium
74	Kamahan	0.64	0.49	0.32	0.17	Medium
75	Rizwan Park	0.75	0.32	0.49	0.17	Medium
76	Dullo Khurd Kalan	0.58	0.49	0.32	0.17	Medium
77	Chung	0.60	0.53	0.35	0.18	Medium
78	Guldasht Colony	0.67	0.52	0.34	0.18	Medium
79	Fateh Garh	0.88	0.61	0.29	0.18	Medium
80	Shad Bagh	0.86	0.42	0.24	0.19	Medium
81	Faisal Town	0.50	0.33	0.52	0.19	Medium

Table A2. *Cont.*

NO.	UC	Exposure Index	Susceptibility Index	Capacity Index	Vulnerability Index	Vulnerability Rank
82	Al-faisal Town	0.80	0.50	0.31	0.19	Medium
83	Rehman Pura	0.82	0.27	0.46	0.19	Medium
84	Sultan Mehmood	0.79	0.62	0.43	0.19	Medium
85	Gulberg	0.46	0.30	0.49	0.19	Medium
86	Township	0.74	0.48	0.29	0.19	Medium
87	Wassanpura	0.83	0.43	0.23	0.20	Medium
88	Farid Colony	0.75	0.47	0.27	0.20	Medium
89	Tajpura	0.82	0.50	0.30	0.20	Medium
90	Ameen Pura	0.85	0.51	0.31	0.20	Medium
91	Township Sec A	0.70	0.51	0.31	0.20	Medium
92	Bahawalpur Hs	0.69	0.29	0.49	0.20	Medium
93	Baghat Pura	0.80	0.48	0.27	0.20	Medium
94	Rehmat Pura	0.83	0.45	0.25	0.21	High
95	Nawan Kot	0.79	0.27	0.48	0.21	High
96	Taj Bagh	0.72	0.52	0.31	0.21	High
97	Gulshan-e-iqbal	0.78	0.27	0.48	0.22	High
98	Babu Sabu	0.37	0.29	0.51	0.22	High
99	Makkah Colony	0.51	0.27	0.50	0.23	High
100	Liaqatabad	0.39	0.30	0.53	0.23	High
101	Makhanpura	0.83	0.45	0.22	0.23	High
102	Begum Pura	0.83	0.45	0.22	0.23	High
103	Siddique Colony	0.20	0.26	0.50	0.24	High
104	Angori Bagh	0.75	0.50	0.26	0.24	High
105	Keer Kalan	0.69	0.52	0.29	0.24	High
106	Maryam Colony	0.64	0.55	0.31	0.24	High
107	Bhamman	0.19	0.50	0.25	0.25	High
108	Mujahidabad	0.83	0.50	0.25	0.25	High
109	Kashmir Block	0.82	0.21	0.47	0.25	High
110	Kot Begum	0.45	0.50	0.24	0.26	Higher
111	Crown Park	0.81	0.50	0.23	0.27	Higher

Table A2. *Cont.*

NO.	UC	Exposure Index	Susceptibility Index	Capacity Index	Vulnerability Index	Vulnerability Rank
112	Bostan Colony	0.79	0.56	0.29	0.27	Higher
113	Samanabad	0.68	0.24	0.51	0.27	Higher
114	Nabipura	0.84	0.58	0.31	0.27	Higher
115	Ghaziabad	0.78	0.58	0.30	0.28	Higher
116	Awan Town	0.82	0.56	0.28	0.28	Higher
117	Ismail Nagar	0.84	0.53	0.24	0.28	Higher
118	Saidpur	0.85	0.53	0.25	0.29	Higher
119	Dhair	0.10	0.58	0.29	0.29	Higher
120	Zaman Park	0.39	0.21	0.50	0.29	Higher
121	Attari Saroba	0.59	0.58	0.28	0.29	Higher
122	Pindi Rajputan	0.66	0.16	0.46	0.30	Higher
123	Naseer Abad	0.53	0.22	0.52	0.30	Higher
124	Mughalpura	0.78	0.61	0.30	0.30	Higher
125	Al-hamra	0.22	0.24	0.55	0.31	Higher
126	Madhu Lal Husain	0.83	0.53	0.22	0.31	Higher
127	Muslim Town	0.50	0.24	0.55	0.31	Higher
128	Aziz Colony	0.56	0.52	0.21	0.31	Higher
129	Rashidpura	0.85	0.61	0.29	0.32	Higher
130	Fateh Garh	0.83	0.47	0.29	0.32	Higher
131	Siddiqia Colony	0.54	0.56	0.24	0.32	Higher
132	Faisal Park	0.54	0.55	0.22	0.33	Higher
133	Androon Texali	0.67	0.56	0.23	0.33	Higher
134	Bakar Mandi	0.83	0.59	0.25	0.33	Higher
135	Sikandar Block	0.57	0.18	0.53	0.35	Higher
136	Raiwind	0.85	0.59	0.24	0.35	Higher
137	Farooq Ganj	1.00	0.50	0.15	0.35	Higher
138	Androon Bhatti	0.58	0.59	0.23	0.36	Higher
139	Siddique Pura	0.41	0.58	0.22	0.36	Higher
140	Rang Mahal	0.82	0.53	0.17	0.37	Higher
141	Model Town	0.39	0.16	0.53	0.37	Higher

Table A2. *Cont.*

NO.	UC	Exposure Index	Susceptibility Index	Capacity Index	Vulnerability Index	Vulnerability Rank
142	Garden Town	0.44	0.14	0.51	0.38	Higher
143	Androon Dehli	0.67	0.59	0.21	0.38	Higher
144	Shahdara	0.47	0.60	0.22	0.38	Higher
145	Qaiser Town	0.27	0.63	0.25	0.38	Higher
146	Jia Musa	0.70	0.58	0.18	0.39	Higher
147	Qila Lachhman	0.74	0.58	0.18	0.41	Higher
148	Bangali Bagh	0.79	0.58	0.17	0.41	Higher
149	Kot Mohibbu	0.72	0.60	0.16	0.44	Higher
150	Sittara Colony	0.73	0.68	0.24	0.44	Higher
151	Fruit Mandi	0.58	0.64	0.19	0.45	Higher

Source: Own data based on index calculations.

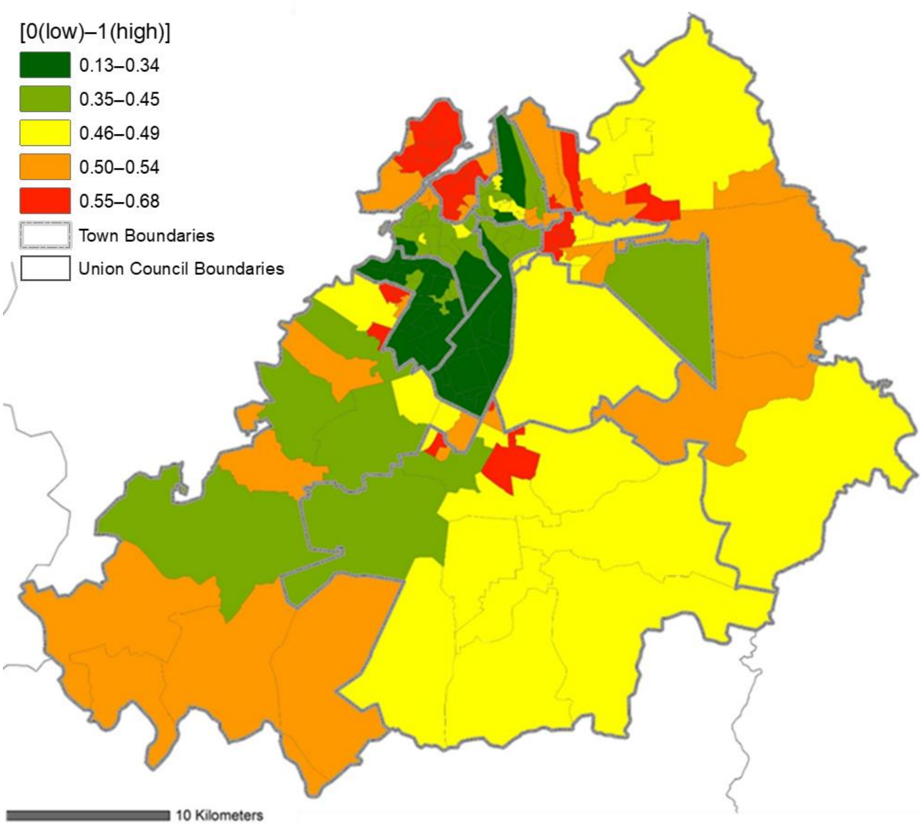

Figure A2. Map showing the susceptibility of residents to heat stress in Lahore city. Source: Own figure based on Population Census 2017, MICS 2008, JICA 2012, and Health Report Lahore 2017.

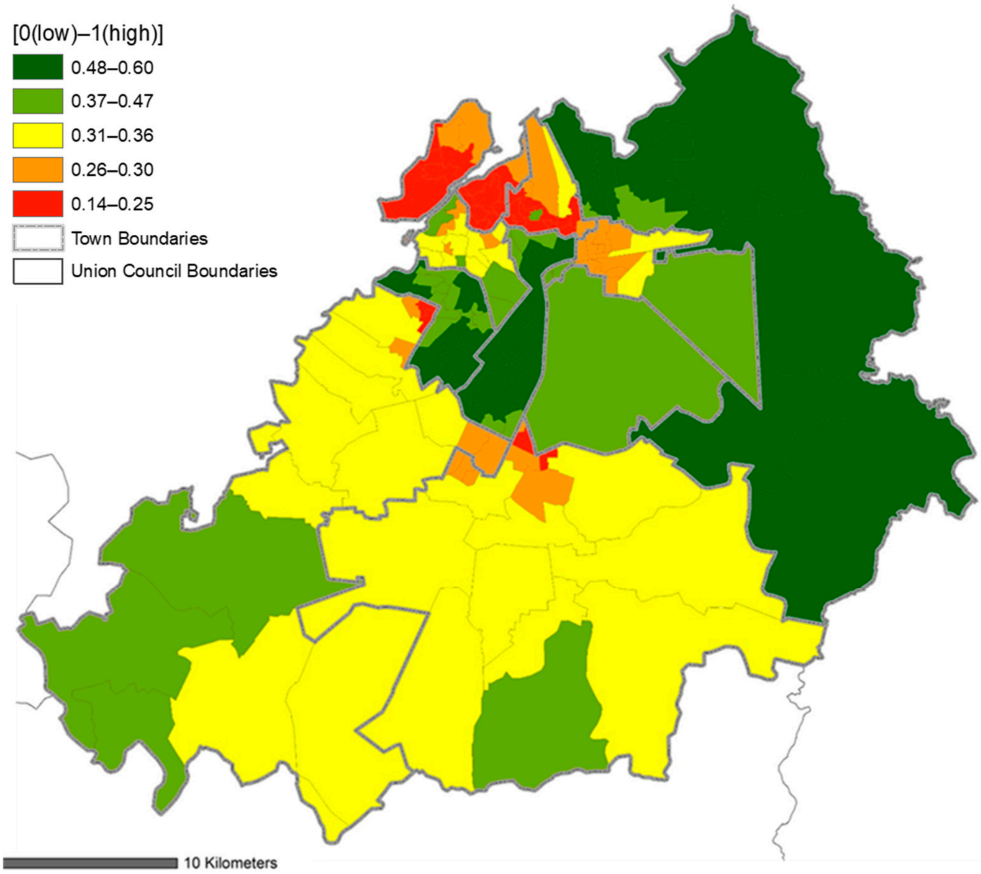

Figure A3. Map showing lack of coping and adaptive capacity of residents to heat stress in Lahore city. Source: Own figure based on Population Census 2017, MICS 2008, and Landsat 8 data.

Appendix D

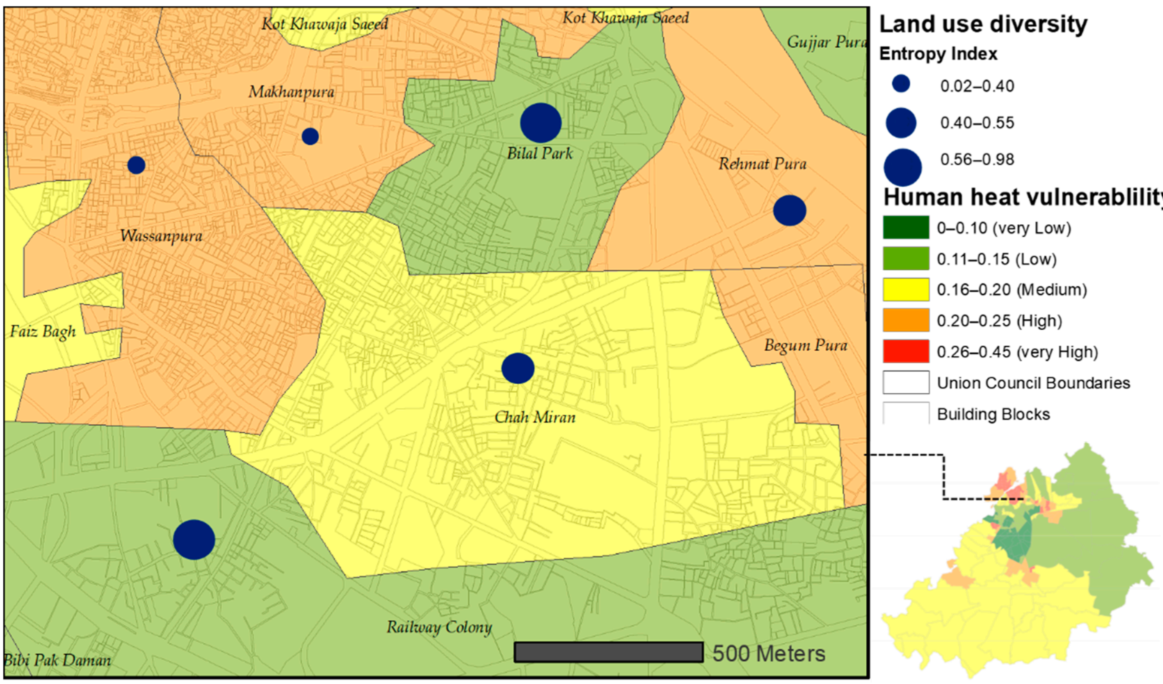

Figure A4. A map showing the settlement patterns, land-use diversity, and human heat vulnerability in a neighborhood in Lahore. Source: Own figure.

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