Identifying the high urban heat vulnerability zones of a city for prioritizing mitigation measures.

Highlights

- Construction of a composite heat vulnerability index (HVI) using the unweighted additive overlay method
- The framework is applicable for obtaining the HVI for any city
- Policymakers and urban planners can utilize the framework to mitigate heat hazards and provide relief

Abstract

Climate warming is raising global temperatures by 0.2°C every decade, generating severe heat waves and health risks. In India, urbanization has increased heat and humidity. The Urban Heat Island effect in Delhi puts many people at risk for heat-related health issues. This research identifies Delhi's high-vulnerability zones based on people's environmental, demographic, and socioeconomic conditions. The study analyzed vulnerability variables such as land surface temperature, land use, land cover, population density, and income level to identify high-risk zones in Delhi using the "unweighted additive overlay" approach. It is found that heat stress is most prevalent in 40 wards in Delhi's central-western and eastern regions. These findings underline the necessity for adaption methods and specialized urban design strategies and policies for heat reduction for those with weak adaptive ability. The study would assist officials in giving heat relief to high-vulnerability wards and include heat mitigation methods in Delhi's new master plan.

Keywords: urban heat island effect, heat vulnerability index (HVI), mitigation, temperature

Introduction

Delhi, located in the north of India and consisting of 289 wards and 11 districts, is one of the largest and fastest-growing metropolitan agglomerations in the country [1]. It also ranks second at the global level for having the highest number of 'person-days' per year [2]. As per the National Building Code (NBC) of India [3], the region exhibits a composite climate characterized by elevated maximum temperatures during the summer season. Additionally, owing to its geographical location, the area falls within the west-central Indo-Gangetic plain airshed, which renders it susceptible to higher temperatures due to high air pollution [4]. The inhabitants of the region are susceptible to a potentially grave concern, namely, exposure to high temperatures, particularly during the summer season, wherein the diurnal temperatures surpassed 45°C six times in May 2020 [5]. The phenomenon of near-surface urban heat island effect (UHIE) in the city contributes to the exacerbation of extreme heat. Numerous research endeavors in Delhi, spanning a significant duration, have demonstrated the interrelationship between diverse physical parameters, namely the built-up area's growth, vegetation alteration, and land surface temperature [6,7]. These parameters are, in turn, associated with the phenomenon of the urban heat island effect (UHIE). From these studies, it can be inferred that the development of urban heat islands in Delhi is primarily driven by the normalized difference vegetation index (NDVI), normalized difference built-up index (NDBI), and land use/land cover changes.

There are two broad ways to curb the UHIE and promote urban cooling – by diminishing the heat accumulation and by applying cooling techniques such as the introduction of greenery in the form of tree-covered walkways and cool pockets [8], shaded places like pedestrian arcades and covered parking [9], and conscious selection of surface finishing materials [10], painting roof surfaces with high albedo materials and green roofs[2][4], and control the energy consumption by buildings [12], are a few of them. The effect of these mitigation strategies in the domains of the building envelope, urban landscaping, pavement, and street geometry have been analyzed by the researchers using software for 3D numerical simulations such as FLUENT-ANSYS, BES with CFD simulations, and MITRAS [13][14]. Though a lot of studies were found on mitigation strategies, there was a lack of studies that considered the direct involvement and role of people in the mitigation of urban heat islands (UHI) [15][16]. In a recent case study of Singapore in 2020, the researcher conducted a survey to determine the willingness of the UHIE-affected population to participate in heat mitigation[17]. It was found that the willingness to pay (WTP) was directly proportional to the income and education of the population, that is, the socioeconomic factors. This study suggests that apart from evaluating the mitigation strategies, it is crucial to involve human perspective and vulnerability to estimate the social benefits of the solutions. Nordin.A.N. et al., in 2020, reviewed the studies that focused on the factors that influence people's WTP [18]. This research suggests that the UHI mitigation strategies, such as urban green spaces (UGS), fail due to insufficient funds by the government for its maintenance as well as a lack of sense of belongingness in people regarding the UGS. The accessibility, quality, and size of UGS also affect its relationship with people belonging to different socioeconomic backgrounds. Hence, there is a need to involve people in suggesting mitigation strategies according to their requirements and behaviour by conducting qualitative as well as quantitative surveys.

It can be said that UHIE is an urban-scale phenomenon that varies by the area's microclimate and can be mitigated through area-specific interventions that affect different populations based on their vulnerability level [19]. Even with the implementation of heat mitigation measures, some populations, such as children, migrants, and people in the low-income group, are more vulnerable to heat-stress-related health risks. Hence, in the absence of epidemiological data, the areas which are at a higher vulnerability risk within a UHI need to be identified using heat vulnerability indices [20].

The utilization of a composite index is a viable approach to evaluating the susceptibility of populations to health hazards associated with high temperatures, commonly referred to as the "Heat vulnerability index"(HVI). This method can effectively identify areas that require prompt intervention to ensure optimal outcomes that are both efficient and equitable [21]. The composite index generally integrates diverse environmental, social, and demographic variables, encompassing air temperature, availability of air conditioning, poverty level, age, and health condition, to generate a holistic representation of a community's vulnerability to heat strain. The computation of the HVI for a particular region enables decision-makers to optimize interventions and allocate resources precisely and efficiently. This is because the HVI offers insights into the communities that are most vulnerable and the specific factors that contribute to their vulnerability. The aforementioned data holds significant importance in strategizing and executing public health measures, such as establishing heat warning systems, disseminating heat-health education initiatives, implementing tree-plantation programs, and facilitating cooling centers to mitigate the detrimental health effects of heat waves[22].

The notion of susceptibility to thermal strain is frequently depicted as the aggregate of three interrelated components: exposure, sensitivity, and adaptive capacity [22].

- **Exposure** pertains to the magnitude of heat stress and how high it can get. The components of exposure can be broadly classified into two categories *Direct measures* and *Indirect measures*. The former includes heatwave days, consecutive hot days, min/mean/max air temperatures, and land surface temperature, while the latter comprises impervious surfaces, vegetation, urban density, land cover, land use, homes without A.C., and population density.
- **Sensitivity** refers to the degree to which an individual can be impacted. The categories of sensitivity are older adults, infants, young age, sex, diabetes, cardiopulmonary, renal, respiratory, and obesity.
- **Adaptive capacity** refers to the resources available to an individual or group to help them cope with heightened exposure to heat. The categories of adaptive capacity are air-conditioning access, living alone, income, homeownership, unhoused, education, ethnicity, language, foreign-born, cognitive impairment, and mobility/transportation.

In a study carried out between 1990 and 2000 in the City of Phoenix, which has higher average temperatures, near-surface air temperature, and NDVI were taken into account as the indicators for exposure, age over 65 as the indicator of sensitivity, and household income, ethnicity, and length of stay as the indicators for adaptive capacity. The study developed a composite vulnerability index using various indicators. Results indicated that social indicators, such as ethnicity and age, are more significant in determining vulnerability as compared to physical indicators [23]. A comprehensive study was conducted in various cities in the United States, utilizing ten vulnerability variables to determine the extent of vulnerability variation from local to national levels [24]. A vulnerability study was conducted in Seoul, Korea, in 2018. The study utilized the principle component analysis method to analyze sensitivity indicators, such as age and diabetes, and adaptive capacity indicators, such as income level and education, to calculate the HVI district-wise [25]. A study was conducted in Delhi to investigate the relationship between greenspace and social vulnerability to the urban heat island effect in urban areas. The study concluded that there was a significant correlation between higher vegetation and increased adaptive capacity of the population [26].

Though many studies have identified a correlation between vulnerability indicators, there is a limited number of research offering a streamlined approach to classify a city's wards based on their heat vulnerability. In the past few years, and with growing casualties due to heat waves, many nations have declared high temperatures a "national emergency" and a disaster [27, 28]. Facing any disaster requires a framework that can identify the people most affected by it and formulate mitigation techniques to decrease its impact. So, by considering high-temperature and heat waves as natural disasters, this study aims to categorize wards based on heat vulnerability. This will aid policymakers and urban planners in identifying priority wards for detailed surveys to determine appropriate mitigation strategies, implementation of those strategies, and summer heat relief measures.

During the period spanning from 2000 to 2020, Delhi underwent a swift expansion in anthropogenic activity and land use practices, which resulted in a persistent reduction in vegetation cover. This phenomenon led to an elevation in land surface temperature [6]. Significant alterations were noted in the minimum and maximum temperatures of the urban area. Specifically, the minimum temperature for May in the year 2000 was recorded at 23.20°C, while the maximum temperature was 34.85°C. These values escalated to 26.31°C and 39.92°C, respectively, in 2010.

Furthermore, in 2020, the minimum temperature was 31.70°C, and the maximum was 46°C. The NDVI has exhibited a decline from 82% to 62%, while the non-vegetated region has undergone a reduction from 82% to 62% over the past two decades, owing to rapid urbanization and land conversion. The swift urbanization process has resulted in significant alterations in surface conditions, leading to a substantial transformation in the region's demography, landscape, and ecosystem. These changes can potentially impact the vulnerability, as evidenced by the rise in reported health issues related to heat waves [27]. Therefore, we have selected Delhi as the city for our case study.

The main objectives of our study are –

i. To identify and map the physical and social indicators that are important and accessible for assessing the vulnerability of a ward.
ii. Design a simplified framework for identifying the heat-vulnerable wards of Delhi.
iii. Defining a heat vulnerability index (HVI) and identifying the vulnerable wards of Delhi.

To achieve our objectives, we formulated a metric to assess the susceptibility of individuals to heat stress in Delhi, India, by considering physical exposure factors such as population density, land surface temperature, land use, and land cover, as well as the adaptive capacity of the human population as indicated by income level. We proceeded to analyze the spatial distribution of this metric for a representative summer day and identified the wards of Delhi with the highest vulnerability to heat waves. According to the Indian Meteorological Department, India is at its peak of heat vulnerability when it experiences heat waves between May to June and sometimes in July[29]. Hence, May was selected as the time period for this study.

Methodology

The present investigation focused on the urbanized region of Delhi, as delineated by the 2011 Census. To derive a composite HVI, these five measures representing physical exposure and adaptive capacity were identified, as shown in Table 1.

Table 1: Measures for heat vulnerability index, their sources, and implications

Measure	Source	Indicator of/relationship to total vulnerability
Physical exposure		
1. Land surface temperature (LST)	Landsat 8 & 9	Ground-level heat stress in the region / positive
2. Land cover (built area)	Landcover map of Delhi	Low albedo and high imperviousness have high heating potential / positive
3. Land use	ESRI living atlas	Residential zones are more vulnerable/ positive
4. Population density	Census India	Higher population vulnerable to heat stress/ positive
Adaptive capacity		
5. Income level	NCAIR report	Lack of wealth/ positive

After identifying these measures, a framework for constructing HVI was derived, as shown in Figure 1.

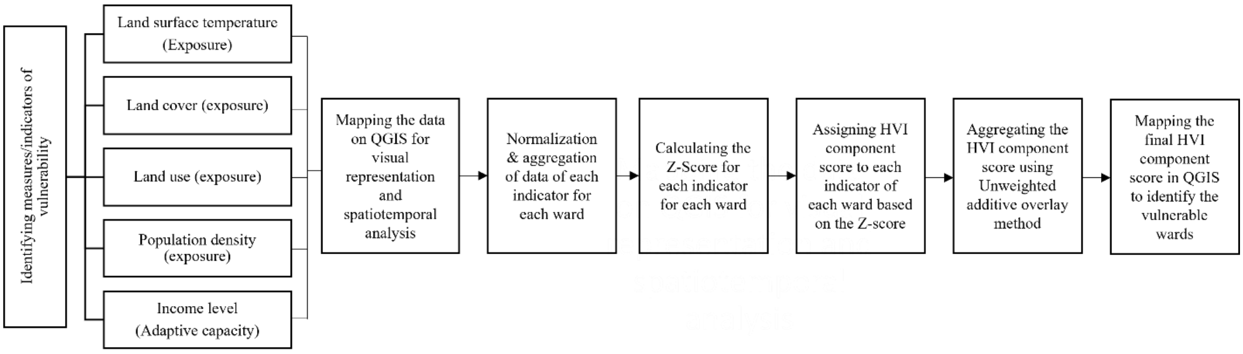

Figure 1: Framework for construction of HVI using unweighted additive overlay method.

The month of May, in which Delhi experiences the highest temperatures and heatwaves, was chosen for obtaining the data for vulnerability measures/indicators. Once, the data was gathered, it was mapped in a geographic information system software called QGIS for spatiotemporal analysis. Previous research in this field shows that regions exhibiting the most significant biophysical susceptibility do not coincide with those demonstrating the highest social vulnerability, and it is challenging to ascertain the relative significance of any particular measure. Therefore, an assumption was made that all measures carry equivalent weightage in evaluating susceptibility to extreme heat. Hence, upon completion of the geo-referencing and conversion of all raw data to shapefiles, an “unweighted additive overlay” method was applied. The approach involved assigning a Z-score to each vulnerability indicator in every ward, with values ranging from below -2 to above 2. Z-score is obtained by applying equation 1 for each value of each vulnerability indicator. Equation 1 is as follows:

$$Z-score=\frac{Observed\ value\ of\ the\ vulnerability\ indicator-mean\ of\ the\ vulnerability\ indicator}{Standard\ deviation\ of\ the\ vulnerability\ indicator} \tag{1}$$

The HVI component score was derived by assigning a value between 1 and 6 based on the corresponding Z-score, with a score of 1 being assigned to Z-scores of -2 or lower and a score of 6 being given to Z-scores of 2 or higher as shown in table 2. The HVI of each indicator was mapped ward-wise. The final value of the unweighted HVI (HVI_{UnW}) is determined by aggregating the HVI component scores of each individual indicator, and the ward that obtains the highest score is deemed the most vulnerable. The unweighted HVI (HVI_{UnW}) was calculated using equation 2:

$$HVI_{UnW}=HVI\ component\ score\ of\ [LST+percentage\ of\ Built\ area+percentage\ of\ residential\ area+population\ density+income\ level] \tag{2}$$

The values from Equation 2 were then used to construct the composite HVI map for Delhi. Table 3 shows the calculation of unweighted HVI (HVI_{UnW}) for four of such wards (183, 184, 185, & 187) of Delhi. In Table 3,

- P_D 2020 = Population density of ward in 2020
- I_L = Income level, where the high-income group is 1, the medium is 2, and the low is 3
- LC = Landcover percentage considering the built-up area percentage of each ward
- LST = Mean land surface temperature (LST) of each ward
- LU = Landuse, considering the residential area percentage of each ward

Table 2: A scoring mechanism for HVI construction

Range of Z-Score	HVI component score
-2 or lower	1
-2 to -1	2
-1 to 0	3
0 to 1	4
1 to 2	5
2 or higher	6

Table 3: Calculation of unweighted HVI for wards 183, 184, 185 & 187

Ward no.	Parameters					Z-Score					HVI score					HVI_{UnW}
	P_D	I_L	LC	LST	LU	P_D	I_L	LC	LST	LU	P_D	I_L	LC	LST	LU	
183	1182.6	3	100	40.1	100	1.3	1.4	0.6	0.56	1.32	5	5	4	4	5	23
184	284.6	1	99.6	39.6	81.6	-0.3	-1.3	0.6	0.25	0.86	3	2	4	4	4	17
185	239.4	3	73.6	40.3	15.4	-0.4	1.4	-0.7	0.68	-0.83	3	5	3	4	3	18
187	372.8	2	45.3	41.9	0	-0.1	0.1	-2.1	1.64	-1.22	3	4	1	5	2	15
	Continued...															

Results and discussion

Land surface temperature (LST) was employed as a physical exposure indicator on a sunny day in May 2020. The thermal image was acquired from the United States Geological Survey (USGS) via Landsat 8 satellite. LST was calculated from thermal data (band 6) utilizing the mono-window algorithm based on the thermal transference equation. May and June in Delhi experienced high temperatures conducive to the UHIE. Our weather station data indicate that these months had frequent hot, clear, and calm days and nights. Early summer heat waves in May may increase the risk of heat-related injuries as residents are not yet acclimatized to the sudden rise in temperature (EPA, 2006). In May 2020, the recorded values for maximum land surface temperature (T_{max}) and minimum land surface temperature (T_{min}) were 56°C and 28°C, respectively, in May. Higher Tmax and Tmin magnitudes indicate greater heat vulnerability. The land surface temperature data was analyzed in QGIS to identify wards with higher heat vulnerability based on the highest and lowest temperatures, as shown in Figure 2 (a). From the temperature data obtained from the LST map, an HVI map was also created to understand the wards with high vulnerability due to high LST, as shown in Figure 2(b).

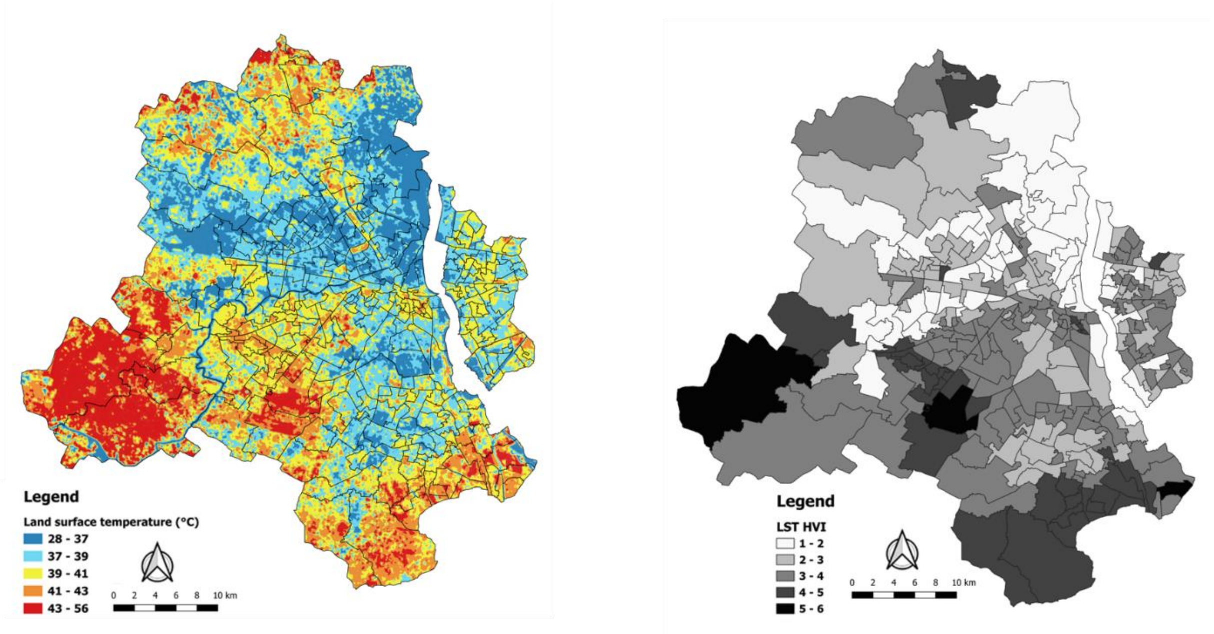

Figure 2 : (a) LST map of Delhi on 16th May 2020 (b) HVI map for LST

The land cover map of Delhi is the second exposure indicator obtained from the Delhi Municipal Corporation (DMC), as shown in Figure 3(a). It comprises seven categories: water, trees, flooded vegetation, crops, built area, bare ground, and range land. Only the built area feature was considered significant in contributing to higher heating effects due to its high imperviousness, low albedo, and potential for increased anthropogenic heat generation. Wards with a built area exceeding 60% were classified as highly vulnerable (HVI 3-4), those with a built area ranging from 40% to 60% were classified as moderately vulnerable (HVI 2-3), and wards with a built area less than 40% were classified as the least vulnerable (HVI 1-2) as shown in Figure 3(b).

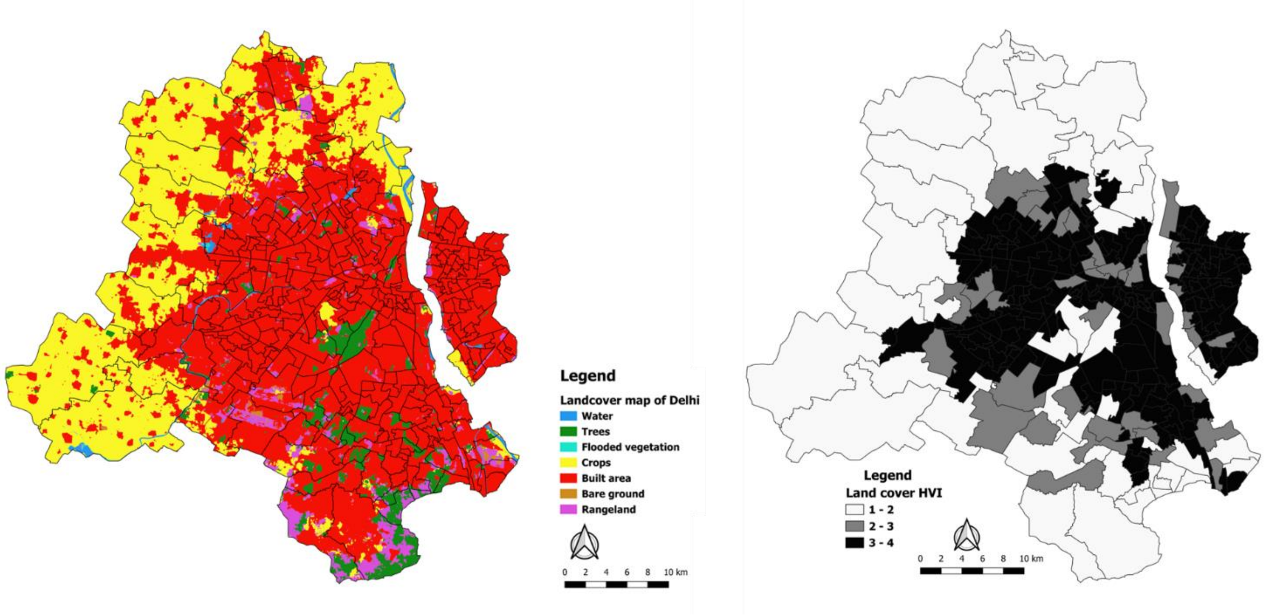

Figure 3: (a) Landcover map of Delhi (b) HVI map for land cover

Figure 3 shows that wards with more built-up area and impervious surfaces have a higher degree of vulnerability and is concentrated in the central and eastern part of Delhi.

The land use plan of Delhi was acquired from the ESRI living atlas through ArcGIS software as the third exposure indicator. The land use plan is classified into 17 categories, including agriculture, commercial, residential, industrial, recreational, and government land, as shown in Figure 4(a). Residential areas have been identified as more vulnerable than other land use categories. Wards were categorized based on the percentage of the residential regions they contained. Those with residential areas of more than 60% were deemed highly vulnerable (HVI 4 and above), those with 40% to 60% were moderately vulnerable (HVI 3-4), and those with less than 40% were considered the least vulnerable (HVI 3 and below) as shown in Figure 4. The spatial analysis was visualized through Figure 3 utilizing the QGIS mapping software.

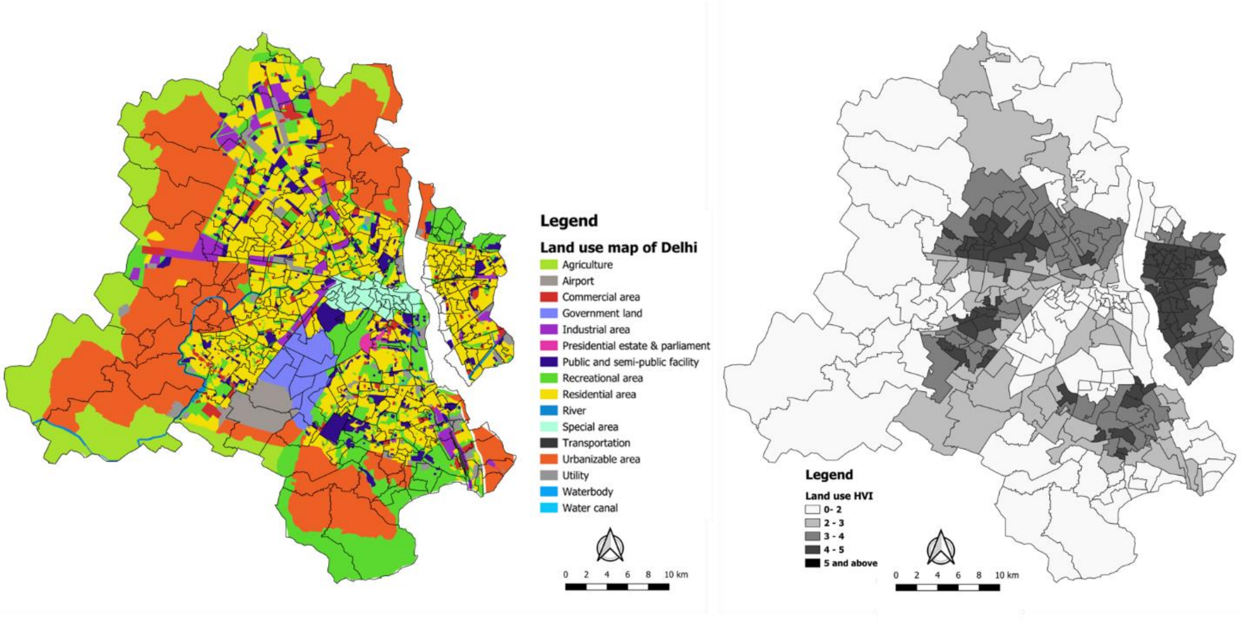

Figure 4: (a) Land use plan of Delhi (b) HVI map for land use

Figure 4 indicates that the wards with higher residential areas at the higher end of vulnerability are concentrated on the eastern side, with a few small concentrations in the central and southeastern parts of Delhi.

One of the purposes of this study is to identify the highest number of people who are most vulnerable to heat stress. Therefore, population density represents the fourth indicator of exposure. The census data pertaining to the population of each ward was obtained from the DMC database for the year 2020. It is believed that wards characterized by bigger population density are likely to harbor a more significant proportion of individuals susceptible to higher temperatures, rendering them more susceptible to adverse effects of heat. The population densities of the wards were categorized into five groups based on their magnitude, ranging from the highest to the lowest, as shown in Figure 5(a). The wards were classified into three degrees of vulnerability- high vulnerability for higher population density (HVI 5-6), moderate vulnerability for medium density (HVI 4-5), and low vulnerability for low density (HVI 3-4). The graphical representation of this phenomenon is illustrated in Figure 5(b).

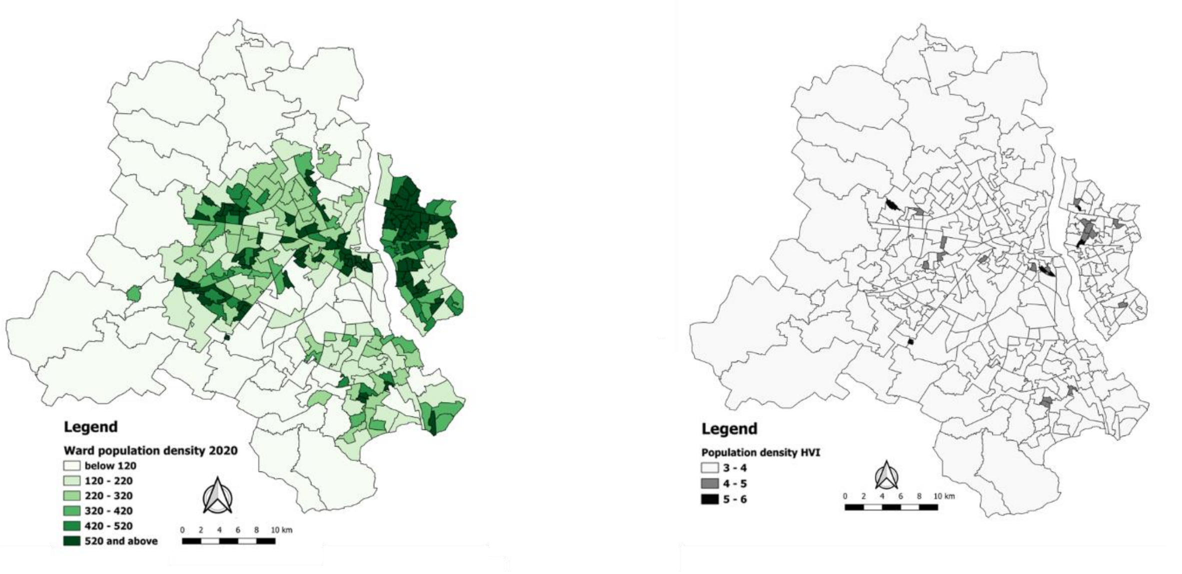

Figure 5: (a) Delhi ward population density for the year 2020 (b) HVI for population density

There are only six wards that have high vulnerability according to the population density of Delhi, as shown in Figure 5.

The adaptive capacity of various wards was assessed based on the income levels of their respective residents. As per the 2022 report by the World Bank [30], a significant proportion of India's populace, approximately two-thirds, subsists on a daily income of less than 2 USD. The acquisition of an air-conditioning unit in India can result in an average expenditure ranging from 260 USD to 500 USD, rendering it a luxury that only 8 percent of Indian households can afford. Therefore, it can be inferred that individuals with lower income levels are likely to be the most susceptible to heat waves. Figure 6(a) displays the income distribution across various wards [31]. So, to keep the indicator unidirectional, we assigned one vulnerability point to the high-income group, two to the middle-income group, and three to the low-income group and created an HVI map based on that, as shown in Figure 6(b). Figure 6 shows that the low-income, high-vulnerability population is concentrated in the western and southeastern parts of Delhi.

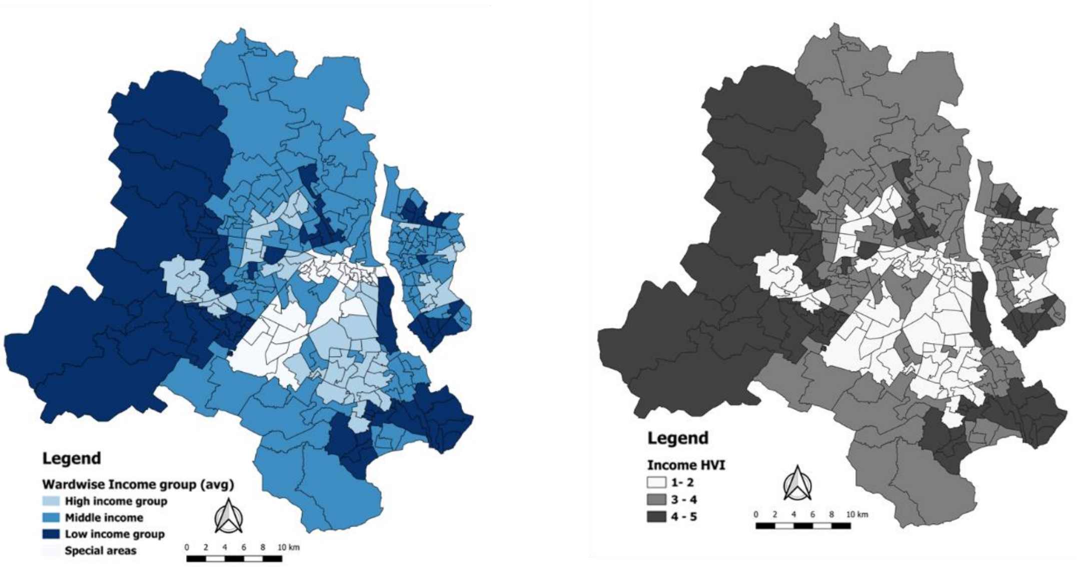

Figure 6: (a) Ward-wise income level of Delhi (b) HVI for income level

The composite heat vulnerability map with HVI_{UnW} is created from the data obtained from equation 1 and is illustrated in Figure 7.

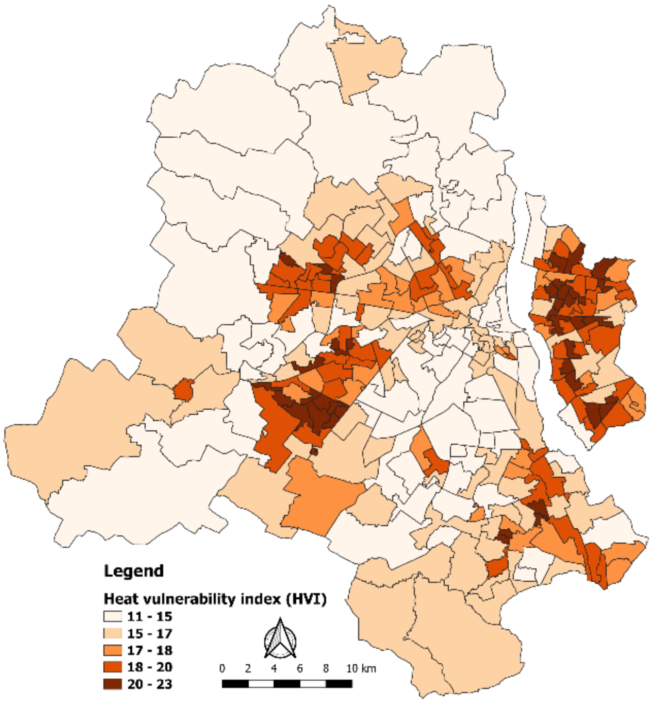

Figure 7: HVI of wards of Delhi using unweighted additive overlay.

Forty wards exhibit the highest degree of vulnerability, as depicted in Figure 7. Wards with HVI 20-23 are primarily located in eastern and central-western Delhi. Whereas the wards exhibiting low vulnerability, categorized as HVI 11-15, are predominantly situated in Delhi's northern and central-southern regions. Figure 8 displays the HVI maps for each indicator and a composite HVI map containing all indicators. The high vulnerability zones on the individual map exhibit partial overlap. Thus, it can be inferred that a single indicator is insufficient in accurately predicting the vulnerability of a group.

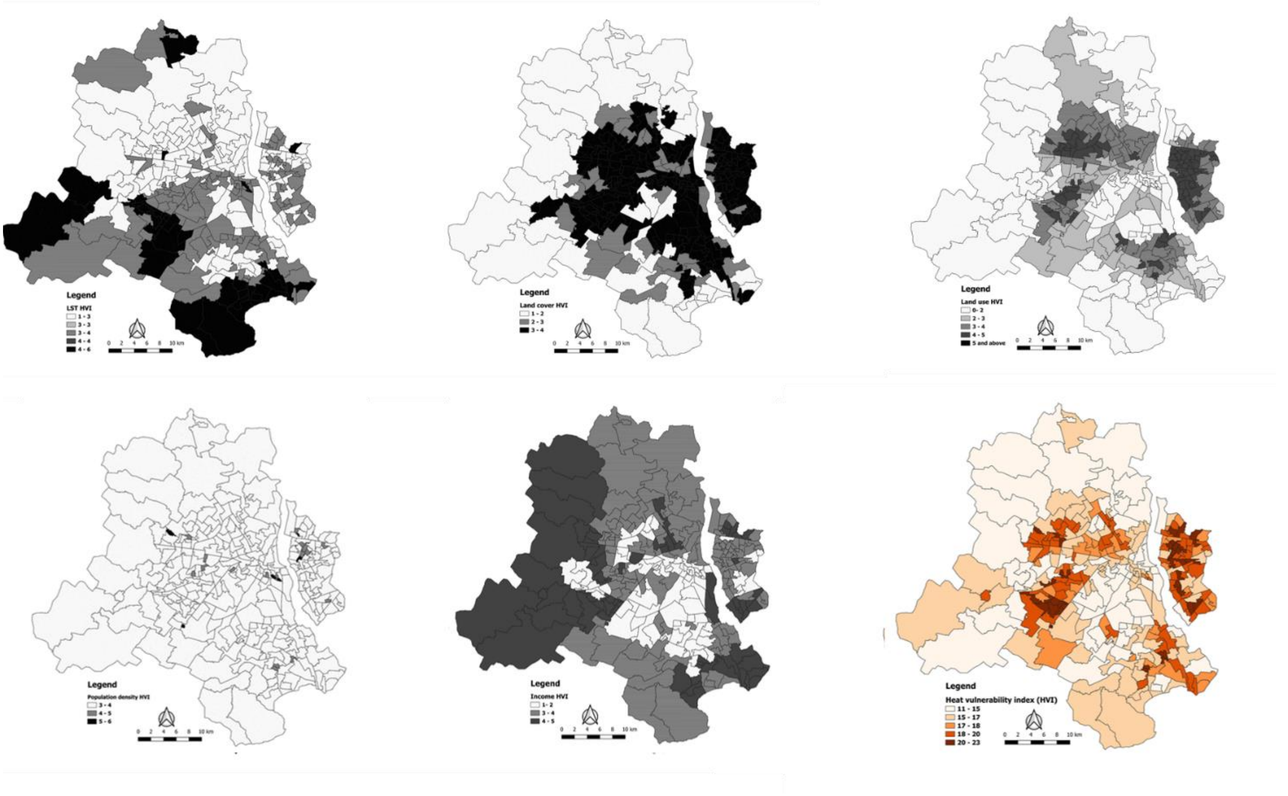

Figure 8: A comparison between HVI maps created using each indicator (top left to right) LST, land cover, land use (Bottom left to right) population density, income level, and composite HVI map of all five indicators

Conclusion

The study has documented how the heat vulnerability index varies with the input of different indicators individually as well as compositely. It also shows that better accuracy in finding the HVI can be achieved if five indicators are used instead of one. The vulnerable wards identified through this study can be prepared for the next heatwave to reduce casualties caused by high temperatures during summer. With Delhi on the way to becoming the most populous city in the world by 2030, it is very likely that more land cover will be urbanized, and the population density will also increase, ultimately resulting in a large population susceptible to heat hazards. This may result in a heightened susceptibility to heat hazards. The study's framework is helpful for policymakers and urban planners to create heat mitigation and relief plans. However, a more detailed analysis utilizing a complex HVI construction method and multiple vulnerability indicators can improve the accuracy of HVI prediction.

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