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Research Article

Mapping of heat vulnerability in Indian Urban Centres under threat of global warming

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Abstract
There is a need for a multi-dimensional approach to map heat vulnerability in urban areas to address the growing threat of heat waves in India. However, heat action planning in India is currently underdeveloped, and previous studies have used diverse and fragmented methods to assess vulnerability. The present study aimed to present a unified framework for mapping heat vulnerability in Indian urban centres based on the systematic review of literature. The framework included three techniques: unweighted additive overlay, weighted additive overlay, and principal component analysis (PCA), for constructing a composite index called the heat vulnerability index (HVI). The PCA-based approach was particularly suitable when multiple criteria were involved in assessing heat vulnerability, as it could capture the underlying relationships between them. Moreover, using GIS-based maps helped to visualize and reveal critical information about vulnerable areas, aiding in identifying priority regions for heat interventions. The study also examines the meaning of HVIs and the sensitivity of the techniques to three factors: the selected indicators, construction method, and scale of analysis. By providing a common framework for assessing heat vulnerability, the study would be helpful to support policymakers in prioritizing interventions to reduce the impact of heat waves on vulnerable populations in Indian cities and beyond, which are also experiencing varying levels of impact from global warming.

Keywords: Heat waves, Public health, Resilience, Spatial analysis, Urbanization

INTRODUCTION

Extreme heatwaves are becoming more frequent and intense due to climate change, with potentially disastrous health and economic consequences for the global community (Witze, 2022; Ford *et al*.,2005). Persistent exposure to extreme heat can lead to increased mortality and morbidity, occupational health problems, and reduced work capacity, thus negatively affecting economic productivity (Campbell *et al*., 2018). The scientific literature on this topic is steadily accumulating, with many studies providing insights into the determinants of heat-related problems and offering lessons with policy relevance (Sheridan and Allen,2018). A recent global study estimated that almost half of the world's population and over 1 billion workers are exposed to high heat episodes, with about a third experiencing negative health consequences (Romanello, 2021).

In India, heat events have already become a public health emergency, with thousands of deaths linked to heat stress reported by the National Disaster Management Authority (NDMA, 2021). The incidence of heat waves with greater intensity has been increasing, and future events are predicted to become even more severe (Eun-Soon Im *et al*., 2017). Tropical countries like India and their urban populations are particularly vulnerable to the risks of heat events compared to other temperate countries (Veena, 2020; Dubey *et al*., 2021; Callahan and Mankin, 2022). Large urban populations concentrated in cities with limited infrastructure facilities and capacities of civic bodies put exposed individuals at a higher risk of suffering (Jha, 2021). Moreover, most urban residents in India are also exposed to urban heat island (UHI) effects, in which urban areas experience higher temperatures than outlying areas (Tuholskea *et al*., 2021). Thus, urban residents in India face both natural heat waves interacting with global warming and UHI effects, compounding health problems for most of the country's 480 million urban residents (Tuholskea *et al*., 2021).

Heat action plans and implementing heat intervention measures have been shown to enhance public resilience to heat stresses and prevent many of the adverse effects of heat hazards (Ebi, 2019). Results of heat vulnerability assessments may guide policymakers to accurately identify heat spots for optimal allocation of adaptation resources and better communicate heat risks to the public. Heat vulnerability assessment is crucial for understanding the processes that contribute to the vulnerability of people and locations to the adverse effects of heat events, including those compounded by global warming. The heat vulnerability index (HVI), a composite index has recently gained popularity as a tool for quantitatively assessing the driving factors of heat-vulnerable populations. Its use of many indicators spanning biophysical, socioeconomic, and demographic factors allows for a comprehensive assessment through a single metric, making it an attractive tool for administrators, health practitioners, and policymakers for implementing targeted heat risk interventions.

However, despite its utility, few studies have mapped the heat vulnerability of Indian cities using HVI, and existing studies adopt a range of methodologies without a common approach. This lack of a uniform methodological framework has created confusion regarding the appropriate assessment approach and has partly hindered the development of heat action plans in India. Therefore, this study aimed to fill the existing gap in the literature by providing a common approach to HVI construction for heat vulnerability assessment in the Indian context, which could aid in the development of an effective heat action plan. The specific objectives were to i) demonstrate the steps involved in composing HVI by presenting three different techniques of varying complexity and ii) examine the sensitivity of HVIs to three design choices: the selected indicators, construction method, and scale of analysis.

MATERIALS AND METHODS

A comprehensive literature search and review were conducted using various keywords related to heat vulnerability in Scopus and Google Scholar databases to propose a methodological framework for assessing heat vulnerability in Indian cities that experience urban heat problems. Articles that contained index-based assessments of heat vulnerability with empirical findings were selected for inclusion in the review process. Studies that contributed to understanding human systems' vulnerability to environmental change were also examined. Moreover, the studies that proposed robust composite indices of complex concepts were consulted to develop the proposed framework.

The systematic review process followed the principles of a structured and rigorous search strategy, with key terms including 'heat vulnerability,' 'heat stress,' 'urban heat island,' and 'heat vulnerability India.' Only highly cited and relevant articles were considered for inclusion in the final review. The review process to the selection of a subset of articles provided critical insights into developing a unified and contextualized heat vulnerability mapping framework for Indian urban centres. Thus, the HVI construction methods presented below are an outcome of synthesizing a large volume of studies that made crucial methodological advancements in the development of HVI-based heat vulnerability mapping. Since the challenges of heat events before the residents of Indian cities are unique, all efforts were made to evolve methodologies that capture nuances of heat vulnerability characteristic to the country.

RESULTS AND DISCUSSION

Construction of Heat Vulnerability Index (HVI)

Although HVIs are composite indices prepared in the context of heat vulnerability, their composition procedure follows generic steps typical of Index-based Vulnerability Assessment (IBVA) index construction. Three steps are differentiated in the literature for developing such an index (Tonmoy *et al*., 2014).The first step involved defining the attribute for which heat vulnerability is to be assessed. The second step involves the selection of heat vulnerability indicators. The third step consists of aggregating indicators into a single measure of vulnerability. The steps mentioned above are elaborated in the subsequent sections as the present study expounds on HVI construction techniques of increasing complexity levels applicable in the context of Indian cities.

Selection of Heat vulnerability indicators

Heat vulnerability indicators are crucial for evaluating the potential impact of heat stress on a population. It is important to distinguish them from harm indicators, which measure the actual effects of a hazard (Tonmoy *et al*., 2014). Previous research on HVI has employed varying numbers of indicators spanning multiple determinants of heat vulnerability related to demographic characteristics, socioeconomic conditions, and built environment domains (Niu *et al*., 2021). To guide the selection of indicators, vulnerability can be viewed as a function of exposure, sensitivity, and adaptive capacity (Fig. 1). Exposure refers to people and things of value in places that could be impacted, while sensitivity denotes the degree to which heat hazards will impact individuals and communities. Adaptive capacity, on the other hand, refers to the ability of individuals and communities to recover and change in response to heat events to reduce vulnerability.

However, previous studies have used different numbers of indicators, ranging from six to twenty-nine, which may lead to oversights or redundancies among the indicators (Fig. 2). To determine the ideal type and number of indicators for HVI studies in Indian cities,

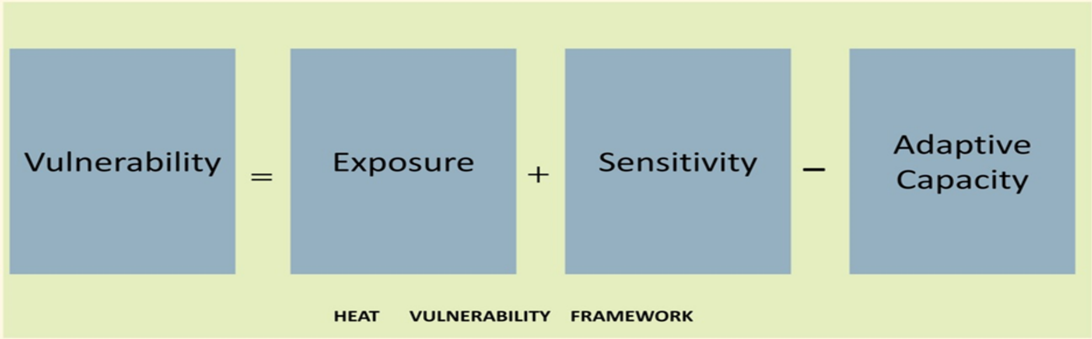

Fig. 1. *Vulnerability framework to guide indicator selection*

multiple approaches should be used to inform the indicator selection process (Hinkel, 2011). The deductive approach involves relying on available scientific knowledge of heat vulnerability to select theoretically informed indicators. In contrast, the inductive approach uses statistically established empirical relationships of heat vulnerability factors to derive indicators from analyses of observed data. Stakeholders can also provide valuable insights for indicator selection based on their deductive and inductive knowledge about heat vulnerability. This can help contextualize HVI to the geographical settings of the study area, increase local relevance, and focus policy interventions in vulnerable areas.

Heat vulnerability index construction techniques

The simplest technique for constructing an HVI is the unweighted additive overlay (UAO) approach, which involves selecting heat vulnerability indicators potentially influencing heat vulnerability and summing their scores without weighting. The resulting HVI score is an aggregate value for a given unit of analysis, such as a city or a neighbourhood (Fig. 3a). The use of Geographic Information Systems (GIS) technology enables the display of HVI scores on maps, facilitating better communication of the results (Reid *et al*., 2009). To enable a comparison of the indicators, a normalisation process is performed to bring them to a comparable unitless scale. The most commonly used normalisation method in the literature is the min-max rescaling transformation method, which transforms each variable into a range between zero and one, where a score of 0 represents the lowest rank for a given indicator, and a score of 1 represents the best (Yoon, 2012). The remaining values are then placed between the minimum and maximum values, followed by subtracting the minimum value (X min) and dividing by the range of the indicator values, i.e. $X_{max} - X_{min}$. This process preserves the order and relationship structure of the observed data (Tran *et al.,* 2010).

Under the UAO technique, the indicators are not weighted to reflect their variable importance and equal contributions are assumed to heat vulnerability (Tapsell *et al*., 2002). It is important to note that the HVI is constructed so that the indicators are unidirectional, meaning that an increase in an indicator value translates into an increase in vulnerability. The UAO approach is a valuable technique for HVI construction due to its simplicity, ease of implementation, and the availability of data. However, it is also important to note that this

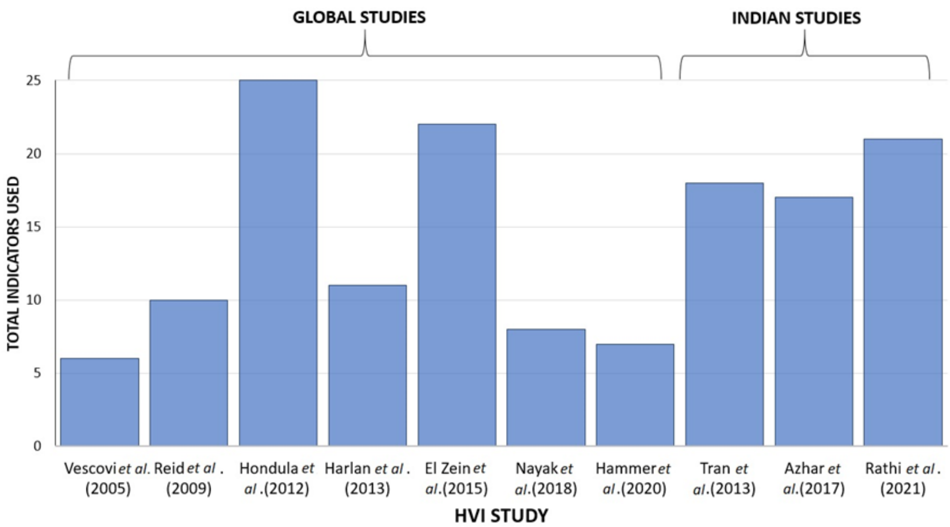

Fig. 2. *Number of indicators used in composing heat vulnerability index (HVI) to map heat vulnerability in studies undertaken in geographical settings outside and inside India*

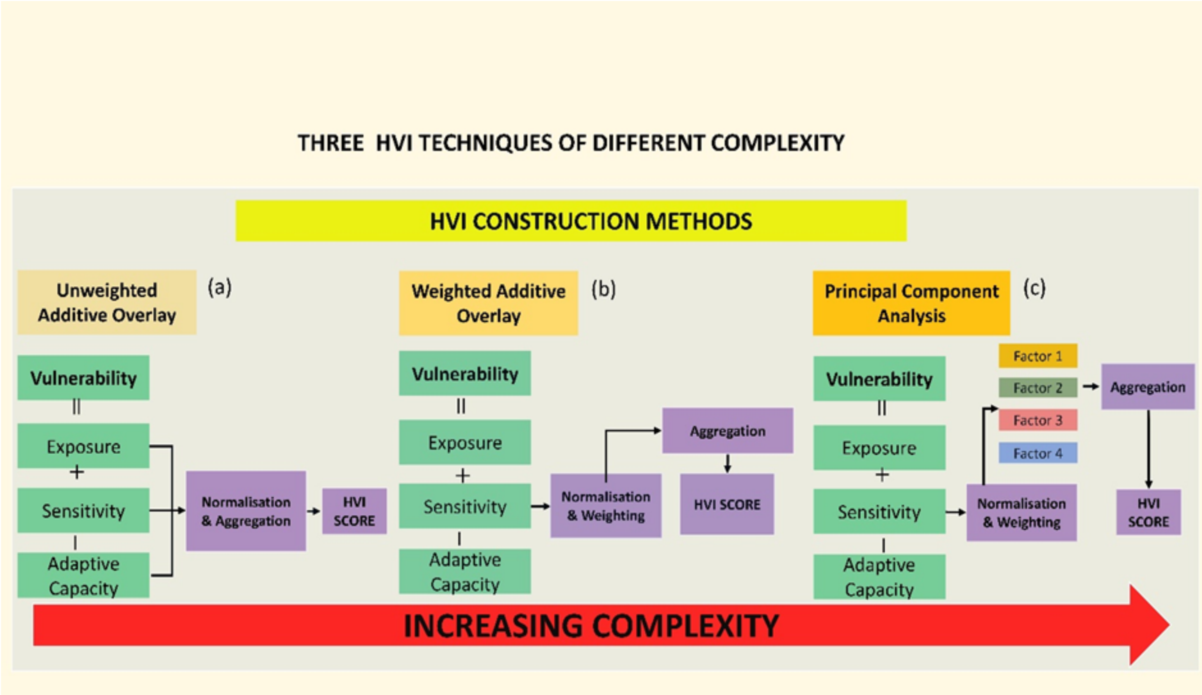

Fig. 3. *Multiple techniques of constructing heat vulnerability index (HVI). Composition complexity increases moving from left technique to the right in the figure :(a) A graphical description simple unweighted additive overlay technique; (b) weighted additive overlay with normalisation and weighting technique; (c) principal component analysis based advanced HVI technique (Source: Drawn by the author after reworking the ARSET (2022) framework to suit Indian context).*

method has limitations, such as the inability to account for the potential interactions among indicators and the lack of consideration for the varying degrees of influence each indicator may have on heat vulnerability (Tran *et al.,* 2010).Therefore, while the UAO technique can be an effective way to construct an HVI, researchers should be aware of its limitations and consider other methods of HVI construction for a more comprehensive understanding of heat vulnerability in a given area.

Weighted Additive Overlay (WAO)

In order to identify vulnerable areas and populations at risk, it is important to use HVIs that recognise the differences in the relative importance of indicators to vulnerability (Nayak *et al*. 2018). While constructing HVIs, the variable weights can be assigned to every indicator before aggregation. This procedure is called the weighted additive overlay technique and it occupies an intermediate level on a scale that shows the complexity of HVI construction compared to the simple UAO technique. Using the same set of normalised indicators obtained in UAO technique, unequal weights are assigned to the indicators before aggregation as shown in Fig. 3 (b). The magnitude of weight must be established through a weight estimation method before assigning to indicators. Relying on expert's judgement to determine weights based on local population or context is useful (Sheffield *et al*., 2013). Considering the place-specific nature of HVI, experts familiar with the vulnerability profile of the location are more appropriate.

An alternative way of weight estimation is to use a normative approach where stakeholders' preferences are elicited based on multi-criteria decision models like the Analytical Hierarchical Process (AHP). In both cases, providing variable weights to indicators and components of vulnerability produces HVI values that reflect underlying differences in contribution from the constituent components to the final vulnerability scores (Reckien, 2018). Assigning weights to indicators allows for a more nuanced understanding of the factors contributing to vulnerability in a given area. This can help decision-makers better allocate resources and prioritize interventions (Tapsell *et al*., 2002). The use of weighted indicators helps avoid the limitation of the UAO technique where indicators are assumed to contribute equally to heat vulnerability.

It is important to note that assigning weights to indicators requires careful consideration and validation to avoid the unintended consequences of over or underrepresentation of certain indicators in the final HVI scores. Therefore, a critical evaluation of the weights assigned to each indicator is necessary to ensure that they accurately reflect the contribution of each indicator to vulnerability (Yoon, 2012).

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a statistical technique used for obtaining HVI weights in studies that employ multiple variables to map heat vulnerability of population (Bao *et al*., 2015; Nayak *et al*., 2018; Rathi *et al*., 2021). PCA can reduce a large set of vulnerability indicators into a smaller set of most influential uncorrelated principal components, uncovering the underlying dimensions of the data (Bao *et al*., 2015). This approach reduces the number of indicators and creates statistically independent factors for obtaining HVI. The most common method of PCA calculation includes varimax rotation, which adjusts the coordinates of data to maximize the variance shared among items and clarifies the relationship among factors (Reid *et al.,* 2009; Nayak *et al*., 2018; Rathi *et al*., 2021). The varimax rotation increases the squared correlation of items related to one factor while decreasing the correlation on any other factor, which maximizes the variance.

However, selecting meaningful factors/components to include in HVI calculation from the many produced by PCA is based on examining a few standard criteria (Azhar *et al*., 2017). These include: 1) retaining factors with eigenvalues greater than one; 2) taking only those factors into account that appear above a sharp break in values in the scree plot, and 3) retaining only those factors that explain a high percentage of variance (individually minimum 10% of variance and cumulative explanation of at least 70% above). After the selection of the retained factors, they are scored and then normalized (mean of 0 and standard deviation of 1) before aggregation to calculate the HVI score (Fig. 3c). To make the index values more interpretable and reduce the impact of outliers, a common practice in HVI studies, introduced by Reid *et al.* (2009), is to categorize the z-scores into six classes, where a score of 1 corresponds to the lowest vulnerability and 6 corresponds to the highest.

Therefore, the PCA technique is a more advantageous approach for constructing HVIs as it simplifies the HVI calculation process, reduces the number of indicators, and enhances the interpretability of index values compared to the unweighted and weighted approaches. Despite its advantages, one disadvantage of PCA compared to the unweighted and weighted approaches is that it can be more complex and time-consuming due to the arduous mathematical steps involved in calculating the principal components.

Meaning, sensitivity and limitations of HVI

The HVI score range provides a relative measure of vulnerability across the selected geography and allows for prioritizing intervention areas. As such, higher HVI scores indicate greater vulnerability and areas with such scores require more interventions than others within the study area (Maier *et al*., 2014). However, it is essential to note that the HVI is sensitive to three design choices: the selected indicators, construction method, and scale of analysis (Conlon *et al*., 2020). The indicators selected must be relevant to the designated interventions, and different construction methods may produce varying results, making it necessary to discuss outcomes within the context of the HVI design used (Mallen *et al.,* 2019). Additionally, the scale of analysis is crucial when considering policy interventions for vulnerability reduction. Results derived from a ward-level HVI analysis may differ from those obtained at the city-region level, even if the same indicators and methods are used. Therefore, policymakers and researchers must take into account the HVI design choices' sensitivity to ensure that policy interventions address the actual vulnerabilities of the study area.

Conclusion

The present study proposed a practical methodological framework for HVI construction on the basis of data available on mapping heat vulnerability that can be applied to Indian urban centres. The development of three HVI construction techniques: unweighted additive overlay, weighted additive overlay, and principal component analysis (PCA), for mapping heat susceptibility significantly contributes to the existing efforts to reduce heat vulnerability and its associated impacts on the human population and the economy. By providing a common framework, the proposed techniques can facilitate better comparison and prioritization of vulnerable areas, thereby supporting the development and implementation of effective heat action plans. The relevance and applicability of the proposed HVI techniques are likely to extend beyond India and be of interest to other regions facing heat vulnerability issues.

Conflict of interest

The authors declare that they have no conflict of interest.

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