Revealing the Spatial Mismatch between Heat Vulnerability and Shelter Provision under Extreme Heat

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Extended Abstract

Extreme heat is increasingly recognized as one of the most severe and deadly climate-related hazards affecting urban populations. Unlike sudden disasters such as floods or earthquakes, heatwaves often unfold gradually and invisibly, yet they can produce devastating health outcomes, particularly for vulnerable groups. For many urban residents, an extreme heat event may represent discomfort or inconvenience. For others—especially older adults, children, individuals with disabilities, and people with chronic illnesses—it can become a life-threatening emergency. The risks intensify when households lack access to adequate cooling. Homes without air conditioning, or with systems rendered unusable by financial constraints, high energy costs, or mechanical failure, may cease to provide safe thermal refuge. In these circumstances, publicly accessible heat shelters play a critical role as emergency adaptive infrastructure, offering temporary relief from dangerously high indoor and outdoor temperatures.

Despite their importance, heat relief networks in many cities have evolved through fragmented and ad-hoc processes. Facilities are frequently designated based on immediate availability rather than strategic evaluation of spatial accessibility, social need, or equity outcomes. This pattern raises a fundamental environmental justice concern: whether life-saving cooling resources are reaching those who need them most. Accessibility, long established as a core concept in regional science, provides a powerful lens through which to investigate this question. However, accessibility is not inherently equitable. The spatial distribution of facilities, the configuration of transport networks, and the social and physical constraints faced by different population groups jointly shape who can realistically benefit from public services. Heat shelters are therefore not merely elements of climate adaptation policy; they are also sites where broader inequalities in urban form, mobility, and socio-demographic vulnerability become visible.

This study develops and applies a comprehensive analytical framework to evaluate the accessibility equity of urban heat shelters, using a major metropolitan area in Arizona as an empirical case. The study area provides a particularly relevant context, as it experiences some of the highest summer temperatures among large urban regions

worldwide, with heatwaves that routinely push the limits of human thermal tolerance. Rapid population growth, low-density urban expansion, car-dependent mobility patterns, and pronounced socio-spatial inequalities combine to create conditions in which heat exposure and adaptive capacity are unevenly distributed. Although the metropolitan region maintains an established heat relief network program, the degree to which this system equitably serves heat-vulnerable populations remains insufficiently understood.

The primary objective of this research is to assess whether existing heat shelter accessibility patterns align with the spatial distribution of vulnerable populations. To accomplish this, the study introduces a fine-scale gravity-based accessibility model that incorporates building-level residential data. Traditional accessibility analyses commonly allocate population to zonal centroids, implicitly assuming uniform distribution within census tracts. Although computationally convenient, centroid-based representations can produce significant distortions, particularly in sprawling urban regions characterized by heterogeneous development patterns. Populations residing at the edges of zones or clustered in specific subareas may be misrepresented, leading to over- or underestimation of travel distances and service reach. These inaccuracies are especially problematic when evaluating emergency resources such as heat shelters, where small differences in distance or mobility constraints can have substantial implications for health and survival.

To overcome these limitations, this study allocates population at the scale of individual residential buildings. Building footprints and residential unit estimates are combined with demographic data derived from census and survey sources to produce a high-resolution representation of population distribution. Heat shelter locations are geocoded, and travel impedance is measured using road network distances. Accessibility for each building is then calculated using a gravity-based model, in which the potential interaction between residents and heat shelters declines gradually with distance and is weighted by facility attractiveness proxies. This modeling approach avoids arbitrary catchment thresholds and reflects the cumulative nature of service opportunities. Unlike binary measures that classify areas as either “served” or “unserved,” gravity-based accessibility captures variations in the intensity of access across space.

To further examine the spatial structure of accessibility, we applied Global Moran’s I to assess whether accessibility levels across the study area exhibit systematic spatial autocorrelation. And Local Moran’s I was subsequently employed to identify significant clusters and spatial outliers, thereby revealing localized patterns of high and low accessibility. However, identifying spatial dependence alone does not determine whether these patterns are equitable. To evaluate the fairness of the observed distribution, we adopted a comprehensive equity framework integrating social, economic, environmental, and cultural dimensions. Grounded in established philosophical theories of justice, this framework enables a more nuanced interpretation of equity in heat-shelter accessibility. Within this perspective, the assessment of distributional equity is inherently contingent upon the normative lens applied, as different conceptions of fairness prioritize different evaluative criteria. The indicators considered in this study were selected based on prior research on heat vulnerability and include accessibility measures, socioeconomic characteristics, and built environment attributes. To examine the interrelationships among these variables, we conducted bivariate Pearson correlation analysis, providing additional insight into the structural associations that inform the subsequent equity evaluation.

The analysis reveals pronounced spatial mismatches between heat shelter accessibility and the distribution of vulnerable populations. Although some central areas of the study case exhibit relatively high accessibility scores, many neighborhoods with elevated concentrations of heat-sensitive residents display limited access. Older adults, minors, and culturally diverse communities are disproportionately represented in areas characterized by longer travel distances and lower cumulative accessibility. These patterns suggest that existing heat relief networks, despite their intended protective function, may inadvertently reproduce structural inequalities embedded in urban form and service provision. From an egalitarian perspective, the observed distribution reflects substantial inequality. Under a prioritarian lens, the results are particularly concerning, as groups facing the greatest physiological risks during heat events also experience reduced accessibility to thermal refuge.

A critical methodological finding emerges when comparing building-level results with those derived from centroid-based models. Centroid approaches systematically obscure fine-scale inequities by averaging population characteristics and travel distances within zones. Areas that appear adequately served under coarse-resolution analysis often contain pockets of severe disadvantage when examined at the building scale. This discrepancy underscores the importance of spatial resolution in accessibility and equity research. Methodological simplifications that are acceptable for routine planning analyses may generate policy-relevant errors in the context of climate risk and emergency infrastructure. High-resolution modeling is therefore not merely a technical refinement but a necessary condition for accurately identifying hidden injustices.

These findings carry significant implications for urban policy and planning. As climate change intensifies the frequency and severity of heatwaves, equitable access to heat relief infrastructure will become increasingly central to urban resilience strategies. The framework proposed in this study offers a transferable methodological and conceptual toolkit for cities seeking to evaluate and optimize heat relief networks. By combining gravity-based aggregated accessibility modeling with normative equity analysis, the approach enables planners to identify underserved populations, prioritize interventions, and design facility siting strategies that explicitly address vulnerability and fairness.

Beyond heat shelters, the framework contributes to broader debates in regional science concerning the measurement of accessibility, the role of spatial resolution, and the integration of ethical reasoning into quantitative analysis.

In conclusion, this research demonstrates that heat shelter accessibility in the study area is characterized by significant inequities that disproportionately disadvantage vulnerable groups. It shows that traditional centroid-based methods can dangerously underestimate these disparities, while building-level gravity modeling reveals micro-scale accessibility deserts that are otherwise hidden. By embedding accessibility analysis within multiple theories of justice, the study advances a more ethically informed evaluation of urban climate adaptation infrastructure. Ultimately, the research argues for a shift from reactive, opportunistic provision of cooling resources toward proactive, justice-centered planning. Ensuring equitable access to thermal refuge is not only a matter of spatial efficiency but also a moral imperative in the face of escalating climate risks.