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Accessibility for pedestrians under heat stress - the example of Heidelberg, Germany

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Abstract. Anthropogenic climate change, combined with specific modifications of the urban climate, is expected to lead to an increase in the intensity, duration, and frequency of heat waves in urban areas. Prolonged heat stress - as expected due to these changes - has serious health consequences for vulnerable urban population groups. This study examines the effects of heat stress on the accessibility of essential services in Heidelberg, Germany. The concept of isochrones was extended to include heat stress factors and applied to the study area, the city of Heidelberg in Germany. The analysis was based on a heat-sensitive routing approach that uses OpenStreetMap data together with a digital surface model that was used to model solar exposure. Results showed that under moderate heat stress conditions, accessibility to essential services (transportation, healthcare, retail and social services) was largely maintained, while under high heat stress conditions, a significant portion of the population was excluded from these services. Differences in the affected population can be identified according to both administrative territorial units and building structures. The results provide relevant information for urban planning as they indicate where city inhabitants will face problems to access essential services under heat spells.

Keywords. public transport, accessibility, heat stress, pedestrian routing, openrouteservice

1 Introduction

Anthropogenic climate change increasingly affects urban areas, with rising heatwaves and extreme weather posing significant health risks, particularly for vulnerable population groups (Intergovernmental Panel on Climate Change, 2023; Amengual et al., 2014). Since the Industrial Revolution, global temperatures have steadily increased, with 2023 marking the warmest year on record (World Meteorological Organization, 2024). In Germany, this trend is reflected in a significant increase in summer days (≥25°C) and hot days (≥30°C), more than doubling since the late 20th century (Deutscher Wetterdienst, 2024).

Urban areas face amplified heat stress due to the urban heat island effect (UHI), caused by dense construction, limited air circulation, and sealed surfaces (Dodman et al., 2023; Oke et al., 2017). Vulnerable population groups, such as older people, children, pregnant individuals, and those with chronic conditions, are particularly at risk during heat spells (European Environment Agency, 2022; WHO Regional Office for Europe, 2021; Ebi et al., 2021). Exposure to extreme temperatures can lead to heat stress, dehydration, or heat stroke and worsen pre-existing cardiovascular, respiratory, or kidney conditions (WHO Regional Office for Europe, 2021; Winklmayr et al., 2023). Even moderate heat conditions have been linked to significant health effects (Bell et al., 2024). Therefore, adaptation strategies and protection concepts are crucial in the face of these challenges in order to safeguard the everyday lives and mobility of vulnerable population groups, particularly in urban areas under extreme heat conditions.

This study is embedded in the HEAL project (Foshag et al., 2024) and examines how heat stress affects the accessibility of essential services in Heidelberg, what proportion of the population is thereby affected and in which areas and urban structures a particularly large number of people lack access to these services. A decreased accessibility to these services is likely to impact the fulfillment of essential needs such as health, food, hydration and mobility for vulnerable groups if alternatives - such as delivery services or help by relatives and friends - are not available. To quantify the effect of heat stress on accessibility, we focus on the following research questions:

1. How many people in Heidelberg are denied access to essential services under heat stress conditions?

2. Where in Heidelberg are particularly high numbers of inhabitants affected by limited access to essential services under heat stress? In which built-up structures (local climate zones) are affected inhabitants concentrated?

The purpose of this paper is to gain insight into the effects of heat stress on the accessibility of essential services and to provide suggestions for urban planning based on these findings.

2 Methods and data

2.1 Study area

Heidelberg has around 160,000 inhabitants (City of Heidelberg, 2022) and is located on the eastern edge of the rift valley, transitioning into the Neckar river valley and the Odenwald low mountain range. Climate change has increasingly given the area a more Mediterranean climate, with hotter summers and more intense heatwaves, alongside heavier winter precipitation (Foshag et al., 2020; GEO-NET Umweltconsulting GmbH and ÖKOPLANA, 2017). Since 1990, city dwellers have been facing 17 heatwaves, defined as periods of at least 14 days, with average daily highs of at least 30°C (Deutscher Wetterdienst, 2022; Ministry for the Environment, Climate and Energy Sector Baden-Württemberg, 2023; GEO-NET Umweltconsulting GmbH and ÖKOPLANA, 2017). Especially the densely built-up inner-city areas, which provide most of critical infrastructures for the population, experience overheating on hot days, with smaller micro-climatic variations (Foshag et al., 2020; City of Heidelberg, 2015).

The inner-city areas are densely urbanized and characterized by a high degree of sealing and a low proportion of green spaces. They are usually open for cars, but provide sidewalks on most streets and bicycle lanes on main roads. The building heights rarely exceed more than three to five stories with exceptions in newer districts such as "Neuenheimer Feld" and "Bahnstadt".

Foshag et al. (2024) identified several heat hotspots in Heidelberg with different scales from squares and streets to neighborhoods. All central districts around "Bergheim" and the Old Town were perceived as hotspots by the citizens, although especially public squares and the Neckar river bank were named more frequently. Districts and areas with a lower degree of sealing and a higher proportion of greenery were perceived as cooler and more pleasant places (Foshag et al., 2024).

2.2 Isocalores: Reachability depending on solar exposure

The analysis builds on an instance of the routing engine openrouteservice (Neis and Zipf, 2008) which has been adapted to incorporate solar exposure of the roads as an additional factor for pedestrian routing (Kolaxidis et al., 2025). Instead of generating the shortest or fastest route, this routing service suggests routes with slight detours to reduce solar exposure. Currently, this specialized service is only available for the city of Heidelberg in Germany. Roads and paths that are suitable for pedestrians are extracted during the pre-processing for the openrouteservice from OpenStreetMap along with relevant road attributes such as access restrictions, or physical obstacles, such as barriers or traffic signals. Relevant roads and footpaths are thereby extracted based on their OpenStreetMap tags and converted into a routing graph. The graph nodes correspond thereby to the intersections of the roads, and graph edges to the roads that connect these intersections. Each edge on the graph is assigned a value matching the actual travel distance (l_i). In addition, each edge is enriched with information on its solar exposure for different times of the day (see 2.2.1) to allow the calculation of routes which are optimized to reduce solar exposure. For this enrichment, the solar exposure of each OpenStreetMap is calculated and linked by the OSM-ID to the road features during the pre-processing. In addition to point-to-point routing, the routing service allows the consideration of solar exposure in reachability analysis (see 2.2.2).

2.2.1 Solar exposure of the road network

Solar exposure of each road was modeled as the percentage of the road surface covered by the shade cast by buildings and vegetation. A 2.5D surface model of terrain, buildings and vegetation within Heidelberg was created using the method by Fan and Zipf (2016). Terrain was modeled using a SRTM digital elevation model with 30m resolution, while buildings and trees were extracted from OSM. Trees mapped in OSM as points were extracted from OSM and converted into a 2.5D raster representation using a default height of 6 meters and crown width of 4 meters. Forests were extracted from OSM as polygons and rasterized using a default tree height of 6 meters as well.

Solar exposure of road features was calculated using CloudCompare (2024) and VOSTOK (Bechtold and Höfle, 2020). Cloud compare was used to generate the 3D surface normals required to subsequently calculate the shadows cast for a given day and time using VOSTOK, resulting in a binary grid indicating full sun (1) or full shade (0) for each location. This raster was aggregated by each OSM road feature to calculate the percentage of the road surface covered by the cast shade. Solar exposure modeling was conducted for specific time periods to account for varying solar angles throughout the day. Sun exposure of

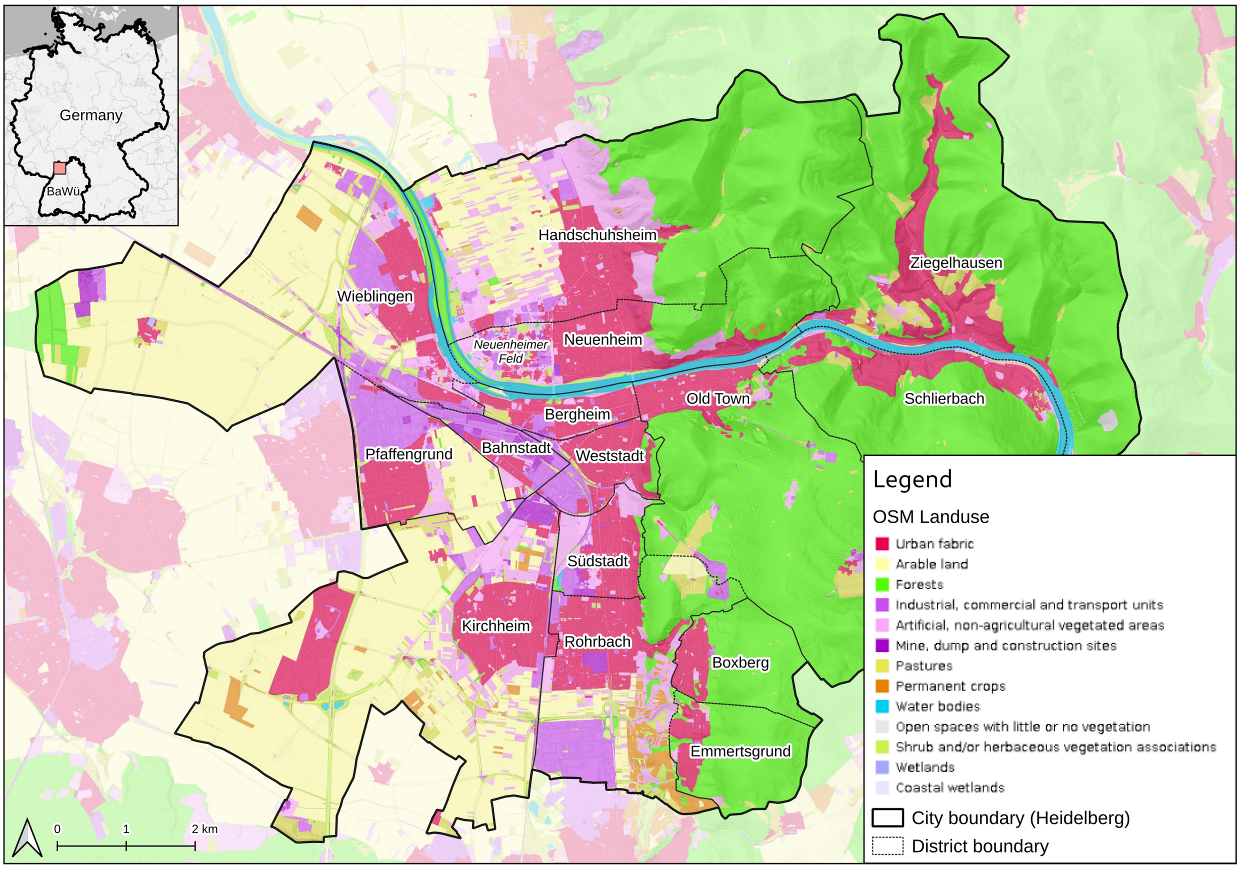

Figure 1. Overview over Heidelberg, Germany and it's city districts with land cover and land use by osmlanduse.org. The eastern part of the city is characterized by the densely forested Odenwald, while the center and western parts show predominantly urbanized areas, including the historic Old Town. Towards the north and southwest, the urban landscape transitions into industrial and agricultural zones. Data source: OSMlanduse (HeiGIT gGmbH), GeoBasis-DE / BKG (2024) CC BY 4.0, OpenStreetMap contributors.

all roads within the research area was modeled on July 9th at four times of the day: morning (10:00), noon (13:00), afternoon (16:00), and evening (19:00). These times are specified in Central European Summer Time (CEST).

2.2.2 Cost function

Pedestrian reachability and accessibility is usually modeled by calculating the area that can be reached from a certain location using the pedestrian road network within a specified cost budget, e.g. duration (isochrones) or distance (isodistances). In this study, we adapted this concept to include solar exposure as another cost factor in addition to the route length naming it *Isocalores*.

$$C_{\text{solar\_exposure}}(P) = \sum_{i=1}^{n} (1 + c'(s_i) \cdot \alpha) \cdot l'(s_i), \qquad (1)$$

where:

- c'_s represents the scaled solar exposure index for road segment s, with values ranging from 1 (high solar exposure) to 0 (no solar exposure),
- α is a weighting factor that determines the strength of the influence of the solar exposure index on the route. The value of α was assumed to range from 0.0 to 5.0 and conceptually represents the individual sensitivity to solar exposure (*Heat sensitivity factor*),
- l'_s is the length of road segment s,

Conceptually, this cost function and the resulting isocalores can be interpreted as follows: Reachability from a certain location is decreased depending on the solar exposure of the road and the person's heat sensitivity. If roads are fully shaded ($c'(s_i) = 0$ in equation 1), the person is assumed to be able to walk for the whole distance budget (e.g. 500m) from the starting location. If roads are fully exposed to the sun ($c'(s_i) = 1$), the person is assumed to be only able to walk half the distance (250m) for $\alpha = 1.0$, because of the added costs due to solar exposure. Higher heat sensitivity by a person can be modeled by increasing the α value, which results in ever decreasing distances that can be reached on roads which are exposed to the sun.

2.2.3 Accessibility analysis

The accessibility of essential services under heat stress conditions was analyzed using selected points of interest (POI) and the isocalor method. This method is an adaption of the isochrone analysis which calculates the area that can be reached within a specified time from designated starting points (Efentakis et al., 2013). Unlike isochrones, the isocalor approach accounts for the impact of heat stress by incorporating solar exposure into the routing weights. The *heat sensitivity factor* captures thereby the individual sensitivity to heat exposure. Isocalors identify the accessible areas under heat stress conditions from a starting point by adjusting the distance based on solar exposure and individual heat sensitivity. Routes with higher solar exposure result in shorter reachable distances, producing smaller isocalors. We used a heat-adjusted travel time concept, referred to as the *heat stress walking distance equivalent*, to reflect the reduced mobility of vulnerable populations during heat waves. The parameter describes the number of minutes that correspond to the same heat intake as walking on a cooler day and was analyzed in intervals of 5,10,15,20 and 30 minutes. The isocalors were calculated by the HEAL routing service (Kolaxidis et al., 2025), built on the openrouteservice (ORS).

While both vulnerable and less vulnerable individuals exhibit reduced mobility under heat stress conditions (Yu and de Dear, 2022), their body's response varies based on factors such as age, gender, health status, physical fitness, and acclimatization to heat (Liu et al., 2022; Asseng et al., 2021), as well as the socioeconomic status (Wang et al., 2022). To reflect theses differences, we introduced the *heat sensitivity factor* (Hsf) into the calculation of the routing weights. The factor ranges from 0 to 5, where Hsf0 excludes solar exposure (yielding traditional isochrones), and Hsf1 to Hsf5 represent increasing levels of heat sensitivity, from very low (Hsf1) to very high (Hsf5).

For the analysis of the affected population we used a fixed *heat stress walking distance equivalent* of 15 minutes in alignment with the concept of the '15-minute city' (Moreno et al., 2021). This urban planning framework emphasizes proximity to essential services within a 15-minute walk, fostering health benefits and reducing greenhouse gas emissions (Weng et al., 2019). A study by Wang et al. (2022) indicates that under moderate heat stress, a 15-minute walking duration is perceived as 'slightly uncomfortable' by participants, while under extreme conditions discomfort escalates significantly after five minutes. Under this conditions 13-15 minutes where deemed as 'extremely uncomfortable'. Given these findings, a 15-minute benchmark was deemed realistic for evaluating accessibility, particularly while keeping the vulnerable population in mind.

By integrating these parameters, isocalors provide a comprehensive view of accessible areas under varying heat stress levels. As heat sensitivity increases, accessible areas shrink, illustrating the compounded impact of heat stress on mobility and urban accessibility.

2.3 POIs of essential services

We calculated the accessibility of the living population to the following POIs: public transport stops, hospitals and clinics, medical practices, pharmacies, supermarkets, childcare facilities, and senior living facilities. Senior living facilities was used hereafter as a collective term for any form of nursing homes, retirement homes, senior residences, and assisted living groups where elderly people reside or where it can be assumed that older adults will be present.

POI group	OSM tags
Public transport stops	highway = 'bus_stop'; 'railway' = 'halt'; 'railway' = 'station'; 'railway' = 'tram_stop'
Hospitals and clinics	'amenity' = 'hospital'; 'amenity' = 'clinic'
Medical practices	'amenity' = 'doctors'
Pharmacies	'amenity' = 'pharmacy'
Supermarkets	'shop' = 'supermarket'
Childcare facilities	'amenity' = 'kindergarten'
Senior living facilities	'amenity' = 'retirement_home'; 'amenity' = 'nursing_home'; 'amenity' = 'social_facility' + 'nursing_home'; 'amenity' = 'social_facility' + 'assisted_living'

Table 1. Points of interest (POIs) used to measure access to essential services under heat stress conditions for vulnerable groups and the tags used to extract them from OSM via Overpass.

POIs were extracted from OpenStreetMap using the Overpass API (Overpass-API contributors, 2024) with the tags listed in Table 1. As the information on senior living facilities in OSM seemed incomplete, we augmented this by additional information from the Office for Social Affairs and Senior Citizens Heidelberg (2024), the healthcare and career portal kliniken.de (VIVAI Software AG Dpt. Kliniken.de, 2024), the database of the federal representation of interests for elderly and care-dependent people (BIVA Pflegeschutzbund e.V., 2024) and a Google Maps search using the tags *'Seniorenheim', 'Altenheim'* and *'Pflegeheim'* (Google Maps, 2024). Compared to OSM, 15 additional facilities were identified. The address data was geocoded via Google My Maps and merged in QGIS 3.34.4 with the senior living facilities extracted from OSM.

In the final analysis, accessibility to essential services under heat stress was evaluated solely by calculating isocalors from public transport stops as starting points.

This approach was based on the hypothesis that once individuals reach a public transport stop, they can access more distant essential services without incurring additional heat stress exposure. Consequently, any area reachable by a public transport stop was assumed as accessible to all essential services across the city. However, this assumption relies on the premise that essential services are effectively reachable from public transport stops. To evaluate this, the analysis will involve intersecting the isocalors originating from public transport stops and quantifying the POIs of essential services representing essential services located within these isocalors.

2.4 Population data and Local Climate Zones

Obviously, the distribution of the population needs to be considered for a risk estimation. Identifying where large numbers of people face limited access to the public transport network and thus to the rest of essential services under heat stress conditions is of particular relevance. Therefore, the resulting areas of the isocalor analysis from public transport stops were intersected with the most recent living population dataset provided by the federal statistical office for May 15, 2022 on a regular grid with a spatial resolution of 100 x 100 meters (Federal Statistical Office of Germany, 2024). Population counts per address were aggregated into grid cells, with cell centroids representing the geometry. To ensure confidentiality for cells with minimum population, the key-cell method was used (Federal Statistical Office of Germany, 2024). These adjustments do not alter the total population count (Enderle and Vollmar, 2019). The origin point data was transformed to grid data in the GeoTIFF format via the Rasterize (vector to raster) tool in QGIS 3.34.4 (QGIS Development Team, 2024), reprojected to EPSG: 25832, and clipped to the research area. To calculate the population inside the respective isocalors the function 'zonal_stats' of the python module 'rasterstats' (Perry, 2013) was used.

In addition, we intersected the accessibility areas with a local climate zones (LCZ) raster, which was derived using the LCZ Generator web application (Demuzere et al., 2021). LCZs, as defined by Stewart and Oke (2012), classify urban and peri-urban environments based on a combination of physical surface properties such as building height, built-up density, land use and surface material. The specific LCZ classification applied to our study area was developed as part of the HEAL project by Mack (2023) and incorporates refinements based on supervised, pixel-based satellite image classification supported by machine learning algorithms. The classification builds on the World Urban Database and Access Portal Tool (WUDAPT), which provides global LCZ classification at Level zero (L0) with a spatial resolution of 100 x 100 meters (Demuzere et al., 2022). The LCZ Generator web application allows refinement of WUDAPT L0 classifications through custom training data (Demuzere et al., 2021). The adapted LCZ map for Heidelberg is publicly available on the LCZ Generator website.

We assessed the sensitivity of our approach to different levels of individual heat sensitivity, we repeated the analysis for different *heat sensitivity factors*. The change in area and affected population of the isocalors for the different Hsf levels was related to the isocalores for the no heat stress scenario (Hsf = 0).

2.5 Data and Software Availability Section

This analysis was conducted by using an adapted version of the openrouteservice, publicly available for the city of Heidelberg at heal.openrouteservice.org. All code, data and QGIS projects used to produce the results are available at: https://github.com/johanneshbr7/accessibility-analysis-isocalors.

3 Results and discussion

Category	Total # POIs	# reachable POIs	Reachable POIs %
Senior Living Facility	30	28	93.3
Childcare Facility	147	111	75.5
Clinic	6	6	100.0
Medical Practice	126	115	91.3
Hospital	5	5	100.0
Pharmacy	39	37	94.9
Supermarket	35	33	94.3
Total	**388**	**335**	**86.3**

Table 2. POIs representing essential services reachable from public transport stops in Heidelberg at Hsf = 5.0 and 15-minute *heat stress walking distance equivalent*.

Without consideration of heat stress (Hsf = 0) the public transport network exhibited excellent coverage of the urban area, with only 1,2% of the population living more than 15 minutes away from a public transport stop. This confirms that the network's baseline accessibility is not a limiting factor, as 97% of the population can reach the public transport within a 5 minutes walk, excluding heat conditions. This lead to the assumption that as soon as an individual can reach a public transport stop, other essential services might also be within their reach, even if they are not in the immediate vicinity of their place of residence.

Not all parts of the city were accessible from public transport stops for a 15-minute *heat stress walking distance equivalent* assuming very high heat sensitivity (Hsf=5, cf. Figure 2). Areas without such access were considered potentially vulnerable areas under heat stress conditions. The spatial pattern can be explained both by the uneven distribution of public transport stops and shading conditions due to varying building heights, terrain and tree coverage.

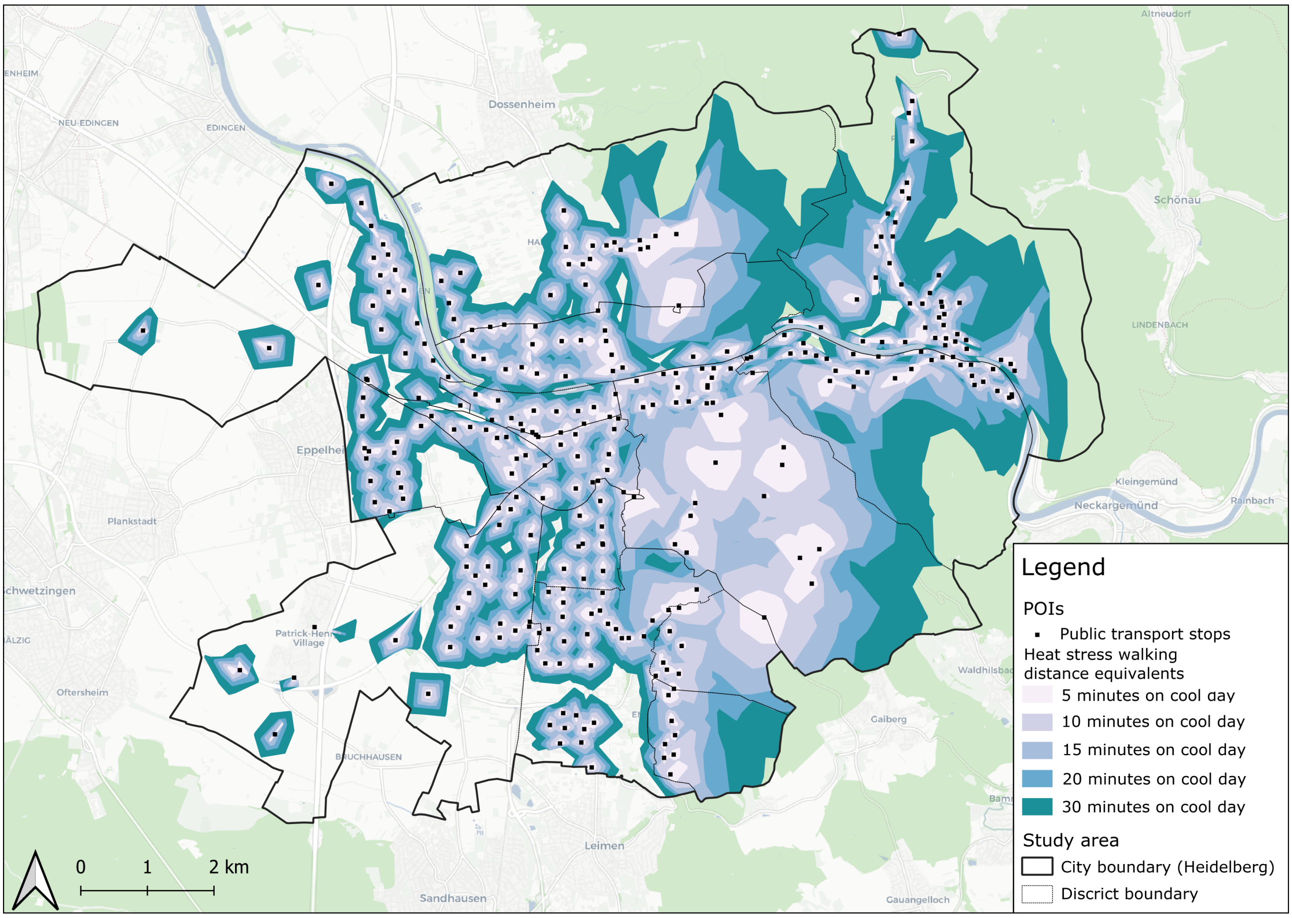

Figure 2. Areas accessible for different *heat stress walking distance equivalents*. Parameter: *heat sensitivity factor* = 5, time of day: afternoon (16:00 h CEST), Day 190 (July 8th/9th). The walking distance is provided as the equivalent for a hot day - i.e. for the chosen day walking distances were shorter due to the heat stress. Data source: OSM Contributors, Map Style by CartoDB.

At 13:00 CEST, using a very high *heat sensitivity factor* (Hsf = 5) and a 15-minute *heat stress walking distance equivalent*, 86% of all essential services remained accessible from public transport stops (cf. Table 2). Accessibility of POIs from public transport stops differed across the different POI categories: hospitals and clinics in the research area achieved full accessibility under these conditions, whereas childcare facilities had the lowest accessibility rates. Excluding childcare facilities, more than nine out of ten essential services were accessible even for the assumption of a very high heat sensitivity. Reducing the *heat sensitivity factor* to Hsf = 4, a total of 94% of essential services - including childcare facilities became accessible. Given the general good accessibility of the different POI categories, on can assume that for most categories at least on POI should be available. However, not all POIs in a group might be good substitutes for each other - it might for example make a big difference which doctor's practice or which childcare facility is accessible.

Peripheral areas exhibited the most significant limitations in public transport accessibility during heat stress (cf. Figure 2). However, specific inner-city areas, such as parts of Kirchheim in the south of Heidelberg and an area on the border of the districts Neuenheim and Handschuhsheim north of the Neckar river, were also strongly affected. Forested areas with consistently low sunlight exposure were expectedly characterized by larger isocalors. Conversely, build-up areas with higher solar exposure in western parts of the city exhibited smaller isocalors. In some cases, the underlying road network strongly shaped the isocalors, which leads to linear patterns along the major roads such as the mayor highway connection road in Kirchheim. Further linear patterns were amplified by topographical constraints such as the Peterstal valley in the northeastern part of the city at the border to the Odenwald low mountain range.

Notable concerns arose for a senior living center located in Handschuhsheim: Here, highly heat-sensitive individuals, represented by *heat sensitivity factor* 5, cannot access the closest tram and bus stops within a *heat stress walking distance equivalent* of 15 minutes. Additionally gaps in the public transport network were identified for highly sensitive individuals. Nevertheless most of these gaps remained accessible for individuals with moderate heat sensitivity, represented by *heat sensitivity factor* 3.

As expected, assumption of a lower heat stress sensitivity led to larger isocalors. Densely populated districts such as

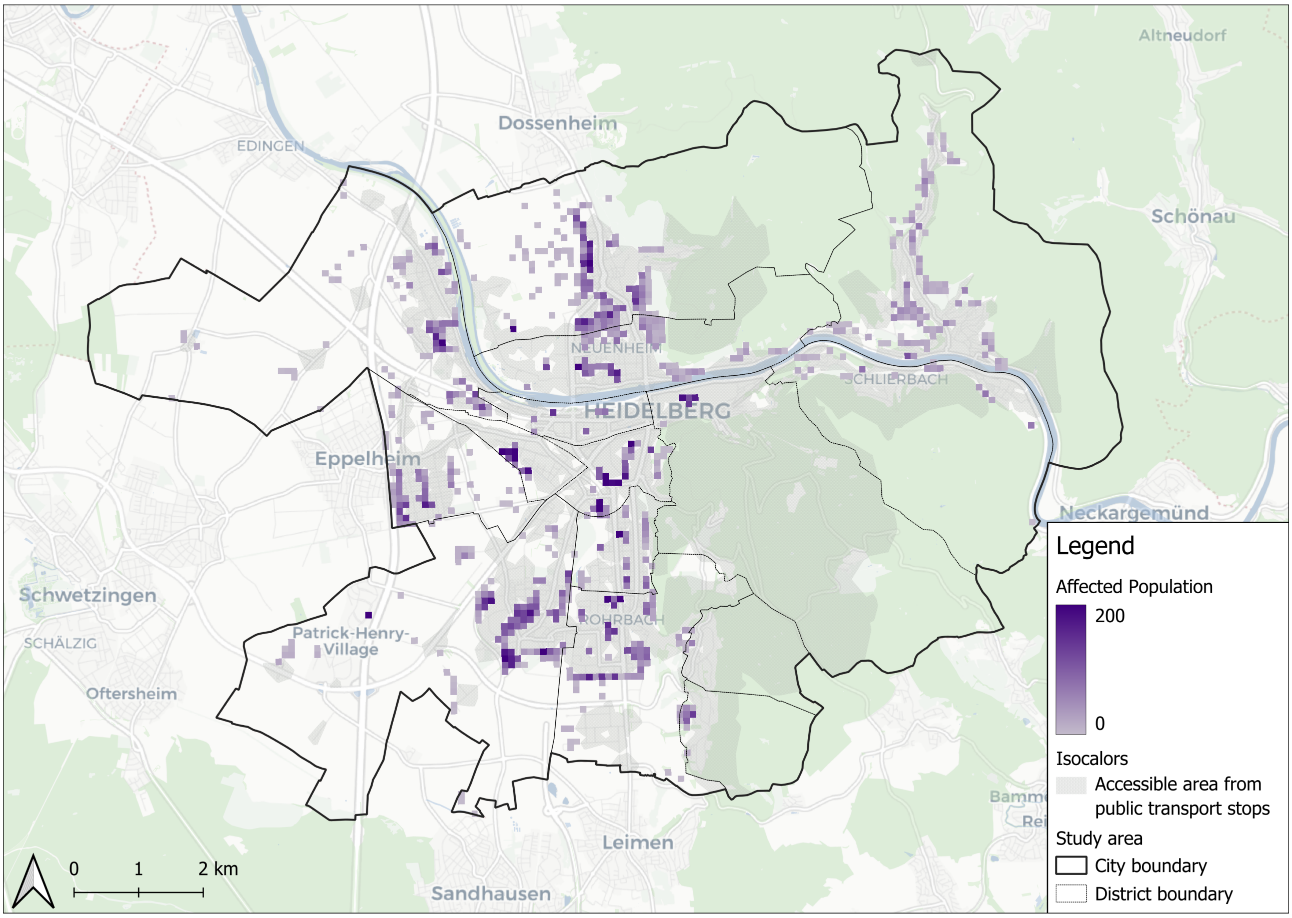

Figure 3. Population without access to at least one public transport stop under heat stress conditions with *heat sensitivity factor* 5 (very high heat sensitivity). The residential population is shown by registration address in 100 x 100 meter grids of the 2022 census. Heat stress conditions: very high heat sensitivity (Hsf 5), noon (13:00, CEST), *heat stress walking distance equivalent:* 15 min. Data source: Census 2022, OSM contributors, map style by CartoDB.

Bergheim and Weststadt experienced the highest reduction of isocalores area relative to the no heat stress scenario for increasing *heat sensitivity factor* values. In less densely populated districts, the difference in affected population also increased with heat stress levels, even though on a smaller scale. Forested areas showed minimal changes due to the mitigating effects of natural shading.

Highly heat-sensitive individuals (Hsf 5) in all districts faced limitations in accessing essential services (cf. Figure 3). However, the impact of heat stress on accessibility was not uniformly distributed across the city. It disproportionately affected residents in districts such as Kirchheim and Handschuhsheim, as relatively high population densities, more sun-exposed streets due to the building structure and greater gaps between public transport stops exacerbate the impact of heat stress. In contrast central districts such as the Old Town, Bergheim and Weststadt showed lower numbers of affected individuals, due to higher stop densities and compact urban forms, which enhanced accessibility under heat stress.

In Kirchheim and Handschuhsheim, nearly 8,000 and 6,000 people were unable to access at least one public transport stop at a *heat stress walking distance equivalent* of 15 minutes assuming very high heat stress sensitivity. For individuals with moderate heat sensitivity (Hsf = 3) under the same conditions the number of affected people dropped strongly to approximately 3,300 and 2,000 people, respectively (cf. Figure 4). While approximately 36,000 people were affected across the whole city under Hsf 5 (23.8% of total population), only about 9,400 faced limitations under Hsf 3 (6% of total population). For the Hsf 3 scenario, all residents in Boxberg and the Old Town were for example able to access public transport stops.

Not all affected individuals belong to a particularly vulnerable population group. Information about the spatial distribution of vulnerable groups across the city is not known. In total 22.4% of the population were above 65 years or under 5 years (Office for Urban Development and Statistics Heidelberg, 2023). If one would assume a homogeneous age distribution, we would expect approximately 8,200 or 500 individuals of these age classes to be excluded from essential services for Hsf 5 or Hsf 3 respectively. For other vulnerable population groups such as inhabitants with chronic illnesses, outdoor workers, and the homeless no information about their share in Heidelberg was available.

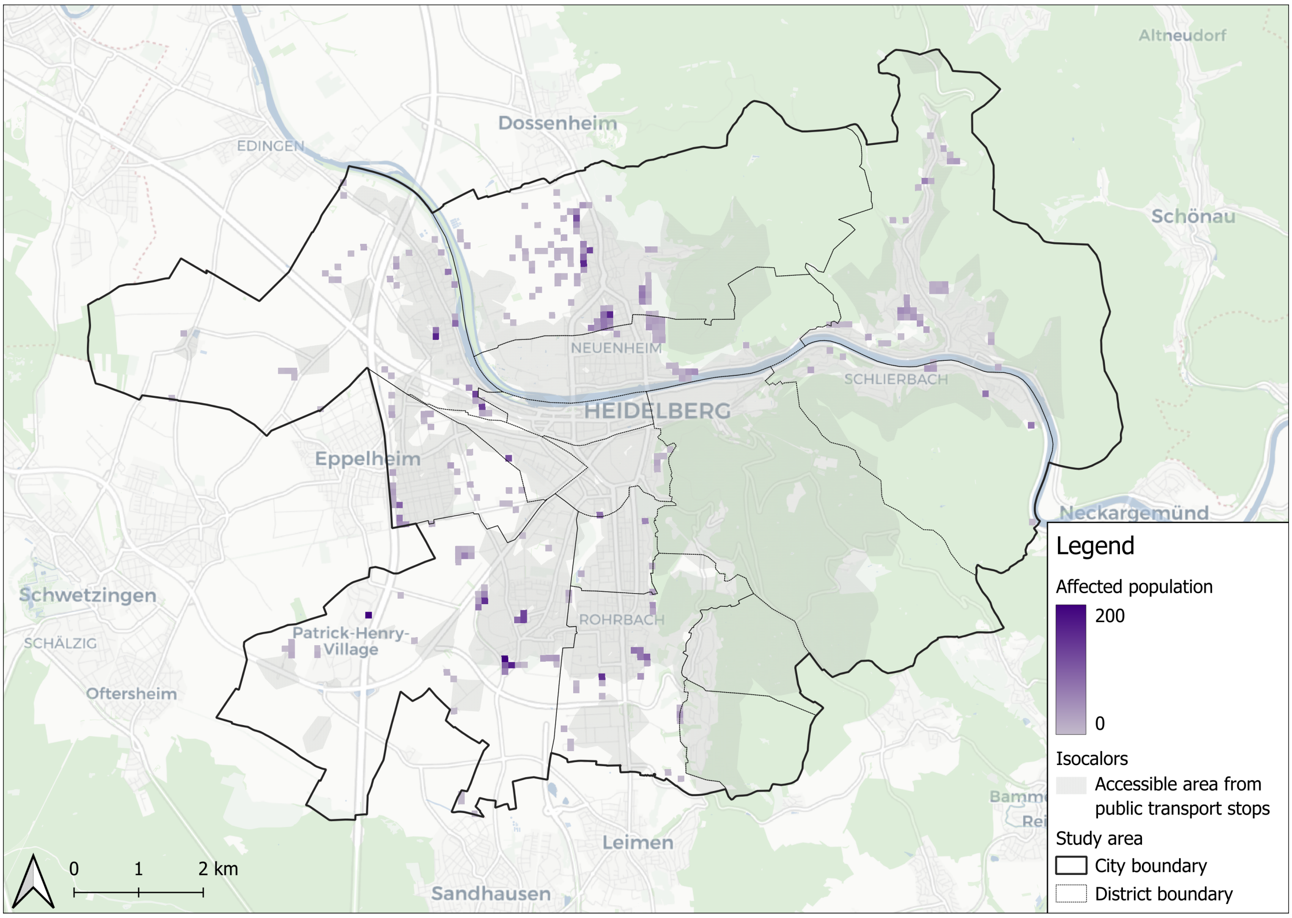

Figure 4. Population without access to at least one public transport stop under heat stress conditions with *heat sensitivity factor* 3 (moderate heat sensitivity). The residential population is shown by registration address in 100 x 100m grids of the 2022 census. Heat stress conditions: moderate heat sensitivity (Hsf 3), noon (13:00, CEST), *heat stress walking distance equivalent:* 15 min. Data source: Census 2022, OSM contributors, map style by CartoDB.

In our research area the most prevalent LCZs in all inhabited areas were LCZ 2 (compact Mid-Rise) and LCZ 6 (open Low-Rise). LCZ 2 dominates the more central city districts (Old Town, Bergheim, Weststadt and Bahnstadt), whereas LCZ 6 is typical for the districts north of the Neckar river (Handschuhsheim and Neuenheim) and more peripheral districts such as Kirchheim, Rohrbach and Südstadt. Notably, 80% of Heidelberg's population resided in either LCZ 2 or LCZ 6, with 58% in LCZ 6 and 22% in LCZ 2.

Similar patterns were observed for the affected population, with approximately 80% of individuals affected by heat stress lived in those two LCZs (cf. Figure 5). Comparing the affected population for very high (Hsf=5) and moderate (Hsf=3) heat sensitivity, strongest differences in absolute numbers were observed for LCZ 6 (open Low-Rise).

The open Low-Rise LCZ (LCZ 6) exhibited the largest numbers of potentially affected individuals. Greater distances from transport stops and higher solar exposure were potential causes of their lack in accessibility to essential services. Densely built LCZs such as the second predominant LCZ type 2 (compact Mid-Rise) show fewer affected individuals, despite higher urban heat island effects. Comparing the relative affected population group per LCZ, densely built LCZs, such LCZ 2 showed similar trends to more open structures (LCZ 6), which suggests that the results can also be partly explained by the unique composition of Heidelberg's urban structure. A comparative study with larger cities such as Mannheim or Frankfurt could be carried out to widen the view about city structures less present in our research area such as LCZ 1 (compact High-Rise) and LCZ 3 (compact Low-Rise).

Further, the impact of heat sensitivity, represented by α in the equation (c.f. 2.2.2), on the affected population is evident in Figure 5, which illustrates how increasing α leads to a greater reduction in accessible areas and a higher number of affected individuals.

The findings assist urban planners to mitigate heat stress impacts and ensure accessibility under heat stress. Enhancing shading along key pedestrian routes in sun-exposed areas could alleviate heat exposure and therefore strengthen accessibility. This could be achieved by planting trees, installing shading structures at heat hotspots and expanding

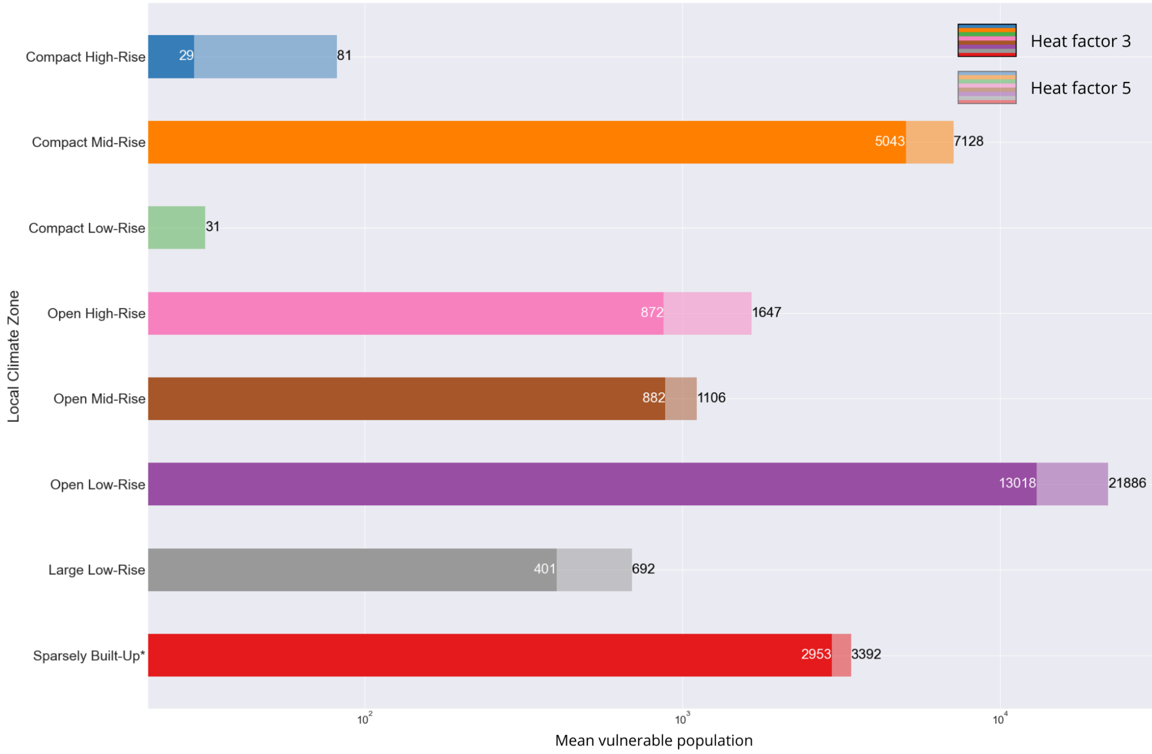

Figure 5. Absolute number of people affected for *heat sensitivity factors* 3 and 5 averaged by local climate zone. The bars show values averaged across the four times of day (10:00, 13:00, 16:00, 19:00 CEST) and the *heat stress walking distance equivalents* for 5, 10, 15, 20, 30 minutes. LCZ 9 (Sparsley Built-Up) is of limited significance due to limitations in the data base. Representation of *heat sensitivity factor* 3: completely opaque, *heat sensitivity factor* 5: semitransparent. Absolute numbers in white font for Hsf 3, in black font for Hsf 5. Please note the logarithmic scale used for the x-axis.

green corridors to improve pedestrian comfort and accessibility.

The introduction of micro-mobility solutions, such as on-demand shuttles of flexible transport services could help to address last-mile connectivity and thereby to support the increase of accessibility in districts with lower transport stop density (Truden et al., 2022). These measures tend to reduce dependency on long walks under heat stress and ensure reliable access to essential services. The city of Heidelberg has initiated such a program, called 'fips' in cooperation with the local transport association in the eastern districts Ziegelhausen and Schlierbach, as well as Rohrbach in the south (City of Heidelberg, 2024). The service could be strategically expanded to cover the entire city, addressing gaps in the public transport network during high heat events. As an initial step, it could focus on peripheral districts with a high number of people unable to access essential services under heat stress conditions, such as Handschuhsheim, Kirchheim and Wieblingen, thereby avoiding the need for time-intensive and costly modifications to existing bus and tramlines.

The isocalor analysis relied on solar exposure data, as actual temperature data and elevation were not yet integrated into the HEAL-Routing Tool during this analysis. Both factors could enhance the precision of future studies, particularly by accounting for additional heat stress experienced due to higher temperatures or on uphill routes. Additionally, the inclusion of more detailed and broader available spatial data for shading, like a digital surface model could improve the accuracy of the isocalor analysis even further and facilitate the transferability of the model to other regions.

The density of public transport stops clearly influenced accessibility results. Areas with higher stop densities expectedly showed fewer inaccessible zones, though vulnerable individuals may still improve their mobility under heat stress conditions by using private vehicles, bicycles, or ride-sharing services.

Lastly, the *heat sensitivity factor* values used in this study require further evaluation to confirm their alignment with actual heat sensitivity perceptions in the use case. Future research could adopt transdisciplinary approaches to refine these parameters. Such approaches could also support a more comprehensive validation of the results, for instance, by comparing the modeled accessibility with real-world observations or conducting sensitivity analyses. However, due to the scope of this project, such validation could not be pursued. While further validation would strengthen confidence in the findings, the results presented here provide valuable insights into accessibility challenges under heat stress conditions.

4 Conclusions

This study highlights the utility of the isocalor concept for analyzing accessibility under heat stress conditions. Building on the established isochrone framework, isocalors integrate the solar exposure via *heat sensitivity factor* and *heat stress walking distance equivalent* into the concept to provide a nuanced understanding of how heat stress impacts the mobility. The results reveal that high heat stress conditions (Hsf 5) significantly reduce accessibility to essential services by vulnerable population groups in Heidelberg, especially in districts with lower public transport stop densities and high sun exposition, resulting in potentially longer walks to the public transport network. Under these conditions, 23.8% of the population of Heidelberg experiences limited accessibility. During moderate heat stress conditions (Hsf 3) accessibility is largely maintained, with only 6% of the population facing limitations.

These findings align with the initial claim that heat stress, exacerbated by urban climatic changes, poses a growing challenge for vulnerable population groups in cities. By extending the isochrone framework, the isocalor concept offers a valuable methodological advancement, facilitating precise analysis of heat stress related accessibility issues. While refinements, such as the inclusion of real-time temperature and elevation data, could further refine its precision the concept already proves effective in identifying accessibility challenges and could inform to potential urban planning strategies.

The study underscores the potential of isocalors to inform evidence-based decision-making in geospatial and urban studies, providing a foundation for future research and practical applications in addressing heat stress resilience.

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