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Heat exposure and resilience planning in Atlanta, Georgia

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Abstract

The City of Atlanta, Georgia, is a fast-growing urban area with substantial economic and racial inequalities, subject to the impacts of climate change and intensifying heat extremes. Here, we analyze the magnitude, distribution, and predictors of heat exposure across the City of Atlanta, within the boundaries of Fulton County. Additionally, we evaluate the extent to which identified heat exposure is addressed in Atlanta climate resilience governance. First, land surface temperature (LST) was mapped to identify the spatial patterns of heat exposure, and potential socioeconomic and biophysical predictors of heat exposure were assessed. Second, government and city planning documents and policies were analyzed to assess whether the identified heat exposure and risks are addressed in Atlanta climate resilience planning. The average LST of Atlanta's 305 block groups ranges from 23.7 °C (low heat exposure) in vegetated areas to 31.5 °C (high heat exposure) in developed areas across 13 summer days used to evaluate the spatial patterns of heat exposure (June–August, 2013–2019). In contrast to nationwide patterns, census block groups with larger historically marginalized populations (predominantly Black, less education, lower income) outside of Atlanta's urban core display weaker relationships with LST (slopes ≈ 0) and are among the cooler regions of the city. Climate governance analysis revealed that although there are few strategies for heat resilience in Atlanta ($n = 12$), the majority are focused on the city's warmest region, the urban core, characterized by the city's largest extent of impervious surface. These strategies prioritize protecting and expanding the city's urban tree canopy, which has kept most of Atlanta's marginalized communities under lower levels of outdoor heat exposure. Such a tree canopy can serve as an example of heat resilience for many cities across the United States and the globe.

1. Introduction

Extreme heat accounts for more deaths than any other weather or climate related hazard in the United States (Karl *et al* 2009, Wong *et al* 2013). The risks of extreme heat are particularly severe in urban areas, where daytime and nighttime temperatures are consistently elevated (Harlan *et al* 2006). High temperature anomalies in urban regions are fueled by the urban heat island (UHI) effect, a result of changes in land use, land cover, and expansion of the urban form (Yao *et al* 2011). Urban development reduces forests, grasslands, and vegetation, usually replaced by impervious, blackbody surfaces that absorb higher amounts of radiation during hours of intense sunlight (Mirzaei and Haghighat 2010). This absorbed radiation is subsequently reemitted, increasing air temperatures during the day and the night (Dixon and Mote 2003, Stone *et al* 2010, Liu and Yang 2015, Ali *et al* 2017, Ogunjobi *et al* 2018). Elevated temperatures in these urban areas often exacerbate pre-existing conditions, leading to increased mortality and morbidity (Kalkstein and Greene 1997, Basara *et al* 2010, Uejio *et al* 2011). With rising temperatures globally and a lack of extreme heat relief, these heat-related deaths are expected to continue to increase (Lo *et al* 2019, Vicedo-Cabrera *et al* 2021). In the state of Georgia, an overall warming trend has been observed, making extreme heat of particular importance among climate change projections for Atlanta, Georgia (figure 1)

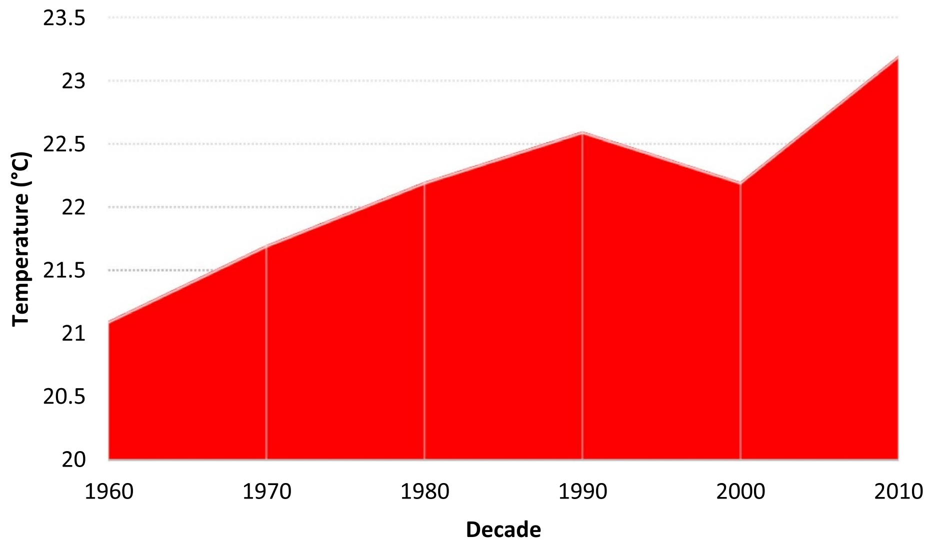

Figure 1. Average daily high temperature per decade for the City of Atlanta, Georgia, between 1960–2010. The daily average daily high temperature between 2000–2010 is 2.1 °C warmer than 1950–1960. Data: NOAA NCEI.

(Binita *et al* 2015, Carter *et al* 2018, Climate Central n.d.). Atlanta also exhibits the characteristics of the UHI, found to range between 0.8 °C–2.5 °C warmer than surrounding areas (Mirzaei and Haghighat 2010, Zhou and Shepherd 2010). This warming trend coupled with the UHI in the urban Atlanta area can amplify extreme heat events, especially during the summer months.

Heat has widespread relevance beyond core themes of urban climate resilience. Heat is relevant to occupational workplace safety, public health, emergency management, energy burden, and social justice, among other sectors relevant to climate resilience (Kovats and Hajat 2008, Tobias *et al* 2012, Licker *et al* 2022, Ortiz *et al* 2022), and requires planning and adaptation across multiple systems simultaneously (e.g. Department of Health, Victoria State Government 2021). Ongoing efforts related to heat resilience build from public health planning approaches, for example in regions with high exposure to heat hazards (e.g. Commissioner Karachi 2017, Ministry of Health & Family Welfare, Government of India 2021). While such plans are essential to emergency management of extreme heat events, they often do not emphasize needs for long-term adaptation and adjustment under climate change, as is the focus of ongoing climate resilience efforts (Meerow *et al* 2016, Keith *et al* 2019). Urban heat resilience policy, seeking to alleviate heat exposure and risks across urban environments and communities, has emerged as an evident priority as urban populations increase and urban regions expand (Weber *et al* 2015, Bolitho and Miller 2017, Gabbe *et al* 2021). For example, New York City has developed a 'Cool Neighborhoods Plan' (de Blasio and Shorris 2017) with initiatives and strategies to reduce heat in its urban communities. Cities such as Los Angeles, CA, and Louisville, KY, have also followed suit with intiatives to reduce the UHI effect in their respective urban regions (Louisville Department of Sustainability 2017, ResilientCA 2017e). Miami-Dade County and the City of Phoenix have established heat officers and offices designed for heat response and mitigation (Phoenix City Manager 2021, St. Hilaire 2021).

Explicit heat planning, however, still remains limited across many urban regions, including Atlanta, Georgia (Luber and McGeehin 2008, Mees *et al* 2015). To better prepare for the present and intensifying heat threat, heat resilience, or increased capacities to adapt to or tolerate extreme heat, will need to become a climate governance priority (Meerow *et al* 2016, Keith *et al* 2019). Planning will need to be comprehensive, collaborative, and coordinated across the research community, municipal governments, non-governmental organizations, and the private sector, across multiple spatial scales (Bernard and McGeehin 2004, Gabbe *et al* 2021). Further, themes of social and environmental justice are relevant to heat resilience planning, ensuring that the benefits and processes of heat policies are equitable and inclusive across the urban landscape (Rohat *et al* 2019).

Racism and other historical discriminatory practices have largely contributed to elevated levels of exposure and risk across urban regions, including heat (Mitchell and Franco 2018, Voelkel *et al* 2018, Hoffman *et al* 2020). Social vulnerability is shaped by the socioeconomic, environmental, and other contextual factors that make populations more sensitive to heat hazards, increasing risks to health and well-being following exposure to heat (Karl *et al* 2009, Mitchell and Chakraborty 2014, Dialesandro *et al* 2021, IPCC 2021, Thomas *et al* 2019). Previous research nationwide has demonstrated that social vulnerability, heat exposure, and heat risks all tend to be higher in urban neighborhoods with lower income, lower levels of education, and higher levels of poverty and minority populations (Jenerette *et al* 2007, Johnson and Wilson 2009, Buyantuyev and Wu 2010, Huang *et al* 2011). Many such communities do not have adequate heat-resilient infrastructure (e.g. extensive green infrastructure, reflective surfaces, cool roofs, weatherized homes, cooling centers) and may lack resources for heat adaptation without external assistance (e.g. access to central air conditioning or energy assistance to support its use) (Byrne *et al* 2016, Wilson 2020). The City of Atlanta's dynamic and historic development is not exempt from these same trends (Runfola and Hankins 2010). Atlanta is one of many areas in the U.S. Southeast where African-American and other non-white populations historically face higher rates of environmental racism and climate hazard exposure (US General Accounting Office 1983, Bullard 1993, Middleton 2020). While other climate hazards such as chronic flooding have been researched under an environmental justice lens in Atlanta, there is a gap present with respect to heat exposure and risk in socially vulnerable communities (GreenLaw 2012).

This study sought to begin to fill this research gap by identifying areas of increased heat exposure in Atlanta, Georgia, within the bounds of Fulton County, based on visual and numerical observations. Subsequent analysis of current climate governance would reveal mitigation efforts of the identified exposure to extreme heat. Phase 1 of the study involved mapping land surface temperature (LST) to reveal the spatial extent and patterns of heat exposure in Atlanta. Further analysis of heat exposure with socioeconomic and environmental variables that characterize socially vulnerable communities can reveal potential predictors of increased exposure in Atlanta. Phase 2 of this study consisted of content analysis of the city's climate governance strategies and plans to determine the level at which the identified spatial heat hazard is addressed in local planning. This research can therefore inform opportunities to enhance heat resilience and equity in a dynamic and heterogeneous city, based on heat exposure mapping and analysis. Urban extreme heat exposure is not limited to just the U.S. Southeast, but to many urban regions across the United States and the planet where disparities in climate risks and resilience are present.

2. Materials and methods

The first step in conducting this research was to map LST in Atlanta, Georgia within the bounds of Fulton County, in order to analyze urban patterns of spatial heat exposure (figure 2). A prime indicator of the UHI, LST has also been used for spatial analysis to identify relationships between heat exposure and socioeconomic variables that characterize marginalized and vulnerable communities (Jun *et al* 2017, Hoffman *et al* 2020). Although in years past, Atlanta, Georgia, has had LST mapped to identify the UHI, such studies have not been recent (Quattrochi and Lavall 1997) and have not explored socioeconomic variables as potential determinants for elevated heat exposure and risk. In order to identify potential socioeconomic predictors, census and environmental data were compared to temperature through a generalized linear regression model. A subsequent assessment was performed on Atlanta climate resilience plans that explicitly referenced climate hazards and resilience strategies pertaining to heat. This assessment of Atlanta climate governance was conducted to reveal the extent to which heat resilience planning in Atlanta addresses the identified heat exposure hazard.

2.1. Heat mapping

LST was used as a measure of temperature and heat exposure for the purpose of this study. Although not a direct measure of ambient air temperature (the temperature that one would feel when outdoors), LST has a direct effect on air temperature via radiative processes (NASA 2009). Because of these radiative processes, LST, which is also known as brightness temperature of the surface, can be a strong indicator of the UHI and its spatial extent—most effective when solar irradiance is most intense (Imhoff *et al* 2010, Quan *et al* 2014, Sheng *et al* 2017).

LST data were retrieved from the NASA/USGS Landsat 8 Satellite, equipped with operational land imager (OLI) and thermal infrared sensor (TIRS) instruments. Launched in February 2013, the satellite orbits Earth on a 16 day cycle, recording images of the planet at 30 m resolution with the OLI instrument, and 100 m resolution with the TIRS instrument (TIRS data are resampled to 30 m resolution to match OLI multispectral bands) (USGS 2019). Data from the satellite were downloaded by individual recorded day from the USGS Earth Explorer website (USGS n.d.), packaged with GeoTIFF images that represent each satellite band and a metadata file containing satellite thermal constants, rescaling factors, and corrections. The image for Band 10 (characterized by 16-bit digital numbers (DNs) that measure energy at the sensor), which is less contaminated with stray light than Band 11, was used for mapping surface temperature (Jiang 2017). Landsat 8 bands and observation parameters are presented in appendix E. In ArcGIS Geospatial Information System

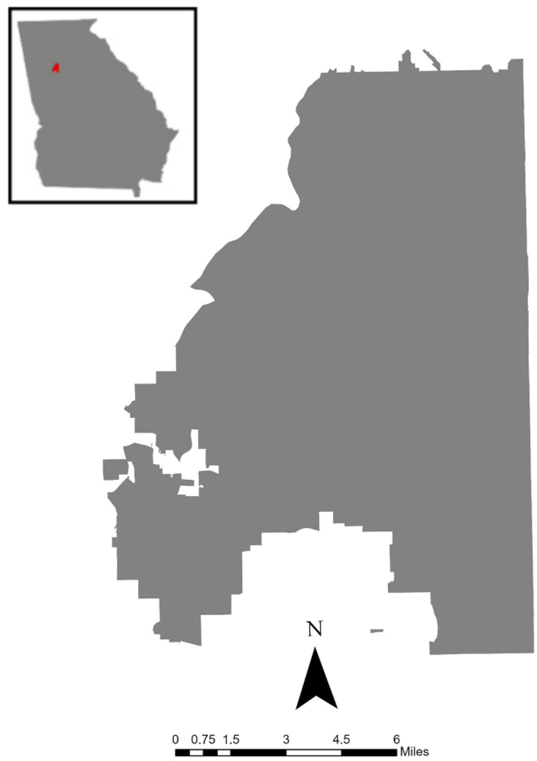

Figure 2. The area of study is the City of Atlanta, Georgia, within the bounds of Fulton County. A large majority of Atlanta's population resides within Fulton County, which contains approximately 90% of the City's area, including the most urbanized regions. Fulton County is located in Northwest Georgia (inset map).

software, the GeoTIFF image can be inserted as raster data and manipulated using the software's raster calculator. The City of Atlanta falls within Path 19, Row 37, in the Landsat record database. Thirteen images with minimal cloud cover during the summer months (June–August) of seven years (2013–2019) were downloaded. The City's official boundaries are within Fulton and DeKalb counties of the state of Georgia. However, only census block groups within Fulton County, which contains approximately 90% of Atlanta's area, were used for the purposes of this study (NACO 2011).

A series of calculations converted the image to surface temperature (figure 3), with equations provided by USGS (USGS 2019). The steps for calculating LST were followed as in Avdan and Jovanovska (2016). The first step was a conversion to top of atmospheric (TOA) spectral reflectance or radiance (L_λ):

$$L_\lambda = M_L \times Q_{\text{cal}} + A_L - O_i, \tag{1}$$

where M_L is the band-specific multiplicative rescaling factor ('RADIANCE_MULT_BAND_10' in the metadata file), Q_{cal} is the quantized and calibrated standard product pixel value measured in DNs, A_L is the band-specific additive rescaling factor ('RADIANCE_ADD_BAND_10' in the metadata file), and O_i is the band-specific correction constant. Once radiance is determined, the next step involves the conversion to TOA brightness temperature (BT). The equation to calculate BT is as follows:

$$\text{BT} = \frac{K2}{\ln\left[(K1/L\lambda) + 1\right]} - 273.15, \tag{2}$$

where $K1$ and $K2$ are band-specific thermal conversion constants ('K1_CONSTANT_BAND_10' and 'K2_CONSTANT_BAND_10', respectively, in the metadata file). For the purposes of calculating temperature in Celsius, temperature was converted from Kelvin by subtracting 273.15.

To complete the final step in calculating LST, land surface emissivity (ε_λ) must first be determined, which in itself requires calculating the proportion of vegetation (P_{v}). P_{v} is obtained by using the normalized difference vegetation index (NDVI), which is calculated using the satellite's 4th and 5th bands, near-infrared and red (R), respectively, where NDVI represents the density of a region's vegetation (Weier & Herring 2000). The equation is as follows:

$$\text{NDVI} = \frac{\text{NIR}\,(\text{band 5}) - \text{R}\,(\text{band 4})}{\text{NIR}\,(\text{band 5}) + \text{R}\,(\text{band 4})}. \tag{3}$$

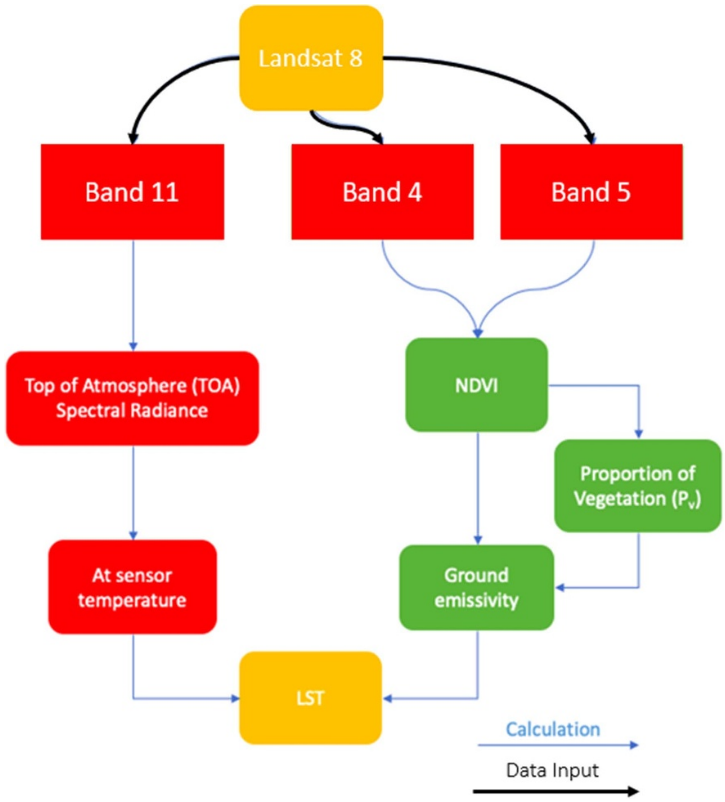

Figure 3. Flowchart representing the data calculations from the source (Landsat 8 satellite) to the desired product (LST). The Landsat 8 satellite has 11 bands, 3 of which are used for the purposes of mapping heat in this study (Band 4: Red, Band 5: Near-infrared, Band 11: Thermal infrared). Both ground emissivity, the measurement of how much radiation is being emitted from a surface (calculated with Band 4 & 5), and the at-thermal sensor temperature, the measurement of how much radiation energy is received at the sensor (calculated with Band 11), are required to determine LST.

Once NDVI is calculated, P_v can be determined:

$$P_v = \left(\frac{\text{NDVI} - \text{NDVI}_{\text{min}}}{\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}}}\right)^2. \quad (4)$$

With P_v determined, it can be substituted into the appropriate land surface emissivity equation:

$$\varepsilon_\lambda = 0.004 \times P_v + 0.986. \quad (5)$$

After all above equations were utilized within ArcGIS's raster calculator, (LST), could be calculated:

$$\text{LST} = \frac{\text{BT}}{\left[1 + \left(\frac{\lambda \text{BT}}{\rho}\right) \ln(\varepsilon_\lambda)\right]}, \quad (6)$$

with ρ defined as:

$$\rho = h\frac{c}{\sigma}, \quad (7)$$

where h is Planck's constant (6.626×10^{-34} J s), c is the speed of light (2.998×10^8 m s^{-1}), and σ is Boltzmann's constant (1.38×10^{-23} J K^{-1}).

2.2. LST validation

Weather underground (www.wunderground.com/history/) stores records for air temperature from hourly to monthly observations at the Atlanta Hartsfield–Jackson Airport weather station. Hourly temperature data were retrieved from the site's archive for validation via comparisons with calculated LST pixel values, on the dates of LST mapping. LST pixel values used for comparison were retrieved from the Airport weather station's coordinates (33.74 °N, 84.38 °W). The validation table displaying differences between the LST values and recorded observations at the weather station are shown in appendix B. Because LST is not a

Table 1. Average coefficients of variation (CVs) for variables across 305 City of Atlanta Census blocks. CVs between 12 and 40 denote medium reliability, while CVs over 40 denote low reliability. Education and racial demographic statistics tend to have lower reliability across census levels.

Variable	Block group coefficient of variation (CV)	Tract coefficient of variation (CV)
Education	43.3	25.5
Median Age	14.1	6.2
Median Income	19.4	12.3
Black Population	41.7	20.2

measure of ambient air temperature, differences between air temperature (measured meters above the surface) and LST values up to 5 °C have also been observed in related studies (Srivastava *et al* 2009, Avdan and Jovanovska 2016).

2.3. Socioeconomic variables

Four socioeconomic variables were used for visual and statistical analysis per census block group: Black population (race), population with a high school diploma (education), median age, and median income. Data were obtained from the U.S. Census 2018 five year estimate American Community Survey (ACS) (2014–2018). Although the Black population has not been the minority demographic in urban Atlanta since the 1960s (51.8% of the City of Atlanta's population in 2019), the Black population is still in the minority in the state of Georgia (32.4%) and nationwide (13.4%) (US Census Bureau 2019). The ACS data provide an aggregated estimate for each variable over the five-year period. Census data reliability was determined using Environmental Systems Research Institute thresholds (ESRI 2018). Coefficients of variations are shown in table 1. Census block group data estimates for chosen variables ranged from medium reliability to low reliability. In our analysis, we therefore conduct a sensitivity test to compare reliability results at both spatial scales.

Because these variables commonly characterize marginalized populations that experience high social vulnerability and have also been most affected by economic disinvestment, racism, and discriminatory practices, they were chosen to identify any potential relationships with LST (Benevolenza and DeRigne 2019, Mazdiyasni and AghaKouchak 2020).

2.4. Statistical analysis

A regression was performed to analyze the relationships between LST and socioeconomic data studied (Zou *et al* 2003). LST served as the dependent variable, while race, education, age, and income (as well as the biophysical predictors NDVI and impervious surface) served as the independent or explanatory variables. City of Atlanta census block group boundaries were placed over calculated LST maps for both visual and statistical analysis. LST and NDVI were aggregated to the census block group level by the mean value within the block group boundary. LST and NDVI mapping and data manipulation were performed within ArcGIS, while statistical analysis was performed in Microsoft Excel via the Analysis ToolPak add-in.

2.5. Heat governance analysis

Atlanta municipal-scale climate governance plans and documents were retrieved via a focused internet search. Documents were then examined for the existence of climate resilience strategies—plans without climate resilience strategies were discarded. A total of 33 plans were found, 14 of which were used for analysis. These 14 plans were within the study time window (2013–2019), addressed the City of Atlanta and/or specific communities within, and contained strategies that mention an explicit climate hazard. Examples of plans that include climate resilience strategies for the Atlanta metropolitan area are citywide plans such as *Resilient Atlanta: Actions to Build an Equitable Future* and *City of Atlanta Climate Action Plan* (appendix C). Plans such as *Resilient Atlanta*, as well as neighborhood master plans and community plans, were analyzed by a single coder for their content referencing explicit climate resilience strategies. Once a climate hazard (i.e. a strategy or target to address flood, drought, or heat) was explicitly identified, the quote (and associated metadata) from the planning document was extracted and placed into a formatted coding database. The codebook for this analysis was slightly modified from the Urban Resilience to Extremes Sustainability Research Network (UREx SRN) governance document analysis codebook (Iwaniec *et al* 2020, Kim *et al* 2021). Specifically, the code for 'non-specific hazards' was renamed and its criteria modified to capture 'general capacity' climate resilience strategies. 'General capacity' strategies are interpreted as strategies that address climate hazards aside from heat, flood, or drought, or address two or more climate hazards. For example, a green infrastructure strategy may be identified in a municipal plan but without explicit mention of a single climate resilience hazard. The new code for ‘general capacity’ now captures this strategy as it can provide ecosystem services to address both flooding and heat.

Strategies extracted from governance documents by the coder were identified as action items, specific goals, or interventions to address climate resilience. Targets were identified as quantitative or qualitative descriptions (i.e. how much, where, and when) provided as metrics for the implementation of identified strategies. Additional notes were also extracted from the governance documents to capture associated information describing normative criteria (i.e. why the strategy/target is needed). Metadata for Atlanta strategies and targets were organized by: (a) the document they were extracted from, and (b) a unique identifier for each strategy (in reference to how many strategies have been extracted from a document).

After the strategies were extracted based on the explicit mention of a climate hazard, additional coding by a single coder was conducted to identify social, ecological, and technological systems (SETSs) features, knowledge system type, geographical/spatial scale, intended beneficiaries, and resilience scope of the strategy (UREx SRN) (appendix D):

- SETS features: Aspect of the urban system the strategy is intended to change (i.e. Social, Ecological, or Technological), coding for key types of social, ecological, or technological changes (e.g. for Social, specifying whether is it an Education, Behavioral, or Legal strategy).
- Knowledge system type: Forms of local, practitioner, and academic knowledge relevant to this strategy.
- Geographical/spatial scale: Where the strategy is to be implemented.
- Intended beneficiaries: For whom are the strategy’s benefits intended.
- Implementation scope of the strategy: How the intended changes will be implemented (e.g. change in governance norms, programmatic implementation).

Analyzing a plan for its different strategies provides insight into how different governance institutions (e.g. city departments) are framing climate resilience, what adaptation strategies they are pursuing, why and where they are pursuing these strategies, and whom these strategies will benefit. In addition, coding allows for quantitative analysis that can highlight city planning priorities. For example, if strategies for drought mitigation are extracted and coded most often, then drought mitigation is likely a priority for the plan’s governing body.

2.6. Review of climate governance analysis

Inter-rater reliability was used for reproducibility and review purposes of initial climate resilience coding (Milne and Adler 1999). Once the full extraction and coding of climate resilience strategies was completed, two other coders were given a random sample of ten, uncoded climate resilience strategies from the coding database. The two coders then independently coded these ten strategies. Once all coding was complete, the three coders convened to discuss the differences and similarities between their coding, as well as interpretations of the codebook and climate resilience strategies. Cohen’s Kappa was calculated as the measure of agreement between each coder. The average Cohen’s Kappa value across all three coders was 0.55, indicating moderate agreement (Hallgren 2012).

3. Results

3.1. Heat exposure analysis

A large spatial variation exists in the City of Atlanta’s average LST across the 13 analyzed summer days during 2013–2019 (figure 4). The average LST of Atlanta’s 305 block groups ranges from 23.7 °C (low heat exposure) in areas with more abundant vegetation, to 31.5 °C (high heat exposure) in areas with increased urban development. There is a definitive area of elevated temperatures in the center of the city, compared to surrounding regions. This area, the urban core, is composed of 53 inner-city census block groups with 70% or more impervious surface and an average NDVI value below 0.23 (figure 5). This urban core region has an average LST of 28.9 °C (above the 90th percentile of average block groups LST), while its surroundings areas have an average LST of 26.7 °C. This difference seems to follow from the impervious surface present in the urban core, including high concentrations of buildings and surrounding roadways, such as the major highway I-85/I-75.

Across the analyzed days, the warmest areas of the city possess average LST values above 30 °C (86 °F). Represented in Atlanta climatology records, July is shown to be the warmest month of the year for the city, followed by August, and then June. Calculated average LST values are consistent with Atlanta climatology, as July was the warmest month, on average. July days analyzed have the highest average LST for the City of

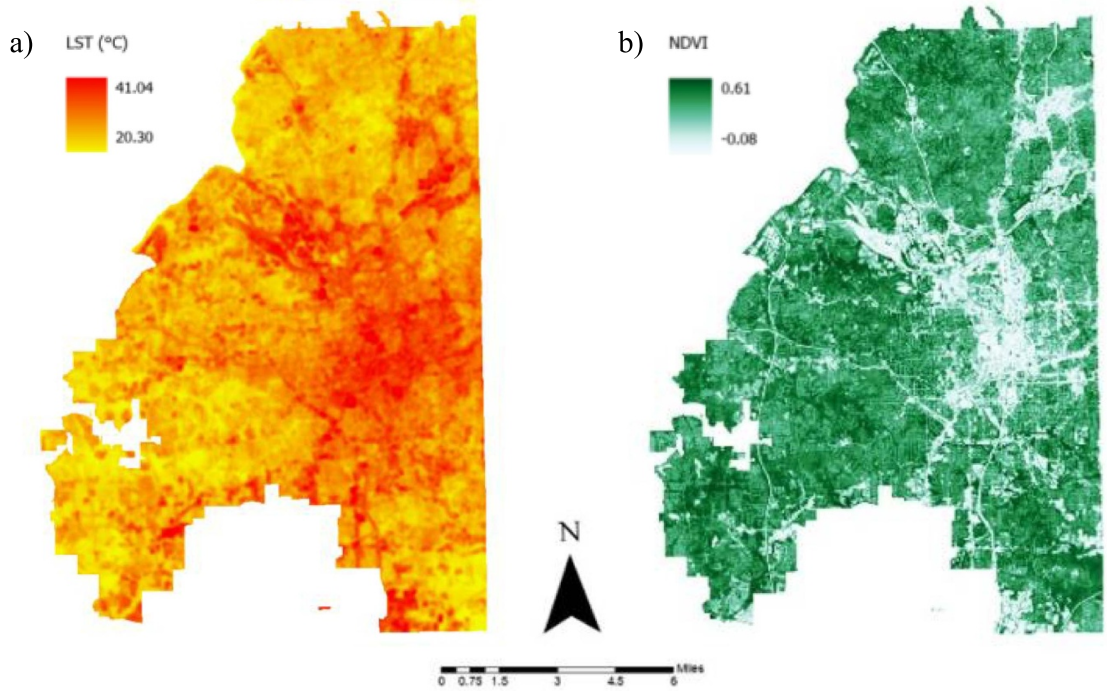

Figure 4. City of Atlanta (Fulton County) average land surface temperature (LST) and average normalized difference vegetation index (NDVI) for 13 summer (June–August) days during the years of 2013–2019. (a) Average LST: the urban core possesses the highest temperatures, characterized by streaks and clusters of reddish color. (b) Average NDVI: greener colors represent higher amounts of vegetation and green infrastructure. Note cooler colors in panel (a) where there are greener colors in panel (b).

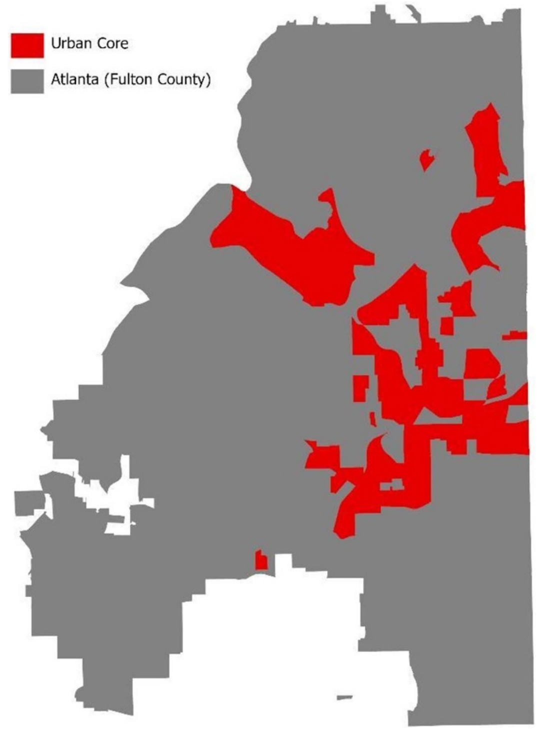

Figure 5. The urban core is composed of 53 inner-city census block groups with 70% or more impervious surface and an average NDVI value below 0.23. These criteria characterize census block groups with an average LST of 28.9 °C (84.02 °F).

Atlanta (42.63 °C or 108.68 °F), followed by August (41.85 °C or 107.33 °F). With the exception of two summer days (14 July 2016 and 21 June 2019), the differences between observed LSTs and recorded air temperatures remained under 5 °C (appendix B).

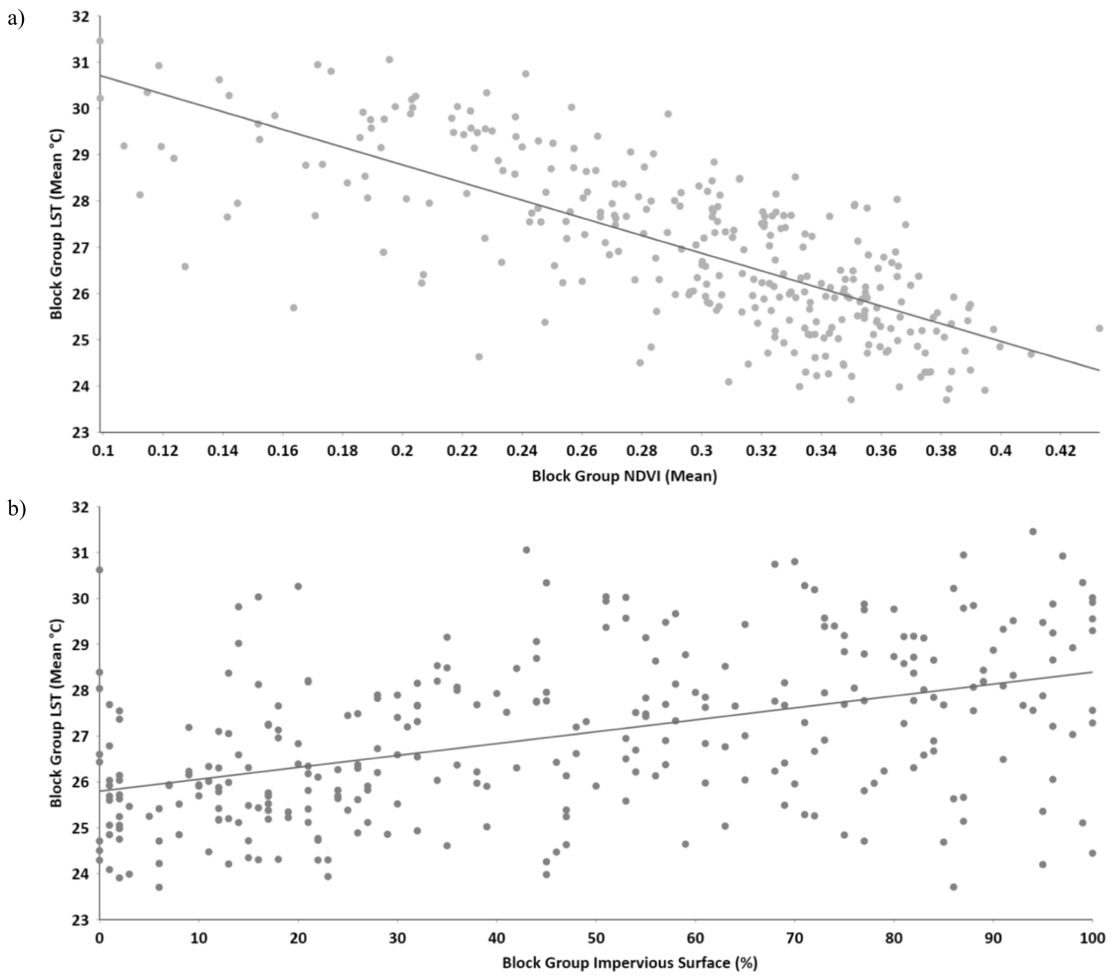

Figure 6. Biophysical predictors of LST in the City of Atlanta. (a) The relationship between the average normalized difference vegetation index (NDVI) and the average LST of each block group ($n = 305$ block groups). LST is inversely related to NDVI—as NDVI values increase, LST decreases ($y = -19.1x + 32.6$, $R^2 = -0.56$). (b) The relationship between percentage of a block group that is impervious surface and the average LST of each block group ($n = 305$ block groups). LST and percentage of impervious surface (which has lower NDVI values) are positively related ($y = 2.59x + 25.8$, $R^2 = 0.22$).

The City of Atlanta has a relatively large urban tree canopy, present in regions with lower LST values and higher NDVI values, characterized by yellow and green colors, respectively, in figure 4 (e.g. Northern and Southwestern Atlanta). LST and NDVI have an inverse relationship—where LST values are higher, NDVI values are expected to be lower (figure 6). Low NDVI values represent low amounts of vegetation, typically characterized by rock, sand, or snow. In Atlanta, low NDVI values closer to −1 likely represent extensively built, anthropogenic environments such as buildings, highways, etc, while higher NDVI values closer to +1 represent vegetation (figure 6). Because the area of study is an urban environment, NDVI values between 0.3 and 0.6 that represent scattered vegetation are typical for urban greenery. In addition to reflecting infrared radiation, trees and greenspace provide environmental services that mitigate heat beyond direct shading. Urban greenspace and trees have lower surface temperatures due to shading and the cooling qualities of evapotranspiration (Qiu *et al* 2017). Other infrastructure such as blue or grey infrastructure and reflective or permeable technologies may also contribute to lower temperatures, and higher NDVI.

During the summer months of 2013–2019, increases in LST are, on average, accompanied by statistically significant decreases with median age, median income, education, Black population, and NDVI (table 2). Across these significant results, slopes are negative, with the exception of impervious surface. Although not extremely strong, impervious surface's statistically significant relationship with LST represents an increase in LST per an increase in impervious surface (figures 6 and 7). As hypothesized, LST is shown to be highest in downtown areas where urban development is at its highest and natural landscape, greenspace, and vegetation are at their lowest. However, in areas where greenspace (measured via NDVI) is at its highest, African-American populations are also most populous—accounting for the negative slope characterizing the relationship between average LST and the percentage of African-American populations per census block

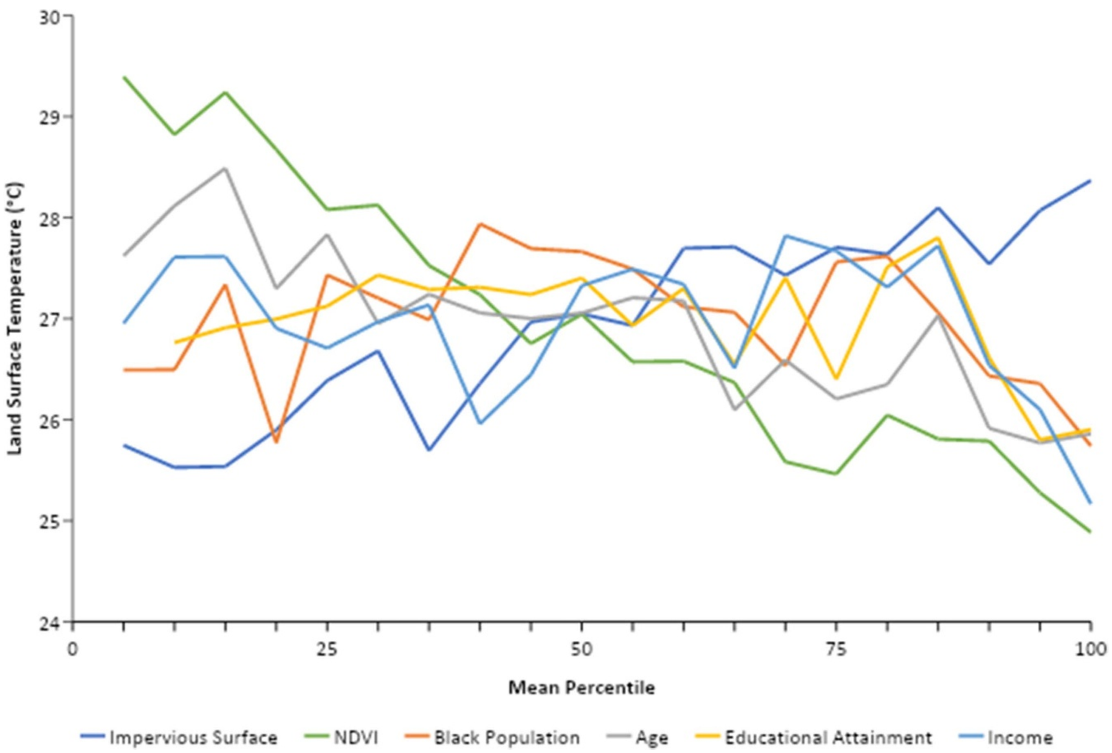

Figure 7. LST varies across socioeconomic and biophysical characteristics of block groups. Data points represent average land surface temperature for each variable (impervious surface, NDVI, Black population, age, educational attainment, and income) binning by block groups on the horizontal axis by percentile for each variable ($n = 305$ total block groups per variable). Impervious surface and NDVI display the most linear relationships with LST, although trending in opposite directions (table 2).

Table 2. Slopes of relationships between socioeconomic variables/biophysical predictors and average LST for 305 block groups in the City of Atlanta (* = significant, $p < 0.05$).

Variable (per block group)	Slope	*p*-value
Education	−0.002	0.005832*
Median Age	−0.065	0.0000001*
Median Income	−0.000008	0.000065*
% African-American	−0.471	0.067372
NDVI	−19.07	0.000009*
Impervious Surface	2.594	0.0000000067*

group (figure 6). Higher income and age, and lower education levels also follow a similar spatial pattern, characterized by higher levels of NDVI.

3.2. Heat in climate governance documents

A search for planning documents after 2019 found no additional or new relevant climate resilience plans. Heat is the climate hazard least explicitly planned for, behind flood and drought (figure 8). Across SETS categories, heat strategies were coded most as ecologically based strategies, followed by social, and then technological (figure 9). In addition to the total number of strategies across climate hazards, figure 9 also breaks down the different types and subcategories of SETS strategies by climate hazard. Addressing climate hazards of heat and flooding can involve overlapping measures frequently, as green infrastructure strategies intended to mitigate flooding also possess ecosystem services that provide heat relief. These overlapping strategies are captured in the 28 general capacity strategies (figure 8). For example, the *Downtown Atlanta Master Plan* explicitly addresses planting more trees in the downtown area to 'help mitigate the 'urban heat island' effect' (Downtown Atlanta Improvement District 2017)—an ecological strategy. Atlanta climate governance placed a large emphasis on the expansion or maintenance of this urban tree canopy and green infrastructure, especially in the urban core or downtown Atlanta where the highest temperatures are most

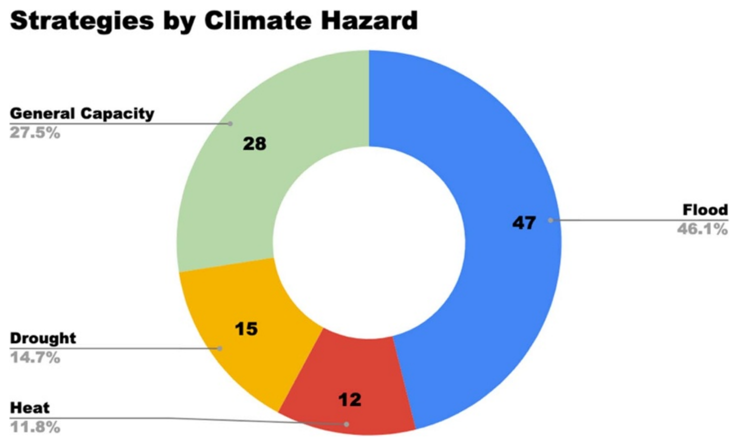

Figure 8. Breakdown of fifty-nine strategies extracted from 14 climate governance documents (2013–2019), coded by explicitly mentioned climate hazard. The majority of extracted strategies were coded as flood, followed by drought, and then heat. General capacity strategies are defined as addressing two or more climate hazards. Strategies can be coded by all relevant climate drivers or hazards.

concentrated. For example, Action 3.4.3: from the *Resilient Atlanta: Actions to Build an Equitable Future* plan outlined 'Protecting and expanding Atlanta's tree canopy' (100 Resilient Cities 2017).

Of the few technological strategies for heat, one strategy was coded from the City of Atlanta's Climate Action Plan, outlining the introduction of 'cool roofs' to buildings downtown (City of Atlanta Climate Action Plan 2015). This technological development or improvement strategy, for example, utilizes cool roof technologies such as light-colored paint or material that reflects more heat energy than it absorbs, reducing the heat transfer to surrounding areas and within the building (Bozonnet *et al* 2011). Such a concept can also decrease a building's energy consumption and output (Konopacki *et al* 1998, U.S. Department of Energy n.d.).

Most coded strategies are meant to be implemented citywide (including strategies at unspecified scales), followed by implementation on government-owned property and then in specific neighborhoods (figure 10). The geographic scales 'ecosystem feature' and 'biophysical defined boundary' are concerned solely with flooding strategies, as they may involve features such as bioswales or riverbed/bank modifications. There are no heat strategies coded for within the 'Other administrative scale' and 'sub-national' geographic scales, showing that heat strategies in the Atlanta Metropolitan area are confined to smaller scales.

4. Discussion and conclusions

There is an absence of explicit resilience planning for heat in the City of Atlanta, likely related to the lack of urban heat studies conducted across the city. This study sought to address this research gap by identifying areas of increased heat exposure in Atlanta, Georgia to inform heat resilience planning and equity. The mapping of LST across 13 summer days in Atlanta between 2013–2019 allowed for the identification of spatial heat variation in areas around the city—pinpointing areas of elevated potential heat exposure and risk. The identification of these areas allowed for statistical analysis with theory-informed potential socioeconomic predictors of elevated LST (table 2), as well as potential biophysical predictors of LST (NDVI, impervious surface) (Yuan and Bauer 2007, Harlan *et al* 2013). Variables that widely denote populations that are socially vulnerable to extreme heat (Mitchell and Chakraborty 2014, Benevolenza and DeRigne 2019, Mazdiyasni and AghaKouchak 2020) proved to have weak or negative relationships with LST. Environmental predictors such as NDVI and impervious surface were found to have strong negative and positive relationships with LST, respectively, consistent with the literature. In addition, content analysis of Atlanta's climate governance revealed few strategies for heat resilience, as it was the climate hazard least explicitly planned for. However, these few strategies were focused in the city's urban core, where LST values were also found to be on average 2 °C higher than surrounding areas and heat exposure and risk were at their highest.

Despite other American cities in the literature possessing positive relationships between LST values and specific socioeconomic factors indicative of communities that are socially vulnerable to heat (table 2), the City of Atlanta proved to not follow the same trend. Weak relationships were found between LST and these variables, contrary to findings in other urban regions such as Baltimore (Huang *et al* 2011), Phoenix (Jenerette *et al* 2007, Buyantuyev and Wu 2010), and Philadelphia (Johnson and Wilson 2009). While there is

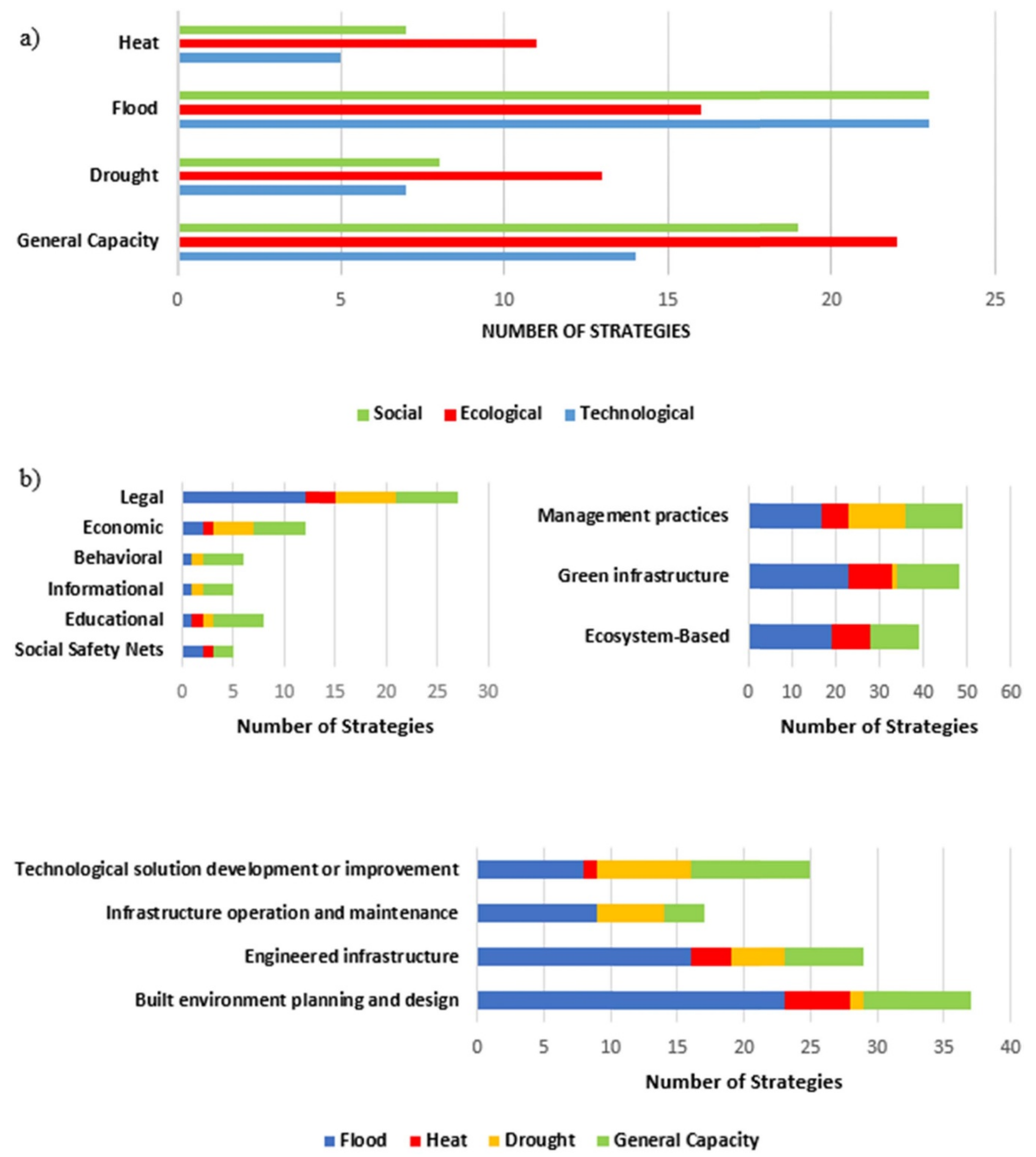

Figure 9. Fifty-nine strategies from 14 different plans (2013–2019) are coded as social, ecological, and/or technological systems (SETS) strategies across three different climate hazards or general capacities. A single strategy can be coded multiple times across applicable categories. (a) Number of SETS strategies extracted from Atlanta climate resilience plans, by explicit climate hazard or general capacity. (b) Breakdown of strategies coded as one or more of six social methods, as one or more of three ecological methods, or as having one or more of four technological methods.

a small portion of Atlanta's low-income or Black population that lives within and around the urban core amongst higher levels of heat exposure, the majority of these populations resides in the Western and Southern areas of the city (figure 11). These same regions of the city also border and overlap with several formerly redlined areas. However, these populations do not experience high levels of heat exposure via LST. This region of the city remains aged, somewhat underdeveloped, and highly vegetated, with corresponding values of lower LST (Kahn 2016). While communities that live in these regions with cooler LSTs may be more socially vulnerable to extreme heat (Basu and Samet 2002, Karl *et al* 2009, Mitchell and Chakraborty 2015, Dialesandro *et al* 2021), they are less exposed to it outdoors, with protection from extensive green infrastructure (where higher levels of NDVI are observed).

North of the I-75/85 corridor, highly developed areas of the city house most of Atlanta's non-Black populations with higher incomes and higher levels of education. In this region, which contains much of what

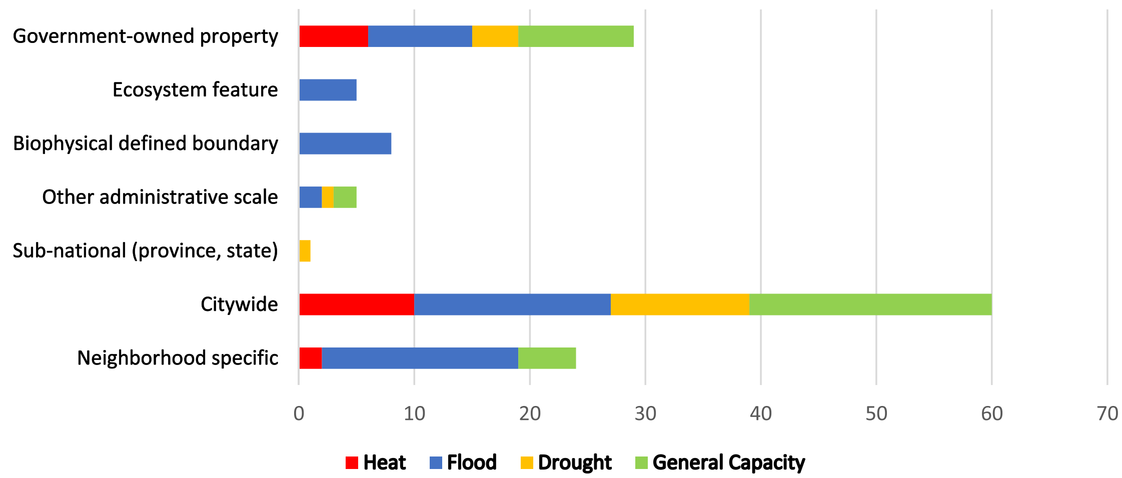

Figure 10. Spatial scale of fifty-nine strategies extracted from Atlanta climate resilience plans. Strategies were coded as applicable to one or more geographic scales, in which the strategy is/was/would be intended to be implemented.

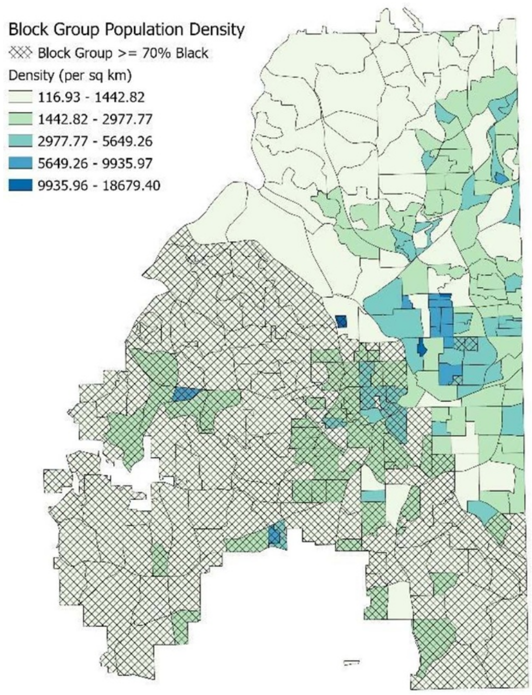

Figure 11. The City of Atlanta's (Fulton County) census block group population density. Overlayed is an indicator of census block groups that have a population that is at least 70% black. Atlanta's Black population is most prominent in western to southern Atlanta.

is known as the 'urban core' for the purposes of this study (figure 5), heat exposure was found to be at its highest levels. Higher levels of impervious surface and lower levels of NDVI create conditions for elevated LST values (NASA 2009). Despite this, social vulnerability to heat is low in these areas. Much of the urban core is home to more affluent, non-Black populations where development is more recent (Kahn 2016). Although this infrastructure may contribute to higher levels of outdoor heat exposure, it is likely that these buildings and structures are more up to date and retrofitted with cooling infrastructure indoors.

Although not a direct measurement of felt temperature, LST can serve as a proxy to felt temperature as it directly affects ambient temperature via radiative processes (NASA 2009). It is important to note that LST does not necessarily represent or imply indoor temperatures within these buildings and structures. Thus, lower values of LST do not necessarily imply lower indoor temperatures, and higher values of LST do not necessarily imply higher indoor temperatures. Such temperatures are subject to mechanisms other than solar radiation or surface emissivity (Liang and Weng 2008). Ambient temperature measurements would best capture the felt variations of temperatures indoors (Tham *et al* 2020). However, LST is an ideal measure of outdoor heat exposure, as it can characterize the level to which the natural and built environment has direct effects on ambient or felt temperature via radiation energy (Arnfield 2003). Reducing outdoor heat exposure can lessen the potential burdens of increased indoor heat exposure, as high indoor temperatures can potentially be even more dangerous than high outdoor temperatures, especially for socially and physically vulnerable populations (Basu and Samet 2002, Kinney *et al* 2008).

The identification of areas of elevated heat exposure and risk in the City of Atlanta also motivated the analysis of local climate governance for heat resilience between the years of 2013–2019. Following phase one of this study, areas of the urban region have been characterized as having low to high heat exposure (figures 4 and 5). To minimize risk of adverse effects on public health in identified areas of high heat exposure, as well as decrease energy burden in these areas, climate governance should address heat exposure in these areas. Atlanta has increased local resilience planning within the last decade, and it is important that such planning addresses much of the world's most prominent threat, in extreme heat (Lo *et al* 2019, Vicedo-Cabrera *et al* 2021). It is also important that local resilience planning should emphasize heat resilience in communities that have elevated social vulnerability relevant to the hazard (Rohat *et al* 2019). Explicit heat resilience planning is not prevalent across Atlanta's climate governance documents and has only been minimally focused in areas of high social vulnerability relevant to heat. Socially vulnerable communities exist in Southern and Western Atlanta where LSTs and resulting levels of heat exposure were fortunately at their lowest. Heat resilience strategies are most focused in the downtown region, the 'urban core' (figure 5), where heat exposure is high but social vulnerability to heat is low.

Strategies for heat were largely green infrastructure oriented and focused on protecting the City of Atlanta's urban tree canopy, most prominent in Atlanta's socially vulnerable communities. Atlanta's urban tree canopy plays an important role in mitigating the UHI as shown in LST observations. The most highly vegetated areas were the coolest across the urban region. In addition to natural cooling mechanisms such as evapotranspiration, vegetation also absorbs less radiation, reducing the heating of nearby air via longwave radiation emission (Buyantuyev and Wu 2010, NASA n.d.). The urban tree canopy also presents adaptive climate responses beyond extreme heat mitigation, captured in coded general capacity strategies (Haaland and van den Bosch 2015). Despite tradeoffs such as tree maintenance and clean up (seasonal changes, post-storm, etc), Atlanta's urban tree canopy's display of numerous ecosystem services can serve as a worldwide example of natural climate resilience, especially in a major city (Robinson and Lundholm 2012). However, much of Atlanta's tree canopy, especially in marginalized communities, may have simply been left intact from disinvestment (redlining, zoning, etc). Following urban Atlanta's massive outmigration of White communities in the early to middle 20th century, a large portion of the urban tree canopy's growth may be the unintentional result of dereliction (Runfola and Hankins 2010, Pooley 2015).

While environmental neglect can also serve as a form of environmental injustice, Atlanta's potential neglect of tree maintenance in disinvested neighborhoods may have contributed to an above average urban tree canopy that shields socially vulnerable communities from direct outdoor heat exposure (Macintyre *et al* 2008, Trees Atlanta 2008). Compared to newly planted and frequently maintained green spaces, older, unchanged green infrastructure has been observed to have higher reflective properties (higher albedo) and increased evapotranspiration (Sun and Chen 2017). While expanding or replacing existing green infrastructure in marginalized communities may present opportunities for increased heat resilience, it can also raise issues of equity, displacement, and gentrification (Immergluck and Balan 2018, Pearsall and Eller 2020, Eck 2021). Inequities in green infrastructure are most pronounced in terms of quality and type of greenspace rather than abundance, as inequities in greenspace access have been found to exist across more affluent communities as well as poorer communities (Macintyre *et al* 2008, Panduro and Veie 2013, Ibes 2015, Kimpton 2017, Xu *et al* 2018). More extensive and newer, higher quality greenspaces attract buyers who are willing to pay higher prices to live within close proximity to them, gradually increasing local home and property values (Saphores and Li 2012, Kolbe and Wüstemann 2014, Black and Richards 2020). Thus, it is important that green infrastructure installation and expansion are performed in a manner that considers and prioritizes existing residents (Byrne *et al* 2010, Nesbitt *et al* 2019).

It is also important to note that this study did not evaluate the effectiveness of climate planning strategies. While many cities have yet to undergo any climate adaptation or resilience planning, many others stall after the planning phase (Araos *et al* 2016). It is common for written strategies to never be implemented due to inaction, funding, institutional barriers, or circumstantial adjustment to plans (Wier 2016). Strategies that are implemented are not all equally effective and do not guarantee the intended results (Tyler and Moench 2012). This study also only evaluated formal planning down to the neighborhood scale, whereas informal planning that may be underway or not publicly available was not included for analysis.

This study does not go without some limitations in methodology. Land use/land cover maps may be more accurate for assessing vegetation cover in an urban region. In the future, this study could be expanded to later years as average temperatures continue to increase and amplify the UHI. Additional summer months and Landsat 8 satellite passes over the region will also provide more LST data to be analyzed, potentially unobscured by cloud cover as well, which limited the selection of summer days used for this study. Such a future study could also assess the efficiency of city governance achieving planning goals that were previously set in these governance documents. Due to limited access to weather station data in the City of Atlanta, the Hartsfield–Jackson International Airport was used for temperature validation. The airport is south of the City of Atlanta periphery and may not always accurately reflect temperatures that are a result of the UHI in the city's urban core. This may have led to larger differences in observed LST and historical temperatures.

This study analyzed urban heat via LST in the City of Atlanta to identify areas of increased heat exposure, and analyze relationships with potential socioeconomic and environmental factors that have been found to be predictors of elevated heat exposure in other urban regions within the United States. While there is an UHI present in Atlanta, this analysis found weak relationships between heat exposure and socioeconomic variables, revealing that the majority of historically marginalized communities that are socially vulnerable to extreme heat are not highly exposed to higher LSTs, contrary to that of many other American cities. This analysis also found that Atlanta's climate governance does not have a strong focus on extreme heat and heat resilience. For heat strategies that were analyzed, they are largely focused on the most developed areas of Atlanta, where heat exposure and risk were high but social vulnerability to heat was low. Across the City of Atlanta's minimal heat governance, was an emphasis on protection of the city's urban tree canopy, and the introduction of additional greenspace. The results of this work highlight areas of interest for future work in heat resilience equity in a city whose past has been riddled with environmental injustice and racism (Middleton 2020) and is the fourth-fastest growing metropolitan area in the United States over the past decade (US Census Bureau n.d.).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgment

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Appendix A

Historical racial characteristics, City of Atlanta, 1850–2010.

Year	Total population—white (%)	Total population—black/ African-American (%)
1850	80.1	19.9
1860	79.7	20.3
1870	54.4	45.6
1880	56.3	43.7
1890	57.1	42.9
1900	60.2	39.8
1910	66.4	33.5
1920	68.7	31.3
1930	66.7	33.3
1940	65.4	34.6
1950	63.4	36.6
1960	61.7	38.3
1970	48.4	51.4
1980	32.4	66.6
1990	31.0	67.1
2000	33.2	61.4
2010	38.4	54.0

Source: Data from Gibson and Jung (2005), U.S. Census Bureau (2019).

Appendix B

Temperature validation.

Dates	Air temperature at Hartsfield–Jackson Airport (°C) at 11 AM	LST (°C)	Difference
23 August 2013	23.88	27.66	−3.78
26 August 2014	26.68	30.38	−3.7
28 July 2015	30.56	32.25	−1.69
12 June 2016	30	31.88	−1.88
14 July 2016	28.89	34.97	−6.08
15 August 2016	28.89	N/A—Clouds	N/A
31 August 2016	28.89	31.88	−2.99
17 July 2017	26.67	28.31	−1.64
18 June 2018	28.89	31.98	−3.09
4 July 2018	30.56	31.02	−0.46
5 August 2018	30	N/A—Clouds	N/A
21 June 2019	27.78	34.13	−6.35
8 August 2019	29.44	31.94	−2.5

Appendix C

List of governance documents used for the study:

Resilient Atlanta: Actions to Build an Equitable Future: www.100resilientcities.org/wp-content/uploads/2017/11/Atlanta-Resilience-Strategy-PDF-v2.pdf

North Georgia Water Resource Management Plan: http://northgeorgiawater.org/wp-content/uploads/2018/03/Water-Resource-Management-Plan_REVISED.pdf

City of Atlanta Climate Action Plan: https://atlantaclimateactionplan.files.wordpress.com/2016/02/atlanta-climate-action-plan-07-23-2015.pdf

City of Atlanta Code of Ordinances: https://library.municode.com/ga/atlanta/codes/code_of_ordinances?nodeId = 10376

North Buckhead Neighborhood Master Plan: www.nbca.org/Plan/Final/NorthBuckhead_Report_05.15.2015.pdf

Lakewood Livable Centers Plan: www.atlantaga.gov/Home/ShowDocument?id = 19143

Downtown Atlanta Master Plan: www.atlantaga.gov/home/showdocument?id = 40541
Turner Field Stadium Neighborhoods Plan: www.atlantaga.gov/home/showdocument?id = 24209
Midtown Garden District Neighborhood Plan: www.atlantaga.gov/home/showdocument?id = 39873
West Side Land Use Framework Plan: www.atlantaga.gov/home/showdocument?id = 39877
Morningside Lenox Park Master Plan: www.atlantaga.gov/home/showdocument?id = 40555
Historic Atlanta Master Plan: www.atlantaga.gov/home/showdocument?id = 39879
Washington Park Visioning Plan: www.atlantaga.gov/home/showdocument?id = 21661
Atlanta Capital Improvements Plan: www.atlantaga.gov/home/showdocument?id = 40523

Appendix D

Target specificity (quantitative or tangible) coding key.

Assigning S, E, T (with additional categories from IPCC)			
Social	S1	Social safety nets	Social safety nets and social protection, food banks and distribution of food surplus, municipal services including water and sanitation, vaccination programs, essential public health services including reproductive health services, enhanced emergency medical services, international trade
	S2	Educational	Awareness raising and integrating into education, gender equity in education, extension services, sharing local and traditional knowledge, integration of local and traditional knowledge into adaptation planning, participatory action research and social learning, community surveys, knowledge-sharing and learning platforms, international conferences and research networks, communication through media, operations training
	S3	Informational	Hazard and vulnerability mapping, early warning and response systems, systematic monitoring and remote sensing, climate services (including improved forecasts), downscaling climate scenarios, longitudinal datasets, integrating indigenous climate observations, community-based adaptation plans (including community-driven slum upgrading and participatory scenario development). *data driven
	S4	Behavioral	Accommodation, household preparation and evacuation planning, retreat and migration, soil and water conservation, storm drain clearance, livelihood diversification, changing livestock and aquaculture practices, crop-switching, changing cropping practices, patterns and planting dates, silvicultural options, reliance on social networks
	S5	Economic	Financial incentives including taxes and subsidies, insurance (including index-based weather insurance schemes), catastrophe bonds, revolving funds, payments for ecosystem services (PES), water tariffs, savings groups, microfinance, disaster contingency funds, cash transfers
	S6	Legal, regulations,	Land zoning laws, building standard, easements, water regulations and agreements, laws to support disaster risk reduction, laws to encourage insurance purchasing, defining property rights and land tenure security, protected areas, marine protected areas (MPAs), fishing quotas, patent pools and technology transfer
	S7	Institutional/ governance	New research/information, evaluate effectiveness of …, develop a plan for…, explore…, coordination, partnerships
Ecological	E1	Ecosystem-based	Ecological restoration, wetland and floodplain conservation and restoration, increasing biological diversity, afforestation and reforestation, conservation and replanting mangrove forest, bushfire reduction and prescribed fire, assisted migration or managed translocation, ecological corridors, ex situ conservation and seed banks, green and open space
	E2	Green infrastructure	Green infrastructure (e.g. shade trees, green roofs), urban gardens, rain gardens
	E3	Management practices	Community-based natural resource management (CBNRM), adaptive land-use management, controlling overfishing, fisheries co-management, ecosystem focused plan?

Technological	T1	Built environment planning and design	Urban planning and design, design storm, building codes
	T2	Engineered infrastructure	Seawalls and coastal protection structures, flood levees, sewage works, improved drainage, beach nourishment, pavement, physical buildings, solar shade, flood and cyclone shelters
	T3	Infrastructure operation and maintenance	System inspection and monitoring, operator training program, facility and equipment maintenance/repair, drainage cleaning, best management practices (BMPs)
	T4	Technological solution development and improvement	New crop and animal varieties, genetic techniques, traditional technologies, efficient irrigation, water saving technologies, conservation agriculture, food storage and preservation facilities, hazard mapping and monitoring technology, early warning systems, building insulation, mechanical and passive cooling, renewable energy technologies, second generation biofuels

Knowledge system	
What form of knowledge system is relevant to this adaptation strategy?	
K1	Local knowledge (not necessarily Indigenous)
K2	Academic knowledge from natural & applied sciences (e.g. climatologists, hydrologists, engineers, urban designers/planners)
K3	Academic knowledge from social sciences (e.g. anthropologists)
K4	Academic knowledge from health sciences (e.g. epidemiologists)
K5	Artistic knowledge (e.g. actors, photographers)
K6	Institutional knowledge (e.g. institutional memory, governance)

Geographical/spatial scale (Adaptation Spatial Scale)	
If relevant, what is the geographical/spatial scale of the proposed adaptation option?	
G1	Neighborhood specific
G2	City-wide
G3	Sub-national (province, state)
G4	National
G5	Another administrative scale (e.g. a health unit, Indigenous territory)
G6	Watershed/basin/catchment
G7	Ecosystem feature (e.g. wetland, delta, mangrove)
G8	Unknown/undefined
G9	City-owned properties

Beneficiaries	
Who are the intended beneficiaries of the proposed adaptation option? Check as many as apply.	
B1	Private business
B2	Collectives (i.e. specific group of people such as women, elderly, marginalized, etc)
B3	General public (including residents)

Scope (Point of Intervention)	
What's the intended scope of the adaptation strategy?	
S1	Change in norms or ways of doing things
S2	Continue, change or implementation of a program
S3	Change in policy, laws or regulation
S4	Change in economic instruments (e.g. subsidies, taxes)
S5	Punctual event or activity (e.g. recommendation, short-term pilot program)

External driver	
D1	Flooding Non-specific
D2	Flooding Urban
D3	Flooding Riverine
D4	Flooding Coastal
D5	Heat
D6	Drought
D7	Non-Specific Hazards
D8	General Capacity

Appendix E

Landsat 8 band glossary.

Bands	Wavelength (micrometers)	Resolution (meters)
Band 1—Coastal aerosol	0.43–0.45	30
Band 2—Blue	0.45–0.51	30
Band 3—Green	0.53–0.59	30
Band 4—Red	0.64–0.67	30
Band 5—Near Infrared (NIR)	0.85–0.88	30
Band 6—SWIR 1	1.57–1.65	30
Band 7—SWIR 2	2.11–2.29	30
Band 8—Panchromatic	0.50–0.68	15
Band 9—Cirrus	1.36–1.38	30
Band 10—Thermal Infrared (TIRS) 1	10.6–11.19	100
Band 11—Thermal Infrared (TIRS) 2	11.50–12.51	100

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