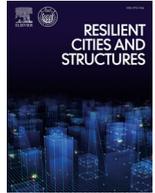




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Full Length Article

## Case study of flood risk and vulnerability in the city of Atlanta – A social, economic, technical, and institutional perspective

Prerna Singh<sup>a,1,\*</sup>, Adjo Amekudzi-Kennedy<sup>a</sup>, Baabak Ashuri<sup>a</sup>, Ty Parrillo<sup>a</sup>, Derek Rizzi<sup>a</sup>, Russell Clark<sup>a</sup>, Brian Woodall<sup>a</sup>, Heejun Chang<sup>b</sup><sup>a</sup> Georgia Institute of Technology, Atlanta, USA<sup>b</sup> Portland State University, Portland, USA

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## ABSTRACT

The negative impacts of natural hazards on communities at all scales have been increasing. Floods comprise one such natural hazard that has emerged as one of the most destructive in the US and worldwide. While a lot of damage is estimated in terms of the cost of rebuilding infrastructure and direct loss of economy, the negative impacts of such disruptions go beyond the physical infrastructure. The impact on (and of) the social and institutional framework is rarely examined in conjunction with the physical and technical aspects. This paper examines flood vulnerability and risk of a community at an intersection of social, ecological, technical, and institutional perspectives, and presents a framework for a holistic flood vulnerability and risk assessment that has a strong foundation in all four aspects of a resilient community. The study builds on the existing risk, vulnerability, and hazard assessment approaches, and refines them with a holistic perspective. The study uses a mixed method approach with qualitative and quantitative methodologies to assess flood occurrence probabilities, vulnerability, and risk from the social, ecological, technical, and institutional perspectives. A case study of the City of Atlanta is conducted using the framework to assess the overall vulnerability and risk of the city. The results of this analysis show that the regions that have the highest probability of flood hazard occurrence also appear to have the highest social, ecological, and technical vulnerabilities in the Atlanta area. While the results are intuitive, the applications support a focus on holistic resilience building across these four criteria. This study is potentially useful to practitioners, researchers, government agencies, and community organizations working to mitigate flood risk particularly as this risk continues to evolve with the changing climate.

## 1. Introduction

The changing climate has introduced new challenges in infrastructure management [1]. Under prevailing challenges of limited funding, fragmented data availability, methodological evolution, and a relatively slow-evolving institutional framework, local agencies must develop processes that enable them to anticipate and address evolving challenges while managing existing ones [2]. The past several years and decades have brought more frequent and extreme floods, droughts, and heatwaves, along with stronger hurricanes, tropical storms, and more intense wildfires, melting glaciers, reduction in sea ice, rise in sea levels and devastation to coastal and inland communities. Each year has also brought new record-breaking weather extremes [3].

In Georgia, climate-related extreme events are showing increasingly significant impacts on property value, infrastructure value, economic value, and human life. A 2018 study found that Georgia lost more than

\$15 million in property value from sea level rise flooding from 2005 to 2017 [4]. Further, the Union of Concerned Scientists issued a report in 2017 warning that Georgia's coastline faces chronic inundation [5]. The climate continues to change. With these changes, inland flood risks are growing, exacerbated by an expanding floodplain, continuous development in floodplains, and institutions lagging behind evolving floodplain management and planning [6]. Also, there is limited data for adequate floodplain management and methodological enhancements in floodplain management [7]. Data development continues however.

More and more agencies at all levels are endeavoring to incorporate resilience and risk-based approaches in their planning in order to reduce the potential impacts of extreme events on their systems [8]. At the same time, various concepts of risk, vulnerability, and resilience have been defined across a vast spectrum of disciplines, and, hence, at times get conflated or are used interchangeably [9,10]. This presents challenges in the application of these concepts in practice. Also, the ter-

\* Corresponding author.

E-mail address: [singh.prerna.207@gmail.com](mailto:singh.prerna.207@gmail.com) (P. Singh).<sup>1</sup> Present Address: Transitions Research, Goa, India<https://doi.org/10.1016/j.rcns.2025.03.002>

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minologies are defined differently across technical, ecological, social, and institutional domains [11]. Given that public agencies will benefit from taking a holistic view at their systems, effective flood management is dependent on correctly applying and interpreting the concepts of risk, vulnerability, and resilience across these various domains.

This study focused on inland flooding hazards in the state of Georgia, with a case study focused on the City of Atlanta. It developed and applied frameworks to assess the flood vulnerability of local communities and provide tailored recommendations to strengthen community resilience. The risk assessment incorporates hazard occurrence probability assessment using multiple data sources. The study also conducted a vulnerability assessment that spans the institutional, technical, ecological, and social domains of the study region. The vulnerability and hazard assessments are combined to identify high-risk areas (i.e., high hazard occurrence probability-high vulnerability areas). Further, the paper presents variations in the hazard data over time, demonstrating the impact of climate change with respect to the increase in the uncertainties in our hazard prediction capabilities and community exposure to inland flood threats. The paper presents recommendations tailored to enhance the resilience to inland flooding in the case study region in this era of climate change and concludes with remarks on data, methodological, and institutional needs for resilience building in local communities.

## 2. Concepts in flood resilience: literature review

Extreme weather and related disasters have been studied extensively in the literature in various fields [12–15]. In response to disasters, changing demand, and other uncertainties, researchers have developed, and the literature has been extended to embrace various concepts to define, measure, and assess the impacts of disasters on systems. Risk, vulnerability, reliability, robustness, flexibility, adaptability, survivability, and resilience are the main keywords used in the disaster management literature. Depending on the type of system, similar concepts are named differently. Given the widespread use of these terms, several are used interchangeably, and lack of clear distinction can lead to misinterpretation in different contexts. While each definition has value in the context it was developed, it is important to analyze critically the existing literature to identify definitions most suited to the contexts of particular problems. After reviewing the literature on resilience, risk, vulnerability, and disaster management, the definitions presented below were applied in this study.

In the context of climate change, hazard refers to any potential occurrence of a natural or human-induced physical event that may cause damage to property, infrastructure, livelihoods, service provision, environmental resources, and other community assets [16]. For example, as sea level rises, increased frequency of inundation of an area during a storm event is a potential hazard for a low-lying coastal community. In this paper, inland flooding hazard is characterized by flood maps and other similar datasets characterizing the probability of flooding in different regions. Hence, the AT&T data is considered hazard data for this analysis.

Understanding hazards alone, however, is insufficient to fully assess climate risks. Exposure builds upon this by referring to the degree to which a system is exposed to a given hazard (e.g., sea-level rise). The 2014 IPCC (Intergovernmental Panel on Climate Change) report defines exposure as “The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected [16]. For example, a coastal community in a low-lying area can be exposed to a certain degree of the hazard of inundation during a storm event.

While exposure identifies who or what may be impacted by a hazard, vulnerability delves into the sensitivity of these systems to harm and their capacity to recover or adapt. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt [16]. For example, older

populations are more sensitive to heat stress and have limited physical capacity to adapt, therefore highly vulnerable during a heatwave. In this paper, we categorize the vulnerability of the system in terms of social, ecological, technical, and institutional vulnerability to inland flooding.

Bringing these concepts together, risk represents the potential for adverse consequences where critical assets, livelihoods, or systems are exposed to uncertain outcomes driven by the interplay of hazard, exposure, and vulnerability. Risk is often represented as the probability of occurrence of hazardous events (likelihood), or trends multiplied by the impacts (or consequences) if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard [16]. In this study, risk is characterized as the product of the hazard with the vulnerability of the region.

Resilience reflects the capacity of a system to anticipate, plan for, and adapt to adverse events while maintaining or quickly recovering essential functions. It encompasses the ability not only to withstand shocks but also to transform in ways that enhance preparedness for future challenges [16]. For instance, a resilient urban community might implement proactive flood mitigation measures, such as enhancing drainage infrastructure or adopting green infrastructure solutions, to reduce the impacts of inland flooding and improve recovery capacity.

### 2.1. The social-ecological-technical systems (SETS) approach

A key aspect of vulnerability assessment conducted in this paper that differs from most vulnerability assessments in the infrastructure sector is the application of the Social-Ecological-Technical-Systems (SETS) approach. The SETS framework presents an interdisciplinary analysis of infrastructure development while thinking more carefully about the environmental and social impacts of infrastructure by expanding on the idea of infrastructure ecosystems [11,17,18]. Fig. 1 presents an overview of the SETS framework.

The SETS model has been applied in various contexts [11,19–21]. Markolf and others [11] use the SETS model to study interconnected infrastructure systems and their resilience through a case-study approach, applying the model on the Atchafalaya and Mississippi River Basins, Nuisance Flooding in Miami Beach, and Flooding and Combined Sewer Overflows in Syracuse, NY. Other applications include the work done by Chang and others [19], where they apply the framework to examine the changing pathways of flood risk management (FRM) in Portland, Oregon; Seoul, South Korea; and Tokyo, Japan, demonstrating the application of the framework across diverse contexts.

In this study, we applied the SETS model to identify and categorize vulnerability indicators for flooding. We further enhanced the framework by adding an institutional component to the vulnerability assessment, thereby working with a modified SETS approach, which we refer to as the I-SETS approach. We also examined, critically, variables in the literature to identify the most suitable in the context of the case study.

## 3. Methodology

The research took a mixed-method approach to assess inland flood risk and resilience in the state of Georgia. A sequential-embedded research methodology (Fig. 2) was applied.

The first quantitative step of the methodology covers the flood hazard analysis - which includes reviewing hazard data from multiple sources and applying statistical estimation methods to fill data gaps for a more robust hazard assessment. The hazard analysis also includes a review of the changes in hazard occurrence over time using multiple datasets from different time periods. This is followed by an embedded approach for vulnerability assessment. The vulnerability assessment expands on the Social-Ecological-Technical Systems (SETS) approach developed by the Urban Resilience to Extremes (UREx) Sustainability Research Network (SRN) [22]. The SETS approach extends the traditional vulnerability assessment methods that focus on only one of the technical, ecological, or social capitals to an interdisciplinary approach. The



Fig. 1. Overview of social, ecological, and technological components and interactions of infrastructure systems. Adapted from [17,18]Depietri & McPhearson (2017), and Grabowski et al. (2017).

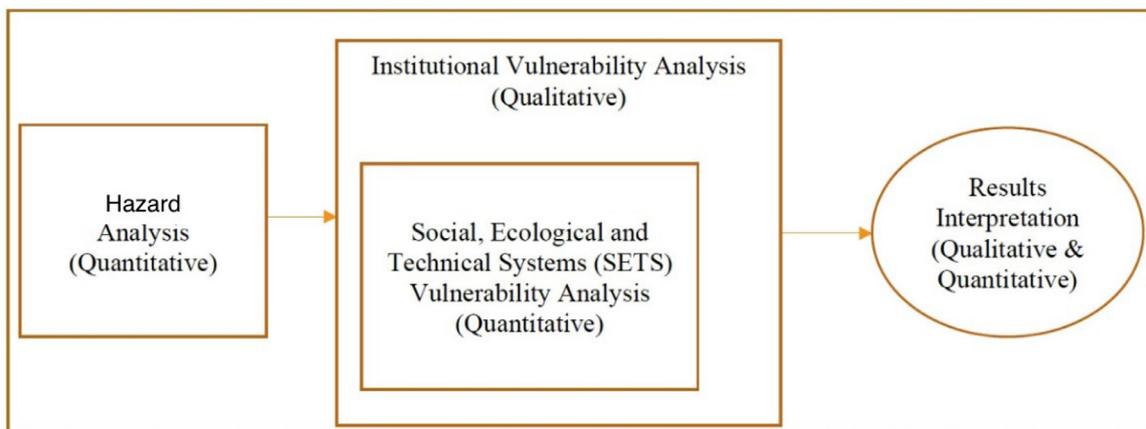


Fig. 2. Research framework.

approach combines the three capitals to better represent the vulnerability of a city or other entity to any given threat. This research further expands on this approach by adding institutional capital as another important capital to be considered formally in the vulnerability assessment of cities.

Institutions refer to both formal and informal practices and customs including laws, policies, and regulations. Within the embedded approach, the institutional analysis is qualitative, evaluating indicators of institutional strength and vulnerability that span various levels of jurisdiction. The quantitative part of the embedded approach conducts the social-ecological-technological systems vulnerability analysis. The results from the quantitative hazard analysis and the embedded vulnerability analysis are combined to present the risk analysis. The City of Atlanta is selected as a case study for the assessment due to its economic importance to the state, exposure to inland flooding, and the availability of data for flood risk and vulnerability variables.

### 3.1. Hazard assessment- data and approach

In the context of inland flooding in this study, we evaluate the historical trends and future projections of inland flooding occurrence to determine if a region is exposed to inland flood risk. This study uses percentage probability associated with a given return period to refer to flood events, i.e., a 100 year-return period flood will be referred to as a 1 %-probability flood event; a 50 year-return period flood and 500 year-return period flood event will be referred to as a 2 % and a 0.2 % probability events, respectively. The study leverages Climate Projection Model data, developed by the Argonne National Laboratory for AT&T, which is the base input data source. The dataset, which was developed by ANL for AT&T, and is subsequently provided as open-source data for researchers, includes flooding and wind data for four southeastern states – Georgia, Florida, North Carolina, and South Carolina. The AT&T data provides flood depth at different points in the region for different return period events. The 2 % probability event (50-year-return period-high) data from the inland flooding dataset was used for the hazard analysis.

Some data gaps were observed in the Metro-Atlanta region in the AT&T dataset. To manage these gaps, we utilized Digital Elevation Modeling (DEM) to estimate potential flood occurrence probability in the study areas with gaps. The DEM data obtained is from the US Geological Survey Interface. The data had been last updated on 2020–03–19 when it was used and is of resolution of 1/3 arc-second (approximately 10 m) [23]. The DEM data was used to develop the Topographic Wetness Index (TWI), which detects regions potentially exposed to flood inundation by identifying regions with a TWI higher than a given threshold. TWI is a purely topographical index presenting the capability of a region to accumulate water. The TWI thresholds were calculated for two scenarios – one following the AT&T hazard dataset, and the other following the FEMA hazard data. The AT&T dataset incorporates climate change modelling, while the FEMA hazard data used did not involve recent hydrological and hydraulic updates. Comparing the TWI-based hazard analysis outputs from two datasets, differing in their recency and integration of climate change considerations, provides valuable insights into how climate change is altering hazard occurrence.

TWI thresholds were calculated corresponding to the FEMA 1 % and 0.2 % probability events (2007 data), and the AT&T 2 % probability flood event (2018 data). Hazard maps were developed using the TWI thresholds corresponding to the 2 % probability events, and the variations were assessed in light of climate change and increasing flood risk over time. The TWI threshold value depends on the resolution of the DEM, the topology of the hydrographic basin, and the constructed infrastructure. To calculate the TWI threshold, we employed a maximum likelihood estimation (MLE) based on inundation profiles provided by the various flood maps (FEMA and AT&T) for a specific spatial window where AT&T data was high quality. To do so, a section of the City of Carrollton was selected from the Georgia dataset of AT&T. The specific spatial window was selected as the FEMA and AT&T datasets are rela-

tively more comprehensive in the region. Furthermore, the TWI threshold was calibrated using Bayesian Parameter Estimation based on inundation profiles calculated for more than one spatial window from other regions with similar dataset availability. The methodology of MLE and Bayesian Parameter estimation was adopted from Jalayer et al. (2014) [24], which can be referenced for details on the approach. The various MLE statistics of TWI (1 % (2007) probability event, 0.2 % (2007) probability event, and 2 % (2018) probability event) were used to generate the maps of the case study with potential flood occurrence based on the respective TWI thresholds, averaged over each census block.

### 3.2. Vulnerability assessment: data and approach

Vulnerability encompasses exposure, sensitivity, and adaptive capacity (US Climate Resiliency Toolkit). The study by Markolf [11] and others presents a list of indicators for the SETS categories as shown in Fig. 3.

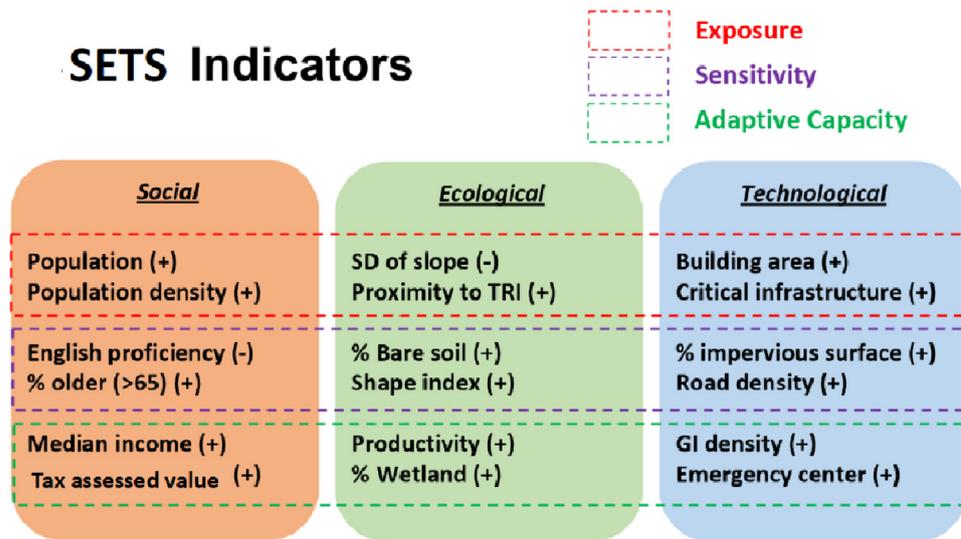
The SETS Vulnerability Assessment methodology allows for the characterization and analysis of social, ecological, and technical indicators of vulnerability. However, it is critical to study the role of the local, state, and national institutions in place, which can significantly affect social, technical, and environmental vulnerabilities of a given region.

Institutional vulnerability is more appropriately characterized at the community scale, and the assessment uses a qualitative approach. In this study, we developed an institutional assessment framework and conducted a qualitative analysis of the case study city to understand the institutional vulnerabilities faced at the city level. Further, the qualitative SETS vulnerability assessment was conducted, evaluating inland flood risk at the census block level. The overall vulnerability results and recommendations for the case study were developed by combining the results of the two vulnerability assessments.

#### 3.2.1. SETS vulnerability assessment approach

To conduct the vulnerability assessment using the SETS approach, performance metrics or indicators of the three criteria (social, ecological, & technical) were identified for exposure, sensitivity, and adaptive capacity, at the census block level. These indicators were then used to calculate a score of the vulnerability of the case study with the SETS criteria. The selection of indicators was based on their applicability in the context of inland flooding in Atlanta. The team reviewed indicators of social, ecological, and technological vulnerabilities from the available literature, and identified indicators that are context-appropriate for Atlanta, and where there was sufficient data. The context applicability was assessed based on expert stakeholder consultation, where the stakeholders included a range of researchers on the various vulnerability aspects, along with public sector officials from the Atlanta Regional Commission, Metropolitan North Georgia Water Planning District, City of Atlanta Department of Watershed Management, and, the Center for Serve-Learn-Sustain and the Smart Cities and Inclusive Innovation Initiative at Georgia Institute of Technology. For replication of this study in another region, a range of peer-reviewed articles [11,25–28] may be used to identify a starting point for the SETS vulnerability indicators, which should then be filtered against the context of the case study region and available credible data sources.

In applying the SETS approach, the goal for the social portion was to determine the equity of inland flood exposure across various population groups in Atlanta. Table 1 presents the social vulnerability indicators used in this study and shows their distribution across the exposure, sensitivity, and adaptive capacity categories. Five-year American Community Survey (ACS) estimates (2018 dataset) obtained from the U.S. Census Bureau's website were used for each indicator at the census block group level. For race variables, the census data indicated the African American population as the key minority population in the study region, making up 48+% of the population. The analysis uses the Environmental Justice approach to identify the vulnerable population, which in this case refers to the racial minority. Hence the race indica-



SD- Standard Deviation; GI- Green Infrastructure; TRI- Toxic Release Inventory | + and – signs reflect correlation to vulnerability

Fig. 3. SETs Vulnerability indicators example.

**Table 1**  
Social vulnerability indicators.

Indicator Category	Indicator(s)
Exposure	•Population density
Sensitivity	•Age (People 65 and Over) •Race (African American vs non-African American) •Education (No High School Diploma or Limited English Ability)
Adaptive Capacity	•Median Income

tor compares areas with African American population with non-African American populations in the region.

The goal for the environmental portion of the model is to classify the ecology of a region and determine vulnerability based on land composition. The Multi-Resolution Land Characteristics Consortium (MRLC) provides data for Land Use for Georgia at a 10 m by 10 m scale. This data supports the first ecological indicator we used: green space. Green space is defined differently across many studies and across different disciplines [29]. We used an ecological approach to define green space and considered all land use categories that were light, medium, heavily forested, or open space developed land to be green space and all other land use categories to be otherwise. This procedure was also adopted from the SETS research conducted by the UREx network [16] and is consistent with the green space evaluation approach used by [25] Fahy et al. (2019) for Portland, Oregon.

The second indicator used was AB Soil Composition. Type A (e.g., clay, silty clay, sandy clay, and clay loam) and Type B (e.g., angular gravel, silt, and silt loam) soils have higher infiltration rates and low runoff rates (Hydrologic Soil Groups); therefore regions with more Type A and Type B soils can absorb more water and reduce inland flood risk. Type C and Type D soils have lower infiltration rates and behave similarly to impervious surfaces (Hydrologic Soil Groups). Therefore, our soil composition indicator determines the percentage of land covered by A and B soil types. This dataset was obtained from the National Resources Conservation Service (NRCS) based on a soil survey done in 2017 [30].

The technological portion of the model attempts to characterize the human interactions that increase vulnerability to inland flooding. The indicators included in this study are Impervious Surface Percentage,

Green Infrastructure Density, and Building Data (Average Age of Building and Average Stories of Building). The impervious surface percentage was found through the same source as green space: the Multi-Resolution Land Characteristics Consortium. Higher percentages of impervious surface will result in more runoff, less infiltration, and a higher risk of inland flooding. Green Infrastructure data was provided by the City of Atlanta’s Department of Watershed Management (DWM). This data included all residential, commercial, and city-owned green infrastructure projects in Atlanta. Green Infrastructure density was calculated to be the summation of all Green Infrastructure projects in a region divided by the area of such a region. Higher Green Infrastructure regions are assumed to be more resilient to flooding due to the increase of absorbance capabilities provided by these projects, thus enhancing adaptive capacity.

Building data was obtained through Fulton County’s GIS program. In general, older buildings and buildings with fewer stories are hypothesized to be more susceptible to inland flood damage. Older buildings are assumed to be built to older codes with less flood preventative measures as well as past damage that weakens the structure, increasing susceptibility, especially for buildings in relatively flat regions, or in low-lying regions. Buildings with more stories have the capability to allow for movement of contents to higher floors, putting the residents’ possessions and persons in less danger in the case of an inland flood.

The data was collected at the Census Block Group (CBG) level and was analyzed using ArcGIS and statistical correlation analysis approaches. The datasets available at higher resolution than CBG were aggregated at the CBG level for consistent analysis. The aggregation was selected based on the nature of the indicator. Hotspot maps were generated for the identified vulnerability indicators as with the TWI hazard data. To compare the CBG results with the results at the Census Block Level, the granular data was similarly aggregated at the census block level, while for indicators where data was only available at the CBG level, it was disaggregated to the census block level, by assigning the same value for all blocks with a block group. These maps provide an initial visualization of the Social, Ecological, and Technical Vulnerability landscapes of each city, as well as the clustering of flood hazard data. The Hotspot maps were generated using the ArcGIS Hotspot Analysis (Getis-Ord Gi\*) function with a fixed distance band and the Euclidean distance method, and the confidence intervals were used as defined by the ArcGIS function.

# Inland Flood Resiliency Maturity Scale

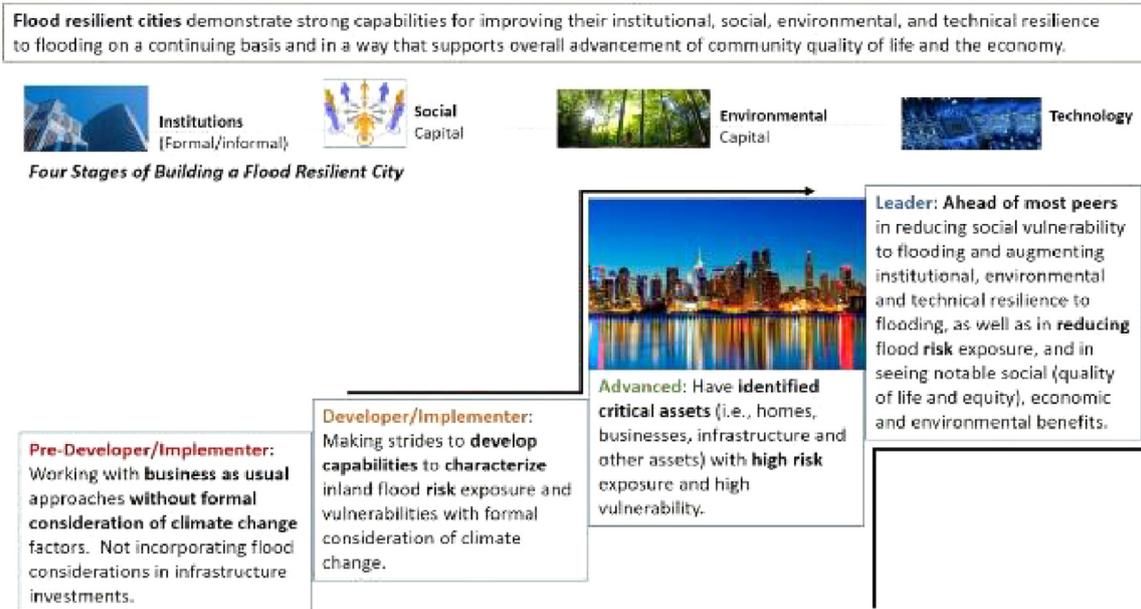


Fig. 4. Conceptual Framework for Assessing Institutional Resilience (developed by the authors using idea of maturity scale for Hyperconnected Cities by ESI Thoughtlab) [38].

Correlations were run through Python using Python’s built in Pearson Correlation Coefficient for all the vulnerability variables. Correlation significance above  $\alpha = 0.05$  were dismissed as insignificant correlations. Correlations were then confirmed using ArcGIS’s Explanatory Regression tool with TWI as the dependent variable. These results helped the qualitative portions of our study by showing the interconnectivity of the indicators being used in the study. The correlations of the indicators to the hazard data (TWI) shed light on the vulnerability variables that are to be prioritized due to their correlation with hazard occurrence, therefore potentially being of greater relevance in the overall vulnerability of the system.

For each category, an indicator was marked as ‘vulnerable’ if it was in the top 25th percentile of vulnerability following the method by Chang et al. (2020) [26]. Each region in the case study was then generalized by the number of indicators where it was marked as ‘vulnerable.’ For example, if a Census Block Group was marked in the top 25th percentile for 3 out of the 5 social vulnerability indicators, it would be given a social vulnerability score of 3/5. A hotspot analysis of the vulnerability score was conducted to study the geospatial distribution of vulnerability. Maps were created for social, ecological, and technical vulnerabilities.

### 3.3. Institutional vulnerability assessment approach

The institutional assessment aims to understand policies, regulations, and informal practices in place to address inland flooding in municipalities and cross jurisdictionally, in the context of the changing climate and broader development goals. Fig. 4 depicts the conceptual framework for assessing institutional resilience developed from our study of inland flooding threats in this era of climate change and institutions in a range of cities, through a Social-Ecological-Technical systems (SETS) lens. Cities at higher maturity levels of inland flood resilience will have more policies, regulations, and informal practices in place to enable them to prepare for, withstand, rapidly recover from, and continue to adapt to the threat of flooding. Table 2 presents practical questions that facilitate the development of institutions to foster maturity in inland flood resilience assembled to support municipal agencies to tackle inland flooding under climate change. The questions are separated into four sections: input accounting for resources and actions necessary for

flood management (e.g., policies, partnerships). Process encompasses activities such as stakeholder engagement and infrastructure planning. Output includes completed projects or formalized plans.

Outcome captures broader impacts, such as reduced flood risk or improved public awareness.

Questions on these four aspects were applied to assess the institutional resilience of the case study region to inland flooding. The conceptual framework and the questions were developed through an extensive literature review of the institutional vulnerability of systems to flooding [31–37]. They were then contextualized for the city through feedback and review from experts and city stakeholders. The involved stakeholders are acknowledged in the acknowledgement section.

### 3.4. Risk assessment: approach

To assess the risk of inland flooding in the case study region, we combined the hazard analysis results and the vulnerability analysis results to identify regions with high hazard occurrence changes and high vulnerability.

The Risk Analysis Results Maps represent the overlap of the vulnerability results and hazard data for each SETS Vulnerability Indicator. The risk analysis value is calculated by multiplying the normalized Vulnerability Indicator value by the normalized Hazard value. In our paper, we are assuming vulnerability to be representative of consequences and therefore define risk to be hazard occurrence probability multiplied by vulnerability. Therefore, the Hotspots in these maps show the areas with the highest vulnerabilities and hazard occurrence probability, and the Cold Spots show the areas with the lowest vulnerabilities and hazard occurrence probabilities.

## 4. Results and discussion

### 4.1. Hazard assessment results

TWI hazard results for the City of Atlanta (Fig. 5) indicate that the urban center of Atlanta is most exposed to flooding, and the northern and western regions are the least exposed. The urban center of Atlanta that is highly exposed is centered around the intersection of I-20, I-85,

**Table 2**  
Questions designed to facilitate the assessment of institutional resilience and vulnerability against floods.

Measures of Performance (Categories)	Measures of Impact/Performance
<b>Inputs</b>	1. Does the City participate in the Community Rating System (CRS) of the National Flood Insurance Program? 2. Is there any government or other agency with responsibilities for floodplain management? Which agency? (I) 3. Does the agency formally include considerations of climate change in its decision-making? (I) 4. Does the agency have a formal floodplain management plan/system? (I) 5. Does the agency's floodplain management/system include formal considerations of climate change? (I)
<b>Process</b>	6. Does the agency include climate-related flood risk as a criterion in resource allocation? (I, T) 7. Does the agency have informal or formal inter-jurisdictional/ multi-jurisdictional institutions to support floodplain management where the factors influencing flooding lie beyond the municipality boundaries? (I, S) 8. Does the agency have plans for improving the traditional stormwater infrastructure system to accommodate for increased inland flooding risk? (I, T) 9. Do the agency's land use regulations include regulations to address vegetative cover? (I, E) 10. Do the agency's zoning ordinances include rules on development in the floodplain? (I, S) 11. Does the agency include green infrastructure treatments to complement the expansion of traditional stormwater infrastructure? (E, T) 12. Does the agency include public awareness/information campaigns as part of its strategy for addressing inland flooding risk? (I, S, T)
<b>Outputs</b>	13. Can the agency show expenditures for climate-resilience-related interventions to curb inland flooding risk? (S=Public awareness, E=Vegetative Cover, T=Green Infrastructure, StormWater Infrastructure, T=Data, Tools, Other Capabilities to enhance inland flood resilience)?
<b>Outcomes</b>	14. Can the agency show a reduction in # of homes and businesses and the percentage of critical infrastructure in the floodplain over time? 15. Can the agency show a reduction in inland-flood-related damage over time? 16. Can the agency show enhanced public awareness of climate-related inland flooding risk over time? 17. Can the agency show expanded traditional stormwater infrastructure, over time? 18. Can the agency show expanded green infrastructure assets over time? 19. Can the agency show expanded technical capabilities for addressing inland flood risk, over time? 20. Can the agency show new and pertinent regulations for addressing inland flood risk, over time? 21. Can the agency show <i>influence</i> in the development of new and pertinent regulations, policies, and laws at the local, state and/or federal level for addressing inland flood risk, over time? (I, Leadership)

I: Institutional | S: Social | E: Ecological | T: Technical.

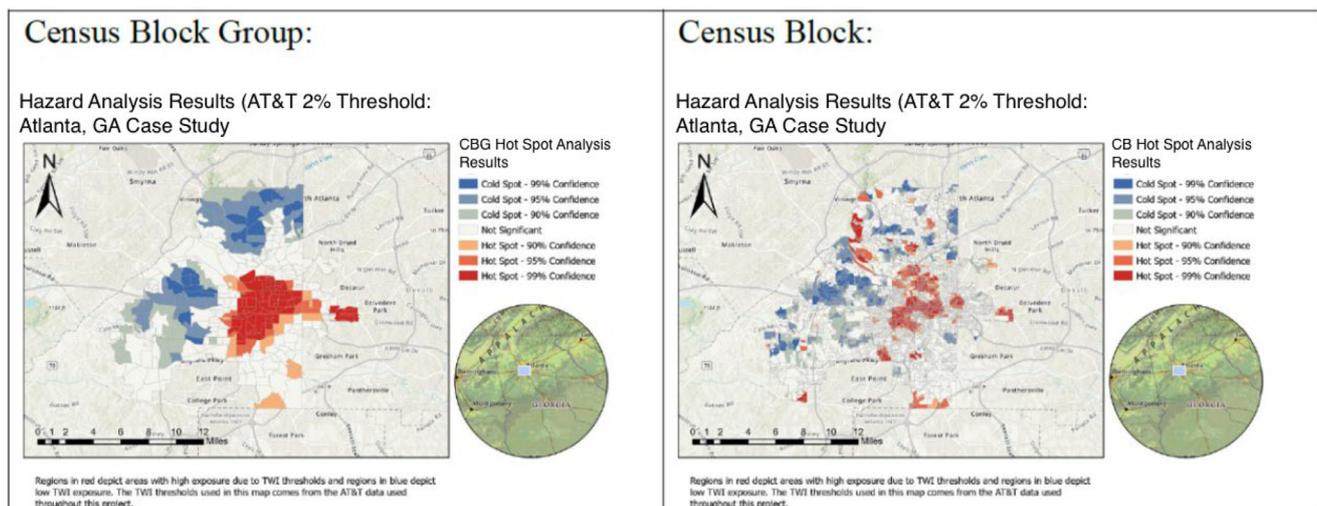


Fig. 5. City of Atlanta flood hazard maps at the census block group and census block level.

and I-75. There is extensive impervious surface in this area, but the elevation is not significantly lower than the surrounding areas. These high TWIs are therefore likely the results of floodwaters not being absorbed and instead accumulating in these highly impervious areas.

There are other local hazard hotspots throughout the City of Atlanta, yet it seems that the main hazard concern is the localized communities in the urban center of the city.

Further, in the process of using TWI as the hazard measure, the research compared the TWI threshold estimates obtained from FEMA and AT&T dataset for different return periods to study the impact of different datasets in generating flood maps. The TWI threshold for a 0.2 % (500-yr return period) event and a 1 % (100-yr return period) event using FEMA's 2007 dataset were 9.5 and 11 respectively, and 8 using the 2018 AT&T data for a 2 % (50-yr return period).

As TWI represents flood risk, a generally expected trend for the thresholds is an increasing value of the threshold for higher probability events (lower return period). For data from the same year, the TWI threshold for a 1 % event (100-yr return period) will be higher than the threshold for a 0.2 % event (500-yr return period), indicating that as we move farther from the river channels (lower TWI values), the probability of getting inundated decreases (1 % to 0.2 %).

Comparing the TWI results using the FEMA data and the AT&T data, we observe a notable difference. The expected trend would be a higher TWI threshold for a 2 % probability event (50-year return period) than that for a 1 % or 0.2 % probability event (100 or 500-year return period events) if the modeled climate trends by FEMA and AT&T dataset are similar. However, we observe that the TWI threshold for a 2 % probability event using the AT&T data is lower than both 1 % and 0.2 % events based on FEMA data. This indicates that per the 2018 data (AT&T dataset), a much bigger region has a 2 % chance of flooding than what the FEMA flood maps indicate to have less than a 0.2 % chance of flooding. This increase in the flooding probabilities, indicating an increase in the spread of flood zones can be attributed to two main reasons:

- 1) Changes in local floodplain and land use over the last decade: As the FEMA data is from the year 2007 (the data available at the time this analysis was conducted in 2020), the historical data used for generating those flood maps dates over a decade. Since then, land use patterns have changed significantly, thus altering the elevation profile of the regions. As land use and elevation profiles are key in forming watersheds, identifying water discharge channels, and consequently generating flood maps, the changes in land use can significantly alter the flood maps.
- 2) Global Climate Change considerations: Over the past few decades, climate change has presented significant variability in rainfall patterns in comparison with the expected trends. The older versions of FEMA data do not account for climate change and extrapolate the historical rainfall trends to identify future predictions. On the other hand, the AT&T data uses multiple climate change models along with historical rainfall data. Most of the current climate models reflect a significant rise in greenhouse gasses (GHG) and a non-linear increase in extreme rainfall. This could indicate why according to the AT&T data a much larger area is under a higher (2 %) chance of flooding than what was anticipated based on the FEMA flood maps.

#### 4.2. Institutional vulnerability assessment results

Table 3 below summarizes the City of Atlanta and Metro Atlanta's management efforts in the context of the changing climate using I-SETS considerations. The framework considers inputs, processes, outputs, and outcomes for flood management organizations. These data were obtained from a literature review along with stakeholder engagement of City of Atlanta practitioners and academics that have studied Atlanta's institutional system.

#### 4.3. SETS vulnerability assessment results

Social vulnerability hotspot maps (Fig. 6) show higher vulnerability in the south and west portions of the city, and much less vulnerability in the north and east regions. The diagonal divide can be seen in the indicator hotspot maps in Fig. 6. The Census Block Group analysis shows one singular major hotspot in the urban center of Atlanta, but the Census Block Group analysis revealed social vulnerability hotspots in the southern and western regions of the city as well. These results suggest that socially vulnerable communities exist throughout the city of Atlanta.

Ecological vulnerability analysis in Atlanta identifies the urban center of the city, with little green space or AB Soil, having a higher ecological vulnerability. As we move away from the urban center the ecological vulnerability decreases.

Technical vulnerability in Atlanta follows a similar trend to social vulnerability where there are two major explanations for the observed vulnerability distribution. The first explanation follows the building data and green infrastructure density data. With these indicators, the northern and eastern regions are less vulnerable, and the southern and western regions are more vulnerable. In the eastern portion of the city, there is an abundance of green infrastructure, and in the northern portion, the average number of building stories is higher, reflecting a larger adaptive capacity to inland floods. The second explanation focuses on impervious surfaces, which are concentrated in the city's urban center, the same pattern followed by population density, green space, and soil composition. Overall, the technical vulnerability results do show that the largest hotspot occurs in the urban center of the city.

#### 4.4. Risk assessment results

The flood hazard occurrence assessment results are reviewed alongside the social, technical, and ecological vulnerability to identify the regions with the highest risk (high occurrence probability-high vulnerability). The results are presented at two scales of analysis: the Census Block Group level, and the more refined Census Block level (Fig. 7).

Areas with high vulnerability and high hazard occurrence probability are highlighted as hot spots in the risk analysis results. These are the areas that are most urgent for cities to focus on, as they are experiencing flooding and do not have the socio-economic, environmental, or infrastructure resources to combat the flooding they experience.

Areas with high vulnerability and low hazard occurrence probability are less visible in the Risk Analysis Results, but more visible in the Vulnerability Analysis Results. These maps show areas that are vulnerable to the impacts of inland flooding if it occurs but are not currently exposed to inland flooding. Monitoring systems in such areas will allow for proactive measures in case the probability of hazard occurrence increases in the future.

Areas with low vulnerability and high probability of hazard occurrence are less visible in the Risk Analysis Results, but more visible in the Hazard Analysis Results. These results show areas that currently experience flooding, but the populations, environment, and infrastructure in these areas contribute to more resilience to these inland floods. Consequently, these areas should be analyzed further to identify best practices for resilience that can be applied in other high-risk areas.

The Risk Analysis results from the City of Atlanta overall tell one unifying story: the urban center of Atlanta is most at risk of inland flooding. The vulnerability index used in this project had several indicators that show vulnerability in the urban center of the city. Furthermore, the hazard analysis results followed a similar trend in which the center of the city had the largest TWI values. The other regions that could be of interest are the localized socially vulnerable communities in the southern and western parts of the city. The northern regions of the city, above the urban center, repeatedly show a lack of vulnerability for nearly all indicators.

This would suggest more detailed analysis and efforts towards risk mitigation should be prioritized for downtown Atlanta, with some efforts also in pockets in south and west Atlanta.

### 5. Key findings and conclusion

The study shows that although some critical datasets are incomplete for formally addressing climate change in flood management, agencies can use various approaches to integrate multiple datasets, model and estimate risk, and generate defensible vulnerability and risk data to identify priority areas for appropriate interventions. The overarching finding of this study is that communities that have the highest hazard occurrence probability to inland flooding hazard also appear to have the highest vulnerabilities to potential flooding and tend to be communities where minority populations are in the majority.

**Table 3**  
City of Atlanta – results of the assessment of institutional vulnerability to floods.

	Measures of Impact/Performance	Evidence
Input	<p>Does the City participate in the Community Rating System (CRS) of the National Flood Insurance Program? – <b>Yes</b></p> <p>Is there any government or other agency with responsibilities for floodplain management? Which agency/agencies? – <b>Yes</b></p> <p>Does the agency formally include considerations of climate change in its decision-making? - <b>Yes</b></p> <p>Does the agency have a formal floodplain management plan/system? – <b>Yes</b></p> <p>Does the agency’s floodplain management/system include formal considerations of climate change? <b>Inconclusive</b></p>	<p>The City of Atlanta has a rating of 7 on the CRS scale.</p> <p>-City of Atlanta Department of Watershed Management -Green Infrastructure Task Force -Other partners</p> <p>The City of Atlanta has identified flooding as one of its major resilience challenges and is undertaking multiple actions to mitigate this threat.</p> <p>The City of Atlanta has a formal flood management strategy articulated in the 2017 Atlanta Resilience Strategy and related City plans.</p> <p>The City’s flood management system indirectly considers climate change by acknowledging the increase in extreme rain-related flood events and developing strategies to address this growing threat.</p>
Process	<p>Does the agency include climate-related flood risk as a criterion in resource allocation? - <b>Inconclusive</b></p> <p>Does the agency have informal or formal inter-jurisdictional/ multi-jurisdictional institutions to support floodplain management where the factors influencing flooding lie beyond the municipality boundaries? <b>Yes</b></p> <p>Does the agency have plans for improving the traditional stormwater infrastructure system to accommodate for increased inland flooding risk? <b>Yes</b></p> <p>Do the agency’s land use regulations include regulations to address vegetative cover to support flood management? <b>Yes</b></p> <p>Do the agency’s zoning ordinances include rules on development in the floodplain? <b>Yes</b></p> <p>Does the agency include green infrastructure treatments to complement the expansion of traditional stormwater infrastructure? <b>Yes</b></p> <p>Does the agency include public awareness/information campaigns as part of its strategy for addressing inland flooding risk? <b>Yes</b></p>	<p>An increase in extreme rainfall events as the cause of flooding events is acknowledged but documents do not show explicit use of climate data in planning for future events.</p> <p>Metropolitan North Georgia Water Planning District</p> <p>The city is pursuing a combined green-gray infrastructure strategy to address flooding risk.</p> <p>The Green Infrastructure Strategic Action Plan aims to increase vegetative cover substantially to address flooding.</p> <p>The City of Atlanta’s floodplain ordinance prevents development within floodplains, with development only allowed 15 ft horizontal distance and 2 ft vertical distance away from the base flood elevation.</p> <p>The city has invested and continues to invest in multiple Green Infrastructure BMP projects to reduce the risk of flooding citywide. The city is developing a Smart H2O Platform using advanced technologies and crowdsourced data to support the management of flood risks in real-time.</p>
Output	<p>Can the agency show a reduction in inland-flood-related damage over time? <b>Yes</b></p>	<p>•A Municipal Option Sales Tax (MOST) was passed generating approximately \$12.5 – 13.5 Million per year for four years to address a backlog of drainage issues with coordination to integrate GI projects into future phases (Powell 2018)</p> <p>•An overhaul of the sewer and stormwater management system completed in 2008, accruing to \$2B in expenditures between 1998 and 2008, has reduced combined sewer overflows (CSOs) from ~100/year to an expected average of 4/year. (Powell 2018)</p>
Outcomes	<p>Can the agency show enhanced public awareness of climate-related inland flooding risk over time? <b>Yes</b></p> <p>Can the agency show expanded traditional stormwater infrastructure, over time? <b>Inconclusive</b></p> <p>Can the agency show expanded green infrastructure assets, over time? <b>Yes</b></p> <p>Can the agency show expanded technical capabilities for addressing inland flood risk, <b>including climate change</b>, over time? <b>Yes</b></p> <p>Can the agency show new and pertinent regulations for addressing inland flood risk, over time? <b>Yes</b></p> <p>Can the agency show <i>influence</i> in the development of new and pertinent regulations, policies, and laws at the local, state and/or federal level for addressing inland flood risk, over time? <b>Inconclusive</b></p> <p>Does the municipality participate in the National Flood Insurance Program Community Rating System (CRS) Program? <b>Yes</b></p>	<p>The broad stakeholder process included in the development of the Atlanta Resilience Strategy has led to increased public awareness of flooding as one of the City’s main resilience challenges.</p> <p>•Completed development of BMP GI projects to address flooding including Southeast Atlanta Permeable Pavers, Adair Park Rain Garden, and Historic Fourth Ward Park. Upcoming projects include the Proctor Creek Greenway, Boon Park West with the Atlanta Urban Ecology Center at Proctor Creek, and Rodney Cook, Sr. Park.</p> <p>•Potential metrics/measures of success identified in Atlanta Resilience Strategy</p> <p>Development of Smart H2O Platform</p> <p>The City of Atlanta Green Infrastructure Strategic Action Plan suggests actions for removing <i>institutional barriers</i> to green infrastructure construction, increasing the cost-effectiveness of green infrastructure, and engaging multiple City departments, citizens, developers, and environmental groups to work toward the goal of reducing City water runoff by 225 million gallons of runoff annually.</p> <p>Fulton County entered CRS April 2000   Rating = 8</p>

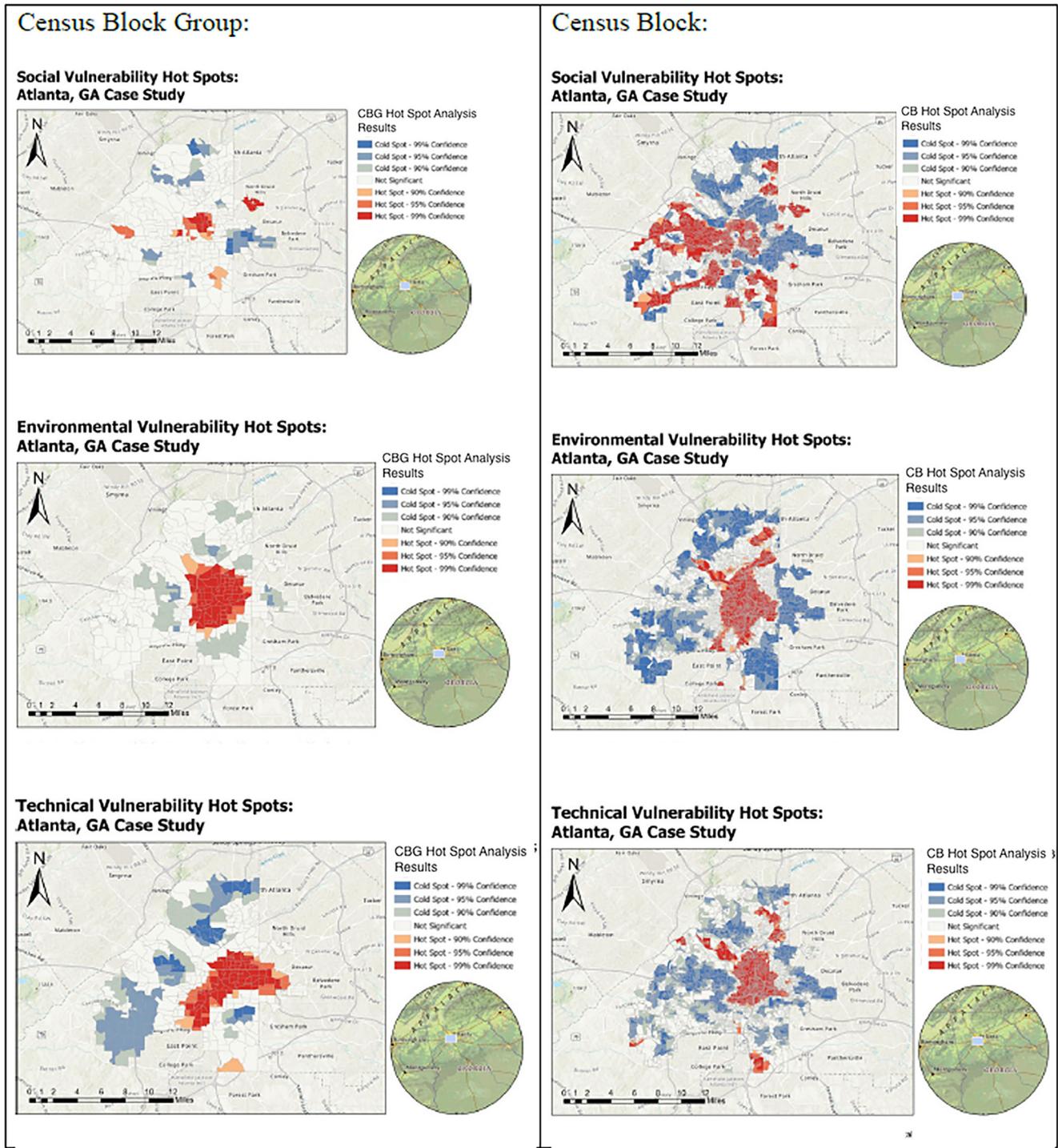


Fig. 6. SETS vulnerability indicators - hot-spot maps for city of Atlanta.

By analyzing different aspects of vulnerability and hazard separately, and at different scales of census block group and census block, the study provides insights to decision makers on the different drivers of risk and focused prioritization of risk reduction and resilience-building efforts.

The recommendations of this study are tailored to be useful to agencies such as the Atlanta Regional Commission (ARC), the City of Atlanta Department of Watershed Management, and Metro District as they move forward with identifying vulnerabilities and implementing appropriate adaptations for flood management for system resilience in municipalities, metro and other areas in the state of Georgia. They are also tailored

to be useful to municipal leaders and agencies searching for ways to enhance their existing capabilities to develop community resilience to inland flood threats. The approach and results were identified in close collaboration with city officials at various stages and have been available to support their resilience thought processes. The results are also useful for decision makers to incorporate resilience in their broader social developmental initiatives, by intentionally incorporating flood resilience measures in social development plans in regions emerging as hot spots of both hazard and social vulnerability. While the study focused on Atlanta, it can be replicated with proper contextualization for any other city. The transferability of the research emerges from its nature of be-

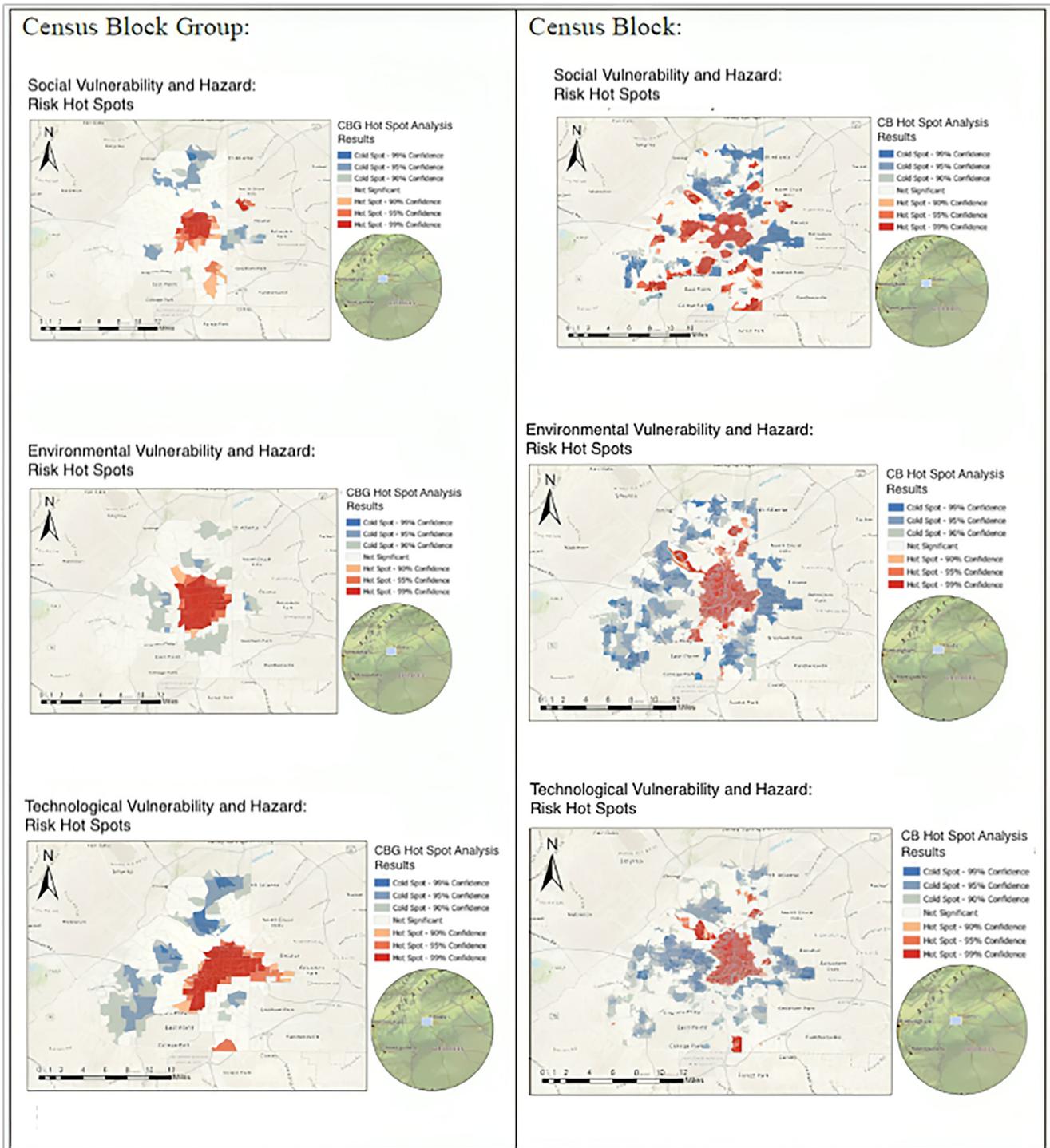


Fig. 7. Risk Hot-spot maps- combining vulnerability and hazard occurrence probability for city of Atlanta.

ing driven by local inputs, and use of methods that can leverage limited data to systematically expand relevant proxy variables. The data on the vulnerability variables used in this study are generally available at the national level, or are sourced from local stakeholder. The only dataset that is has limited availability is the AT&T hazard dataset, which was developed for four states in US at the time of this research. We expect more climate modeling based hazard project datasets to emerge as the awareness on the subject increases across the globe.

In addition, the project demonstrates an approach to modeling community and infrastructural vulnerability using precipitation projections, with formal considerations of uncertainty. It demonstrates the

necessity of exploring practical and cost-effective hybrid (i.e., green and gray) infrastructure and technology solutions, and improved policies and regulations to address inland flooding. In addition, it demonstrates procedures for fusing incomplete datasets to characterize inland flood risk.

## 6. Limitations

The major limitation of the study was data availability. The indicators used in this study reflect available data and stakeholder priorities. For instance, population density was selected as the primary exposure

metric, and green infrastructure projects were used as a proxy for ecological vulnerability. While these indicators align with the study objectives, they have inherent limitations. Population density does not fully capture infrastructure exposure, and the number of green infrastructure projects does not account for their quality or performance. Addressing these gaps requires access to more detailed, spatially resolved data and metrics that better represent functionality and effectiveness.

Further, the hazard dataset from AT&T, which overcame some of the limitations of the older FEMA dataset, especially accounting for climate change in the outputs, had gaps in the available data points. The data also only included flood inundation levels above 0.5 feet, making it challenging to identify less inundated but still potentially flooded regions. Future datasets will add more value if higher granularity is made available in the datasets.

The analysis primarily focuses on pluvial flooding in urban setting, but an integrated approach accounting for fluvial flooding and its interactions with urban flooding can provide further nuanced results.

For vulnerability assessment, the SETS framework, incorporates social, ecological, technical, and institutional dimensions, expanding on the traditional individual vulnerability approaches. However, the absence of certain aspects, such as health or economic resilience, limits the comprehensiveness of the analysis. Expanding the framework to include such indicators, if data become available, could provide a more holistic assessment. The material aspects can also be different for different cities, and research on identifying the material aspects of vulnerability to be incorporated in the regional assessment will add significant value to the outputs.

The analysis is conducted at the Census Block and Census Block Group levels, which may not fully capture micro-scale variations in vulnerability or hazard occurrence. Additionally, the datasets used are snapshots in time, limiting the ability to analyze temporal trends. Future research could explore finer-scale spatial analyses and incorporate time-series data to capture dynamic changes in vulnerability and hazard patterns.

Finally, while the approach is designed to be transferable, the applicability is still dependent on data availability at the city level, and alignment with local stakeholder priorities. In contexts with limited data, replicating the approach may require significant modifications, such as incorporating qualitative data or community-based assessments to fill gaps. Developing robust methods for these steps will help with higher replicability of this study.

## Relevance to resilience

The research presented in this paper is highly relevant for practitioners in institutionalizing resilience in their infrastructure and community systems. With a holistic view of risks and vulnerabilities from the standpoint of physical exposure, technical gaps and strengths, social vulnerabilities, ecological impacts, and institutional vulnerability, a city practitioner can build the capacity to better prioritize the most vulnerable segments of the community for resilience development. It also provides an understanding to navigate disaster planning and preparation with datasets that vary in granularity, scope, and timeliness. Given the existing challenges with climate change data, approaches like the ones presented in this paper will help policymakers continue to make timely resilience decisions.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Adjo Amekudzi-Kennedy reports financial support was provided by AT&T. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CRediT authorship contribution statement

**Prerna Singh:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Adjo Amekudzi-Kennedy:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Baabak Ashuri:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Ty Parrillo:** Writing – original draft, Software, Formal analysis, Data curation. **Derek Rizzi:** Writing – original draft, Software, Formal analysis, Data curation. **Russell Clark:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Brian Woodall:** Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Heejun Chang:** Validation, Supervision, Methodology, Conceptualization.

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