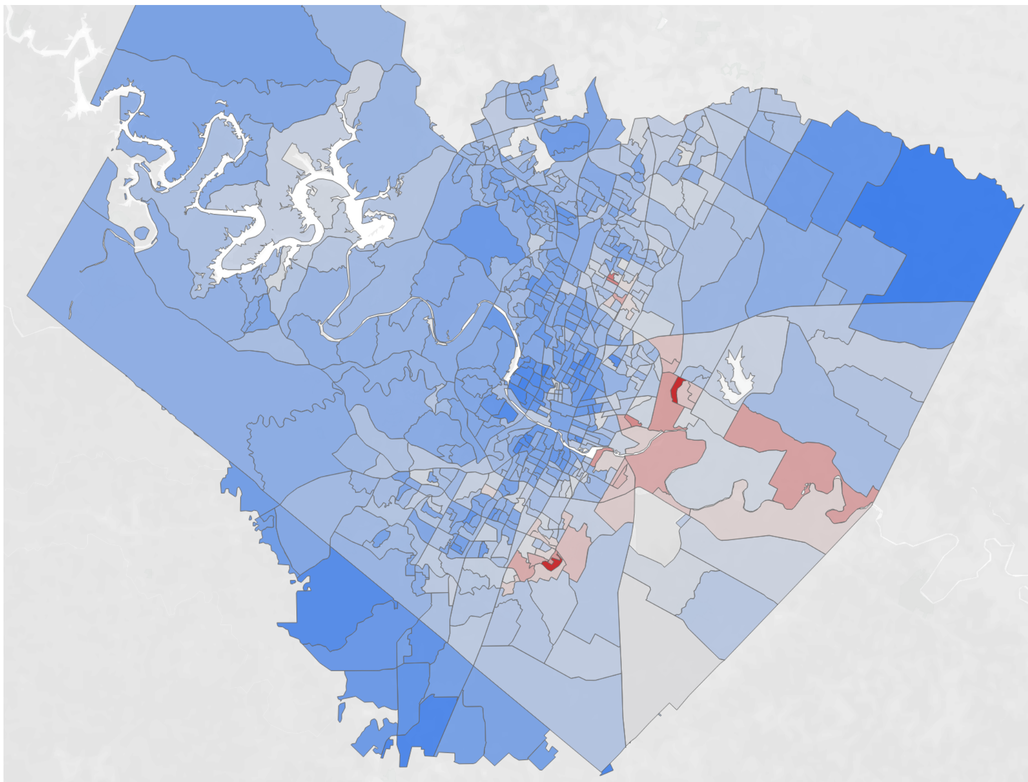
Climate Vulnerability in Austin:
A multi-risk assessment



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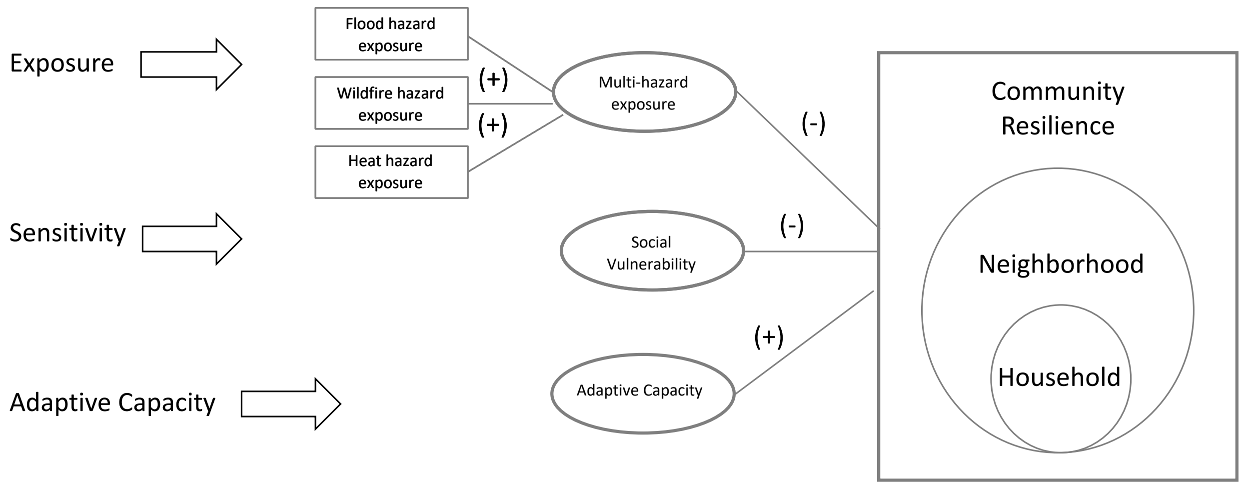
1. Introduction

Climate change refers to natural or human-induced changes in the climate that persists for an extended period, typically decades or longer. Climate-related hazards – flood, wildfire, extreme heat, among others – cause damage and loss to property, infrastructure, livelihoods, service provision and environmental resources. Climate change is likely to further increase the exposure to multiple hazards by affecting the magnitude, frequency and spatial distribution of disastrous events (Field et al. 2012). This report focuses on spatially-distributed quantitative estimates of urban neighborhood vulnerability to climate change related hazards in Austin, Texas.

Our study explicitly links vulnerability, hazard risk, and resilience. Although varying definitions for resilience exist, common characteristics include the ability to absorb disturbance and return to a desired state (Folke 2006); recover, learn, and adapt from adverse events (Adger et al. 2005); and a process to link community capacities in response to disturbance (Norris et al. 2008). Resilience is thus a process, a capacity, and an outcome – from a policy perspective we want resilient communities and cities. Vulnerability is a measure of exposure to hazards, as well as the sensitivity of a population to a natural hazard and its ability to respond and recover from the impact of hazards (Cutter, Boruff, and Shirley 2003). Vulnerability and resilience are tightly coupled concepts where increasing resilience is likely decreasing vulnerability. Figure 1 visually depicts the relationships between hazard exposure, sensitivity, and adaptive capacity.

The multi-risk assessment presented here considers how social vulnerability and hazard risk interact. The findings identify specific neighborhoods (spatially designated as census block groups) that score relatively high on social vulnerability and face relatively high hazard risk. In some socially vulnerable census block groups, there may exist risk from a single hazard. In other census block groups, the exposure to multiple hazard risks is relatively high. The possibility of cascading or domino effects amplify the overall risk and present challenges to community resilience. A multi-risk assessment considers hazard and vulnerability interactions (Gallina et al. 2016). In this approach, risks are analyzed separately (considering for each hazard a specific analysis of exposure and vulnerability) and then the aggregation creates a multi-risk index. Table 1 summarizes the concepts and definitions for this report.

Figure 1. Relationship between vulnerability and community resilience.



Our approach includes four primary steps (each elaborated below):

1. Assess the spatial sensitivity to hazards and difference across communities in their overall capacity to prepare for, respond to, and recover from hazards. We do this by adapting a well-vetted and oft-used tool – The Social Vulnerability Index (or SoVI®).
2. Assessing the spatial exposure of independent hazards. These include:
    a. Flooding (specifically, riverine/creek flooding)
    b. Wildfire
    c. Extreme heat
3. Conduct single risk assessments by analyzing the interaction between sensitivity (SoVI®) and exposure for each independent hazard.
4. Develop a composite multi-climate risk index.

This analysis and information provide a starting point to assessing, and building, capacity for preparedness or response and where resources and social programs might be used more effectively to reduce vulnerability prior to an event.

Table 1. Concepts and Definitions for a multi-risk approach (adapted from Gallina et al. 2016).

Concept	**Definition**
Hazard	Represents the physical phenomenon related to climate change (e.g., flood, wildfire, heat) that has the potential to cause damage and loss to property, infrastructure, livelihoods, service provision and environmental resources.
Exposure	Represents the presence of people, livelihoods, environmental services and resources, infrastructure, economic, social, or cultural assets that could be adversely affected.
Vulnerability	Represents the propensity or predisposition of a community, system, or asset to be adversely affected by a certain hazard.
Sensitivity	The degree to which a population or asset is susceptible or resistant to impacts from weather or climate events.
Adaptive capacity	The ability of a system (i.e., people, environmental services and resources, or cultural assets, etc.) to cope with stress or adjust to new situations.
Social Vulnerability	Social vulnerability is a measure of both the sensitivity of a population to natural hazards and its ability to respond to and recover from the impacts of hazards.
Hazard Risk	It quantifies and classifies potential consequences of a hazard events on the investigated areas combining hazard, exposure and vulnerability.
Multi-hazard	Represents the totality of relevant hazards in a defined administrative area with or without temporal coincidence (cascade effects).
Multi-risk	Represents the whole risk from several hazards, taking into account possible hazards and vulnerability interactions.
Community resilience	Represents a process, a capacity, and an outcome of the ability to manage and respond to hazards and long-term stressors related to climate change and weather extremes.

2. Social Vulnerability

Vulnerability represents the predisposition of a community, system, or asset (in our case, a neighborhood) to be adversely affected by a certain hazard. Social vulnerability is a measure of both the sensitivity of a population to natural hazards and its ability to respond to and recover from the impacts of hazards. It is a multidimensional construct, one not easily captured with a single variable, and varies across time and space since potential for losses vary temporally and geographically and among different socio-demographic characteristics, such as income, education, occupation, household composition, home ownership, minority status, gender, age (elderly and children), housing tenure, and vehicle access (Cutter and Finch 2008; Flanagan et al. 2011; Cutter, Ash, and Emrich 2014; Haron 2016; Scherzer, Lujala, and Rød 2019).

Reducing social vulnerability can decrease both human suffering and economic loss (Flanagan et al. 2011). Since the late 1990s, it has generally been acknowledged that a holistic assessment of risk needed to include socioeconomic and demographic factors (Flanagan et al. 2018; 2011; Huynh and Stringer 2018; Vincent 2007; Cutter, Boruff, and Shirley 2003). The Social Vulnerability Index (SoVI®), created by Hazards and Vulnerability Research Institute at the University of South Carolina (Cutter, Boruff, and Shirley 2003), is the most frequently cited tool for estimating social vulnerability in the United States.

2.1 Social Vulnerability Index (SoVI®)

The original calculation of the social vulnerability index (Cutter, Boruff, and Shirley 2003) synthesized 42 socioeconomic and built environment variables to quantify the social vulnerability to environmental hazards and generate a comparative metric that facilitates the examination of the differences between U.S. counties. After modifications and omissions over time, the newest version (SoVI® 2010-14) contains 29 variables (listed in Table 2). Appendix A includes a broader set of variables utilized in different vulnerability indices derived from the literature.

Table 2. Full List of variables and description (n=29) in SoVI® (2010-2014)

	Variable	Description
1	MDHSEVAL	Median Housing Value
2	HOSPTPC	Hospitals Per Capita
3	MDGRENT	Median Gross Rent
4	MEDAGE	Median Age
5	PERCAP	Per Capita Income
6	PPUNIT	People per Unit (Average household size)
7	QAGEDEP	Percent Population under 5 years or 65 and over
8	QASIAN	Percent Asian
9	QBLACK	Percent Black or African American Alone
10	QCVLUN	Percent Unemployment for Civilian in Labor Force 16 Years and Over
11	QEDLESHI	Percent Less than high school education for population over 25 years and older
12	QESL	Percent Speaking English as a Second Language with Limited Proficiency
13	QEXTRCT	Percent Employment in Construction and Extraction Industry
14	QFAM	Percent Children Living in Married Couple Families
15	QFEMALE	Percent Female
16	QFEMLBR	Percent Female Participation in Labor Force
17	QFHH	Percent Female Headed Households (Out of unmarried-partner households)
18	QINDIAN	Percent Native American (American Indian and Alaska Native alone)
19	QMOHO	Percent Mobile Homes
20	QNOAUTO	Percent Housing Units with No Car
21	QNOHLTH	Percent population without health insurance
22	QNRRES	Percent population living in Nursing Facilities/Skilled Nursing Facilities
23	QPOVTY	Percent Poverty
24	QRENTER	Percent Renters (Percent out of total Occupied housing units)
25	QRICH	Percent Households Earning over $200,000 annually
26	QSERV	Percent Employment in Service Industry
27	QSPANISH	Percent Hispanic
28	QSSBEN	Percent Households Receiving Social Security Benefits
29	QUNOCCHU	Percent Unoccupied Housing Units

2.2 Social Vulnerability Index at the Census Block Group Level in Austin

This study quantifies a Social Vulnerability Index score in the City of Austin at the **block group level** adapting the SoVI® for the context in Austin. Austin is grouped into 640 Census Block Groups (CBGs) via the 2016 United States Census (American Community Survey). The CBG scale is the highest resolution of which census-based socioeconomic data exists in Austin. This scale is large enough to dampen outliers and potential errors in sociodemographic data, and yet small enough to capture variation in demographic makeup across the city.

Data for SoVI variables at all CBG levels in Austin are derived from the U.S. Census Five-Year American Community Survey (ASC) 2013-17. Of the 29 variables listed in Table 2, six variables – (1) percent of female headed households (QFHH), (2) percent of population without health insurance (QNOHLTH), (3) number of hospitals per capita (HOSPTPC), (4) percent of population living in nursing facilities (QNRRES), (5) number of hospitals per capita (HOSPTPC) and (6) percent of population living in nursing facilities (QNRRES) – are not available at the block group level for this time period in Austin. Of the total number of block groups in Austin (640), the block group that correspond to Austin-Bergstrom International airport (1) has been excluded from the data.

The process of calculating the Social Vulnerability Index score is summarized in Figure 2. In order to conduct statistical procedure, all missing values from the ASC survey data were replaced by the mean value of the surrounding block groups. This was executed by identifying intersecting polygons and calculating simple average values, using the GIS software (QGIS). Then, data was normalized using the Min-Max Feature Scaling method (see equation below).

$$X_{Normalized} = \frac{X_{original} - X_{min}}{X_{max} - X_{min}}$$

Normalization refers to scaling all the variables using one method so that all the data have comparable reference points. The min-max method is a straightforward normalization technique common in social indicators research (Tarabusi and Guarini 2013). Min–max normalization assigns a value of 0 to the minimum value and 1 to the maximum value. All other values are scaled between zero and one by subtracting the minimum value and dividing by the range (the minimum subtracted from the maximum). One disadvantage of using normalization, however, is that the final score is not an absolute measurement of social vulnerability for a single CBG location, but rather a relative value in which all CBG's in Austin can be compared, which provides easily understood comparisons between places at a particular point in time. Utilizing such normalized values is useful for benchmarking progress in reducing vulnerability and enhancing resilience over time and across space.

With the normalized dataset, a principal component analysis (PCA) with varimax rotation (Comrey and Lee 1992) was performed to reduce the dimensionality of a data set with statistically optimized components. The variables are evaluated based on eigenvalue (greater than 1.0), variance explained by each component, loading score for each factor (≥ |0.50|), and meaningfulness of each component.

Figure 2. Process of SVI score calculation

As a result of principal component analysis, 7 variables were eliminated and 6 components (i.e., Wealth, Language and Education, Elderly, Housing Status, Social Status, and Gender) were obtained (summarized in Tables 3 and 4), explaining 74.48% of the total variance.

Table 3. Austin social vulnerability principal component summary

Variables		Category/ Cardinality	Components / Loading scores					
			1	2	3	4	5	6
1	QRICH	**Wealth (-)**	**0.915**	-0.13	0.059	0.014	-0.085	-0.042
2	MDHSEVAL		**0.892**	-0.09	-0.065	-0.145	-0.072	-0.006
3	PERCAP		**0.86**	-0.258	0.093	-0.223	-0.2	-0.016
4	MDGRENT		**0.61**	-0.384	-0.177	0.158	-0.171	0.03
5	QESL	**Language & Education (+)**	-0.134	**0.806**	-0.105	0.175	-0.002	-0.09
6	QSPANISH		-0.288	**0.739**	-0.104	0.379	-0.104	-0.066
7	QED12LES		-0.365	**0.732**	0.022	0.291	0.131	-0.126
8	QSSBEN	**Elderly (+)**	-0.161	-0.041	**0.896**	-0.02	0.053	0.022
9	QAGEDEP		-0.003	-0.001	**0.859**	-0.116	-0.012	0.114
10	MEDAGE		0.235	-0.181	**0.658**	-0.357	-0.196	-0.008
11	PPUNIT	**Housing Status (+)**	-0.083	0.216	-0.138	**0.874**	-0.038	-0.067
12	QFAM		-0.064	0.159	-0.162	**0.844**	0.055	0.096
13	QCVLUN	**Social Status (+)**	-0.09	0.054	0.135	0.243	**0.723**	-0.097
14	QBLACK		-0.185	-0.278	-0.178	-0.056	**0.666**	0.151
15	QNOAUTO		-0.12	0.486	0.039	-0.299	**0.559**	0.095
16	QPOVTY		-0.144	0.432	-0.166	-0.111	**0.533**	0.082
21	QFEMALE	**Gender (+)**	0.052	0.031	0.146	0.067	-0.021	**0.877**
22	QFEMLBR		-0.081	-0.173	-0.021	-0.048	0.105	**0.836**

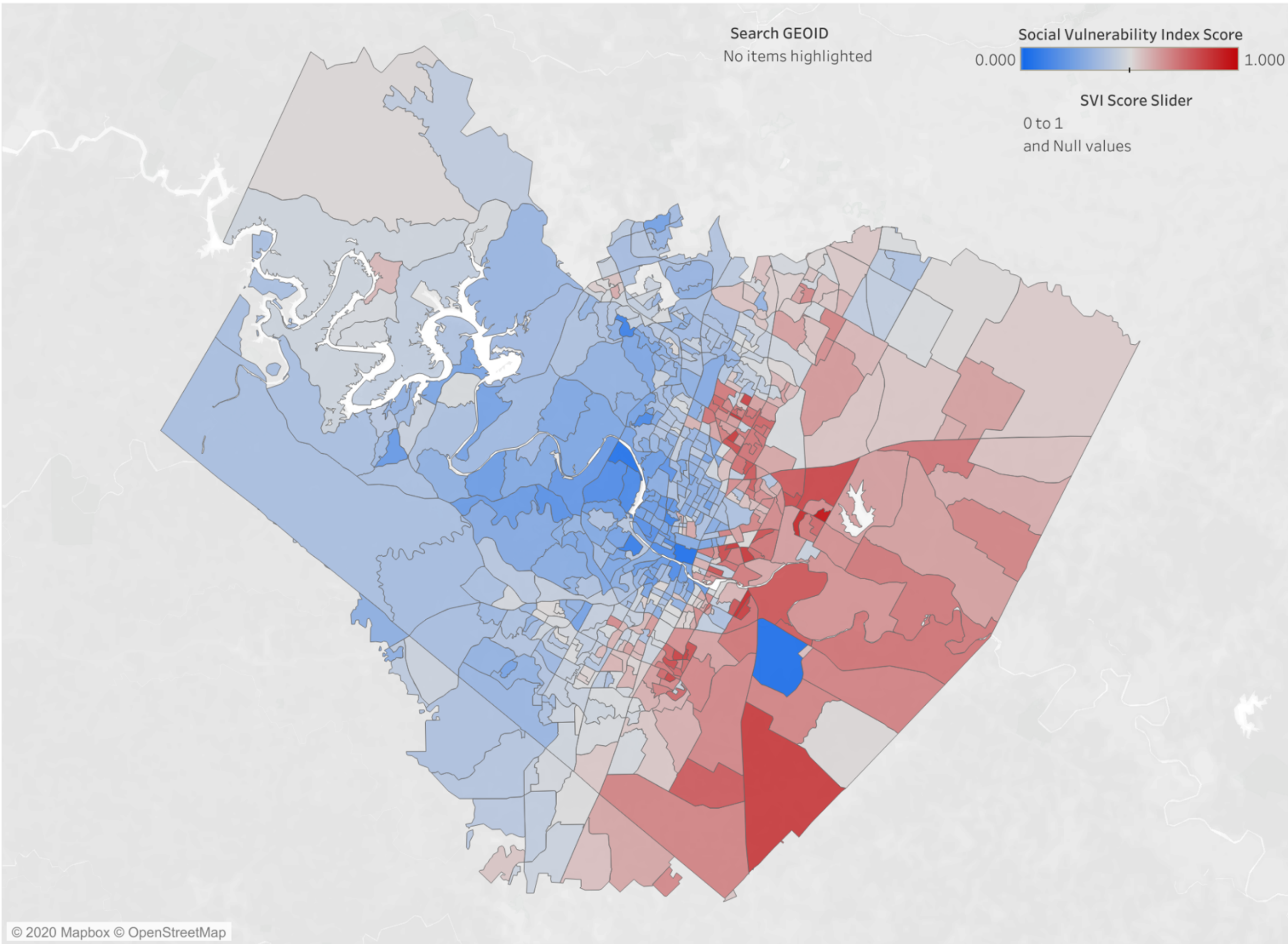
*Rotation Method: Varimax with Kaiser Normalization.

Table 4. Principal component analysis summary (variance) at block group level

	Component	Cardinality	Variance Explained (%)	Variables	Loading scores
1	Wealth	(-)	17.53	QRICH	0.915
				MDHSEVAL	0.892
				PERCAP	0.86
				MDGRENT	0.61
2	Language & Education	(+)	14.51	QESL	0.806
				QSPANISH	0.739
				QED12LES	0.732
3	Elderly	(+)	12.17	QSSBEN	0.896
				QAGEDEP	0.859
				MEDAGE	0.658
4	Housing Status	(+)	11.91	PPUNIT	0.874
				QFAM	0.844
5	Social Status	(+)	9.61	QCVLUN	0.723
				QBLACK	0.666
				QNOAUTO	0.559
				QPOVTY	0.533
6	Gender	(+)	8.75	QFEMALE	0.877
				QFEMLBR	0.836
	Total Variance Explained		**74.48**		

Finally, the orientation of each component was adjusted so that the directionality of the factor effect corresponds theoretically to higher social vulnerability. Positive component direction is associated with increasing vulnerability, while negative component direction is associated with decreasing vulnerability. Normalized and direction-adjusted values were summed together to determine the numerical composite social vulnerability score for each census block group. Figure 3 shows the SVI scores mapped to visually compare census block groups in Austin. The normalized SVI score ranges between 0 and 1 with mean value of 0.462. The SVI score of 0.0 indicates the least vulnerable (blue in the figures), and 1.0 indicates the most vulnerable (red in the figures). Note that Austin-Bergstrom Airport has a “null value”, or score of 0, and stands out in southeast Austin.

Figure 3. Social Vulnerability Index in Austin



2. Multi-risk Climate Vulnerability Assessment

To develop a multi-risk climate vulnerability assessment for Austin, individual indices must first be developed for hazard risks most common in Austin: flood, wildfire and heat.

2.1 Flood Vulnerability

Structural flooding most frequently occurs outside of the creek but within a flood plain, and property damage is caused by the rapidly moving floodwater and depth of water on the ground outside of the creek banks. The flood vulnerability scores are calculated based on the Creek Flooding Problem Score values developed by the Watershed Protection Department of the City of Austin (Watershed Protection Department 2015). The problem scores account for public safety and property protection concerns for structures and low-water crossings using modeled flood depths for 2-, 10-, 25-, and 100-year storm events. The deeper and more frequent the predicted flooding, the higher the score.

$$Flooding\ Problem\ Score = f\binom{Problem\ Severity}{Resource\ Value}$$

Numeric problem severity scores are calculated for each property based on resource values (see Table 5) and modeled flood frequency and depth. The flooding threat to property ($FT_{property}$) is calculated as follows:

$$FT_{Property} = RV * \left(\frac{1}{2}D_2 + \frac{1}{10}D_{10} + \frac{1}{25}D_{25} + \frac{1}{100}D_{100}\right)$$

RV = Resource value

D_2 = Depth of flooding (ft)at the 2-year storm interval

D_{10} = Depth of flooding (ft)at the 10-year storm interval

D_{25} = Depth of flooding (ft)at the 25-year storm interval

D_{100} = Depth of flooding (ft)at the 100-year storm interval

Table 5. Resource values for each type of resource for flood problem score

Resource Type	Resource Value (RV)	Resource Type	Resource Value (RV)
Public Care Facilities	100	Residential: Single Family	60
Residential: Multifamily	80	Non-Residential	60
Mixed Use	80	Parking Garage	40

The calculated $FT_{Property}$ is a “Raw” flood score for each property. These raw scores are adjusted (normalized) to range from 0 to 100: with a score of 0 reflecting ideal watershed conditions and a score of 100 representing the worst problem identified. Based on the flood score for properties, the creek flooding vulnerability scores for census block groups are calculated by summing all individual structure scores within the block group and normalized to range from 0 to 1. Since the structural flooding mostly occurs within a flood plain, the proportion of the floodplain area within the block group was multiplied as a weight value. The Flood Vulnerability Score is calculated as follows:

$$Flood\ Risk\ Score\ for\ block\ group = \left(\sum_{\substack{within \\ Block\ Group}} FT_{Property} \right) *\ WeightValue$$

$$Weight\ Value = \frac{Area\ of\ floodplain\ within\ the\ block\ group}{Total\ Area\ of\ the\ block\ group}$$

Total number of 199 block groups that do not contain floodplain have weight value of 0.0, resulting the flood exposure score of 0.0. These block groups were indicated as “Not in floodplain” on the map. The flood exposure score ranges between 0.0 and 0.948 with mean value of 0.114 (median value of 0.08). The normalized flood exposure score ranges between 0 and 1 with mean value of 0.121. The score of 0.0 indicates the least exposure (blue in the figures 4 and 5), and 1.0 indicates the most exposure (red in the figures 4 and 5). Then, flood risk scores, combining flood exposure and vulnerability, were calculated for all block groups. The risk score (flood exposure + vulnerability) range 0.0 and 1.738 with mean value of 0.179 (median value of 0.122). The normalized risk score ranges between 0 (least vulnerable) and 1 (most vulnerable) with mean value of 0.103. The block group of Austin-Bergstrom Airport has a “null value” for the composite (flood + vulnerability) score. Descriptive statistics for each hazard and risk score can be found in Table 6.

Figure 4. Austin Flood Hazard Exposure

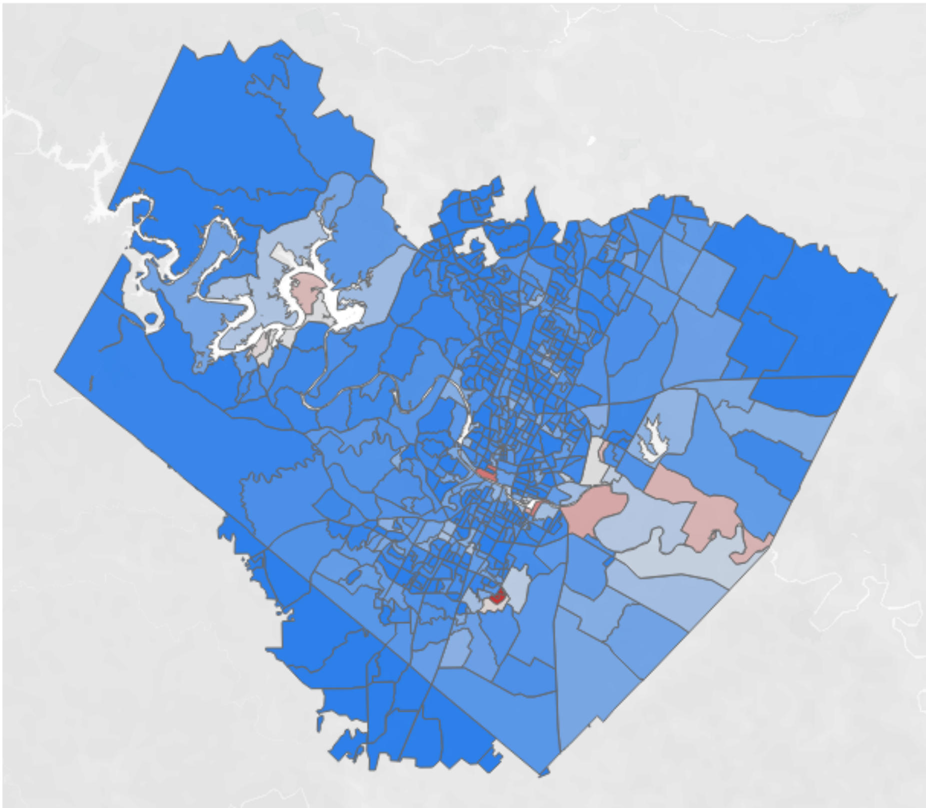
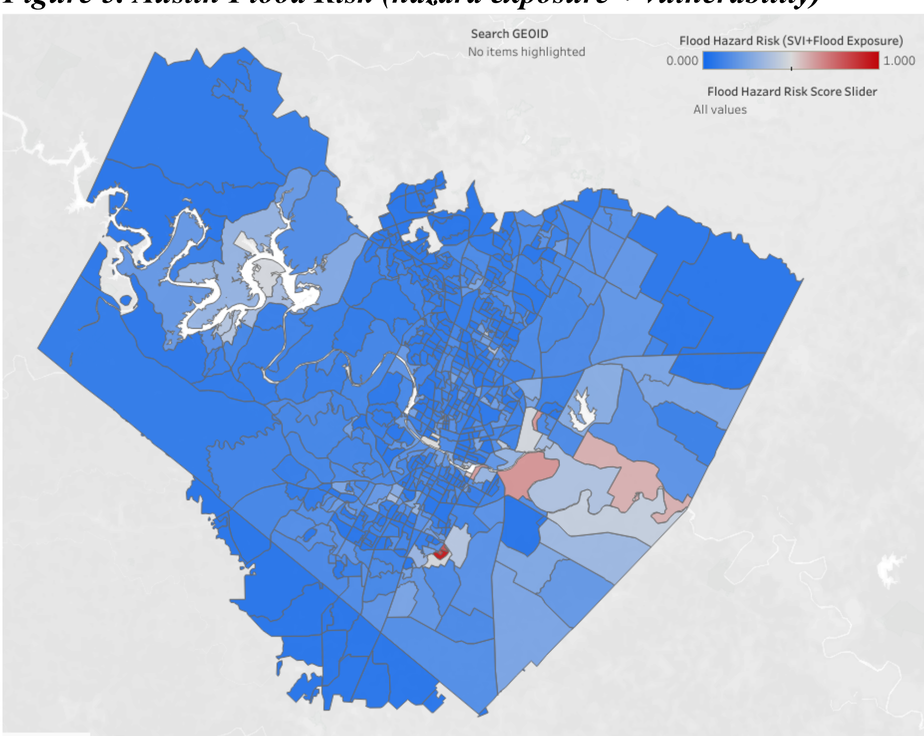


Figure 5. Austin Flood Risk (hazard exposure + vulnerability)



2.2 Wildfire Hazard Exposure and Risk

This work used the Wildfire Risk scores calculated for the Community Wildfire Protection Plan (CWPP) in 2014.

$$Wildfire\ Risk\ Score = f\begin{pmatrix} Probability\ of\ wildfire\ events, \\ Fire\ line\ intensity\ +\ Spotting\ distance \end{pmatrix}$$

The Austin-Travis County CWPP defined wildfire risk as the product of the probability of a wildfire under conditions conducive to large, fast-moving fires that burn through fuels producing high heat energy and flaming embers, and the negative consequences associated with the events. The wildfire risk scores from the CWPP were calculated for over 300,000 parcels, providing the complete coverage of the Travis County. The scores are calculated based on two factors (i.e., Spot Risk and Structure Combustion Risk).

The first factor, Spot Risk, is defined as the probability that spot fire ignition would occur due to embers. For the risk associated with spot fires, Burn Probability and Spotting Distance parameters from the fire behavior simulation modeling (FlamMap) outputs were used where the model had predicted the lofting and transport of embers. The Burn Probability is an estimate of the likelihood that a pixel will burn given a random ignition within the study area and calculated by “number of fires per pixel” divided by the “maximum number of fires per pixel”. The Spotting Distance is a fire behavior that produces firebrands transported by ambient winds, fire whirls, and/or convection columns causing spot fire ahead of the main fire perimeter (Andrews 1996; NWCG 2005). The vector length of the Spotting Distance is calculated in m/s, while the orientation is measured as the degree from North.

The second factor, Structure or Radiant Combustion Risk, is defined as the probability of structure loss during a wildfire. Risk from radiant combustion was calculated as Burn Probability multiplied by Fire Line Intensity. The Fire Line Intensity, which is also one of the outputs of the FlamMap, indicates the rate of heat release along the fire front, and it is calculated in kilowatts/meter (kW/m). For the purpose of Austin-Travis County CWPP, structures were assumed to be wooden, with a wooden roof framed and decked at a pitch ≥10° with yard vegetation that was ≥5 m in height, utilizing the worst-case scenario.

In order to match the resolution of this study, the 30-meter resolution (raster) of the wildfire exposure score was aggregated and averaged into the block groups (polygon) using the GIS software. The normalized wildfire exposure score ranges between 0 and 1 with mean value of 0.501. The score of 0.0 indicates the least exposure (blue in the figures 6 and 7), and 1.0 indicates the most exposure (red in the figures 6 and 7). The risk score (wildfire exposure + vulnerability) range 0.0 and 1.560 with mean value of 0.730 (median value of 0.738). The normalized risk score ranges between 0 (least vulnerable) and 1 (most vulnerable) with mean value of 0.468. The block group of Austin-Bergstrom Airport has a “null value” for the wildfire risk score as well.

Table 6. Descriptive statistics for each hazard and risk score

		Minimum	Maximum	Mean	Median	# of Null Values	Note
SVI only	Raw	0.00400	0.26349	0.12380	0.11933	1	Airport
	Norm	0.00000	1.00000	0.46166	0.44445	1	Airport
Flood Only	Raw	0.00001	0.94803	0.11433	0.08023	199	Not in Floodplain
	Norm	0.00000	1.00000	0.12059	0.08461	199	Not in Floodplain
SVI+Flood	Raw	0.00000	1.73795	0.17876	0.12194	200	Not in Floodplain + Airport
	Norm	0.00000	1.00000	0.10286	0.07016	200	Not in Floodplain + Airport
Wild Fire Only	Raw	-	-	-	-	0	-
	Norm	0.00000	1.00000	0.57252	0.58205	0	-
SVI+Wildfire	Raw	0.00000	1.61907	0.83693	0.84058	1	Airport
	Norm	0.00000	1.00000	0.51692	0.51918	1	Airport
Heat Only	Raw	-4.63818	79.74158	28.50806	27.58166	1	Airport
	Norm	0.00000	1.00000	0.39282	0.38184	1	Airport
SVI+Heat	Raw	0.00000	1.65558	0.57968	0.55109	1	Airport
	Norm	0.00000	1.00000	0.35014	0.33287	1	Airport
Composite CVI	Raw	0.22762	1.97481	0.93789	0.92877	1	Airport
	Norm	0.00000	1.00000	0.40652	0.40130	1	Airport

Figure 6. Austin Wildfire Hazard Exposure

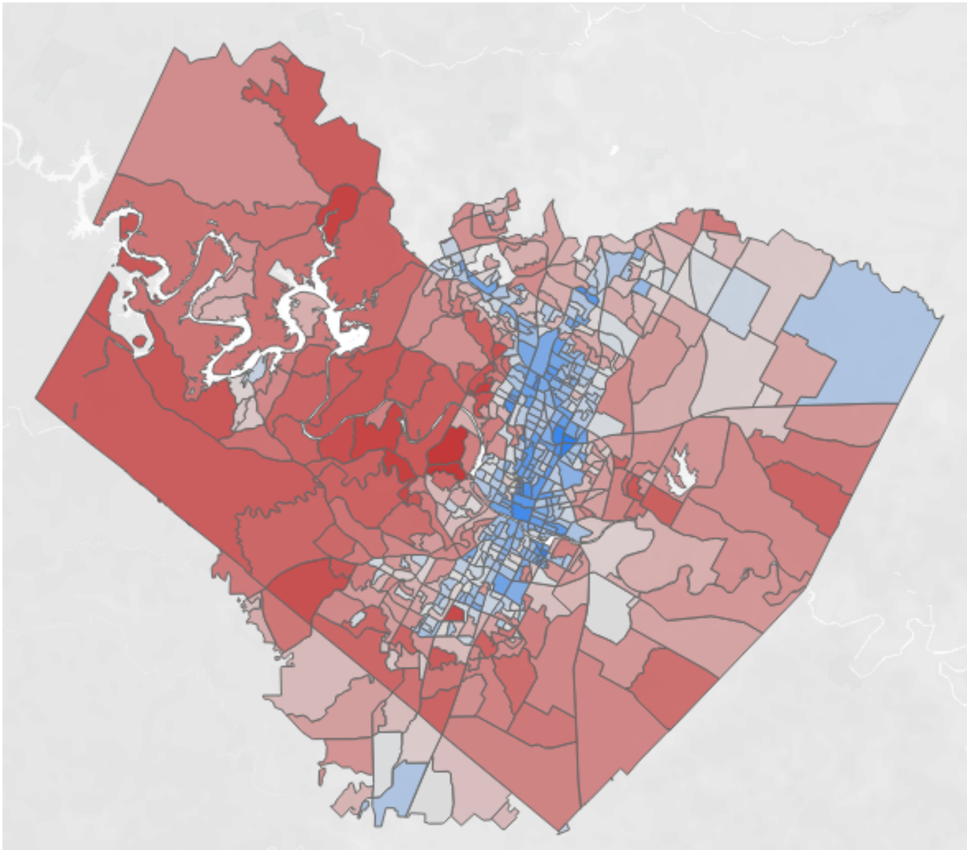
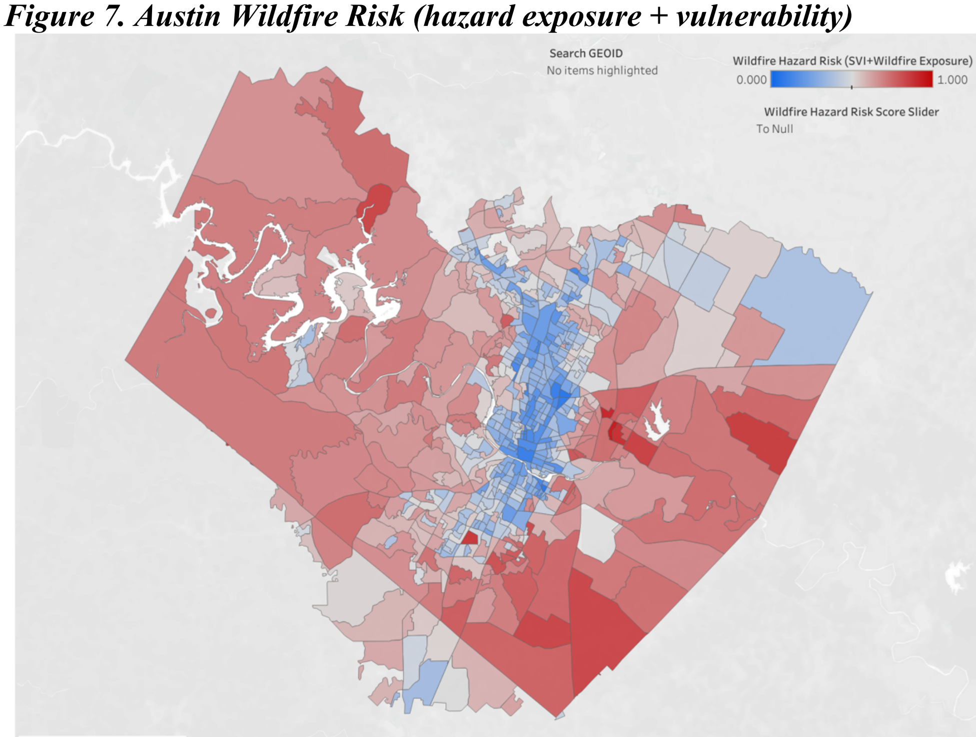


Figure 7. Austin Wildfire Risk (hazard exposure + vulnerability)



2.3 Urban Heat Hazard Exposure and Risk

The urban heat island effect, in which temperatures are higher in urban compared with surrounding rural environments, presents a significant climate-related hazard. Urban heat, and extreme variations in local air temperatures, are a key metric for public health outcomes (White-Newsome et al. 2013). A variety of methods are utilized to index urban heat, many of which include specialized temperature sensors not currently available for this study. Many studies focus on either impervious surfaces, which absorb and retain heat, or greenspaces and tree cover that have a cooling effect, or a combination of both (Ziter et al. 2019).

The urban heat hazard exposure scores for census block groups are calculated based on the 2016 National Land Cover Data (Imperviousness and Tree Canopy), for the Austin Metropolitan Statistical Area (MSA). Average Imperviousness (%) and average Tree Canopy (%) across block groups are calculated. In order to develop the Heat Hazard Exposure Score, this study used Imperviousness as the primary indicator and modified to (reduce) the score based on the Tree Canopy.

$$Heat\ Vulnerability\ for\ block\ group = Imperviousneess - 0.1 * TreeCanopy$$

The exposure score for urban heat ranges between -4.638 and 79.742 with mean value of 28.508 (median value of 27.581). The normalized heat exposure score ranges between 0 and 1 with mean value of 0.393. The score of 0.0 indicates the least exposure (blue in the figures 8 and 9), and 1.0 indicates the most exposure (red in the figures 8 and 9). The heat risk scores range 0.0 and 1.656 with mean value of 0.580 (median value of 0.551). The normalized heat risk score ranges between 0 (least vulnerable) and 1 (most vulnerable) with mean value of 0.350. The block group of Austin-Bergstrom Airport has a “null value” for the heat risk (heat + vulnerability) but displays as a 0 (least vulnerable) in Figure 8 and 9.

Figure 8. Austin Heat Hazard Exposure

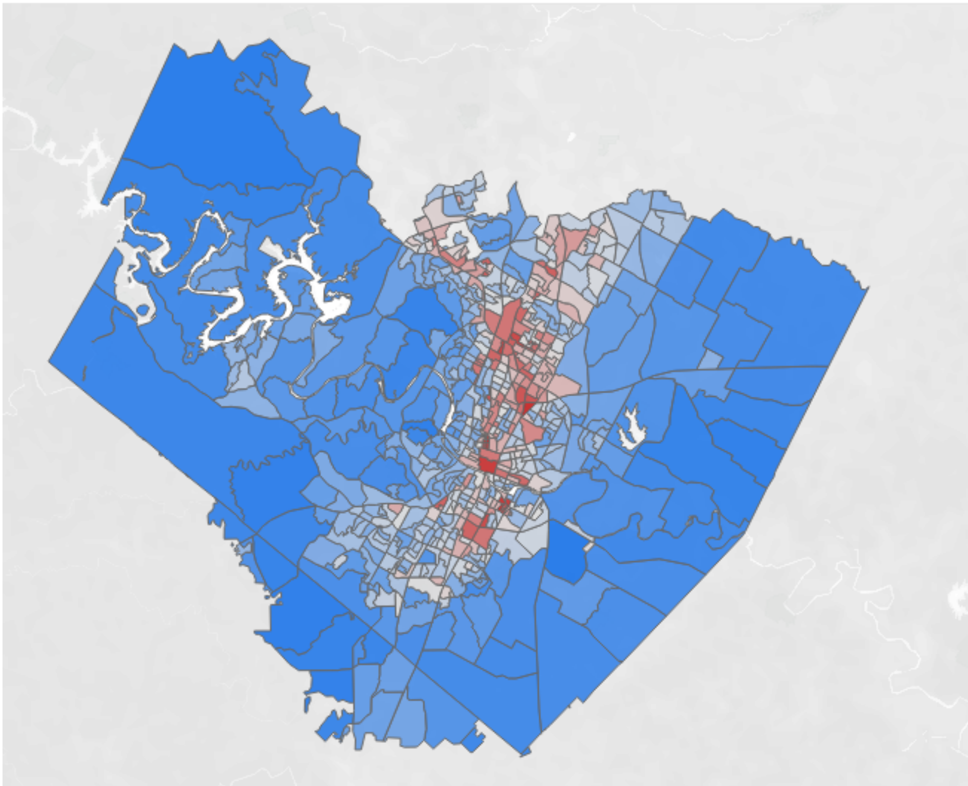
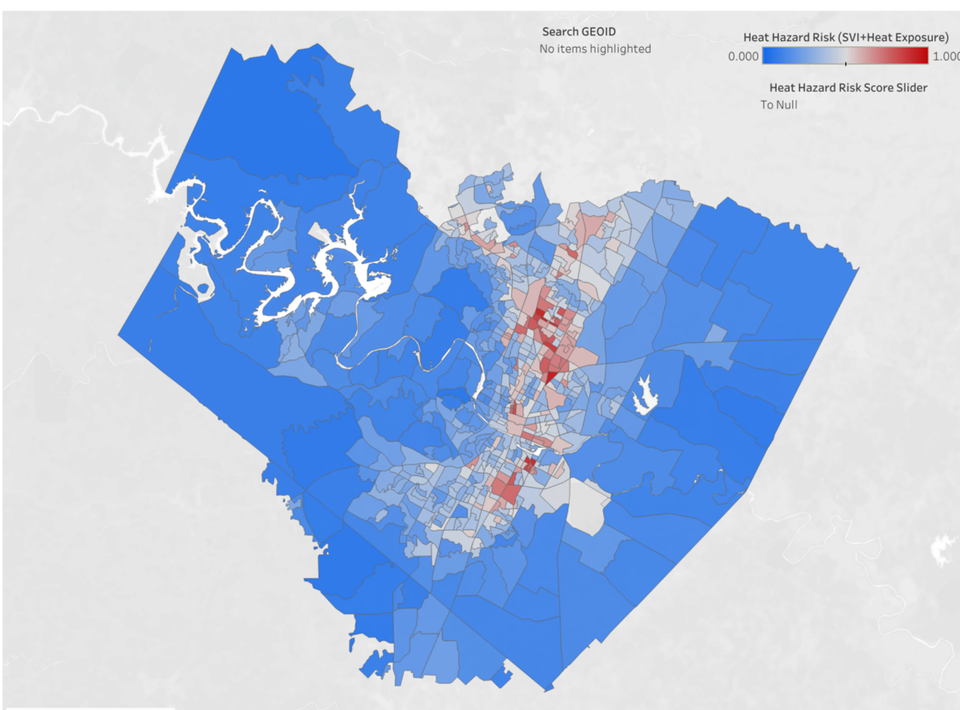


Figure 9. Austin Heat Risk (hazard exposure + vulnerability)



2.4 Climate Multi-Hazard Exposure and Risk

In this study, the multi-hazard and multi-risk scores were calculated at all census block group level for Travis County. We refer to this as the Climate Vulnerability Index (CVI). The CVI score for each hazard was calculated as Social Vulnerability Index score (normalized into the range from 1 to 2) multiplied by the corresponding risk score (normalized into the range from 0 to 1), and re-normalized into the range from 0 to 1. This assures the census block group with low risk for climate shock/stressor would have lower CVI score.

$$CVI_{Flood} = SVI * Flood\ Risk\ Score$$
$$CVI_{Wildfire} = SVI * Wildfire\ Risk\ Score$$
$$CVI_{UrbanHeat} = SVI * Urban\ Heat\ Risk\ Score$$

How the risk score for three climate shock and stressors (i.e., Creek Flooding, Wildfire, Urban Heat) is described in the following sections (2.1-2.3). Then the Composite Climate Vulnerability Index score was calculated as follows.

$$CVI_{Composite} = w_{flood} * CVI_{Flood} + w_{wildfire} * CVI_{Wildfire} + w_{urbanheat} * CVI_{UrbanHeat}$$

The w_{flood}, $w_{wildfire}$, and $w_{urbanheat}$ indicate weight factors for each shock/stressor, which were all assumed to be 1, representing the equal importance across the three. The Climate Vulnerability Index score ranges between 0.414 and 1.974 with the mean value of 0.889 (median value of 0.877). The normalized composite climate hazard risk score ranges between 0 (least vulnerable) and 1 (most vulnerable) with mean value of 0.304. The block group for the Austin-Bergstrom International Airport has a “null value”.

Figure 10. Austin Multi-hazard Exposure (flood + fire + heat)

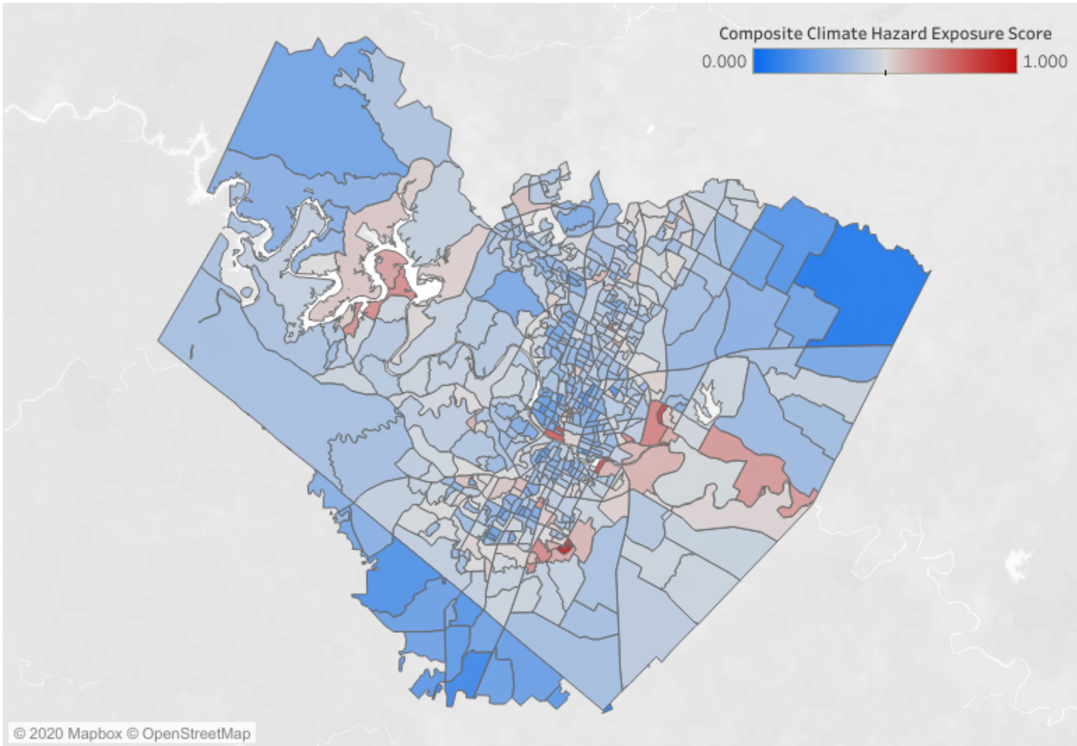
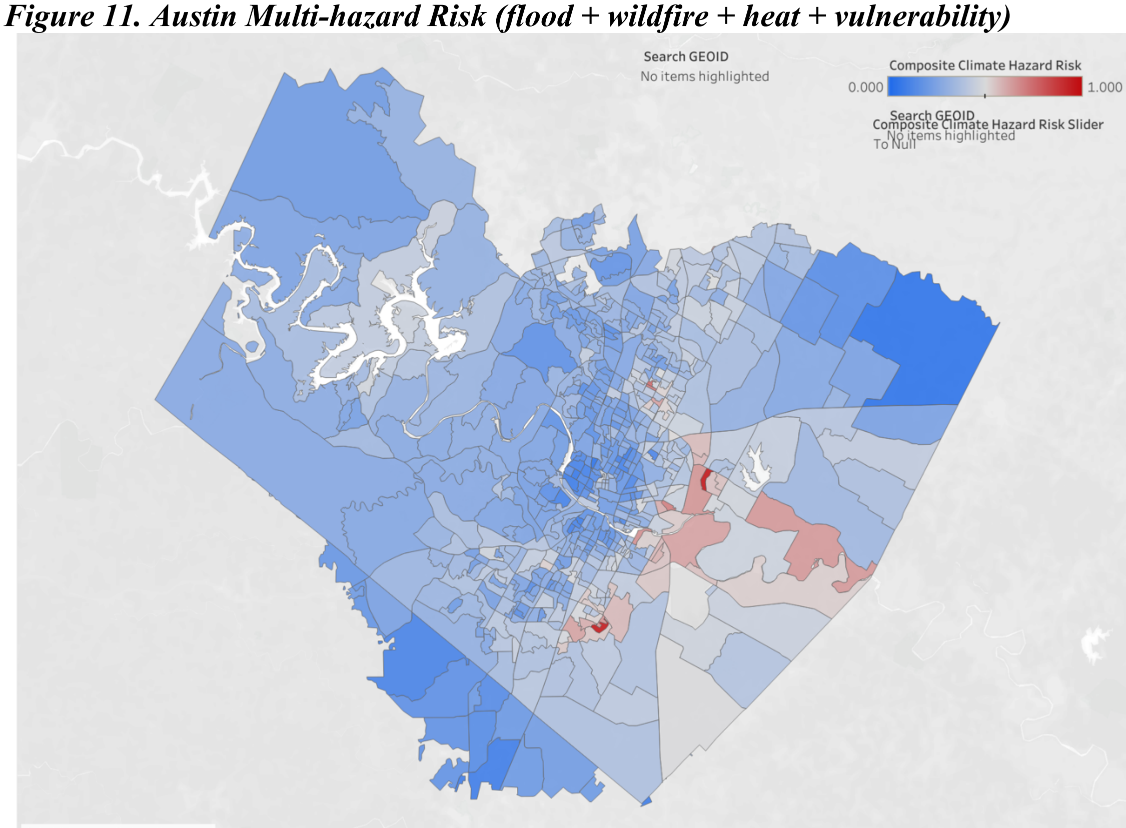


Figure 11. Austin Multi-hazard Risk (flood + wildfire + heat + vulnerability)

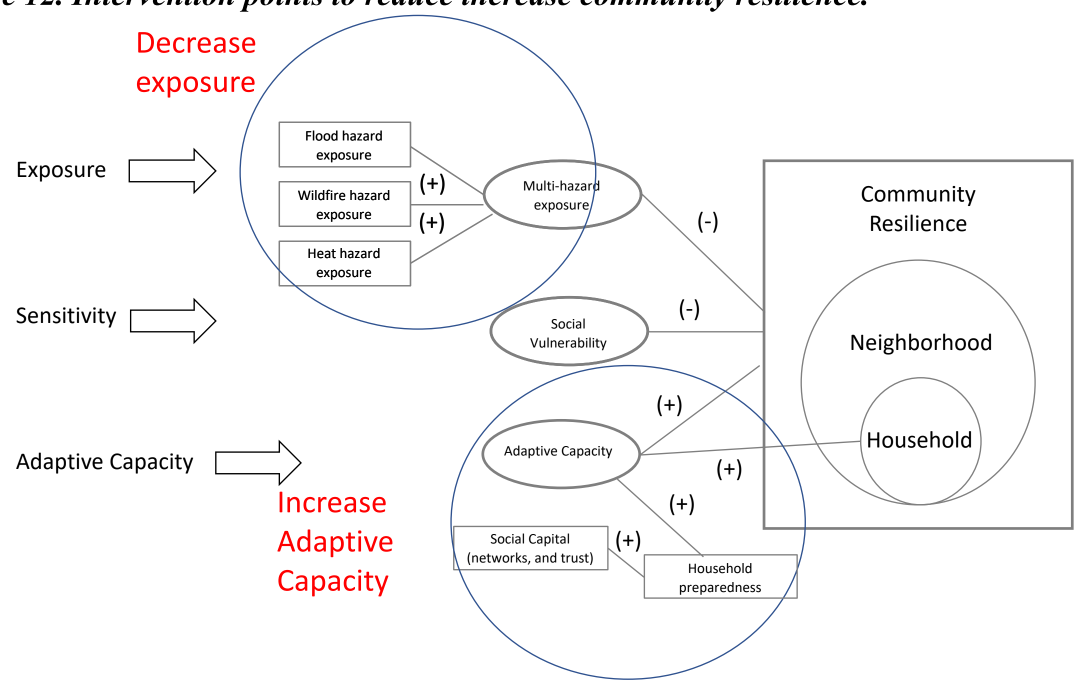


3. Conclusion

The multi-risk assessment provided here offers a coherent combination of hazards, exposure and vulnerability of census block groups (i.e., neighborhoods) at risk. We believe this approach is justifiable and a meaningful measure of the relative risk and resilience and how the spatial variation across Austin. Importantly, our approach is reproducible utilizing publicly available data for the social vulnerability index (American Community Survey, U.S. Census Bureau); urban heat exposure (National Land Cover Dataset); and utilizing City of Austin data for flood and fire.

Utilizing this tool, specific geographies can be identified with relative high degrees of exposure to one or multiple hazards, coupled with relatively high social vulnerability (populations with characteristics associated with high sensitivity to the impacts of hazards and characteristics of low ability to adapt, respond, and bounce forward to shocks or long-term climate related stressors). There are leverage points where policy can work to decrease exposure and/or increase adaptive capacity See figure 12.

Figure 12. Intervention points to reduce increase community resilience.



Investments in nature-based solutions (green and blue infrastructure) and/or grey infrastructure can decrease exposure to hazards, and effective community engagement can increase household preparedness and increase social capital, thus increasing adaptive capacity and increasing community resilience. Assessment and prioritization of options will require additional research.

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Appendix A. Literature review generated vulnerability and community resilience variables

Cutter, Ash, and Emrich 2014

Social	Economic	Community	Institutional	Housing/Infrastructure	Environmental
1. Educational attainment equality 2. Pre-retirement age 3. Transportation 4. Communication capacity 5. English language competency 6. Non-special needs 7. Health insurance 8. Mental health support 9. Food provisioning capacity 10. Physician access	1. Homeownership 2. Employment rate 3. Race/ethnicity income equality 4. Non-dependence on primary/tourism sectors 5. Gender income equality 6. Business size 7. Large retail-regional/national geographic distribution 8. Federal employment	1. Place attachment-not recent immigrants 2. Place attachment-native born residents 3. Political engagement 4. Social capital-religious organizations 5. Social capital-civic organizations 6. Social capital-disaster volunteerism 7. Citizen disaster preparedness and response skills	1. Mitigation spending 2. Flood insurance coverage 3. Jurisdictional coordination 4. Disaster aid experience 5. Local disaster training 6. Performance regimes-state capital 7. Performance regimes-nearest metro area 8. Population stability 9. Nuclear plant accident planning 10. Crop insurance coverage	1. Sturdier housing types 2. Temporary housing availability 3. Medical care capacity 4. Evacuation routes 5. Housing stock construction quality 6. Temporary shelter availability 7. School restoration potential 8. Industrial re-supply potential 9. High speed internet infrastructure	1. Local food suppliers 2. Natural flood buffers 3. Efficient energy use 4. Pervious surfaces 5. Efficient Water Use

Flanagan et al. 2018

Social	Economic	Institutional	Housing/Infrastructure	Community Capital	Environmental
1. Working age 2. Cars 3. Internet 4. Not-non-western immigrants 5. Not-single-parent 6. Not-social assistance 7. psychologists 8. Doctors 9. Gender equality index	1. Owner-occupied 2. Employed 3. Female employed 4. Ratio female to male avg. income 5. Employed Not primary industry or tourism 6. Ratio large to small business (# of employees) 7. Commercial enterprises 8. Banks 9. Turnover retail	1. Operating expenditure on Fire & Accident protection 2. Operating surplus 3. Distance to county capital 4. Employed to public admin, defense, social security, or municipal activities	1. Hotels 2. Fire, police, ambulance stations, shelter 3. Distance to fire or police station 4. Distance to hospital 5. Schools 6. Traffic accidents 7. Length of major road 8. Length of railway 9. Distance to airports 10. Employed to public utilities 11. Living in urban area	1. Employed to creative class 2. R&D Firm 3. Places of worship 4. Museum, libraries, zoos, botanic gardens 5. Sports facilities 6. Voting age population 7. Cinemas, youth center, clubs 8. Kindergartens 9. Broadcasts 10. In- & out-migration	1. Not flood area 2. No impervious surface 3. Not landslide zone 4. Not covered by water 5. Natural flood buffer 6. Developed open space 7. Arable (cultivated) land 8. Extreme weather events 9. Agricultural holdings

(continued…)

Scherzer, Lujala, and Rød 2019

Socioeconomic Status	Household Composition & Disability	Minority Status & Language	Housing & Transportation
1. Below poverty	1. Age 65 or older	1. Minority	1. Multiunit structures
2. Unemployed	2. Age 17 or younger	2. Speaks English “Less than well”	2. Mobile homes
3. Income	3. Older than age 5 within a disability		3. Crowding
4. No high school diploma	4. Single-parent household		4. No vehicle
			5. Group quarters

Balica, Wright, and van der Meulen 2012

Hydro-geological	Socio-economic	Politico-administrative
1. Sea-level rise	1. Cultural heritage (CH)	1. Existence of Flood hazard maps (FHM)
2. Storm surge	2. Population close to coastline (PCL)	2. Existence of Institutional organizations (IO)
3. # of cyclones	3. Growing coastal population (GCP)	3. Uncontrolled planning zone (UP)
4. Max River discharge	4. # of Shelters (S)	4. Flood protection (FP)
5. Foreshore slope	5. % of disabled persons (%Disable)	
6. Soil subsidence	6. Awareness and preparedness (A/P)	
7. Length of Coastline	7. Recovery time (RT)	
	8. Length of canalization (Drainage)	