Geospatial Vulnerability Framework for Identifying Water Infrastructure Inequalities

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Abstract: Recent infrastructure failures in the United States have brought attention to the ways and extent to which water security is unevenly distributed in urban areas. For many marginalized communities, infrastructure interdependencies (e.g., water, wastewater, stormwater, transportation) have created significant vulnerabilities in the face of aging or inadequate water treatment and delivery systems. In these communities, cascading failures precipitated by environmental hazards such as flooding often propagate across multiple infrastructure systems, sometimes resulting in poor water quality and/or lack of access to water for significant periods. However, little is known about how specific environmental and social factors combine with water infrastructure vulnerability and interdependencies to create enduring infrastructure inequalities. This paper presents a geospatial vulnerability framework for identifying water infrastructure inequalities, using the City of Tampa, Florida to demonstrate the framework. For this framework, we integrate GIS analysis of environmental hazards, a factor analytic model of socio-demographic data, and a network topology-based performance indicator for the water distribution network. The resulting framework models the environmental and social vulnerabilities, quantifies hydraulic vulnerability and infrastructure interdependence, and maps their distributions across the urban environment. We find that the highest levels of social and environmental vulnerabilities in Tampa are present in low-income areas and communities of color that have high hydraulic vulnerability and infrastructure interdependency, which creates pockets of low resilience capacity.

Author Keywords: Environmental hazards; Social vulnerability; Infrastructure interdependency; Water insecurity; Geographic information systems; Marginalized communities

Introduction

Access to a reliable and affordable supply of safe and clean water is essential for human wellbeing (UNESCO 2019). While continuous efforts through the United Nations Millennium Development Goals and, more recently, the Sustainable Development Goals, have succeeded in improving water quality and providing water access to millions of people globally (Dar and Khan 2011; UNICEF & WHO 2019), 2.1 billion people still lack access to potable water, mostly in developing countries (Mihelcic et al. 2017). At the same time, although high-income economies have made significant progress toward universal access to water through advances in treatment technologies and rapid expansion of water infrastructure networks (Sedlak 2014), recent infrastructure failures have exposed the growing problem of water insecurity for many marginalized communities in developed nations (Graham 2010). Recent studies in the U.S. and Canada, for example, reveal chronic and systemic failures of infrastructure systems and organizational management in communities of color, low-income communities in both urban (e.g., *colonias*) and rural (e.g., agricultural) settings as well as tribal communities (Allaire et al. 2018; Butler et al. 2016; Deitz and Meehan 2019; Jepson and Vandewalle 2016; Leker and Gibson 2018; Meehan et al. 2020).

In metropolitan areas, these failures are often attributed to aging infrastructure, dwindling resources, and lack of political will to address problems in minority and high-poverty communities (AWWA 2018; Butler et al. 2017; Steele and Legacy 2017). For example, from 2014-2015, lead leaching from municipal water pipes in Flint, Michigan exposed approximately 99,000 residents of mostly low-income, minority communities to elevated levels of lead, *E. coli*, and *Legionella* bacteria (Clark 2018). In this case, dual failures of both infrastructure and its management were to blame (Pauli 2019). Moreover, as cities become smarter and more connected, water and other utilities have become increasingly interdependent, creating a varied array of infrastructural vulnerabilities (Mohebbi et al. 2020). Water treatment and distribution failure, for instance, can be precipitated by power outages (electricity infrastructure) and road maintenance (transportation infrastructure). Research has shown that infrastructures in densely built environments are often physically interdependent because of their high degree of physical colocation (e.g., water/wastewater pipes and roadways), which makes them vulnerable to cascading failures (Abdel-Mottaleb and Zhang 2020). The social, economic, and political relations between infrastructure institutions coupled with the connectivity of information systems also result in social and cyber interdependencies that influence the resilience of infrastructures (Wells et al. 2019).

In many cases, the impacts of infrastructure failures reveal infrastructure inequalities between communities, particularly for marginalized populations in middle- and high-income economies (Deitz and Meehan 2019). In these settings, infrastructural conditions, interdependencies, and sociopolitical decisions intersect, leading to water inequalities and insecurity across socio-economic divides such as race, class, and citizenship (Switzer and Teodoro 2017). For instance, in border towns in south Texas, low-income migrants receive significantly inadequate water services (Jepson and Vandewalle 2016). Another study investigating the relationship between race and water services in North Carolina found that the probability of having community water services is lowest in census blocks with 100% Black residents (Leker and Gibson 2018). These examples join a growing number of studies that specifically recognize the social dimensions of hydraulic vulnerabilities (Linton and Budds 2014).

In addition to race and class inequities in the distribution of water provision, flooding from climate-induced extreme weather events has exposed the vulnerability of water infrastructures (due to age and interdependencies) and further increase the severity of cascading failures, especially in coastal cities. For example, flooding (stormwater infrastructure) caused by Hurricane Katrina led to road closures (transportation infrastructure) and made it inaccessible to water and wastewater treatment facilities for repairs; over 1,000 drinking water supply systems and 172 wastewater treatment plants were impacted (Mohebbi et al. 2020). In such circumstances, studies have shown that low-income and minority groups disproportionately endure the burden of infrastructural failures. In the wake of Hurricane Katrina, for instance, the poor in primarily Black, highly concentrated districts did not have an opportunity to escape and remained stranded in their homes without access to water (Scheper-Hughes 2005). Here, social and political systems intersected with environmental hazards to produce infrastructure inequalities.

In sum, a growing number of studies demonstrate many instances in which marginalized communities lack access to potable water or are forced to rely on inadequate infrastructure systems and processes, creating water service inequalities across racial and socioeconomic categories. Methodological innovations in quantitative and qualitative research, including geospatial approaches, are becoming increasingly useful for documenting these kinds of challenges (Jepson et al. 2017; Wutich et al. 2017; Young et al. 2019). However, there has been very little research examining the extent to which environmental, social, and infrastructural vulnerabilities synergistically contribute to water infrastructure inequalities that create intermittent (i.e., sporadic or periodic) water insecurity and low levels of resilience. The lack of understanding about the collective influence of these factors on the overall vulnerability of communities means state and non-state actors have limited capacity to assess the social and economic impacts of temporary infrastructural failures on local communities (Boin and

McConnell 2007). The significant challenge in evaluating the effects of infrastructural inequalities on society, then, lies in understanding the contexts in which these failures occur. To address this issue, in this study we use a network analysis approach to model water infrastructure vulnerability and situate it within the environmental and social context of an urban environment (the City of Tampa, Florida) using factor analysis within a geospatial framework. Our primary research question is, in what ways and to what extent are water infrastructure vulnerabilities associated with social and environmental vulnerabilities, and how can publicly available data be used to model these associations? The greater goal of this effort is to develop an analytical framework for producing actionable information that communities can use to explore and explain socio-hydraulic inequalities to policymakers.

Methods

Study context

Tampa is a ca. 150-year old, mid-sized, coastal city in the southeastern United States with a population of approximately 400,000 (U.S. Census Bureau 2019). Its location on Tampa Bay makes transportation, water, and stormwater infrastructure vulnerable to storm surge from the Gulf of Mexico (e.g., Weisberg and Zheng 2006). While the city has only experienced three direct hits from hurricanes over the past century (in 1921, 1960, and 1968), hurricanes elsewhere in the region and annual local tropical storms regularly cause significant flooding throughout the city and storm-force winds impact critical infrastructures including the power grid (Bigger et al. 2009). These conditions threaten the city's aging water infrastructure (established in 1924), which draws on surface water from the Hillsborough River and serves over 620,000 connections within the city and adjacent regions (Park et al. 2010). During Hurricane Irma in 2017, for instance, strong winds (up to 185 km/h) uprooted trees causing main breaks throughout the city that interrupted both water deliver and transportation. Similar to many U.S. cities of comparable size and age, deferred maintenance in the infrastructure network over the years has contributed to frequent infrastructure failures (Folkman 2018; Graham 2010; Patz et al. 2008). For example, city officials reported at least 1200 water main breaks between 2017 and 2018, normalized as 55 breaks per 100 miles of pipeline per year (WFTS 2019). While the main breaks interrupted water services to many residents across the city, they also caused widespread flooding that closed roadways and temporarily displaced families.

As our research shows, many of these infrastructure failures occurred in Black and Hispanic communities characterized by high poverty and low homeownership rates, which we refer to as marginalized communities (Lehigh et al. 2020; Wakhungu 2020; Wells et al. 2020). Tampa has an overall poverty rate of 20% compared to the national average of 12% (U.S. Census Bureau 2017). Likewise, homeownership in Tampa is 48%, which is below the national average of 64%. As of 2019, the racial composition of the city was 45% White, 26% Hispanic or Latino, and 24% Black (U.S. Census Bureau 2017). As in many metropolitan regions in the U.S., a large proportion of the low-income, minority population is concentrated in distinct neighborhoods (Curley 2005; Wilson 2012). The settlement pattern for marginalized communities in Tampa is partly an outcome of historical segregation laws that delineated neighborhoods based on race and ethnicity (Jackson 2020; Mirabal 1993), and has resulted in six marginalized communities in the eastern and western portions of the city: East Tampa, Jackson Heights, Ybor City, Sulphur Springs, West Tampa, and West Hyde Park.

Data modeling

To understand how environmental, social, and infrastructural conditions intersect to create or amplify water insecurity in these Tampa communities, we draw on the place-based vulnerability framework of Cutter (1996), which accounts for three components of vulnerability: environmental, social, and infrastructure. We present our overall analytical framework in Fig. 1, which is described in more detail below.

[insert Figure 1 here]

Environmental Vulnerability

While there are many factors that constitute "environmental vulnerability" (e.g., air and water quality, chemical exposure risk, etc.), for this study we characterize it as proximity to physical or environmental hazards such as floods, contaminated properties (e.g., brownfields), and hazardous waste following research reported by several studies that link these variables to marginalized communities (Borden et al. 2007; Cutter 1996; Cutter et al. 2008; Sapir and Lechat 1986; Wisner et al. 2012). We also selected these factors because the data are publicly available in the United States and relatively easy to access, thus permitting reproduction of our analytical framework in other contexts. In this study, we combined quantitative modeling and GIS to assess the spatial distribution of environmental vulnerability using census block groups as the geographic units of analysis. We considered two drivers of environmental vulnerability for this coastal environment: flooding and proximity to brownfields and hazardous waste.

To compute a Flood Vulnerability Index (FVI) in ArcGIS Pro (Version 10.3, manufactured by ESRI), we relied on U.S. FEMA flood zone classification and data from the National Flood Hazard Layer (NFHL), created and maintained by the U.S. Department of Homeland Security

(2016). One-hundred-year flood zones or Special Flood Hazard Areas have a high probability of flooding. Thus, census block groups marked Zone A or Zone V (and their variants) were assigned a FVI score of (3), the highest in our classification. Census block groups in five-hundred-year flood zones (labeled Zone B or Zone X) have a moderate risk of flooding, and were assigned a FVI of (2). Census block groups in Zone C that have minimal risk of flooding were assigned a FVI of (1).

We also computed a Hazardous Waste Proximity Index (HWPI) for each census block group in the city using data obtained from the Florida Brownfields Redevelopment Atlas (Center for Brownfields Research and Redevelopment 2020), which records the locations of documented brownfields and Superfund sites in the state and includes hazardous waste disposal permit data from the U.S. EPA Environmental Justice Screening Tool (U.S. Environmental Protection Agency 2016). These data indicated the proximity of block groups to hazardous waste sites in percentiles. We used quartiles to classify these percentiles and assigned a HWPI score for each census block group. In the end, the flooding and hazardous waste proximity indices were aggregated with equal weighting into an Environmental Vulnerability Index (EVI). While equal weighting makes sense in this case study (as indicated by simulations of different weights across the study area that produced similar results), this may not be the case in other places. Different weighting schemes may thus be appropriate elsewhere.

Social Vulnerability

In addition to the environmental conditions discussed previously, the susceptibility to harm or potential social disruptions posed by hazardous events at a particular location are created by socio-economic characteristics (e.g., age, gender, race, education, income, unemployment, housing, disability, and household size) that limit the ability of people in a particular place to respond and recover from hazards and disasters (Adger 2006; Borden et al. 2007; Cutter 1996; Cutter et al. 2003, 2008). Vulnerability studies have shown that impacts of these environmental hazards as well as infrastructure failures are also disproportionately located between social categories (Bjarnadottir et al. 2011; Sweeney 2006). Drawing on the social dimension of the place-based model (Cutter 1996), we evaluated the social vulnerability of census block groups in Tampa, in which we view social vulnerability as the disproportionate inability to respond and recover to environmental and infrastructural disruptions because of one's social position in society (see Clark et al. 1998; Wisner et al. 2012). Table 1 provides a summary of significant social factors used in our model that contribute to social vulnerability in Tampa.

Table 1. Social vulnerability variables

Variable	Source
Social Class %Households below Poverty Level %Less than High School Diploma Population per Acre	Adger (2006); Bjarnadottir et al. (2011); Cutter (1996); Cutter et al. (2008); Flanagan et al. (2011); Fothergill et al. (1999); Morrow (1999); Reid et al. (2009)
Household Composition & Sensitive Population Average Household Size %Population under 14 years %Population over 64 years %Population 20-64 with Disability	Clark et al. (1998); Cutter et al. (2003); Flanagan et al. (2011); Morrow (1999); Reid et al. (2009); Tate (2013)
Minority %Limited English-Speaking Households %Minority Race	Clark et al. (1998); Flanagan et al. (2011); Fothergill et al. (1999); Sweeney (2006)
Housing Tenure %Renter Occupied %Occupied Units %Multi-family Units	Borden et al. (2007); Clark et al. (1998); Deitz and Meehan (2019); Flanagan et al. (2011); Morrow (1999)

Quality of Life	Emrich (2005); Flanagan et al. (2011)
Travel Time to Work	
%Households with No Internet Access	

The data for these variables were obtained from the 2016 American Community Survey (with 2017-2019 updates) and the U.S. Census Bureau (2017). Some of the factors we considered are similar to those used by the University of South Carolina and the Centers for Disease Control and Prevention, which created social vulnerability indexes for the U.S. using 2010-2014 data at the county level. Similarly, we considered factors used by the Utility Resilience Index (URI) of the American Water Works Association (AWWA 2013), which examines vulnerabilities at the system level. For our index, however, we used the census block group as the geographic unit of analysis because block groups are smaller and more homogenous subdivisions of census tracts and provide a granular evaluation of social vulnerability in city neighborhoods (see Harlan et al. 2012). Our social vulnerability model consisted of 14 variables shown in Table 2. The descriptive statistics of the variables in Table 2 corresponded with recent U.S. census data on social class, household composition, race, and housing tenure in Tampa (U.S. Census Bureau 2017). Because none of the 14 variables were perfectly correlated, they were all included in our model. Some of the block groups were missing values for some variables; our model therefore considered 309 valid census block groups.

Table 2. Social vulnerability indicators for census block groups in the Tampa

Category/ Indicator	n	Mean	Std. Dev
Social Class			
%Households below Poverty Level (2016)	309	20.3	17.0
%Less than High School Diploma (2017)	310	8.9	7.4
Population per Acre (2016)	311	8.3	5.4
Household Composition & Sensitive Population			

Average Household Size (2016)	311	2.5	0.6
%Population under 14 years (2017)	310	17.3	9.5
%Population over 64 years (2016)	311	0.1	0.1
%Population 20-64 with Disability (2016)	311	11.7	9.1
Minority			
%Limited English-Speaking Households (2017)	309	7.1	9.7
%Minority Race (2017)	310	33.9	27.8
Housing Tenure			
%Renter Occupied (2017)	310	47.7	26.6
%Occupied Units (2017)	310	89.1	8.8
%Multi-family Units (2016)	309	30.2	31.5
Quality of Life			
Travel Time to Work (2017)	311	474.2	283.5
%Households with No Internet Access (2017)	309	20.5	17.8

Since social vulnerability is a latent variable, we used R-mode factor analysis (SPSS v. 25) to derive a Social Vulnerability Index (SVI) for each census block group. The factor analysis empirically reduced our large number of sociodemographic variables into a small set of linear components derived from a correlation matrix that explain a large proportion of the variation in the data, but also addressed the problem of multicollinearity. Such an approach is necessary for how we use the resulting factor scores, which is not possible with other statistical decomposition techniques. Using the Kaiser criterion, we retained four components with eigenvalues greater than 1. Each of the four component scores was weighted by the percentage of variance explained, then aggregated into a cumulative factor score. For ease of interpretation, the cumulative factor scores were grouped into quartiles, scored, and mapped with ArcGIS Pro (Version 10.3; manufactued by ESRI). Here, the higher the cumulative factor score, the higher the Social Vulnerability Index (SVI) score. The SVI data table was spatially mapped using block group IDs obtained from the US Census 2017 Tiger shapefile (U.S. Census Bureau 2017). By calculating the placement of each block group on the component distribution, it was possible to assess the vulnerability of a census block group relative to others. In hazards research, Borden et al. (2007), Reid et al. (2009), and Harlan et al. (2012) have used this type of factor analysis in a similar way to determine the social vulnerability of states, census tracts, and census block groups.

Infrastructure Vulnerability

Aging infrastructure, a warming climate, increasing population, and decreasing budgetary resources are some of the drivers of water insecurity in Tampa (Abdel-Mottaleb and Zhang 2020; Park et al. 2010). There are many ways of characterizing vulnerable water distribution network (WDN) components related to these challenges (Christodoulou and Fragiadakis 2015; Hernandez and Ormsbee 2021; Laucelli and Giustolisi 2015; Maiolo et al. 2018; Soldi et al. 2015; Wéber et al. 2020; Yazdani and Jeffrey 2012). In this study, we evaluated the hydraulic vulnerability of WDN segments based on how reachable a segment is to water sources when other segments are isolated. A segment is the minimum isolatable unit of a WDN that can contain several pipes or only part of a single or multiple pipes. Many end users reside along the pipes in a segment. When failures occur in WDNs, segments must be isolated (from water flow) for repairs to take place. An unintended isolation is when a segment is unintentionally isolated, resulting in the end users within it not receiving water, in the process of repairing another segment. In Tampa, many pipes in the network are severely aged, and there can be as many as 50 breaks in a single day (Tampa Bay Times 2019). For this reason, it is important to evaluate how vulnerable segments are to unintended isolation so that the unsupplied demands for end users can be minimized.

A vulnerability score for each segment is calculated from the reachability matrix of a given WDN as described in Abdel-Mottaleb and Walski (2020). First, segments are identified using WaterGEMS (Bentley Systems 2019). Then, the segment-valve (or dual) representation is constructed in python using the *networkx* package, where nodes are segments and edges are the valves that separate them. The reachability matrix (**R**) is constructed using python, with rows corresponding to isolated segments and columns corresponding to affected segments. Values are assigned to the matrix cells as follows. If an isolated segment (S_m) (row *m*) results in loss of connection of the segment S_n (column *n*) to any water source, a value of 2 is assigned to **R**[S_m, S_n]. If the isolation of S_m results in loss of connection of S_n to a reservoir but maintains a connection to a tank, a value of 1 is assigned to **R**[S_m, S_n]. If S_n is connected to the water reservoir regardless of S_m's isolation, a value of 0 is assigned. The existence of a connection, or flow path, between source(s) and segments is evaluated using the *has_path()* function in the *networkx* package. The sum of the values in column *n* is the vulnerability score of segment S_n, and indicates how vulnerable segment S_n is to other segments' isolation. For this study, the GIS data for the WDN model were provided by the City of Tampa. The City of Tampa Water Department is responsible for pumping 257,000 m^3/day of water through approximately 134,000 pipes to about 600,000 customers (Abdel-Mottaleb et al. 2019; Park et al. 2010). There is one reservoir in the network and five storage tanks. The WDN model was a skeletonized version of the field-validated model used by the city at the time of our research, consisting of 1978 segments and all isolation valves were assumed to be operable.

Census block group polygon features were overlaid with the segment line features, as shown in Fig. 2 so that the length of segments within given census block groups could be determined. The vulnerability score for a segment *i*, $S_{v,i}$, was weighed with the ratio of its length within a given census block, $L_{b,i}$, to its total length, L_i. The hydraulic vulnerability per polygon was calculated using the *summarize within* geoprocessing tool within GIS by aggregating the weighed vulnerability scores of the segments contained in the polygon according to equation 1, where *k* is the number of segments in a given census block. The higher the vulnerability scores of segments in a census block group, the higher the Hydraulic Vulnerability Index (HVI) score of that census block group.

$$HVI_b = \sum_{i=1}^{i=k} S_{v,i} \times \frac{L_{b,i}}{L_i} \qquad \text{Equation 1}$$

[insert Figure 2 here]

It is important to note that not all aspects of hydraulic vulnerability are accounted for or considered by this method since this study focuses on vulnerability due to the network configuration. Namely, this method does not consider the likelihood or consequence of failure, and implicitly assumes that all segments have an equal probability of failing (or being isolated). Finally, only one segment at a time was simulated as isolated. In reality, there could be different types of failures simultaneously in WDNs. These are model limitations that need to be considered in future research on our framework.

To account for infrastructure interdependencies that can lead to cascading failures, we evaluated the vulnerability of the potable water network based on its physical colocation with other infrastructure networks under the assumption that increasing colocation can contribute to the propagation of failure (but does not determine vulnerability). While this assumption may be generally appropriate for this study of a dense, urban environment, it may not be so for rural contexts where areas with lower levels of colocation could be equally or more vulnerable because of their greater difficulty to access in emergencies (Clar 2019). Our model considered four infrastructure networks: potable water, sewer, stormwater, and roads, all of which are completely separate systems in Tampa. All data were provided by our partners in the City of Tampa. The data layers for each infrastructure were imported into GIS and the multi-layer sets for a single infrastructure were merged (e.g., gravity and pressurized pipes). Each pair of infrastructures (line features) were intersected to provide point features indicating colocation between the pair of infrastructures. The six colocation point layers were merged into a single feature class, which was used to calculate the density of co-located infrastructures within each census block group. The point densities were then used to assign an Infrastructure Colocation Index (ICI), where census block groups with higher ICI were considered more vulnerable in the context of infrastructure interdependencies. However, it must be noted that, while this approach views infrastructure colocation as a vulnerability, the model does not provide a complete representation of the interdependencies between infrastructures. Moreover, this approach also does not take into account the potential impacts of weather-related events, such as roadway flooding, which can impede access to broken systems and therefore increase vulnerability (Wang et al. 2019). In the end, the hydraulic vulnerability and colocation indices were aggregated with equal weighting into a Water Infrastructure Vulnerability Index (WIVI).

Finally, we used the identified environmental and social vulnerabilities to compute an aggregate Vulnerability of Place Index (VPI), which allowed us to map the spatial distribution of combined environmental and social vulnerabilities across the city. Despite the breadth of scientific literature on placed-based vulnerability, many studies fail to consider the effect of the infrastructural vulnerability on the overall vulnerability of communities (see Borden et al. 2007; Cutter et al. 2003). We therefore sought to situate water infrastructure vulnerability within place-based models. This required a GIS intersect of the VPI and WIVI layers to identify highly vulnerable urban spaces within environmental, social, and infrastructural context.

Results and Discussion

Our quantitative models described previously yielded four main vulnerability indices, which we mapped in GIS. In this section, we discuss the Environmental Vulnerability Index (EVI), the Social Vulnerability Index (SVI), the Vulnerability of Place Index (VPI), and the Water Infrastructure Vulnerability Index (WIVI). We conclude with observations on the aggregation of VPI and WIVI layers.

Environmental Vulnerability Index (EVI)

Our assessment of environmental vulnerability considered the risk of flooding across the city. Our GIS model shows that the southeast parts of the city are highly vulnerable to flooding (Fig. 3). This region includes the area surrounding MacDill Air Force Base, Sun Bay South, Palma Ceia, and Davis Islands. We also found a high risk of flooding for neighborhoods such as Temple Crest, Sulphur Springs, Seminole Heights, and Tampa Heights, which are all situated along the Hillsborough River. Perhaps due to their proximity to the Lower Hillsborough Wilderness Preserve and surrounding wetlands, neighborhoods farther north such as Tampa Palms, New Tampa, and Pebble Creek were also highly vulnerable to flooding.

[insert Figure 3 here]

While the risk of flooding cuts across the city, we found that marginalized communities in eastern parts of the city were more vulnerable to the dangers posed by the proximity to hazardous waste sites compared to surrounding communities. As shown in Fig. 3, there was a distinct corridor of census block groups with high hazardous waste proximity and a higher number of brownfields running from the southeast to the northeast parts of Tampa. Our model suggests that the most affected neighborhoods in southeast Tampa were around the Port of Tampa Bay (with several Superfund sites), historic Ybor City (with several brownfields), and the historically Black community of East Tampa. Other neighborhoods farther north include Jackson Heights, Sulphur Springs, North Tampa, Temple Crest, and University Square — all low-income, predominantly Black or Hispanic communities. Within the context of flooding and proximity to hazardous waste sites, we found that the corridor running from the southeast to the northeast part of the city had more census block groups with a high Environmental Vulnerability Index. However, there are pockets of environmental vulnerability in Forest Hill and Carrollwood, both in the northwest of the city.

Social Vulnerability Index (SVI)

Our factor analytic model yielded four factors with eigenvalues greater than 1, which together accounted for approximately 66% of the variance for the 14 social vulnerability variables. As shown in Table 3, the first component accounted for 26.4% of the variability, and was strongly correlated with households below the poverty line, lower education levels, a high number of people living with disabilities, minority races, rental units, and households with no access to the internet. The second component correlated strongly with population characteristics (high population density, large household sizes, and multi-family housing units) and accounted for 16.5% of the variance. The last two factors accounted for 13.6% and 9.8% of the variance.

Table 3. Factor analysis of social vulnerability indicators

Variable	Component 1	2	3	4
% Variance Explained	(26.4)	(16.5)	(13.6)	(9.8)
	Factor Loadings			
Social Class				
%Households below Poverty Level (2016)	.877	-	-	-
%Less than Highschool Diploma (2017)	.548	-	-	-
Population per Acre (2016)	-	.411	-	-
Household Composition & Sensitive Population				
Average Household Size (2016)	-	.649	-	-
%Population under 14 years (2017)	-	-	.678	-
%Population over 64 years (2016)	-	-	-.685	-
%Population 20-64 with Disability (2016)	.686	-	-	-
Minority				
%Limited English-Speaking Households (2017)	-	-	-	.704
%Minority Race (2017)	.733	-	-	-
Housing Tenure				
%Renter Occupied (2017)	.669	-	-	-
%Occupied Units (2017)	-	-	-	.400
%Multi-family Units (2016)	-	.875	-	-
Quality of Life				
Travel Time to Work (2017)	-	-	-	.507
%Households with No Internet Access (2017)	.801	-	-	-

The component scores were weighted by variance and summed into a cumulative vulnerability score. The cumulative scores for the 309 valid block groups ranged between -63 to 131, with a mean of .2 and a median of -5. Based on standard deviation (36), skewness (.7), and kurtosis (.4), the vulnerability scores had a normal distribution. For ease of interpretation, the scores were re-coded into social vulnerability indices between 1-4, with (1) representing census block groups below the 25th percentile and (4) for those above the 75th percentile (Fig. 4).

[insert Figure 4 here]

As with environmental vulnerability, we found pockets of high social vulnerability in the eastern parts of the city and a few neighborhoods to the west. Some of the areas with high social vulnerability in the eastern parts of the city included Ybor City, East Tampa, Jackson Heights, Temple Crest, Sulphur Springs, and North Tampa. West and North Hyde Park, Drew Park, Plaza Terrace, and Old West Tampa were areas with high social vulnerability in the western parts of Tampa. The block groups with high ($\geq$4) indices (n=80) correspond to communities that have a majority of households living below the poverty level. These neighborhoods had a poverty rate of 46% or higher compared to the city's overall rate of 20%.

We observed that areas with a large proportion of minority races (68% or higher) also had high social vulnerability indices. The influence of race and class was no surprise, given the strong positive correlation with the first factor in our factor analysis results. More importantly, studies have shown that income and race/ethnicity significantly influence how people cope with and respond to environmental, social, and infrastructural disruptions (e.g., Borden et al. 2007; Cutter 1996; Cutter et al. 2003; Flanagan et al. 2011; Sweeney 2006).

Vulnerability of Place Index (VPI)

When taken together, environmental conditions and social makeup intersect to produce a distinctive corridor of high vulnerability in the eastern parts of the city (Fig. 5). The corridor begins in Ybor City, extends northward to the University Community area, and then west to neighborhoods around Nebraska Avenue. There is also a distinct pocket of high VPI around West and North Hyde Park, Drew Park, Plaza Terrace, and Old West Tampa in the northwest part of the city. Interestingly, these northwest parts are separated from the eastern corridor with a narrow band of low overall vulnerability.

[insert Figure 5 here]

Water Infrastructure Vulnerability Index (WIVI)

Whereas vulnerability of place (due to environmental and social conditions) shows an eastern and northwestern bias, the results in Fig. 6 reveal that vulnerability of water infrastructures is far less distinct. Besides the neighborhoods in the north-central part of the city, such as Sulphur Springs and Old Seminole Heights, block groups with high WIVI were mostly spread out in the southeast and southwest parts of the city. These included some parts of Ybor City, Tampa Heights, and North Hyde Park. The WIVI pattern was much like that observed from the distribution of infrastructure colocation indices.

[insert Figure 6 here]

Many of the block groups with high infrastructure colocation are in the southeast parts of the city (including East Tampa and Ybor City), Tampa Heights, Downtown Tampa, and Old West Tampa. The high ICI levels were expected in these densely built areas of the city (Ouyang 2014; Rinaldi et al. 2001). Because of the high ICI, water infrastructures in these areas are highly interdependent and vulnerable to cascading failures from transportation, stormwater, and wastewater infrastructures. However, the most hydraulically vulnerable census block groups regarding reachability to water sources are located in East Tampa, New Tampa, and near the Port of Tampa. They have the highest HVI values because there are non-redundant paths between these locations and the water sources. In addition, there is a lack of redundancy inherent within the census block groups of these locations. It is interesting to note that the same community could have census block groups with both high and low HVI values. This is likely due to the redundancies in connectivity being concentrated in certain census block groups over others. The census block groups with the lowest vulnerability scores are located in New Tampa, South Tampa, Downtown Tampa, Seminole Heights, and University Square.

Environmental, Social, and Water Infrastructure Vulnerabilities

To understand the spatial distribution of water infrastructure vulnerability within the environmental and social context, we aggregated the WIVI and VPI layers in GIS (Fig. 7), which enabled us to identify highly vulnerable areas across the city that were also highly susceptible to water infrastructure failures. The results indicate that 11% of the 309 census block groups had a high WIVI and High VPI. In other words, these block groups were environmentally and socially vulnerable and had a high risk of water infrastructure failure. These block groups were primarily in the eastern neighborhoods of the city, including North Tampa, Sulphur Springs, Old Seminole Heights, Terrace Park, and Temple Crest (to the north), and East Tampa and Ybor City (to the south). We did not find block groups with High WIVI and VPI in South Tampa and New Tampa.

[insert Figure 7 here]

The intersection of place vulnerability and water insecurity reveals three key insights about water infrastructure inequalities in marginalized communities in Tampa. First, residents in the eastern parts of the city are disproportionately susceptible to the impacts of environmental hazards. Although the risk of flooding has a northwest and southeast bias, the proximity to brownfields and sites producing hazardous wastes contributes to the overall environmental vulnerability of the neighborhoods in the eastern part of the city, which represent predominantly low-income Black communities. The unequal distribution of environmental risks reveal long-standing environmental injustices where studies have shown that people of color in low-income communities often bear the greatest burden when it comes to environmental pollution and contamination (Mohai et al. 2009).

Second, we find that social vulnerability was unequally distributed in the eastern and western areas of the city, which consist of neighborhoods that have been racially segregated following the passing of segregation laws in the late 19th century. One such community is Sulphur Springs, which also has a high level of environmental vulnerability. Although it was once a tourist hub for visitors across the city and state, years of racial segregation and out-migration of wealthy residents in the 1980s turned it into a minority and low-income neighborhood (Jackson 2020). Other areas that have been racially segregated and have a high degree of social vulnerability include West Tampa, West Hyde Park, East Tampa, and Ybor City. Studies have shown that federal housing policies such as Section 8 assistance and the Hope VI project concentrated low-income residents and people of color in these racially segregated communities (Greenbaum et al. 2008).

Third, our study finds that the overall risk of communities becoming disconnected from water sources in events that require segment isolation (e.g., pipe maintenance, failure, repair, and replacement) is lower in socially vulnerable areas. Environmental and social conditions in Tampa intersect with water infrastructure vulnerabilities to create pockets of infrastructure inequality. In other words, residents in environmentally and socially vulnerable areas such as Sulphur Springs, North Tampa, North Hyde Park, West Tampa, Old Seminole Heights, Terrace Park, Temple Crest, East Tampa, and Ybor City are predisposed to the impacts of segment isolation and potential cascading failures from co-location interdependencies. Densely built areas of the city potentially have highly interdependent infrastructures and are more susceptible to cascading failures. Therefore, addressing water infrastructure inequality in Tampa requires attention to infrastructure interdependencies in the densely built areas of the city.

Finally, given the age of the city's water distribution network and years of underinvestment in new water infrastructure, high hydraulic vulnerability might be expected in the oldest neighborhoods of the city. However, due to the high level of redundancies compared to surrounding areas, the results of our hydraulic vulnerability model indicate that some of the oldest communities are less vulnerable to disconnection from water sources in events of segment isolation. In the future, infrastructure improvement efforts should pay close attention to environmentally and socially vulnerable neighborhoods that also have high water infrastructure vulnerability (identified in Fig. 7). At the time of this study, for example, the city began planning for an infrastructure renewal initiative called Progressive Infrastructure Planning to Ensure Sustainability (PIPES, https://www.tampagov.net/initiatives/pipes), which includes creation of a $2.9 billion, 20-year plan to upgrade water and sewer infrastructures (WFTS 2019). Through our National Science Foundation CRISP ("Critical Resilient Interdependent Infrastructure Systems and Processes") project, which supported the research for this study, we are working with the city's water department to share the results of our simulations and modeling with the goal of informing their capital improvement plan, especially as it relates to the city's underserved communities.

Conclusion

Mapping water infrastructure inequalities within environmental and social contexts is crucial for assisting stakeholders in prioritizing resources by identifying areas of low resilience. Our study adds to the growing body of work on environmental and social injustice by showing how the unequal distribution of water infrastructure vulnerability is linked to race, social class, and environmental hazards. The framework we use examines environmental hazards with GIS and uses a factor analytic approach with weighted component scores for computing a cumulative vulnerability score to account for the varied contributions of different variables to social vulnerability in each community. The framework also draws on network analysis of a water distribution network to evaluate the reachability to water sources under failure scenarios to assess vulnerability and uses GIS to examine the physical colocation of infrastructures to identify interdependencies. Taken together, these analyses provide a reproducible, geospatial vulnerability framework that quantifies and maps environmental, social, and infrastructure vulnerability to identify water infrastructure inequality in marginalized urban communities, which can be utilized in the development of a community's capital improvement and asset management plans.

Data Availability Statement

All data, models, and code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

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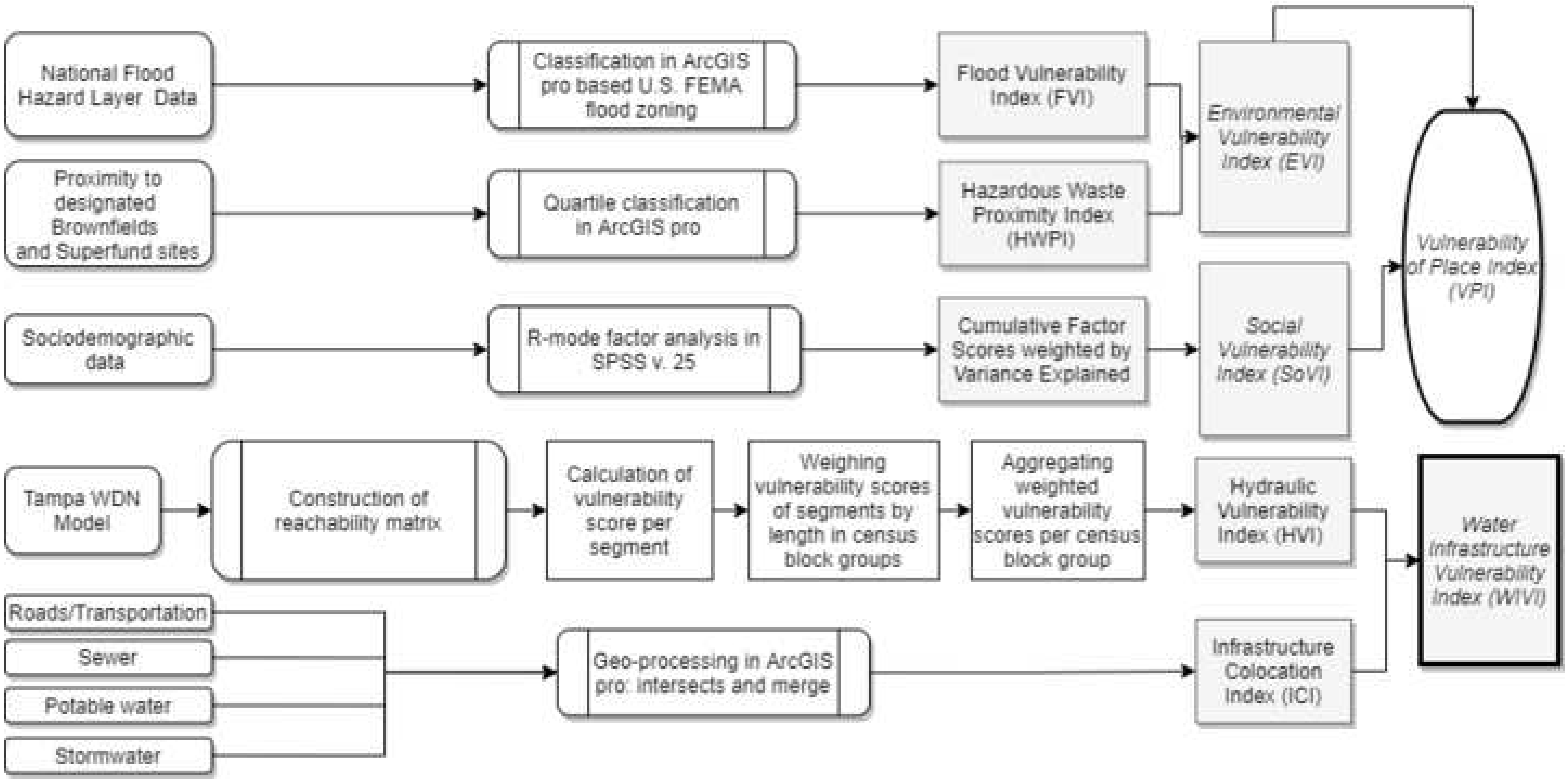

Figure

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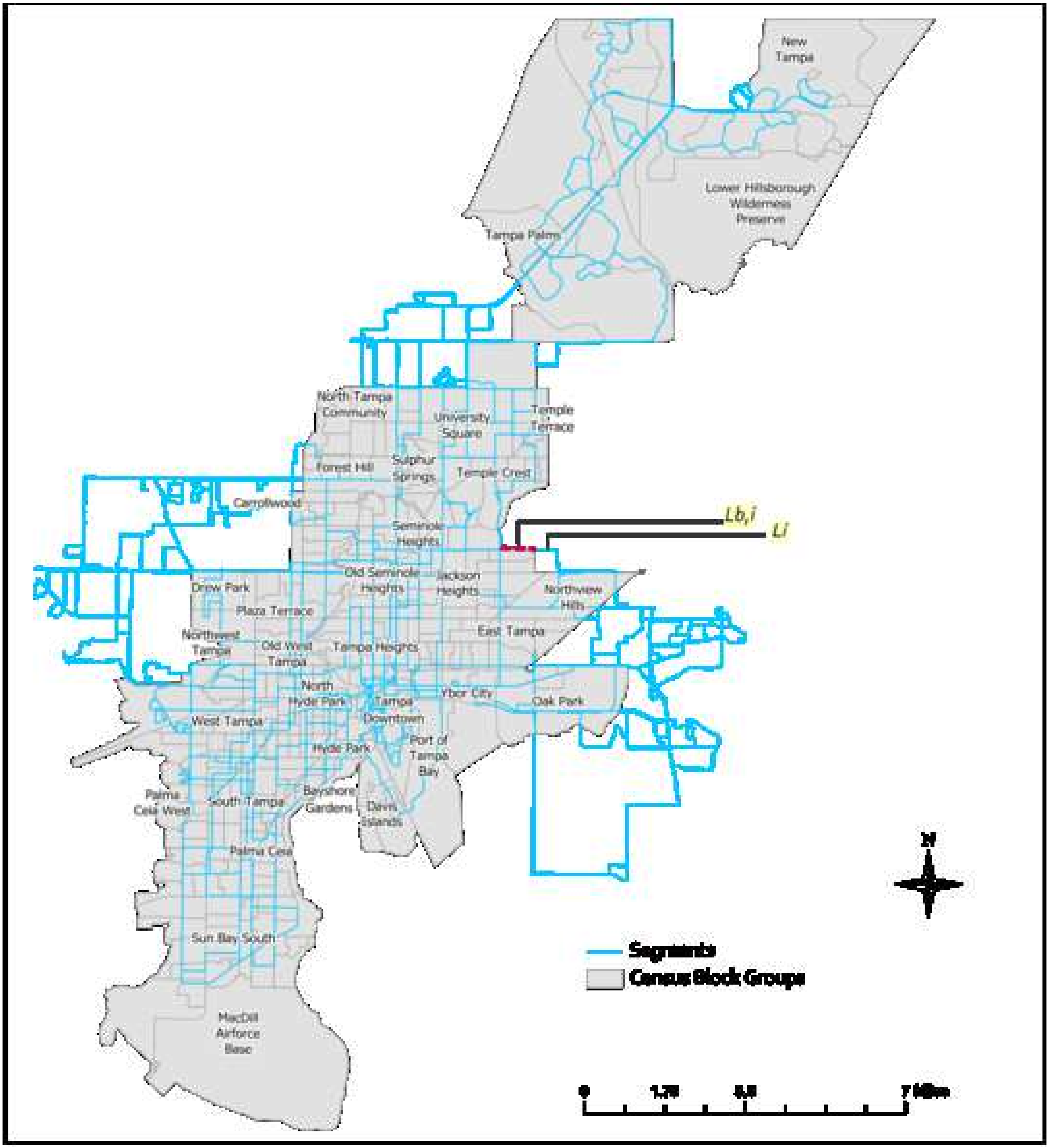

Figure

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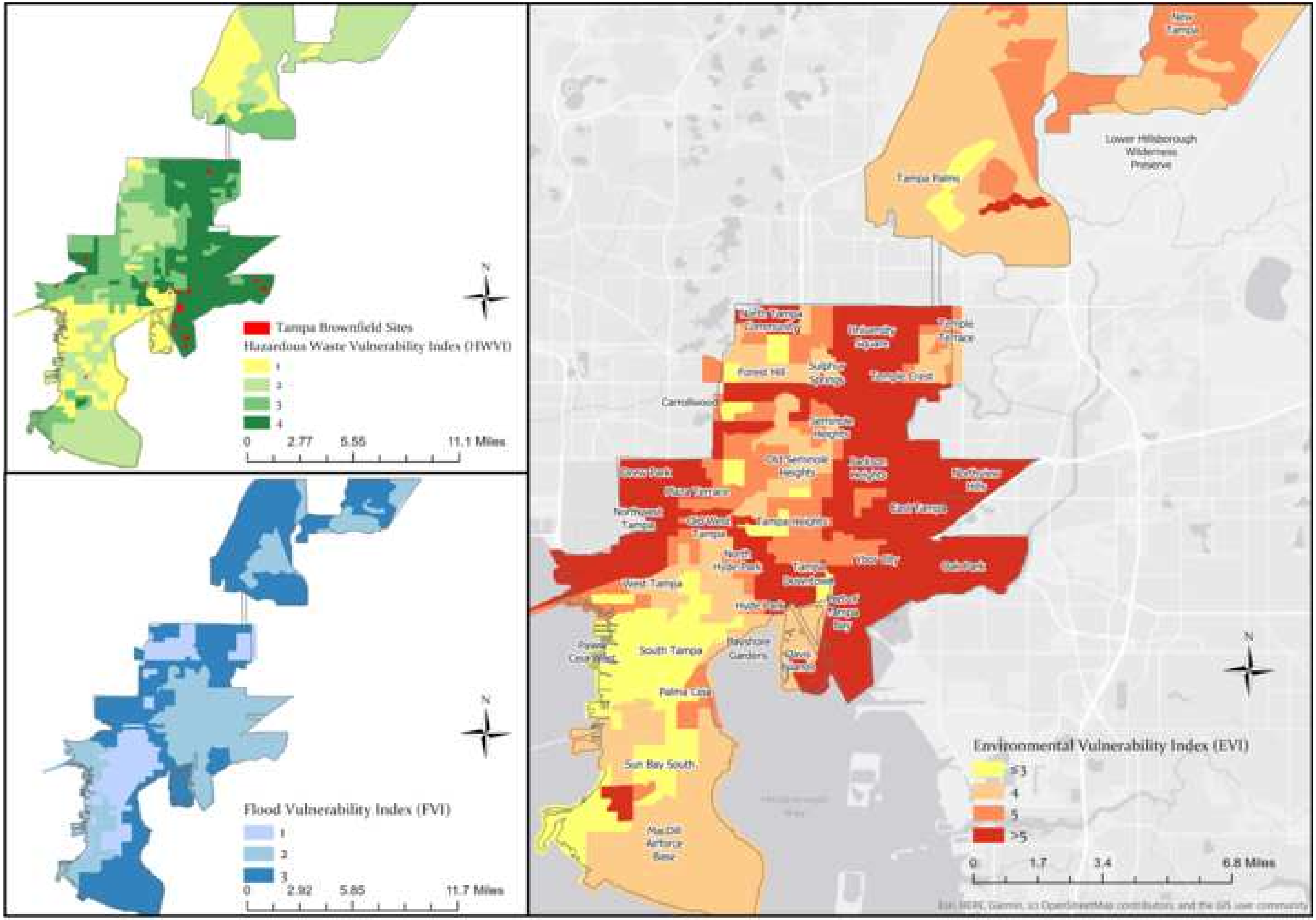
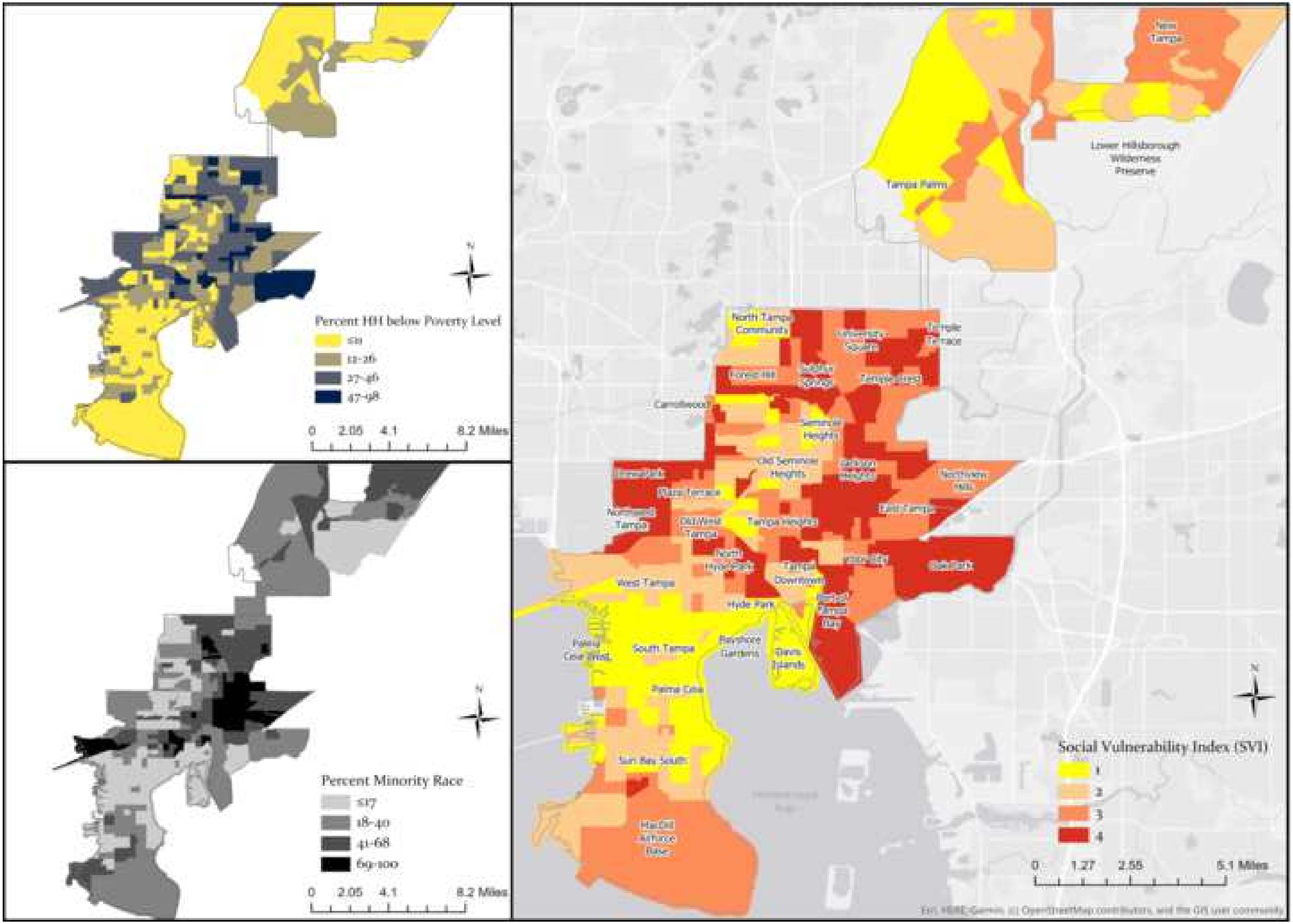
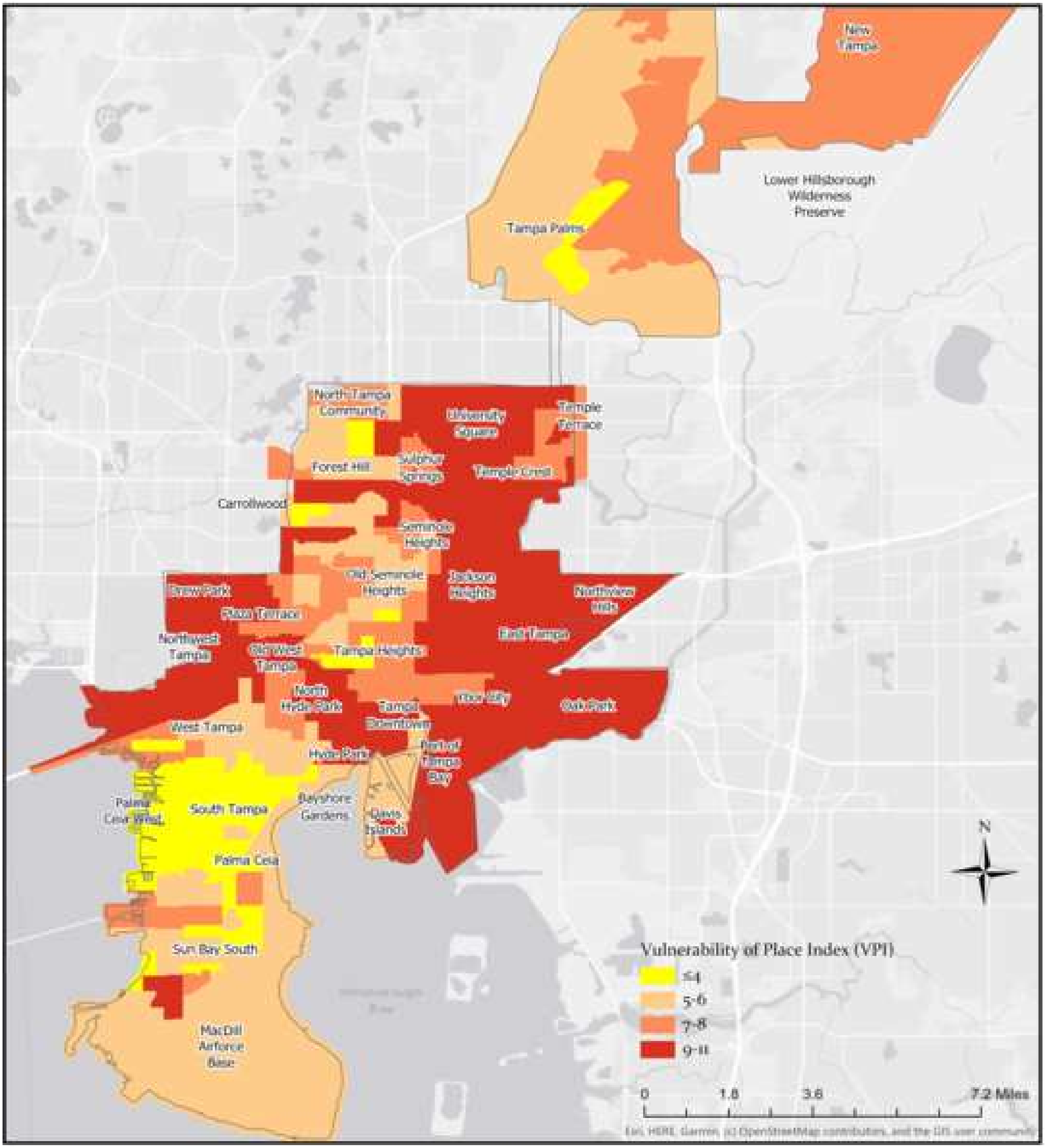



Percent HH below Poverty Level
≤11
12-26
27-46
47-98
0 2.05 4.1 8.2 Miles
Percent Minority Race
≤17
18-40
41-68
69-100
0 2.05 4.1 8.2 Miles
New Tampa
Lower Hillsborough Wilderness Preserve
Tampa Palms
North Tampa Community
University Square
Temple Terrace
Forest Hill
Sulphur Springs
Temple Crest
Carrollwood
Seminole Heights
Old Seminole Heights
Jackson Heights
Northview Hills
Drew Park
Plaza Terrace
Northwest Tampa
East Tampa
Old West Tampa
Tampa Heights
North Hyde Park
Tampa Downtown
Ybor City
Oak Park
West Tampa
Hyde Park
Port of Tampa Bay
Palma Ceia West
South Tampa
Bayshore Gardens
Davis Islands
Palma Ceia
Sun Bay South
MacDill Airforce Base
Social Vulnerability Index (SVI)
1
2
3
4
0 1.27 2.55 5.1 Miles

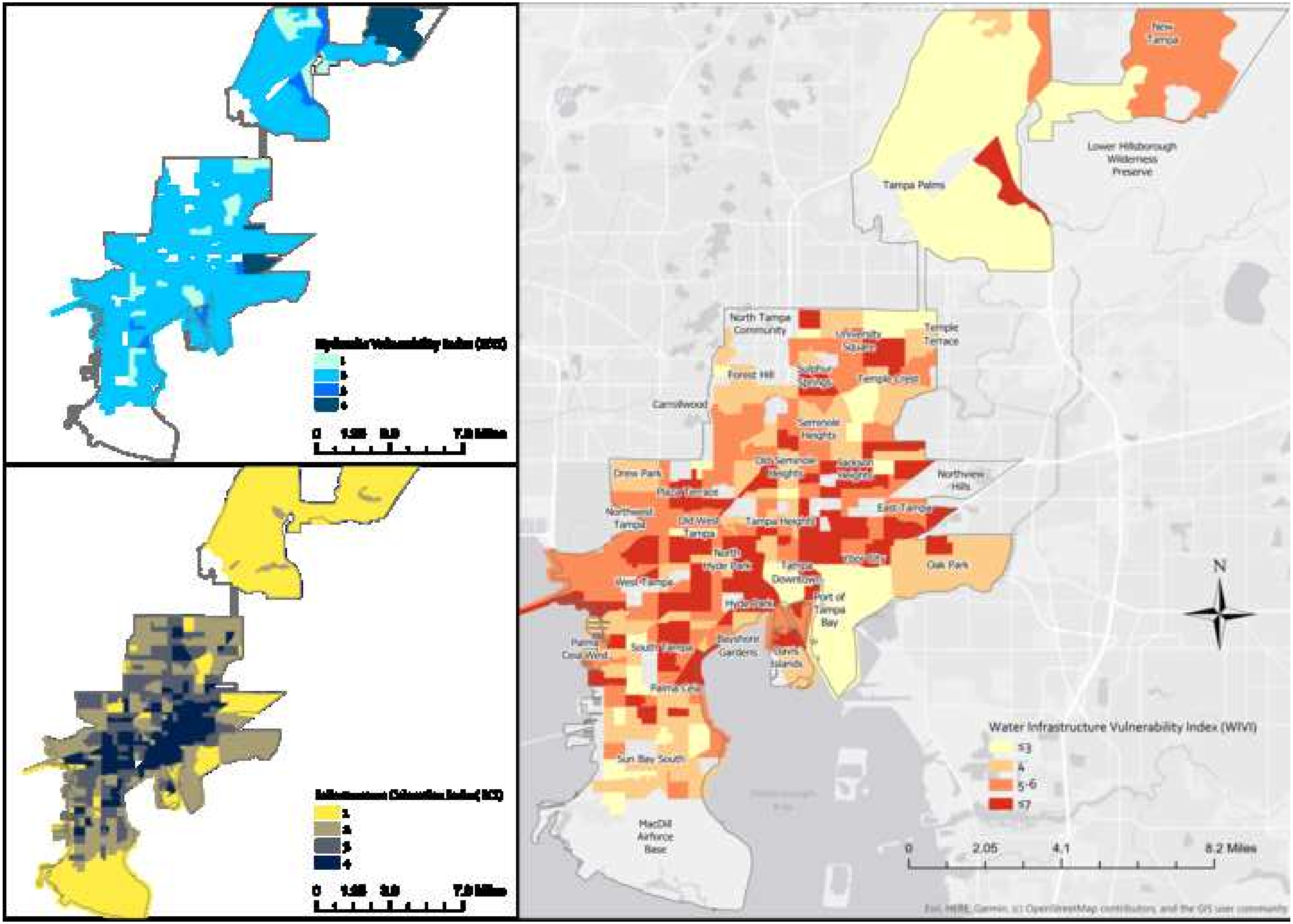
Figure

Click here to access/download;Figure;FIG 5.tif



Figure

Click here to access/download;Figure;FIG 6.tif



Figure

Click here to access/download;Figure;FIG 7.tif