Sponge City for whom? A categorization model combining flood and social vulnerabilities

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1. Introduction [BX]

China's rapid urbanization since the late 1970s transformed a sheer volume of the natural landscape into impermeable surfaces, resulting in prevalent problems in many cities' urban water systems (Chan et al., 2018, p. 773; Guan, Wang, & Xiao, 2021, p. 2; Jia, Wang, Zhen, Clar, & Yu, 2017, p. 1; Liu, Jia, & Niu, 2017, p. 1). In 2015, the central government initiated the Sponge City program to tackle these issues, particularly the flooding risks in urban centers (the General Office of the State Council, 2015). (Yu, 2016) After being tested in more than 30 pilot cities (Ministry of Finance, Ministry of Housing and Urban-Rural Development, & Ministry of Water Resources, 2015, 2016), this top-down program became a national policy and cost billions of dollars. However, acknowledging the political ambition to improve urban water management, researchers expressed concerns about this sensational movement. Environmentalists evaluated some Sponge Cities' hydrological performance, criticizing the program's competency in addressing extreme floods while confirming its contribution to stormwater management (Leng et al., 2020, p. 13; Q. Li et al., 2019, p. 18; Mei et al., 2018, p. 1406). Scholars also pointed out the potential implementation challenges from technical, planning, financial, governance, and monitoring perspectives (Jiang, Zevenbergen, & Fu, 2017, p. 524; Nguyen et al., 2019, pp. 157, 158).

Regardless of the environmental and economic obstacles discussed in the existing literature, a recent flooding disaster raised attention to justify the Sponge City program from the neglected social perspective. On July 20th, 2021, a record-breaking flood hit Zhengzhou, the capital city of Henan Province, and caused 293 deaths and economic losses of about 18 billion USD (U.S. dollars) (Chan, Chen, Gu, Peng, & Sang, 2021, p. 99). Ironically, as one of the pilot Sponge Cities in Henan, Zhengzhou had invested more than 8.25 billion USD in Sponge City planning and construction prior to the hazard (Chan et al., 2021, p. 99). The current Zhengzhou Sponge City Plan (Zhengzhou Urban and Rural Planning Department, China Academy of Urban Planning and Design, & Zhengzhou Urban Planning Design & Survey Research Institute, 2017) focuses on flood vulnerability by building hydrological models to achieve the city-level stormwater management benchmarks. Nevertheless, Sponge Cities must be planned and evaluated from multiple perspectives, not limited to the hydrological assessment of drainage performance (Nguyen, Ngo, Guo, & Wang, 2020, p. 5). Considerations of Zhengzhou's demographic disparity are limited – neither social vulnerability nor community differences were integrated into the existing Sponge City plan. The deaths and losses in the Zhengzhou flood disaster cast doubts on Sponge City from the social perspective: For whom is Sponge City planned and constructed?

More specifically, how could planners incorporate the social dimension into Sponge City plans to prioritize the vulnerable communities? To answer such a question, this Zhengzhou-based research aims to (1) identify the flood vulnerability and social vulnerability in the city with accessible geospatial datasets, (2) train a clustering model to categorize all neighborhoods by flood risk and social characteristics, and (3) build an interactive toolkit to help planners to develop ad hoc strategies for various community types.

This research contributes to existing Sponge City research and practices for multiple groups of participants. For researchers, it fills the gap in social considerations of Sponge City and explores the application of the multivariate clustering method. For policymakers, this study depicts the city's flood and social vulnerabilities so that policy and investment allocation can prioritize the most at-risk neighborhoods. For planners, the interactive toolkit visualizes each community's social and physical conditions, providing designers with nuanced details and helping them draft equitable Sponge City plans.

2. Literature Review [BX]

Since being promoted as a national strategy in China, Sponge City has drawn increasing research interest from thousands of authors and scholars (Zha et al., 2021, p. 4). (Yu, 2016) Given the deep engagement of China's political system in the Sponge City program, this topic quickly stood out in the late 2010s from its counterpart concepts in other regions, including Low Impact Development (LID) and Best Management Practice (BMP) in North America, Sustainable Urban Drainage System (SUDS) in the United Kingdom, and Water Sensitive Urban Design (WSUD) in Australia (Griffiths, Chan, Shao, Zhu, & Higgitt, 2020, p. 2). Existing Sponge City literature was largely published by water scientists, with Storm Water Management Model (SWMM), stormwater management, stormwater, runoff, and green infrastructure as the most frequently used keywords (Zha et al., 2021, p. 10).

From a concept to a nationwide movement, Sponge City arose out of China's urban water management context and was promoted by milestone policies and practices. Back in the early 2010s, the increasing flooding hazards raised public attention to the urban stormwater management system in many cities. The ubiquitous urban flooding issues resulted from two reasons – China's rapid urban expansion and cities' over-reliance on gray infrastructure for drainage. Since the Reform and Opening Up in 1978, millions of rural inhabitants migrated to cities, driving substantial urban expansion and land changes from permeable landscapes to concrete surfaces (Campanella, 2012; Miller, 2012). Over the decades of rapid urbanization, cities favored engineering mindsets and built many infrastructural projects, including the prevalent construction of concrete drainage and sewer systems (Jiang, 2015, p. 110). Such context, in addition to the increasing extreme climate events caused by global warming, resulted in the outbreak of urban water issues in many Chinese cities.

Therefore, Sponge City took center stage as a national policy, demonstrated by pilot projects across the country, to manage urban stormwater and alleviate flooding risks by converting the conventional engineering approach to an ecological approach (Jiang, Zevenbergen, & Ma, 2018, p. 141; F. Li & Zhang, 2022, p. 1645; Ma, Jiang, & Swallow, 2020, p. 2). At the first Central Government Urbanization Conference (December 13th, 2013), President Xi advocated for "building Sponge Cities of natural stormwater storage, infiltration, and treatment" (CCTV.com, 2017). The central ministries and State Council pushed forward the concept by releasing construction guidelines and guiding opinions in 2014 and 2015 (Ministry of Housing and Urban-Rural Development, 2014; the General Office of the State Council, 2015). The Ministry of Finance later selected 30 pilot cities (16 in 2015 and 14 in 2016) and subsidized each from 57 to 85 million USD per year for Sponge City planning and construction (Griffiths et al., 2020, p. 3; Ministry of Finance et al., 2015, 2016). The program kept growing in 2021 and 2022 when the central ministries called for more pilot cities to move forward with Sponge City as a systematic strategy for all the jurisdictional areas rather than a demonstration technique for some scattered projects (Ministry of Finance, Ministry of Housing and Urban-Rural Development, & Ministry of Water Resources, 2021, 2022).

Admitting the opportunities brought by the Sponge City program to pursue long-term sustainability, researchers are also concerned about the potential obstacles from multiple perspectives. According to existing literature, Sponge City's challenges reside in technical constraints, financial burden, organizational ambiguity, public acceptance, and so on (Jiang et al., 2017; Jiang et al., 2018; F. Li & Zhang, 2022; H. Li, Ding, Ren, Li, & Wang, 2017; H. Wang, Mei, Liu, & Shao, 2018; Xia et al., 2017). Technical capability appears as the most challenging obstacle due to the lack of Sponge City knowledge, ranging from hydrological modeling, planning method, and building techniques to post-construction monitoring and evaluation. Merely relying on the central government's financial support is insufficient to cover the enormous cost. As the top-down policy moves from the central government to local municipalities, each local department's role in Sponge City planning, construction, and management is not clear. The doubtful public perception of this ambitious but costly program is also worth concern.

Scholars conducted diverse research in response to these potential Sponge City challenges. Based on the Storm Water Management Model (SWMM), existing publications focused on quantitative evaluations and hydrological simulations to provide technical support for Sponge City practices. Some water scientists shed light on constructing a comprehensive assessment framework (Leng et al., 2020; Q. Li et al., 2019; Luan et al., 2019; Mei et al., 2018), whereas others contributed by simulating real-world cases (Cheng, Qin, Fu, & He, 2020; Hu, Zhang, Li, Yang, & Tanaka, 2019; Randall, Sun, Zhang, & Jensen, 2019; Rong et al., 2021). Economists investigated the current Sponge City funding difficulties (X. Liang, 2018; Zhang, Sun, & Xue, 2019), which political scientists further explained through their examinations of the governance factors and trans-jurisdictional management (Qiao, Liao, & Randrup, 2020; Qiao, Liu, Kristoffersson, & Randrup, 2019; Xiong et al., 2021). Public perception of this nationwide program was also studied through qualitative surveys (Ding, Ren, Gu, & Che, 2019; Y. Wang, Cai, Zuo, Bartsch, & Huang, 2021; Y. Wang, Liu, Huang, Zuo, & Rameezdeen, 2020).

However, existing literature lacks explorations of Sponge City's social dimension. Notwithstanding Sponge City's goal to alleviate *urban flooding*, current practice and research over-emphasized the noun *flooding* and neglected the adjective *urban*. The program's scope differs from that in non-settlement areas, and the main objective is to prevent flooding events from damaging the welfare of cities and communities. Cities are agglomerations of diverse communities whose vulnerabilities to flooding events are subject to urban form, physical condition, population density, demographic profile, and so on. When extreme weather events hit cities, prioritizing and protecting the most vulnerable neighborhoods is the bottom line. Unfortunately, as Sponge City practitioners were improving the complexity and accuracy of hydrologic models, such a social dimension was hardly taken into consideration. Therefore, this paper calls for attention to the issue of not incorporating social vulnerability in Sponge City plans. The social gap is also where this research fits in the existing literature.

3. Materials and Methods [BX+HG]

3.1. Study Area (Zhengzhou) [BX]

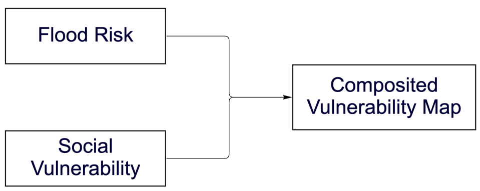
To explore the Sponge City program's potential social contribution, this study specifies the study area in Zhengzhou, the capital city of Henan Province, with complex hydrologic conditions and a large urban population in China's Central Plain area. Before modernization, Zhengzhou was a historic settlement where the past inhabitants were involved in agricultural production for more than 3000 years. Today, 10.08 million people lived in Zhengzhou's urban areas by the end of 2021, whereas the urban population was only 1.42 million in 1978. Millenniums of crop cultivation and decades of drastic expansion of built-up areas resulted in the co-existence of hydrologic challenges of water shortage, drought, and flood simultaneously in Zhengzhou, like many other cities in central China. Limited precipitation (491.2mm in 2018) and excessive groundwater exploitation (160km^2 funnel) directly led to water shortage (Zheng, Duan, & Lu, 2021, p. 2). Meanwhile, urban flooding has been threatening the city increasingly in recent years due to Zhengzhou's unique geographic condition, intense precipitation in summer, and limited underground drainage infrastructure. Zhengzhou is located about 30km away from the Yellow River downstream, yet its stormwater drains through the Jialu tributary to the Huai River, meaning that the city can be easily affected by Yellow River floods while its drainage capacity is limited in the flat Huai Watershed. Zhengzhou's precipitation distributes unevenly across the year, with nearly 70% of annual rainfall concentrated from July to September (Dong, Zhang, & Li, 2019, p. 3; Lv, Guan, & Meng, 2020, p. 1825; Wu, Shen, & Wang, 2019, p. 3).

Therefore, Zhengzhou designated about 25.70% of its administrative area near the center city for Sponge City construction to mitigate the urban water issues. This 1,945km^2 land is also this research's study area, where both gray and green infrastructure were planned. The city proposed to renovate the aging sewage system, including 160km of pipes built before 2000 and 360km of pipes built between 2000 and 2010. Planned or constructed green infrastructural projects include floodways, sponge parks, riverfront buffers, and stormwater gardens in residential units. The Zhengzhou government manages these projects based on city-scale and community-scale benchmarks. At the city scale, the three benchmarks are that (1) more than 75% of annual rainfall shall be captured, (2) more than 50% of non-point source pollution shall be treated, and (3) more than 5% of stormwater shall be harvested and reused. Planners then simulate SWMM (Storm Water Management Models) and convert the three city-scale benchmarks to four community-scale indicators, including (1) sunken green space coverage and depth, (2) permeable pavement percentage, (3) green roof coverage, and (4) the capacity of retention facilities. The community-scale indicators vary by neighborhood depending on building density, open space coverage, land use, and (built-up status?). To meet the benchmarks, designers can refer to the Sponge City Facility Catalog and work on specific projects such as building and neighborhood, urban road, green space and plaza, and urban water system.

Zhengzhou's current Sponge City planning approach shows a prevalent disadvantage: policymakers determine each community's plan merely based on flood risk through the perspective of natural and built conditions. According to Sponge City Plan, planners regulated the standards geospatially and adjusted the designated community-level benchmarks based on the land-use plan and the SWMM-simulated map. The inputs range from elevation to slope, stream pattern, land cover, sewage location, proposed land-use, and so on, though specific information is not publicly available. Such a decision-making process omits the diversity of neighborhoods and assumes that all community members are equally vulnerable to flooding risks. Therefore, this research proposes a categorization model combining flood risk and social vulnerability to address the disadvantage of the current planning approach.

3.2. Data and Method [HG]

3.2.1 Identifying composited Vulnerability area



In addition to flood risks, I incorporated the social vulnerability to come up with the composited vulnerability map. It will prioritize the vulnerable area and help to revise the current sponge city plan. The first part of this study is flood risk map, and the second part is social vulnerability map. The composited map was overlayed by flood risk map and social vulnerability map after standardizing.

1) FLOOD RISK

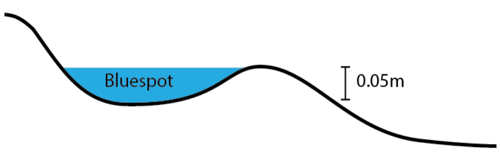


Figure 1 Blue Spot Diagram

The input data for flood risk is 1/3rd arc-second Digital Elevation Models[1] and Sentinel-2 Land Cover [2].
With the hydrology tool in ArcGIS, I included four factors to calculate the flood risk map.

Table 1. Flood Risk Factors

Factor	Description	Unit	Data
Slope	Slope of terrain	Degree	DEM
Stream	Distance to stream	m	DEM
Blue spot	Distance to blue spot	m	DEM
Impervious Surface	Impervious or pervious surface	0/1	Landcover

Stream feature was calculated by streamlink tool by ArcGIS, and Euclidean distance Tool was used to have distance to stream. Blue spot is defined as a landscape depression with over certain depth.[3] It is not necessarily close to stream or at the low point. I use 5cm as the threshold to define the blue spot. For impervious surface, I reclassified the landcover data with developed area as 1, and undeveloped area as 0.
With four factors' results prepared, I standardized each layer by reclassifying them from 1 to 10. Lastly, I used Raster Calculator tool to overlay and calculate the mean value for each pixel.

2) SOCIAL VULNERABILITY

[1] https://www.sciencebase.gov/catalog/item/4f70aa9fe4b058caae3f8de5
[2] https://www.arcgis.com/apps/instant/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2
[3] https://storymaps.arcgis.com/stories/bc7fdca84e6c48c08e24b951da374c42

Every community must prepare for and respond to hazardous events like flood events. A number of factors may weaken a community's ability to prevent human suffering and financial loss in a disaster and these factors are known as **social vulnerability**.

Consolidating the features and methodology from the CDC Social Vulnerability Index (SoVI) model

Table 2. Social Vulnerability Data Resources and types

Categories	Index	Unit	+/- Vulnerability	Data Resource
Population Composition	Age <14	%	+	6th National Census
	Age >65	%	+	
	Population	pp	+	
	Female ratio	%	+	
	Non-transient People Ratio	%	-	
	Tertiary Industry Employment ratio	%	-	2020 yearbook
	Primary Industry Employment ratio	%	+	
Socioeconomics	GDP per capita	10,000 ¥/ pp	-	
	Disposable personal annual income			
Medical Condition	Medical technician / 1000 people	pp / 1000 people	-	
Living Condition	Housing price	¥/m^2	-	lianjia.com

and based on Disaster Vulnerability Definition in China context from Lufu Zeng's article, I decided to utilize 11 factors, in four categories to indicate the social vulnerability. Due to the lack of data in living condition and accessibility to facilities, I extracted housing price using python from the most prevalent real estate website lianjia.com and use IDW tool to specialize on the map. Since housing price indicates most part of living condition, I increase its significance and double the weight. Except for that, all the other factors have the same weight.

3) COMPOSITED VULNERABILITY MAP

With flood risk and social vulnerability map, we are ready to have the composited vulnerability map by standardizing them from 1 to 10 and using raster calculator to have the mean value for each pixel.

3.2.2 Categorization

Zhengzhou's urban fabric and land use, especially city center is quite uniformed. Thus, it is very likely that planners consider the city center as a whole and overlook the feature of neighborhood. In order to use community feature to define the neighborhood typology, the second part of my research is to do the neighborhood clustering. There are two benefits to do the neighborhood clustering: 1) The first one is to help to differentiate the nuances among the communities. 2) If a designer has many successful hands-on experiences and wants to implement it into a similar neighborhood. This methodology will help to find a similar neighborhood and it's also of significance for improving typological design.

I decided to use K-Means Algorithm to categorize the neighborhood. K-Means Algorithm is an unsupervised clustering algorithm with machine learning. It will look for a solution where all the features within each cluster are as similar as possible in all the clusters themselves are as different as possible. [4] I use neighborhood unit from current Sponge City Plan and utilize points of interest, physical condition, land use mix, social vulnerability, flood risk, plus existing Sponge city planning target as the analysis fields parameter.

Table 3. K-Means Clustering Feature

Categories	Index	Unit	Data Resource
Points of Interest	Culture Asset	Number	PKU Open Research Data Platform [5]
	Plaza	Number	
	School	Number	
	Medical Place	Number	
	Train Station	Number	
	Subway Station	Number	
	Senior Care Center	Number	
	Bus Station	Number	
Physical Condition	Tall Building ratio	%	Third Party Data Platform
	Building Footprint Area ratio	%	
	Green Coverage ratio	%	NDVI
Land use	Residential land use ratio	%	Zhengzhou Land use Plan (2008-2020)
	Commercial land use ratio	%	
Vulnerability	Social Vulnerability	Score (1/10)	From 3.2.1
	Flood Risk	Score (1/10)	

4. Results [HG]

4.1. Maps [HG]

4.1.1 Composited Vulnerability Map

1) FLOOD RISK

[4] https://pro.arcgis.com/en/pro-app/2.8/tool-reference/spatial-statistics/how-multivariate-clustering-works.htm

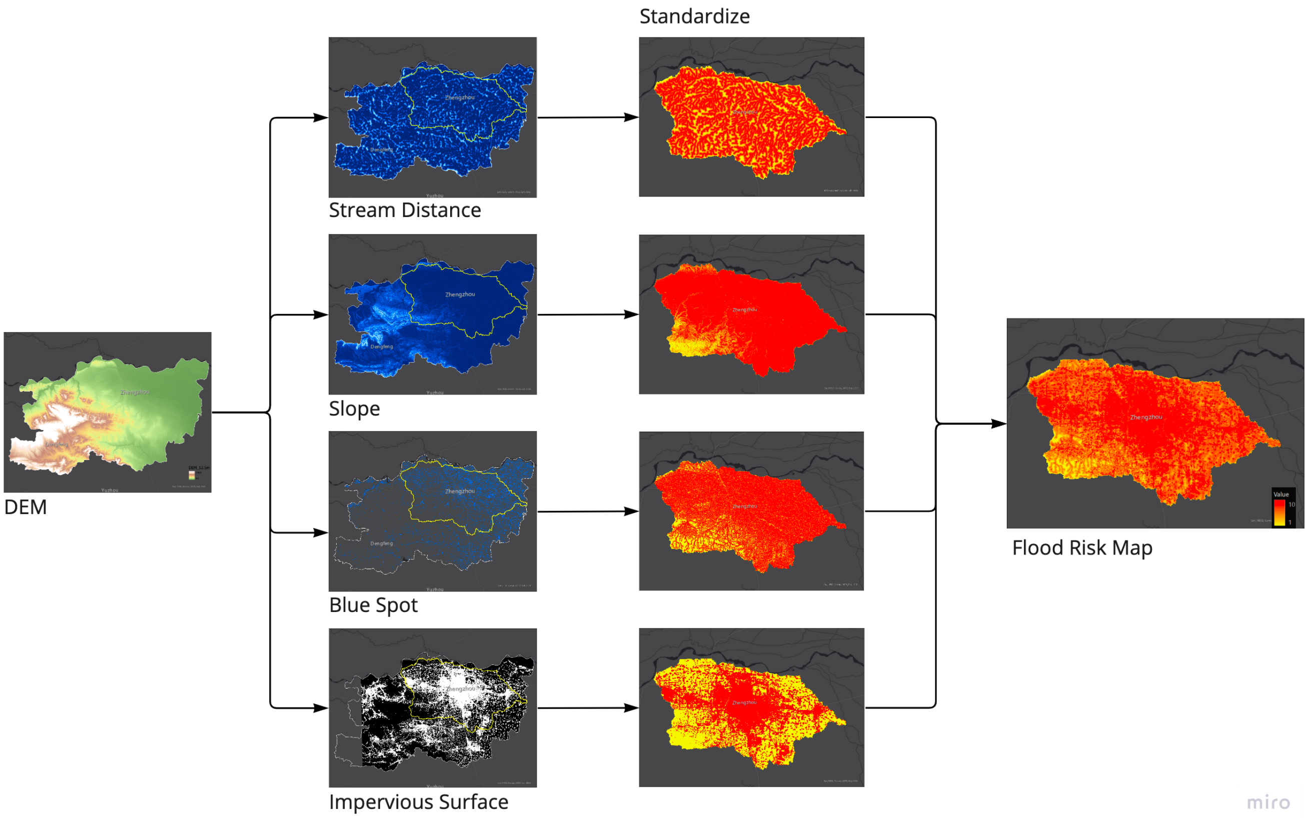


Figure 2 Flood risk

2) SOCIAL VULNERABILITY

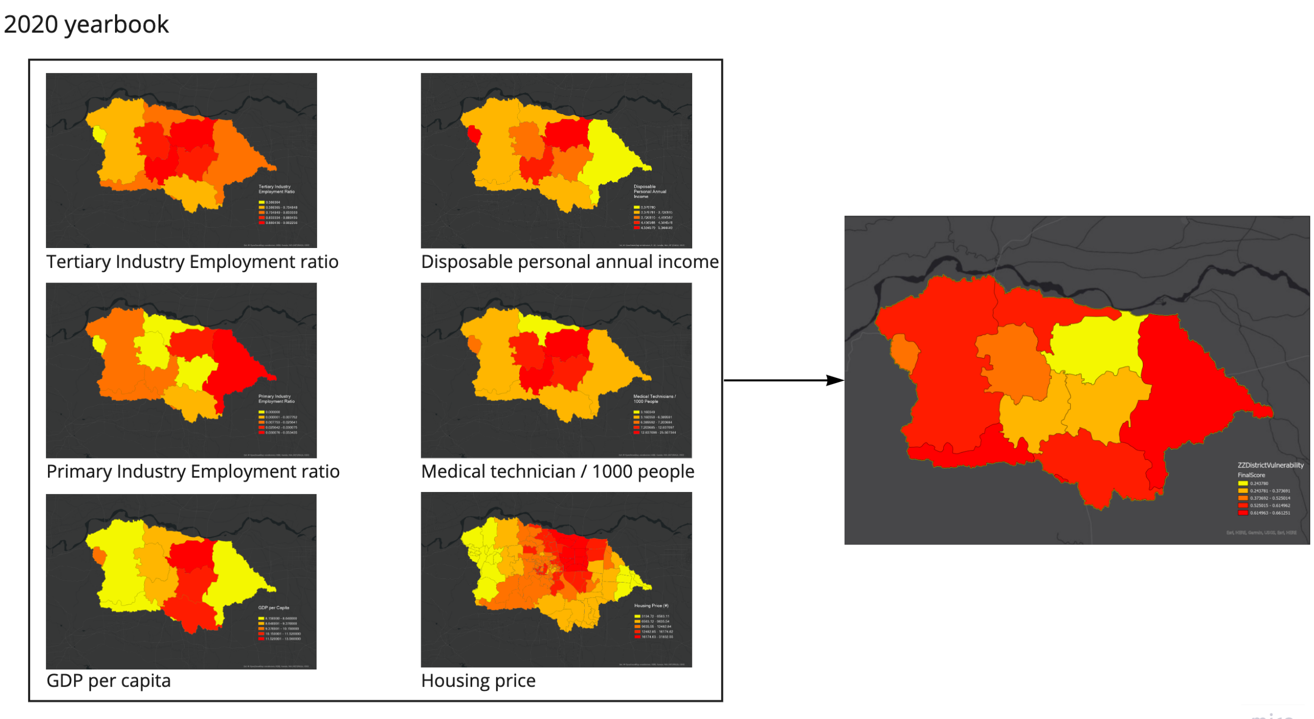


Figure 3 scocial vulnerability from 2020 yearbook

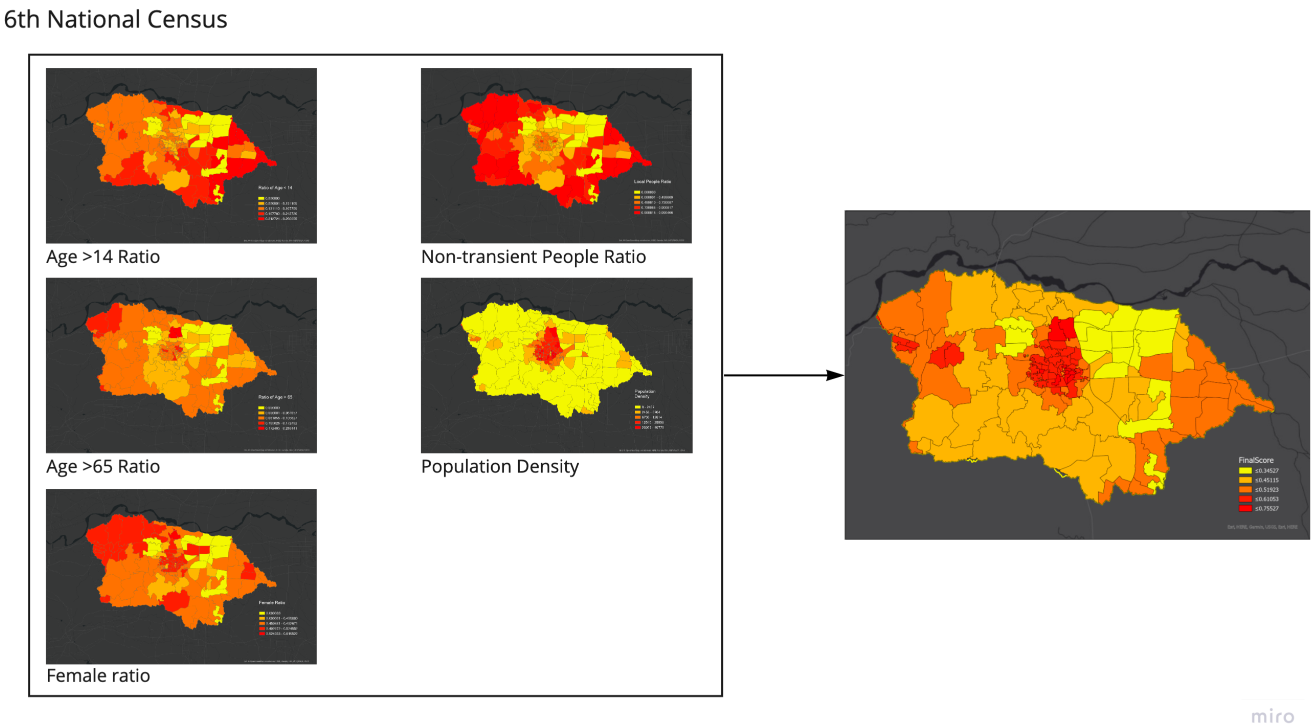


Figure 4 Social Vulnerability map from 6th National census

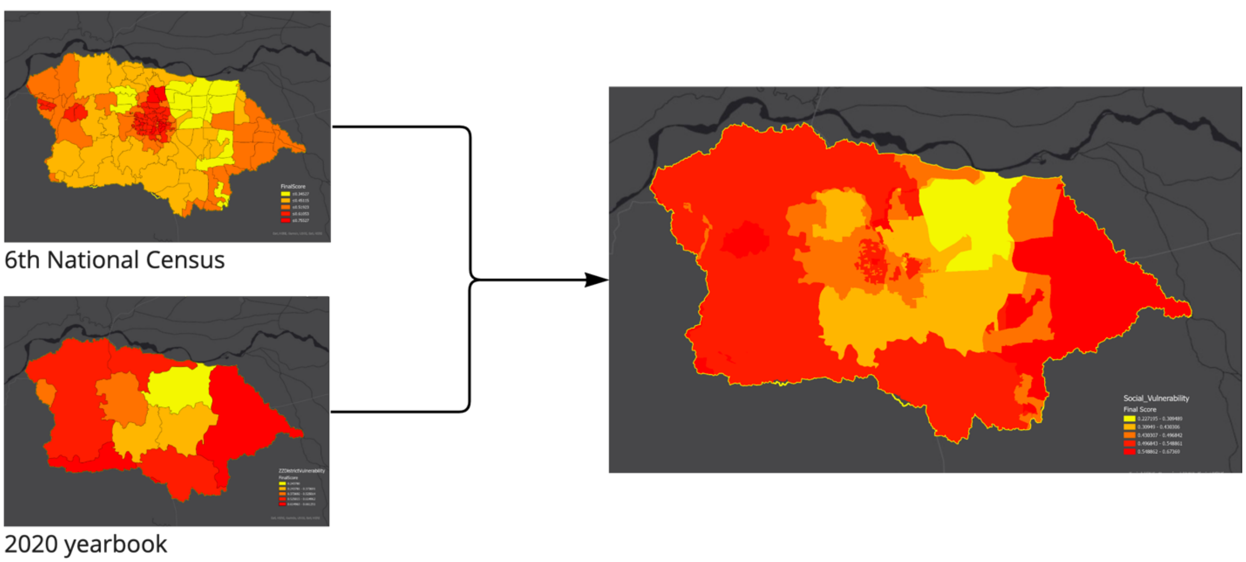


Figure 5 Overall Social Vulnerability

3) COMPOSITED VULNERABILITY MAP

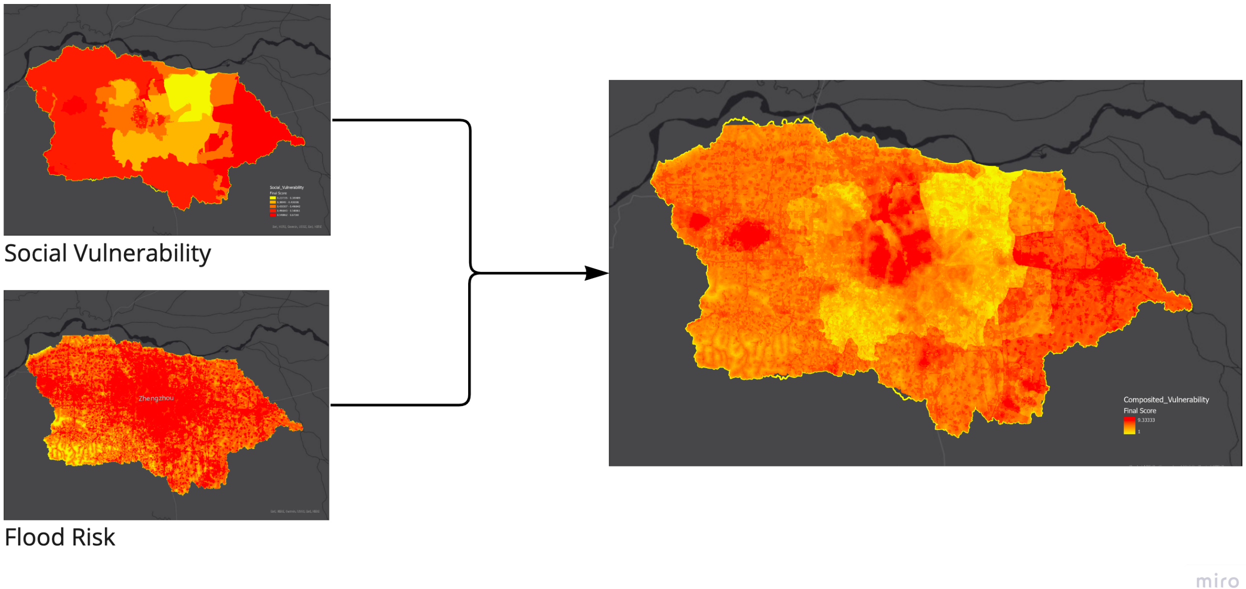


Figure 6 Composited Vulnerability Map

4.2. Typology [HG]

1) K-MEANS CLUSTERING FEATURE

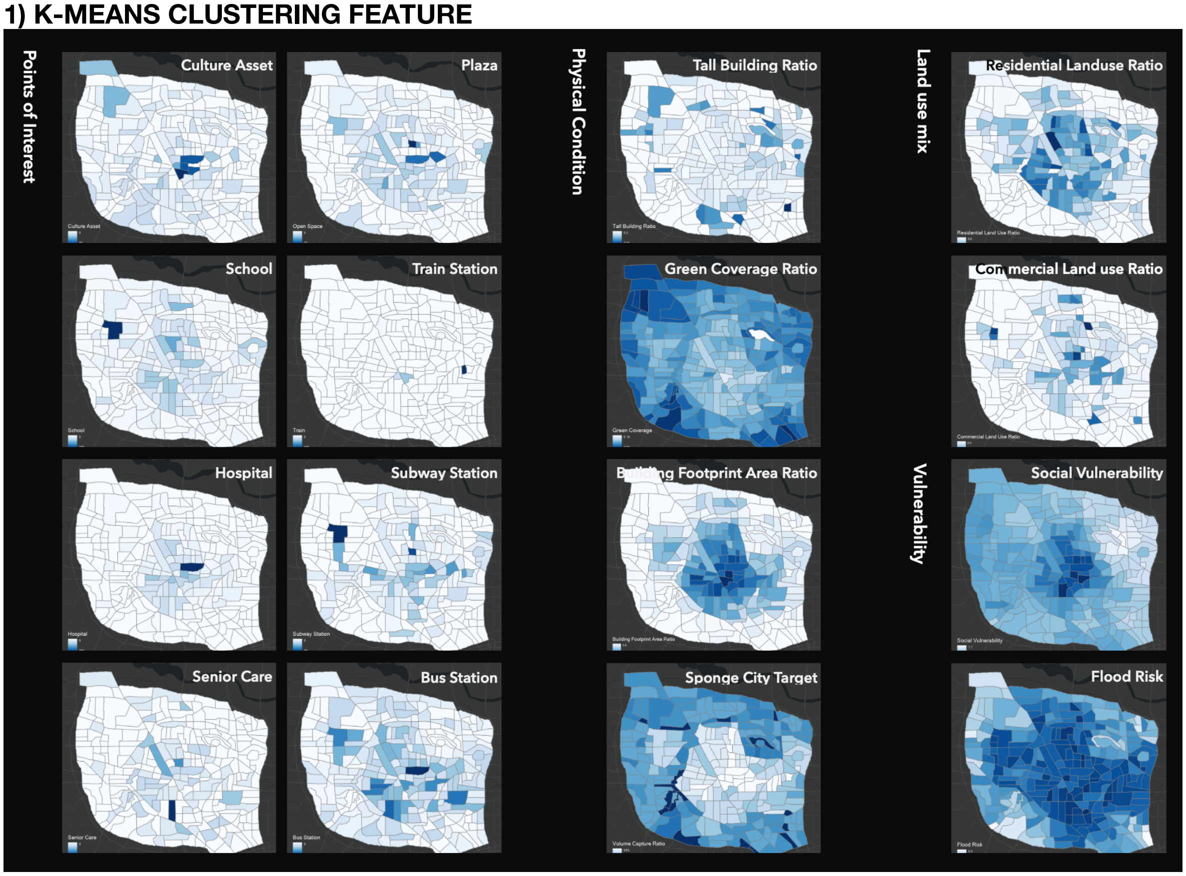


Figure 7 K-Means Clustering Feature

2) K-MEANS CLUSTERING RESULT

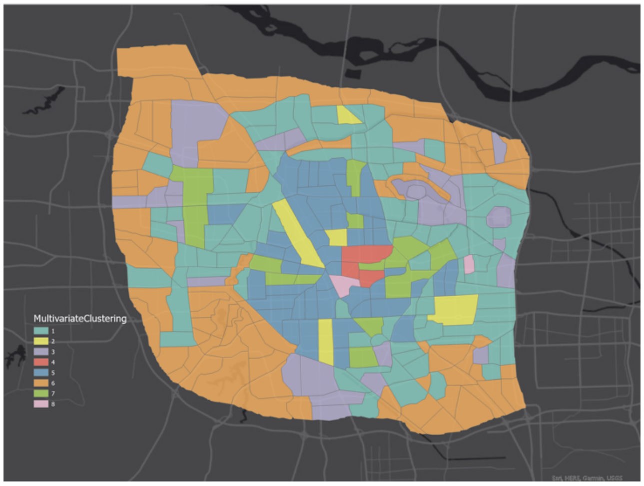


Figure 8 K-Means Clustering result

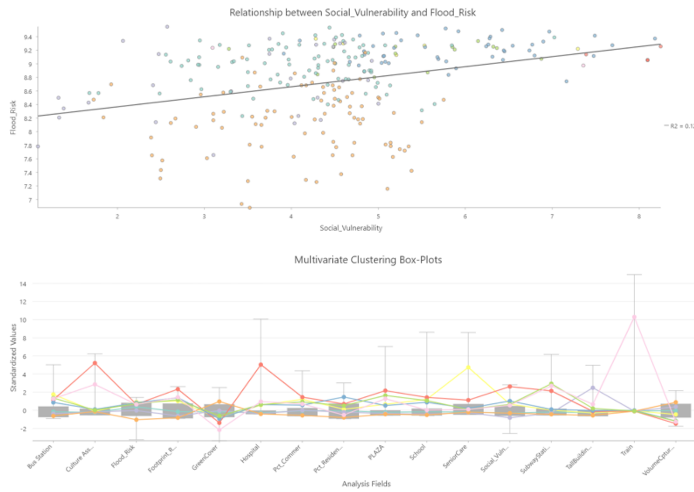


Figure 9 Multivariate Clustering Box-plots

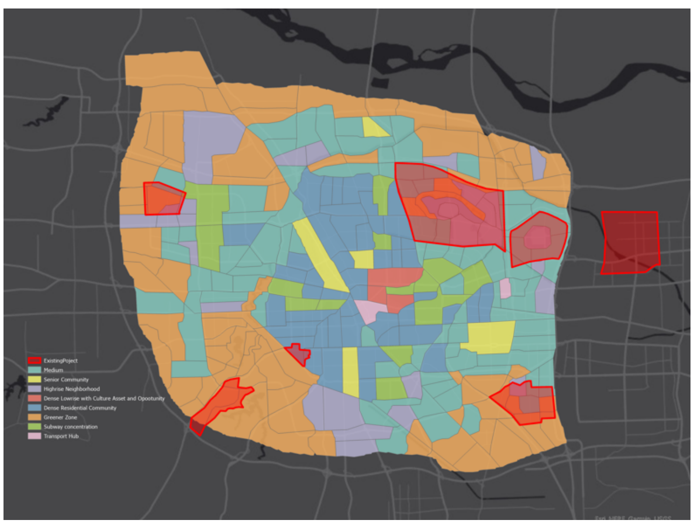


Figure 10 8 types of Neighborhoods and Existing Project

After testing different number of classes, 8 has the best result to differentiate each type. The multivariate clustering box-plots show the feature of each typology. After summarizing the data, I defined 8 categories as 1) Average Neighborhood, 2) Neighborhood with Senior Care, 3) High-rise Neighborhood, 4) Dense Low-rise with Culture Asset and Opportunities, 5) Dense Residential Community, 6) Green and Vacant Neighborhood 7) Subway Concentration, 8) Transport Hub.
Among them, Neighborhood with Senior Care, Dense Low-rise with Culture Asset and Opportunities, Dense Residential Community, Subway Concentration are both socially vulnerable and at high flood risk. They are four types that needs to be prioritized or focused. However, overlaying with existing projects, we could see the existing projects are mostly located in average neighborhood, green area, and high-rise neighborhood, which are relatively less vulnerable.

5. DISCUSSION [HG]

5.1. A practical toolkit [HG]

I created a web tool to visualize the distribution, feature, and data in different type. Here are the screenshots for each type:

Figure 11 Average Neighborhood

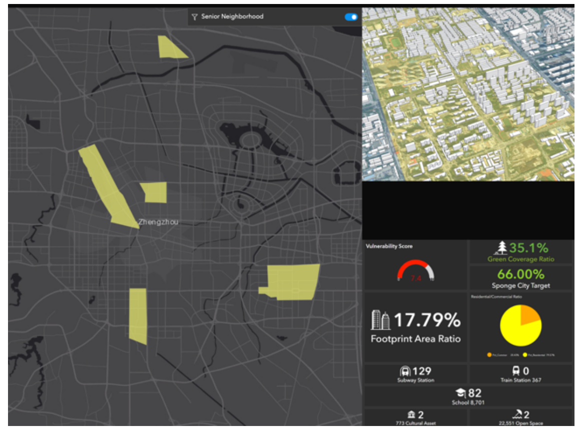


Figure 12 Neighborhood with Senior Care

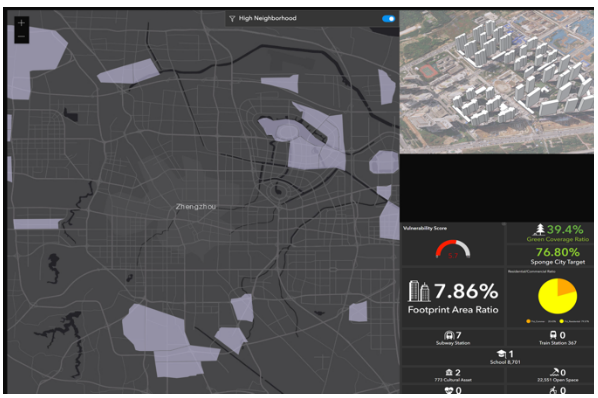


Figure 13 High-rise Neighborhood

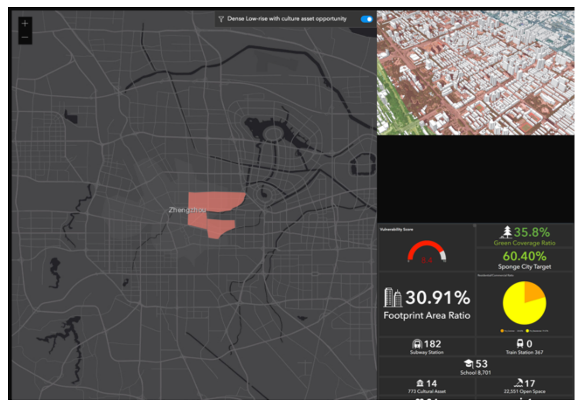


Figure 14 Dense Low-rise with Culture Asset and Opportunities

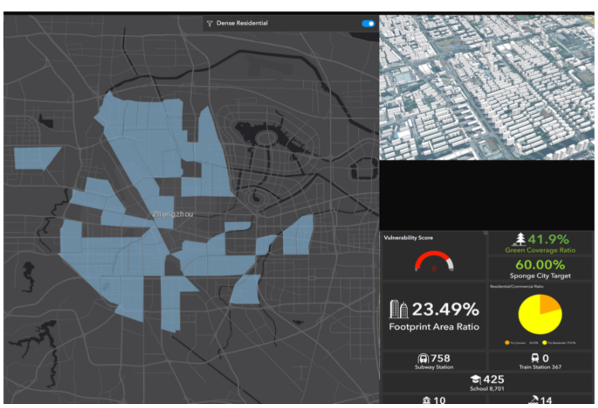


Figure 15 Dense Residential Community

Figure 16 Green and Vacant Neighborhood

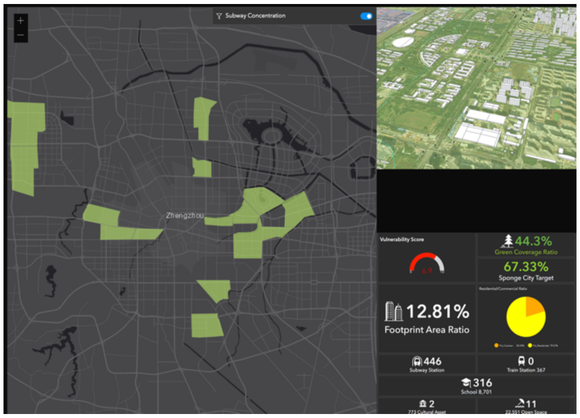


Figure 16 Subway Concentration

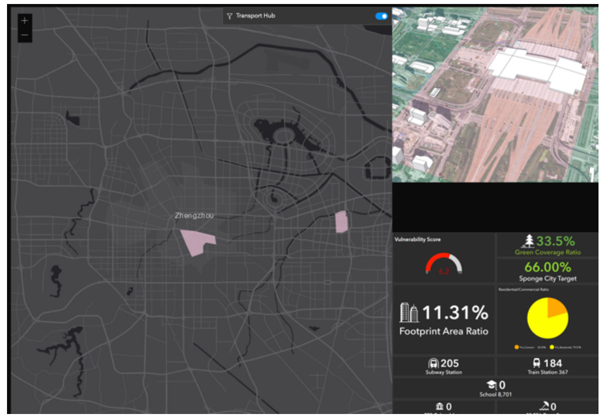


Figure 17 Transport Hub

With this web tool, planners or designers could easily understand the feature of communities by panning or zooming to the focus area. It will help designers to develop the typological design for sponge city as well as implement the previous experience from a similar neighborhood.

5.2 Future directions [HG]

With the categorization and the web tool, we are able to develop the typological design for sponge city and marry the neighborhood type with sponge city facility, which will benefit for both communities and flood control.

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