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AN INTEGRATED GIS AND FLOOD VULNERABILITY INDEX APPROACH TO EVALUATING RISK AND ENVIRONMENTAL EQUITY IN URBAN KARST COMMUNITIES

A Thesis
Presented to
The Faculty of the Department of Earth,
Environmental, and Atmospheric Sciences
Western Kentucky University
Bowling Green, Kentucky

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

By Chloe Cooper

August 2022

AN INTEGRATED GIS AND FLOOD VULNERABILITY INDEX APPROACH TO EVALUATING RISK AND ENVIRONMENTAL EQUITY IN URBAN KARST COMMUNITIES

Date Recommended 08/12/2022

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ACKNOWLEDGEMENTS

Completing this research would not have been possible without the support and care of so many people that I am exceptionally lucky to have in my life.

I'd like to thank my mom for always being my biggest cheerleader, for always making sure I know how proud you are of me (that matters way more than you know), for always making the time to listen and be there, and for being my favorite person to binge watch Friends with on a Saturday night. There's no one else I'd rather be a carbon copy of than you.

I'd like to thank my dad for always picking up the phone when I call (even though you are always on the top of a ladder, without fail), for being the best person to bounce ideas off of when the words just don't want to make sense, and for unfailingly being the absolute most difficult person to get off the phone with because neither of us know when to stop talking.

I'd also like to thank my sister, Lauren, for being the best friend I've ever had and ever will have. No one can make me feel better than you can, pull me out of my grumpy moods so easily, or make me laugh harder. I wouldn't know how to get through life without you.

Steve (Stephen), thank you for being one of the most dependable and solidly good people in the world. You make life a thousand times easier for so many people, and I will never take that for granted.

Erik and Brady, I owe you a special thank you for being the best life rafts possible, the most willing to drop everything and be there for me, and for being some of the best friends I've ever had.

Amy Hourigan! My rock! The one keeping me sane for two years straight; I love you and will never stop appreciating you for being such a constant source of comfort in my life.

To all of my friends and family, thank you for being there for me. You all know who you are, and even though there is zero chance any of you will read past the first 5 pages of this, I love you all immensely.

Finally, I have to thank all of my professors and advisors at WKU that have helped me get here. Dr. Polk, all I can say is thank you, truly. I promise I'll finally make you those cookies I've been promising for the last two years.

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AN INTEGRATED GIS AND FLOOD VULNERABILITY INDEX APPROACH TO EVALUATING RISK AND ENVIRONMENTAL EQUITY IN URBAN KARST COMMUNITIES

Chloe Cooper August 2022 188 pages

Directed by: Dr. Jason Polk

Dept. of Earth, Environmental & Atmospheric Sciences Western Kentucky University

This study examines how the usage of an integrated GIS (Geographic Information Systems), flood vulnerability assessment, and management approaches can aid in hazard response planning in karst groundwater systems, particularly in urban environments. In order to also better understand the impacts of flood events on socially vulnerable groups, this research was focused on historically excluded communities. Additionally, place-based vulnerabilities were primarily assessed based upon three main factors in the vulnerability framework and how these components intersect: social, environmental conditions, and economic. By understanding which areas of the City of Bowling Green, an iconic urban karst area, are most vulnerable and the precise ways in which these areas are vulnerable with respect to karst features and floodplain identification, management can be focused to specifically target those areas and the susceptibilities present. Utilizing the developed karst flood vulnerability index (kFVI), it was determined that some areas of the CoBG have higher levels of vulnerability to flooding than others and that there is some variability in how these different areas are able to handle recovery, including potentially diminished abilities to recover based on environmental inequities. Based upon the acquired knowledge of flood vulnerabilities in the CoBG by applying the created framework, recommendations are made on how flood mitigation and recovery may be improved through improved management strategies and comprehensive development planning.

Chapter One: Introduction

1.1 Research Overview

While there are many anticipated impacts of global climate change, one of the more prevalent predictions in many areas is the increased frequency of weather events that result in flooding. Increased intensity and frequency of weather events could bring about destruction to communities around the world with flooding, damage, and loss of life. Even without the onset of rapid climate change, flooding around the world already causes profound impacts annually, from small nuisance floods to dangerous storms that can decimate entire communities. On any level, flooding has the power to disrupt the everyday systems and routines of humans and the physical environment. The effects of climate change and flooding will be felt globally, but karst landscapes could be particularly vulnerable to these various scenarios, since they are already sensitive by nature.

Karst landscapes are characterized by sinkholes, caves, aquifers, and other subsurface features that can allow for the transport of water (Ford and Williams 2007). Groundwater movement in karst aquifers differs greatly from that in porous media aquifers; both transport water, but karst conduits do so much more rapidly and without filtration, giving karst landscapes higher potential for water quality degradation (TWDB 2022). The groundwater reserves and systems that exist in the karst hydrology can provide many communities and environments with necessary resources to sustain life in the surrounding areas (Ford and Williams 2007); however, due to the high levels of connectivity and subsurface travel, karst areas can be sensitive to changing environments or hazards, in addition to being particularly difficult to manage at times (Parise 2010). Karst landscapes can vary greatly in their geography and geomorphology, thus management strategies can also vary greatly from area to area.

Flooding often exacerbates water quality impacts in karst areas, which amplifies the impacts of flood events. One of the main issues associated with flooding of karst landscapes across the world is how to protect water quality from contamination, as the water that karst aquifers and subsurface features are able to store and provide serves as a major resource for many communities. Studies in some karst areas have already found contaminants in the water following storms and runoff events, including substances such as fecal coliform bacteria, nitrates, and pesticides (Hallberg et al. 1985; Ryan and Meiman 1996). Contaminated water sources impact not only the humans and communities in the surrounding areas that might draw upon the water for bathing or drinking, but also the natural environment and all the plants and animals that inhabit the area. This degradation of water quality can lead to habitat loss or destruction, forced migration, extinctions and endangerment, and general loss of life.

In the United States, about 25 percent of the land contains karst features, with all fifty states containing karst features or having the potential for karst (USGS 2014). The state of Kentucky features some of the most iconic karst landscapes in the world, with many towns and cities throughout the state located on karst. The presence of significant karst regions in Kentucky can contribute heavily to flooding and subsequent impacts, with sinkhole flooding more damage to buildings than any other geologic hazard in Kentucky (KGS 2021). In the City of Bowling Green (CoBG) in southcentral Kentucky, karst-related flooding has been a recurring problem that has been difficult to address, particularly as the city has grown and developed at a fast pace in the past decades (Crawford 1982; Crawford et al. 1989; Feeney 1986; Shelley 2018). Areas that are known to flood can be designated as flood zones by the Federal Emergency Management Agency (FEMA), an agency that officially designates the types and locations of flood zones, creates flood maps, and evaluates flood risk for communities throughout the U.S. (FEMA 2022).

While there are FEMA designated flood hazard zones in the CoBG, there are still regions and neighborhoods that currently flood, but are not officially recognized as flood zones.

Knowing the types of features that correlate with flooding in karst regions can help to identify regions to focus on or study more intently. The areas with the identified karst features are typically more likely to experience flooding, which is focused more on water quantity issues associated with flooding (Zhou 2007). Features related to pollution, hazardous waste, or toxic chemicals are not generally associated with ability to cause flooding but rather the potential impacts to water quality during a flood event if the pollutants and chemicals were to enter the water (BRADD 2022). In communities such as the CoBG with relatively small populations, or of lower socio-economic status, persistent issues such as flooding may not always be documented or reported, since community members may not know who to contact regarding the issues, have the financial ability to address the issues, or be of the belief that the responsibility of fixing the flood problems is left to the citizens rather than the local government (Anderton et al. 1994).

This research study examines how the use of an integrated GIS (Geographic Information Systems) risk and a vulnerability analysis management approach can aid in flood response planning in karst groundwater systems, particularly in urban environments. This study focuses on communities with histories or perceived potential for flooding in order to better understand the impacts of flood events on socially vulnerable groups in karst areas. Drawing upon work completed by Cutter (1996) and Wakhungu et al. (2021) regarding place-based vulnerabilities, this study focuses on three main factors in the vulnerability framework: social, environmental conditions, and economic, and how these components intersect. By understanding which areas of the city are most vulnerable and the precise ways in which they are vulnerable, both in environmental equity and actual flood risk, management can be focused to specifically target those areas and the susceptibilities present.

1.2 Intellectual Merit

Because of the dynamic nature of Earth's systems and the constantly changing landscapes around societies, being able to quantify and assess potential risks while building flexibility into every plan is going to be one of the best and most important ways to strategize for this uncertain future. There is a need for effective management planning that is both robust and flexible, yet still affordable, for communities and areas that are at high risk for flood events but may not have the economic resources to implement some of the same strategies compared to more affluent communities. Despite the number of research studies conducted that utilize the Flood Vulnerability Index (FVI), there exists a gap regarding flood vulnerability assessments in urban karst landscapes and particularly with regards to environmental justice. There is a need for a better understanding of how to assess a community's vulnerabilities in order to better manage and plan for the future, in terms of what the specific threat is (type of flooding), the ways in which an area might be vulnerable that might reach beyond solely physical environment factors, and the specific locations that these vulnerabilities exist. This study creates a more holistic approach to flood vulnerability assessment in urban karst areas.

1.3 Research Questions

The results from this project answer the following research questions:

- Can application of a flood vulnerability index modified to include karst impacts identify urban karst flooding vulnerabilities in a community?

  - How can urban karst flood vulnerabilities in the City of Bowling Green, Kentucky be assessed using an index evaluation approach?
- Does karst flooding disproportionately affect certain populations or demographics due to human-environment intersections in urban karst areas?
- Can calculation of social and environmental vulnerabilities to flooding specific to karst landscapes aid in making recommendations for flood mitigation and inequities?

Chapter Two: Literature Review

In many regions around the world, flooding is a continuous problem that can cause devastating impacts to the inhabitants of the communities. In karst landscapes in particular, flooding and mitigation is incredibly important to study as the sensitive nature of these landscapes makes karst particularly vulnerable to environmental changes and flooding (Ryan and Meiman 1996); however, due to a variety of factors, there are still many communities that are failing to adequately plan for flood impacts. Many areas already experience flooding that can disproportionately affect economically depressed regions of cities, where little to no strategies have been implemented to mitigate these impacts. Developing effective flood mitigation plans is becoming even more important as regions around the world attempt to prepare for a future in which climate change will impact the resources karst landscapes provide and the lives that depend upon these resources, whether they are human or part of the natural environment. While there is still uncertainty as to exact impacts that will come about as a result of climate change, planning and mitigation needs to begin now in order to prevent or prepare for the worst-case scenarios. This study identifies the environmental equity dynamics associated with flooding locations in karst landscapes, so that these areas can better plan for the future in the event of flooding and plan accordingly. With this understanding, places and localities around the world that face this dilemma, especially those that lack substantial financial resources, should be able to build plans that can alleviate any environmental injustice if it is present in these areas.

2.1 Karst Landscapes

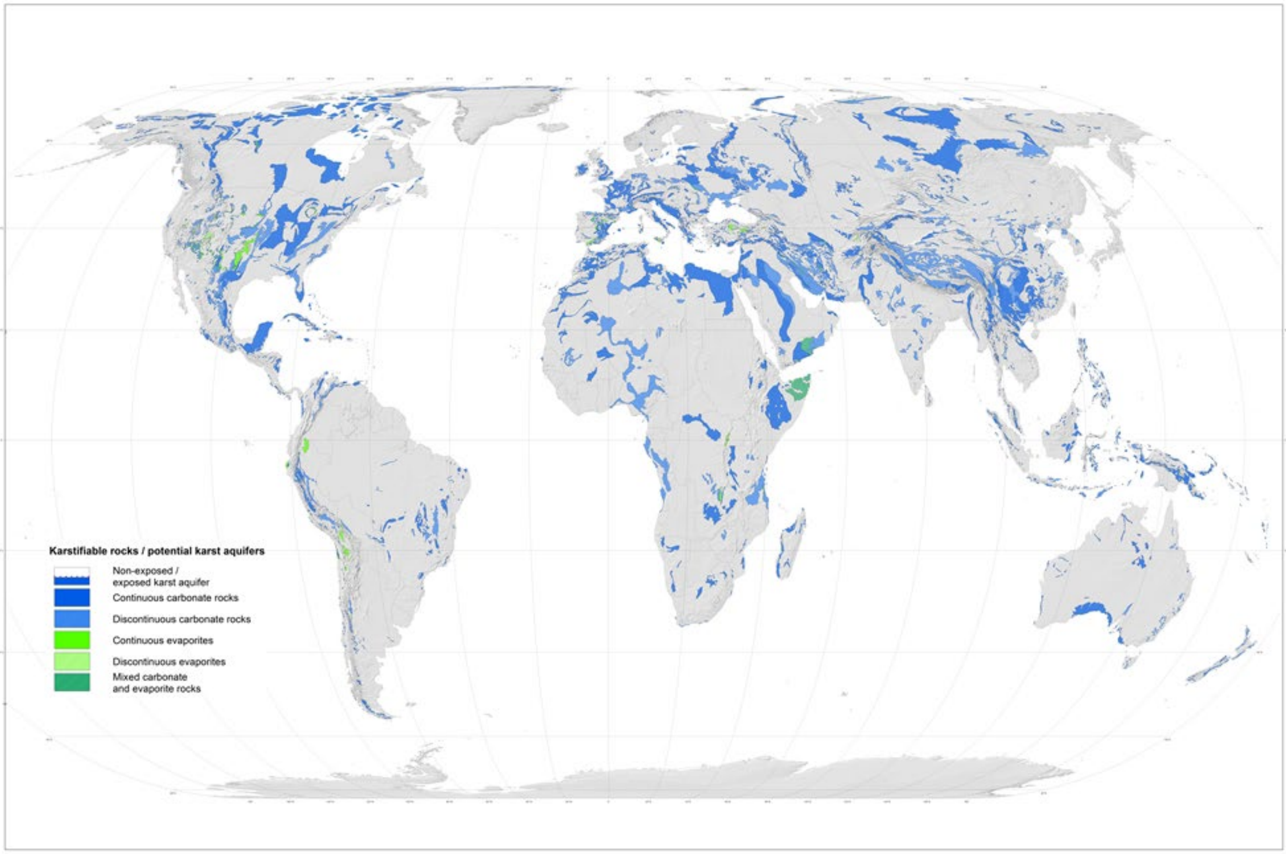


Figure 2.1 Distribution of karst rocks across the globe (Source: Chen et al. 2017).

Karst regions are characterized by the caves and underground water systems that are formed primarily due to the landscape being made up of soluble or carbonate rock, such as limestone or dolomite (Ford and Williams 2007). The word ‘karst’ can be traced to Slovenia and translates broadly to ‘barren’ or ‘stony’ ground, as Slovenia has an extensive karst landscape (Ford and Williams 2007). Nearly a quarter of the world’s landscape sits upon karst, with regions around the world in Europe, Asia, Africa, and the Americas featuring karst terrains (Figure 2.1) (Ford and Williams 2007). Because these landscapes are composed primarily of soluble rock, the development of caves, depressions, and other landforms is much easier, as water can erode and travel through the rock, creating passageways, sinkholes, springs, etc. (Figure 2.2) (Bonacci 1987). Well-developed karst landscapes also have a propensity for fracturing, which is considered to be a 'secondary porosity' of the karst landscape (Bonacci 1987).

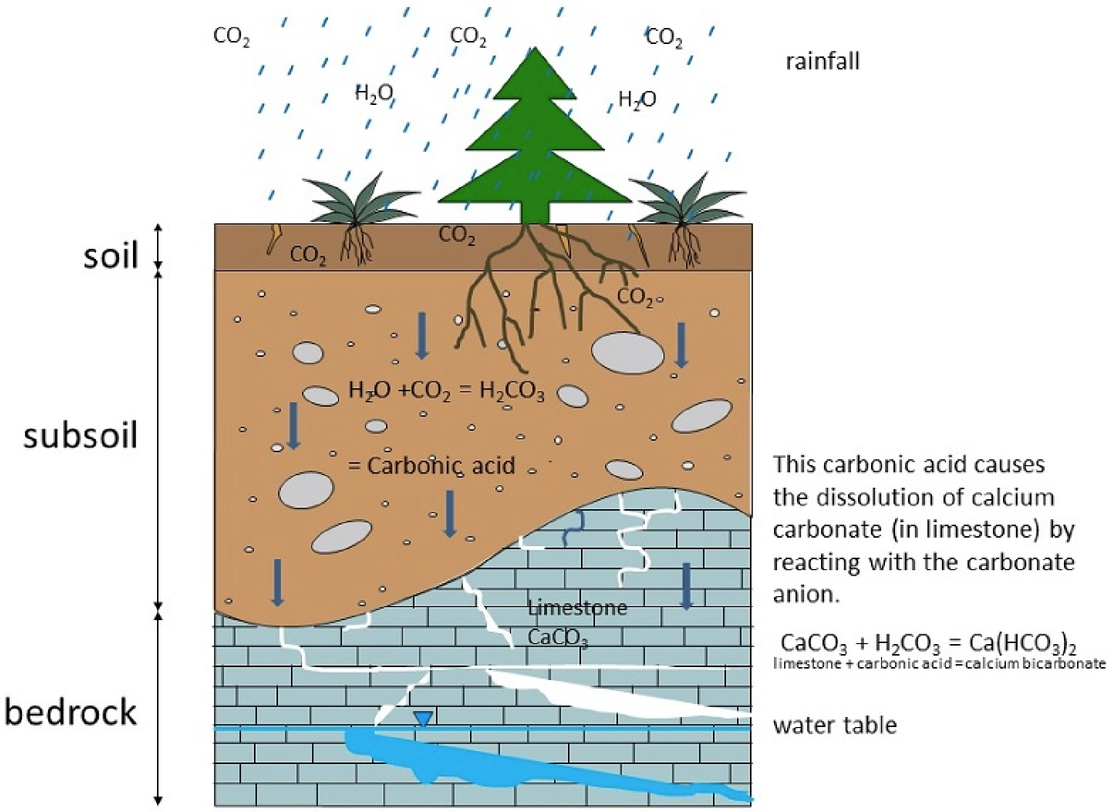


Figure 2.2 The basic process of formation of karst landscapes (Source: Geologic Survey Ireland 2021).

Karst landscapes are typically divided into three different categories based upon the relative evolution and age of the rock, or the time-porosity stage that the landscape is in (Choquette and Pray 1970). Eogenetic karst is the youngest karst relatively and is characterized by deposition and early exposure, while telogenetic karst is the oldest karst and is demonstrated by erosion and post burial exposure (Florea and Vacher 2006). Mesogenetic karst is less widely used to describe karst landscapes, though it is characterized by deep burial (Florea and Vacher 2006). In addition to these time-porosity stages, karst landscapes can also be characterized by many other factors, such the zonal group that the karst is located within, including tropical, temperate, or tundra karst (Veress 2020). Bare karst and covered karst are two other common distinctions that are made, which indicate the level of bedrock exposure to the atmosphere, with bare karst featuring heavy exposure and covered karst featuring little to no exposure (Jennings 1971). Fluviokarst describes karst landscapes that were predominately formed by rivers and streams, or fluvial processes, but generally refers to areas where the drainage may be underground (Veress 2020). Many karst areas have similar characteristics that tie the landscapes together as karst, but each has defining characteristics that prevent completely uniform management of all karst areas around the world. This presents a need for specialized management strategies based upon the specific characteristics of different karst areas.

2.1.1 Hazards to Karst

Largely due to the porous nature of karst landscapes and lack of filtration, karst areas can be incredibly sensitive to environmental changes. Water can be transmitted from place to place very rapidly in karst areas, which leave these areas vulnerable if the water is contaminated in any way (Ford and Williams 2007). Much of the areas surrounding karst areas are influenced by, or utilize, karst features to function, such as the health of groundwater or farmers' knowledge of recharge areas or other features affecting where crops are planted (Ford and Williams 2007). If the karst landscape is changed, this could have significant impacts on not only the health of the karst system, but also the people, plants, animals, and ecosystems that depend upon the karst system for resources. Because much of karst water is subterranean, karst landscapes can be particularly vulnerable to pollution and contamination (Parise 2010). This can be problematic because this could make it difficult for land managers and inhabitants of the area to know when there are issues with the karst landscapes, or the problems simply are ignored or misunderstood. This vulnerability presents a growing need for a better understanding of ways in which karst areas could be affected in the future by climate change.

Climate change is anticipated to bring about increased flooding in various regions around the world, due to sea level rise, increased precipitation, longer monsoon seasons, and various other hydrological, climatological, and land-use changes or conditions (Chang and Franczyk 2008). Flooding, in general, is already a major global problem, but different areas can require very different responses and management strategies; in karst landscapes, flooding can cause many of the same problems that river or coastal flooding causes, but karst areas add the element of underground passageways and systems that can transport water great distances very quickly unseen, which can make management very difficult (Ryan and Meiman 1996).

Climate change is anticipated to exacerbate these already difficult management problems by altering atmospheric variables, such as temperatures, precipitation, atmospheric pressure, wind speeds, cloud cover, which can all have impacts on the hydrologic cycle (Lian et al 2015). Changes to the hydrologic cycle could have profound effects on karst landscapes, as flooding could increase or the waterways could dry up, flowpaths could change and lead to the redistribution of resources, or plants and animals that depend on the resources karst areas provide, as well as certain vulnerable populations, could be forced to migrate, along with various other impacts (Lian et al 2015). These changes to karst landscapes due to climate change could have significant impacts on economic, social, and environmental life in the karst landscape.

In southwest China, researchers found that climate change led to higher degradation in karst catchments than catchments in non-karst areas (Liu et al. 2016) This could be incredibly important in the future, as karst covers about ten percent of the Asian continent and provides resources for much of the population (Day and Urich 2000). In Texas, researchers determined that one of the largest aquifer systems in the United States, the Edwards Balcones Fault Zone (BFZ) aquifer, could be threatened by climate change with modelling revealing that the aquifer's groundwater resources could be significantly depleted in the future if a warmer climate becomes reality (Loáiciga et al. 2000). Problems arising with karst areas such as these could prove to be disastrous as many people and natural systems depend upon these landscapes. This emphasizes the need to understand the ways in which climate change and its effect on flooding will impact karst areas, so that the landscapes can be properly managed to avoid the worst outcomes.

2.1.2 Managing Karst Systems

Karst systems are perpetually difficult to manage and protect due to the high variability of properties and differing behaviors within the systems, which can make successful modelling challenging at times. Additionally, karst features an incredibly wide array of hazards that can make effective management difficult as regulators attempt to encompass all possible scenarios. In general, the main characteristics of a karst area will typically remain consistent, excluding extreme situations of urban development or drastic changes to the landscape, making management and protection feasible; however, even with regulations and management practices in place, karst areas can still be contaminated, and resources mistreated with lack of enforcement (Fleury 2009). In many countries around the world, there are no protection measures put into place to aid in management of karst (Fleury 2009). There exists a need for effective management practices that can be enforced while balancing feasibility for lower income countries or areas around the world.

One of the major issues associated with managing karst systems is determining how to protect water quality, as karst landscapes are particularly susceptible to nonpoint source pollution and contamination (Ryan and Meiman 1996). This is largely due to the ability of runoff to travel quickly in the subsurface network through streams and sinkholes with little to no filtration or absorption (Ryan and Meiman 1996). In a study conducted at Mammoth Cave National Park, researchers found that the concentrations of fecal coliform bacteria and suspended sediment, two nonpoint source pollutants, widely exceeded pre-runoff values for shorter periods of time (Ryan and Meiman 1996). These high concentrations of nonpoint source pollutants after runoff events were also found in a study conducted in Iowa, where nitrates, pesticides, and suspended sediments caused extreme water degradation (Hallberg et al. 1985); however, these studies indicate that the contaminants only impacted the water quality for short periods of time following runoff events, rather than having significant long-term impacts. The effects of frequent events causing water degradation over time is not thoroughly examined. These short periods of water degradation can still have significant impacts on the health of both humans and the environment, as the water supplies can be used for drinking water, irrigation, other municipal utilities, and many more.

As climate change increasingly impacts the global environment, changes to precipitation are anticipated, which could include significant increases in the sheer number and intensity of events (IPCC 2018). In karst regions, an increase in number and intensity of precipitation events could have particularly disastrous impacts, due to the easy transference of runoff and contaminants. Additionally, homes and businesses could be damaged or destroyed, environments altered, or degradation or destruction of resources that karst provides. Generally, if risk perception of flooding or droughts is high, then the assumption could be made that the behaviors of policy makers would reflect this in their mitigation strategies, but this was largely disproven in empirical studies (Bubeck et al. 2012). Bubeck et al. (2012) identified possible factors that could derail flood mitigation strategies even when risk perception is high, including the need for a coping appraisal to accompany the high-risk perception. Their research indicated that governmental agencies and risk-transfer instruments, such as insurance, need to be implementing flood infrastructure and mitigation strategies because individual households generally fail to take on flood mitigation measures even when flood risk perception is high. This presents a need for better management strategies in karst systems to mitigate or prevent flood events from occurring, while also factoring in potential scenarios and the associated uncertainty that could occur due to climate change. These changes could be especially important in low-income communities that could end up being the most heavily impacted and disadvantaged by flood scenarios.

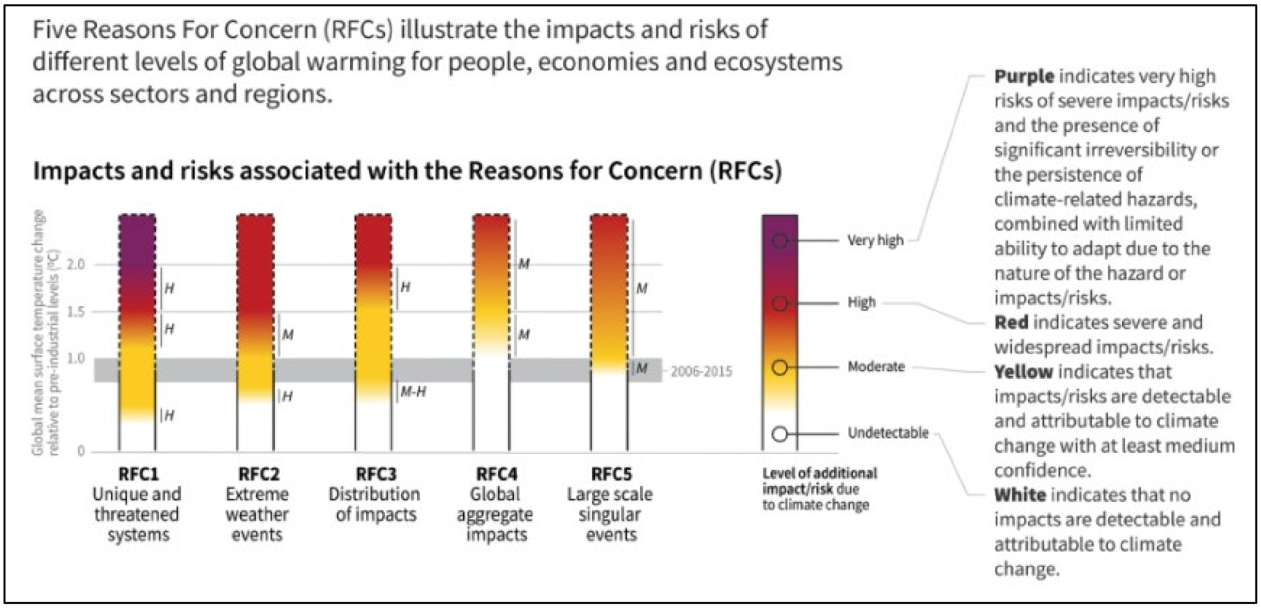
2.2 Flooding

Flooding is one of the most common natural disasters in the world, which also makes it one of the most damaging (WHO 2021). Flooding can occur due to a variety of factors, including heavy precipitation events, coastal events such as hurricanes, tsunamis, or sea level rise, or even from snowmelt, among others (WHO 2021). While floods are a relatively common occurrence compared to some other natural disasters, flooding can still be an incredibly destructive and deadly event. According to the United Nations Office for Disaster Risk Reduction (UNISDR), more than two billion people globally were impacted by flood events in the years between 1998 and 2017 (2018). Flooding alone accounted for almost a quarter of all economic losses caused by natural disasters from 1998 and 2017, with more than $656 billion USD, while it was also the most frequent disaster, composed of 43 percent of all recorded events (UNISDR 2018). In a review completed by the Food and Agriculture Organization (FAO) of 53 developing countries around the world, two-thirds of all damage and crop loss in the decade between 2006 and 2016 was caused by flooding (UNISDR 2018).

The most common types of flooding are flash floods, coastal floods, and river floods (WHO 2021). Flash flooding and river flooding typically occur when heavy precipitation events cause water levels to rise dramatically, especially in a short amount of time, which can lead to road blockages, damage to homes, and overtaken rivers or waterways (WHO 2021). Coastal flooding relates more specifically to storm surges from events such as hurricanes or tsunamis, in addition to rising sea levels encroaching on coastlines (WHO 2021). Despite the type of flooding, these events can have damaging impacts to landscapes and human health that extend beyond damage to infrastructure, road blockages, or drownings. These events can also contribute to pollution and contamination, as hazardous waste, sharp or heavy objects, oil, gas, sewage, and other harmful objects and substances can be transported over long distances in short amounts of time (Nunez 2019). Water damage to buildings and structures can lead to mold blooms that can negatively impact human health (Nunez 2019). When water sources are contaminated, people are left without access to safe drinking water until aid can arrive, which can lead to waterborne diseases such as cholera or hepatitis A as people resort to drinking whatever water is around in order to survive (Nunez 2019).

Climate change-induced flooding is anticipated to manifest in a wide variety of ways, such as through extreme weather events, increased frequency and magnitude of precipitation events, or sea level rise (Figure 2.3) (IPCC 2018). Islands around the world may be overtaken by the rising sea levels, groundwater supplies may be contaminated by various pollutants around cities and people, in addition to salinization as oceans infiltrate freshwater resources (IPCC

2018). These increased levels of flooding could damage infrastructure in cities around the world, including destruction of homes and property. While many places are designing new constructions to account for flooding, there is a need for updates and increased flood protection measures to be put in place for infrastructure that has already been created.



Five Reasons For Concern (RFCs) illustrate the impacts and risks of different levels of global warming for people, economies and ecosystems across sectors and regions.

Impacts and risks associated with the Reasons for Concern (RFCs)

Purple indicates very high risks of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.
Red indicates severe and widespread impacts/risks.
Yellow indicates that impacts/risks are detectable and attributable to climate change with at least medium confidence.
White indicates that no impacts are detectable and attributable to climate change.

Figure 2.3 The various risks and impacts associated with Reasons for Concern and level to which each is affected by climate change (Source: IPCC 2018).

In most cities and countries, water infrastructure is built with the intention of it lasting anywhere between 30 to 200 years (Gersonius et al. 2012). Often, the governmental agencies planning the infrastructure and its implementation will use incredibly in-depth impact and risk assessments, but they largely only plan for an average scenario that may prove to be not enough (Gersonius et al. 2012). Because this idea of planning for the general future to save money instead of creating plans that include specific types of events has obvious flaws, Gersonius et al. (2012) advocated for a method that utilizes and accounts for this lack of certainty by implementing a flexible and adaptive strategy called Real In Options (RIO) analysis; this strategy is intended to “adjust to future uncertainties as they unfold” (Gersonius et al. 2012, 1).

Flexible plans such as this are typically scrutinized for their economic viability because accounting for more than one scenario can be much costlier than less robust plans; however, Gersonius et al. (2012) argued this is actually an economically beneficial method to utilize because their plan avoids investments that cannot be changed or fixed in the event that the models are incorrect. Instead, the RIO analysis prepares a more modest plan that can be adjusted or added to when new information is acquired or presented; this kind of environmental planning is incredibly important, especially in lower-income countries and areas, because a frequent barrier to flood risk management is the costliness of new infrastructure.

In order to make loss estimations to help advise policy makers and insurance companies on what precautions to take to avoid the most damaging scenarios, Hansson and Ekenberg (2002) developed a computer modelling simulation targeting some of the least desireable scenarios, including loss of lives, homes, and schools in the event of flooding or sea-level rise. In developing areas, it is particularly important that policy makers understand which areas are most vulnerable to a changing climate and precisely *how* they are vulnerable. With this knowledge, going forward the decision makers of a locality can choose and develop a method or plan that best fits the area and its needs, given climate predictions and vulnerability analyses. Anandhi et al. (2011) researched various climate change impact assessments, specifically different variations or categories of the Change Factor Methodology (CFM), in order to fill in the gaps in the literature regarding which methodologies are best suited for different applications. In addition, there are substantial gaps in the literature regarding what variables to use (temperature, precipitation, solar radiation, etc.) or how to apply the variables to the methodology, such as additive versus multiplicative or wind speed, which makes it difficult for other researchers to recreate the same methodology or modelling (Anandhi et al. 2011).

2.2.1 Urban Flooding

Flooding can be split into two broad categories in terms of location of flooding: urban flooding and rural flooding. These two types of flooding can manifest in very different ways. Urban flooding occurs in populated areas with urban development. The development changes made to the landscape by humans can impact and alter drainage patterns of the environment, which can lead to flooding when the amount of precipitation exceeds the capacity for the drainage system to handle the water effectively (NCBI 2019). Impermeable surfaces such as roads and sidewalks in cities make it impossible for water to follow the natural path, so this forces precipitation to create a new path. Storm sewers are a common method to provide water an easy path from the streets and lead the precipitation through pipes down to an outlet that is further downstream (NCBI 2019).

Climate change is anticipated to have significant impacts on the frequency and magnitude of storm events, which will have direct impacts on the intensity of flooding around the world. In a case study of three separate areas in Australia, researchers estimated that the one in 100-year floods in these areas would likely become one in 44-year events, 1 in 35-year events, and one in 10-year events for each of the three study areas (Schreider et al. 2000). This accentuates the need for improved management strategies, while also emphasizing the variability of flooding between different regions. This variability indicates that while management strategies in a broad sense can be applied in multiple areas, specialization of plans based upon the specific area at hand could greatly increase the chances of success.

As cities grow and urbanization increasingly changes landscapes, not only must new developments be designed to account for flooding and precipitation, but also existing structures and areas must be updated to continually be effective. The construction of new developments can greatly impact the waterways and paths that precipitation takes as new hardened surfaces and structures are created, which can affect existing management efforts by inhibiting the infiltration of storm water (NCBI 2019). Given that more than 80 percent of the population in the United States currently lives in urban areas with even more growth anticipated, urban flooding poses a significant issue for the country (NCBI 2019). One of the four main trends affecting urban flooding, particularly in the United States, is the growing population that is heavily concentrated in urban areas, which can place strains on the storm water systems of cities (NCBI 2019). This growth in population can lead to increased occupancy of areas already prone to flooding, in addition to changes to land cover and construction of more impervious surfaces, all of which can lead to increased flooding, changes in flood patterns, and subsequent increased damage to property and lives.

2.2.2 Karst Flooding

While urban development in flood plains is not uncommon, as these areas can provide resources, recreation, access to transportation, and aesthetics, flooding can be a persistent and costly issue. Flooding can be a relatively common occurrence in karst terrains, as groundwater, waterways, and other features of the landscape can overtake the land, especially after precipitation events, including rising from the ground upward due to overfilled conduits and an increase in water table elevation. Karst flooding can be particularly dangerous given the presence of underground passageways and conduits made accessible by sinkholes and soluble rock. These features of the karst landscape can more easily transport contaminants and pollutants across great distances in short amounts of time. As with urban flooding, population growth can have negative impacts on karst areas as the landscapes attempt to account for the changes being made to accommodate the growing population. Projections of population growth in the United States between 2010 and 2050 show that some areas with karst topography, such as southern Florida and southcentral Kentucky, are anticipated to have some of the most extreme growth in population (NCBI 2019). This can place major stressors on the landscape, as land development in urban areas has led to the filling in and leveling of sinkholes and drainage areas, leaving a smaller area of infiltration for precipitation (Zhou 2007). When the drainage areas are reduced, more stressed is placed on the area that remains, which can lead to increased flooding in urban areas as the water attempts to find new paths and sinkholes to drain into (Bonacci et al. 2006).

Karst-related flooding typically falls within one or more of three different types of flooding: recharge-related sinkhole flooding, flow-related flooding, and discharge-related flooding (Zhou 2007). Recharge-related sinkhole flooding occurs when the amount of stormwater runoff exceeds a sinkhole's capacity to drain the water or transfer the water to the subsurface areas of the landscape (Zhou 2007). The sinkhole may have blockages that prevent it from utilizing the full capacity in storm events, or human construction could alter runoff and drainage patterns so that the rate of runoff exceeds the rate of drainage from the sinkhole (Zhou 2007). Flow-related flooding occurs when the incoming flow rate of water exceeds the capacity of the various conduits in karst landscapes as water flows through the system (Zhou 2007). When flow capacity is reduced, flooding can occur. Discharge-related flooding occurs when increased water levels at output or discharge points reduce groundwater discharge, which can temporarily reverse the flow direction (Zhou 2007). The solution or mitigation strategy necessary for alleviating karst flooding can depend heavily upon the type of flooding, so understanding the source of the problem is crucial.

Because of the presence of groundwater and passageways below the surface of the land, flooding can be difficult to manage as it differs quite drastically from other types of flooding such as coastal or river flooding. Flooding in karst areas cannot be fixed solely using levees, floodwalls, or dams that might be helpful in other areas. Groundwater, in particular, prevents these methods from being as effective, as the water can seep into homes and onto roads from below the surface (Macdonald et al 2008). When precipitation exceeds recharge rates and capacities of sinkholes and other karst features, the water must find other outlets, which can pop up in places all around the urban area, including under homes, businesses, roads, and cause damage and hazardous situations across the city (Macdonald et al 2012). This was exemplified in 2008 when the Danube River flood plain in Europe heavily flooded and caused extensive damage to homes and building as water pressure built up due to unusually high groundwater levels and high river levels (Macdonald et al. 2012).

While flood walls and levees could keep the river from spilling into cities, these structures would not have been able to block groundwater from traveling in the subsurface. In a study developed after the 2002 floods of the Danube and Elbe rivers in Germany, flood loss assessments were conducted to compare damage and impacts associated with groundwater flooding versus river flooding (Kreibich and Thieken 2008). Researchers found that the damage and impacts due to groundwater flooding were significantly different than those due to river flooding, specifically with regards to water level, flood duration, flow velocity indicators, and contamination indicators (Kreibich and Thieken 2008). This emphasizes the need for management specific to groundwater flooding in areas with this problem, instead of focusing solely on river or ocean flooding. Flooding in karst areas can be mitigated and managed, and in some cases prevented, but this requires different methods of management than various other types of flooding.

In some areas around the United States, developments have begun to be regulated to take into consideration flooding in karst landscapes in order to prevent flooding or to mitigate existing flood problems (Richardson 2003). Various strategies of flood prevention and mitigation include runoff and erosion control plans that take into account the specific characteristics of the karst landscapes, in addition to building retention basins or clearing out blocked sinkholes and drainage basins (Richardson 2003). Because flooding in karst areas can pose a significant threat to groundwater and the overall viability of water used in urban areas, the usage of resources such as Class V Injection wells can be beneficial (EPA 2016a). Class V Injection wells are intended to inject non-hazardous fluids underground and are regulated by the EPA through the Safe Drinking Water Act (EPA 2016a). In karst areas, injection wells typically are used as stormwater drainage wells to protect drinking water in the event of flooding, though these wells have proven to be less advantageous in wide and shallow sinkholes (Zhou 2007). Land managers have also experienced issues with injection wells when proper preparation is not taken before drilling, which can lead to backflooding when the drainage capacity of the well is exceeded (Crawford 1982). Communities continuing to build in already strained areas only serves to exacerbate the existing problems. Although there are methods and practices in existence that can alleviate stresses placed upon karst areas with regards to flooding, there is still a need for more substantial and permanent solutions to urban flooding in karst areas.

2.2.3 Policies

Flooding in its various forms is a global problem that is only anticipated to worsen, though the policies regarding flooding can look very different depending on the country and the type of flooding. In the UK, in the early 2000s, flood risk policy was revised after the "Future Flooding" project examined various flood scenarios with drivers and responses that could occur in the coming 100 years (Samuels et al. 2006). These scenarios were generated along with simulations of the climate in the future and IPCC global emission scenarios in order to investigate flooding from all possible causes throughout the UK, such as coastal, urban, river, and determine the specific drivers of flooding and the potential damage associated (Samuels et al. 2006). This project culminated in a policy framework that considers all types of flooding that are possible or anticipated, with management approaches catered to each kind of flooding that align with both national and local priorities (Samuels et al. 2006). This project marked a shift in flood management and policies that attempt to encompass all types of flooding and consider them at both the national and local level, while incorporating climate change impacts into modelling.

In the United States, flood risk management really began in the wake of the 1927 Mississippi floods with the development of the Flood Control Act of 1936 (Samuels et al. 2006). After the passing of this act, many flood protection measures were built throughout the United States such as floodwalls, levees, or embankments, in addition to various non-structural measures such as insurance policies and regulation (Samuels et al. 2006). The United States has reviewed and revised flood management policies throughout the years since the passing of the Flood Control Act of 1936 but has yet to develop a sole flood or water act that addresses flood risk management in modern times. Additionally, while there are flood management policies that exist throughout the United States, there is significant gap surrounding groundwater flooding. There is no official policy or legal literature in a comprehensive and impactful nature, in addition to insurance policies, that relates to groundwater flooding in the United States. Despite the destructive and damaging impacts that groundwater flooding and inundations can have on not only property, but also human health, the United States has failed to successfully address this issue, particularly in karst areas.

In 1968, the National Flood Insurance Act was passed, creating the National Flood Insurance Program (NFIP) through FEMA, with the intention of protecting property owners throughout the U.S. and reducing future flooding (FEMA 2018). The NFIP has been instrumental across the country in the wake of catastrophic flood events. In the year following Hurricane Katrina in 2005, NFIP damage claims exceeded $17 billion, Hurricane Sandy in 2012 caused more than $8 billion in NFIP claims, and Hurricanes Harvey, Irma, and Maria in 2017 resulted in more than $6.3 billion in NFIP claims damage (FEMA 2018). In the years since its inception, the NFIP has become the current management paradigm for floodplains in the U.S. beyond solely those impacted by catastrophic hurricanes, as many states and localities utilize the same minimum criteria for floodplain management ordinances as dictated by the NFIP (EEC KY 2022). Unfortunately, many of these programs do not identify karst-induced flood areas.

2.3 Flood and Karst-Related Indices and Assessments

In the past few decades, numerous environmental indices related to flooding, karst, or social demographics have been developed in attempts to better understand sources of vulnerability, hazards, levels of risk, and a variety of other goals (van Beynen and Townsend 2005; Balica 2007; Fekete 2009; Flanagan et al. 2011; van Beynen et al. 2012). Disturbance indices related to karst have been developed to identify impacts to the physical environment (van Beynen and Townsend 2005), while vulnerability indices related to the environment or hazards have been developed more so to identify potential impacts to humans (Balica 2007; Fekete 2009). There exists a gap in the literature between flood vulnerability assessments and karst landscapes specifically, particularly as environmental equity and flooding as a hazard may be included in karst-specific indices or assessments but have generally not been the primary focus of study.

The Karst Disturbance Index (KDI) was developed in 2005 to assess and quantify levels of disturbance to karst landscapes associated with five main categories of impacts: geomorphology, atmosphere, biota, hydrology, and cultural (van Beynen and Townsend 2005). The KDI was intended to provide a more holistic view of impacts to karst landscapes that can be adapted to different karst landscapes around the world and has since been refined and applied in a variety of karst regions such as Mexico (Kovarik and van Beynen 2015), Italy (Calò and Parise 2006; De Waele 2009), Slovenia (Ribeiro and Zorn 2021). The KDI is primarily concerned with the health of the karst landscape itself, so the indicators related to human-environment intersections that are utilized in assessments are chosen to attempt to quantify the impacts humans may have on the environment. While the KDI assesses impacts of flooding to the karst landscape, flooding is only one of many indicators that can be utilized in KDI assessments, rather than the focal point.

The Social Vulnerability Index (SoVI) has been adapted and refined in a variety of regions and situations, but the original index is generally attributed to Cutter et al. (2003). The SoVI was designed to assess a community's vulnerability to environmental hazards based primarily upon socioeconomic demographics and levels of resiliency based upon a variety of factors and variables such as race, gender, income, education, or employment (Cutter et al. 2003). Flanagan et al. (2011) implemented the SoVI with relation to disaster events, as socially vulnerable groups were found to be more likely to experience adverse effects to disaster events. The researchers emphasized the importance of assessing social vulnerability by stating, "Effectively addressing social vulnerability decreases both human suffering and the economic loss related to providing social services and public assistance after a disaster" (Flanagan et al. 2011, 2). In a study utilizing SoVI methodology and past river-based flood events, Fekete (2009) determined that observations of actual events matched the patterns of presumed vulnerability based upon the SoVI methodology, further validating the idea that socioeconomic demographics can play a role in vulnerability to environmental hazards.

The Karst Sustainability Index (KSI) was developed in 2012 to establish standards for sustainable development in karst landscapes, with relation to social, economic, and environmental resources (van Beynen et al. 2012). The KSI does include indicators associated with environmental equity that are largely excluded by other indices, but the indicators are chosen specifically with relation to karst, such as equitable access to karst resources or karst-related employment opportunities. Fedeski and Gwilliam (2007) developed an environmental hazard vulnerability assessment related to urban sustainability that incorporates social and economic factors similarly to the KSI; however, the assessment employed by Fedeski and Gwilliam (2007) focuses primarily on the cost of damage from environmental hazards on the sustainability of an area and largely excludes consideration of demographics.

While some of the flood-specific indices attempt to quantify levels of risk for different areas based upon the physical environment and potential for flooding (Fedeski and Gwilliam 2007), others are designed to incorporate the human characteristics of an area in the vulnerability assessments. While not karst-specific, the Flood Vulnerability Index (FVI) is designed to assess sources of vulnerability to flooding related to both the physical environment and socioeconomic demographics to aid in the formulation of management and mitigation strategies (Balica 2007); however, karst features may impact an area’s vulnerability and need consideration as well.

2.3.1 Flood Vulnerability Index

The Flood Vulnerability Index (FVI) has been modified and adapted numerous times in research to align with various scenarios or environments, such as coastal, urban, or arid areas, but has yet to be utilized or adapted for karst environments; the FVI generally incorporates indicators that focus on three main factors of flood vulnerability: exposure, susceptibility, and resilience (Figure 2.4) (Balica and Wright 2010; Balica et al. 2012; Nasiri et al. 2019, Salazar-Briones et al. 2020). Exposure relates generally to the level or likelihood that humans or property may experience flood impacts based upon their location. Susceptibility is associated with the social characteristics associated with flood impacts, such as level of preparedness communities have for flood events, or the ability for appropriate institutions to provide aid before, during, or after flood events. Most specifically, susceptibility is defined by Balica and Wright (2010, 322) as “the extent to which elements within the system are exposed, which influences the chance of being harmed at times of hazardous floods.” Resilience refers to the ability of a community or system to maintain or adapt basic operations and functions within its social, environmental, physical, and economic realms when events like floods happen, while continuing to provide essential resources and services to the community. In the context of flood events, resilience can really only be assessed in areas where there is knowledge of previous events as the term is used to describe circumstances both during and after a flood event. Exposure relates more to the time during a flood, while susceptibility generally describes experiences before and during events. Overall exposure and susceptibility are added together and contribute to vulnerability of an area, while resilience is subtracted as a community's level of resilience can reduce vulnerability.

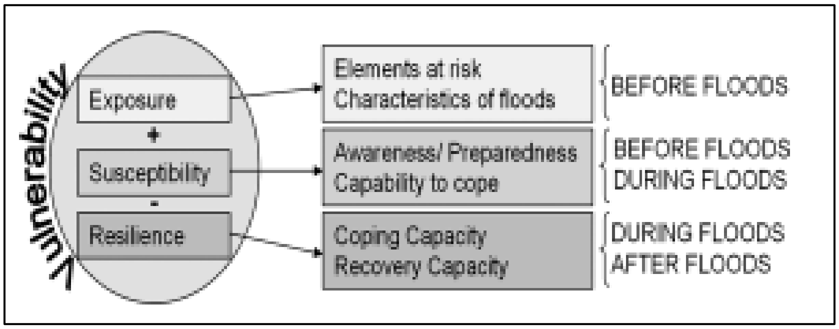


Figure 2.4 The three main factors of vulnerability (Source: Balica and Wright 2010).

Within the FVI, exposure, susceptibility, and resilience are generally determined based upon four components: social, physical, environmental, and economic vulnerabilities (Figure 2.5). The intersection and associations between the three main factors and the four components are what provide the basis of the FVI and allow for analysis of a region's vulnerability to flood events. These four components are assessed using various indicators, which can vary depending upon the study area at hand. Economic vulnerability is important to address, as communities can be made more or less vulnerable based upon economic factors, as more affluent areas generally have better flood infrastructure in place, thus reducing flood impacts, while also having more resources that allow for recovery after flood events. Economic status of an area can also determine ability to continue basic functions and services during or after a flood event, as communities need access to basic products and services. In the context of this study, environmental and physical vulnerability will be assessed together into one category referred to as 'environmental conditions,' as the two are closely related. Assessing vulnerabilities associated with the environmental conditions of an area is inherently and obviously important, as the physical environment and conditions of an area can determine location and magnitude of flooding, in addition to exacerbating damage and hazards associated with flooding. A person or community's vulnerability to hazards extends beyond environmental or economic vulnerability to social vulnerability as well. Socioeconomic demographics can have profound impacts on the susceptibility of an area to harm from hazardous events like flooding, based upon a number of factors including age, gender, household size, or race/ethnicity (Cutter 1996; Cutter et al. 2008).

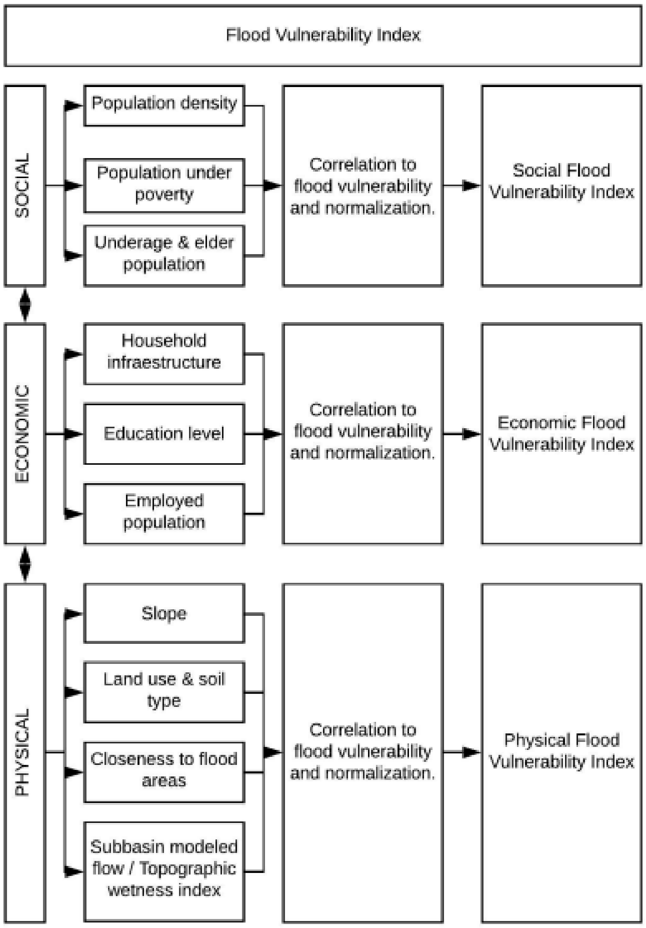


Figure 2.5 Social, economic, and physical indicators used to create an FVI (Source: Salazar-Briones et al. 2020).

Despite the application of the FVI in a variety of environments, many researchers around the world have reported similar conclusions related to flooding and vulnerability. Many researchers who have utilized or adapted the FVI have concluded that assessing various types and sources of flood vulnerability can help to make both the inhabitants of a community and the governing bodies more aware and educated about flooding, which can help to inform policies, regulations, and mitigation strategies (Balica et al. 2012; Kumar et al. 2021; Salazar-Briones et al. 2020; Sebald 2010). Implementation of the FVI has also highlighted in many areas the lack of data available regarding flooding, vulnerabilities, and equity, which can be a substantial issue for land managers or governing bodies when attempting to mitigate or recover from flood impacts and there is not enough data available to make informed decisions (Balica et al. 2012; Kumar et al. 2021; Salazar-Briones et al. 2020; Sebald 2010). In the conclusions of research regarding the application of the FVI in arid regions of developing countries, researchers stated,

> "The FVI results obtained allow the authorities of different government orders, urban planners, local communities, insurance companies, real estate developers and citizens in general, to have the necessary information for correct decision making, as well as to change from a reactive to proactive response in the management of disasters caused by floods, contributing to the migration of traditional planning schemes towards a sustainable urban planning process" (Salazar-Briones et al. 2020, 15).

The FVI has been simplified or adapted by many researchers to align with various environments but has not yet been applied to a karst region, presenting a gap in the literature regarding wholistic assessments of flood vulnerability in karst areas of the world. The FVI is intended to focus on not solely the physical environment, but to include the human aspects of flood vulnerability. When an area floods, the people inhabiting the land are impacted; when people move into an area and change the landscape, the nature and patterns of flooding are impacted. Examining the human-environment intersections and understanding the ways in which an area is vulnerable to flooding can have profound impacts on the success of management.

2.4 Environmental Equity

The concept of environmental equity refers to the idea that both known or potential environmental risks can disproportionately affect certain demographic groups more than others (Anderton et al. 1994). Poor management practices or complete lack of any type of management can lead to undue hardship for some groups, particularly ones of lower socio-economic status with less resources available to prevent or mitigate environmental problems themselves. Environmental equity can be closely associated with 'environmental racism,' which describes environmental hazards or disasters that place undue hardship upon racial or ethnic minorities (Anderton et al. 1994). Environmental inequity can manifest in many different situations, such as through location of hazardous waste treatment and disposal facilities, inadequate flood measures, or contaminated drinking water. When these situations impact marginalized communities that may not have the financial resources to rebuild or fix the new problems, economies could be further burdened and families may choose to move out of these neighborhoods.

Lack of resources or ability to relocate when regions become uninhabitable due to flooding is not unique to developing or low-income countries. Even in the United States, people around the country experience damaging impacts to homes and environments without the ability to mitigate the impacts or repair the damage that occurs. Low-income areas are disproportionally affected by climatic phenomena, as homes and structures are generally built with lower standards that may not always be built to account for the worst (Flanagan et al. 2011). These low-income areas can lack the resources to plan for the damage, repair it, or even to leave the area when these events occur (Flanagan et al. 2011). There is still much disagreement on how climate change impacts will manifest, meaning there is variability in the modelling telling exactly how much flooding to expect or where exactly to plan for it. For example, an intergovernmental report released by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2018 stated, “Although global assessments of climate change impact can provide a rough indication of trends and expected impacts, the local conditions define how vulnerable the communities are to these water security threats” (Mendoza et al. 2018, 8). This also further emphasizes the diparity between higher and lower income localities, as more affluent areas are inherently going to be able to develop flood risk management plans much more easily. This presents a growing issue throughout not only the United States, but also low-income areas around the world. Understanding how areas that lack the resources to prevent, mitigate, or respond to various climatic events, with particular respect to flooding, can develop and implement management plans will be crucial in the future as the global climate changes.

In 2005, Hurricane Katrina arrived on the Gulf Coast of the United States in what would be one of the most expensive and deadliest natural disasters that the United States had ever seen (Morse 2008). New Orleans, Louisiana was one of the hardest hit cities, mainly due to the failure of the levee system the city had in place, which led to major flooding around the city with ruptured canals and overwhelmed drainage systems (Morse 2008). The flooding from the hurricane emphasized the extreme racial disparity as predominantly white neighborhoods that exist along the Mississippi River, where the colonial plantation homes were concentrated, saw very little flooding due to higher elevations and the natural levee system the Mississippi River provides (Morse 2008). The layout of the city also proved to be disadvantageous for communities of low-socioeconomic status as federal housing and poor access to transportation isolated the 30 percent of households around the city that did not own personal vehicles (Morse 2008). A significantly higher proportion of African American residences than any other ethnic group were still flooded over a week after the hurricane occurred, while white populations were able to recover much more quickly (Morse 2008).

A term that has been closely associated with environmental justice is the acronym 'NIMBY,' which stands for 'not in my back yard' (Mohai et al. 2009). This refers to the idea of communities or individuals objecting to perceived hazardous or unsightly developments or other changes in the local community, particularly when the same individuals or communities do not object to these things occurring in other areas (Mohai et al. 2009). NIMBY, in theory, is an understandable mindset by the standards of not wanting potentially hazardous situations to occur in the local communities. Rather ironically, this practice can sometimes result in environmental inequities as the perceived hazards end up in the 'backyards' of the politically powerless communities who do not have the same resources to protest against the presence of such developments (Saha and Mohai 2005). Many of these developments have to occur in some form or fashion, so when the more advantaged communities protest the presence of these projects, the socially marginalized communities end up bearing the brunt, resulting in even more disadvantaged communities (Pastor et al. 2001). Following the Love Canal Crisis in the 1970s, the concept of NIMBY became a much broader environmental equity issue as hazardous facilities began to be drastically disproportionately sited in neighborhoods composed of working-class and people of color, which was largely attributed to the greater success of wealthy, white neighborhoods at keeping the locally unwanted land uses (LULUs) out (Saha and Mohai 2005).

In the late 1980s, Earickson and Billick (1988) studied environmental inequity and racism in the United States. The researchers focused on Louisville, Kentucky and Detroit, Michigan, where residences of working class, low-income, and mostly African American families were found to be closely concentrated around polluted areas (Earickson and Billick 1988). Further research conducted in the United States indicated that working class, low-income, and African American communities, in particular, were disproportionately impacted by pollution (Bullard 1990). In 1992, the EPA released a report that acknowledged that lower socio-economic and minority groups are generally more likely to be exposed to environmental pollutants than other groups, which could result in adverse health effects (Roque 1993); however, the report also maintained that while differences existed between racial or economic groups in terms of death or disease rates, this could not be definitively attributed to exposure to environmental pollutants (Roque 1993).

Within the policy making process, equity, fairness, and justice can be assessed based upon a set of criteria developed by researchers (Hay and Trinder 1991; Trinder et al. 1991). The criteria are: procedural fairness, maintenance of conditions, formal equality, substantive equality, need as demand, basic need, wider needs or wants, liberty rights, and claim rights (Trinder et al. 1991; Hay and Trinder 1991). The researchers developed the principles to encompass a wide variety of scenarios and potential inequities in order to appropriately evaluate and address environmental injustice. These criteria can aid in achieving environmental equity when public participation is utilized during the policy making process, if these principles are sufficiently maintained. In research conducted by Kasperson et al. (1992), the authors argue that benefits and burdens must be evenly distributed in order to achieve equity, though reduction of inequalities is a more morally correct option than mere compensation for burdens, as avoiding harm from the beginning is the just choice.

Unfortunately, there is not very explicit policy in the United States that directly addresses environmental justice or inequities. Typically, it is a problem left to land managers, local officials, and the general public to solve through work with community leaders, politicians, non-profits, and legal recourse. Environmental inequity can be a difficult problem to solve, especially when there is potential hesitancy on the part of government and land managers to admit to the presence of inequity. Public participation has been shown to aid in reducing environmental inequities and promoting changes that benefit disadvantaged groups (Hampton 1999). Darokin and Schulkin (1994) studied the co-evolution of social justice and environmental concerns and found evidence that groups with higher socio-economic status or more advantaged communities generally have improved access to the decision-making processes than the disadvantaged communities. Using public participation methodologies that are specialized for different cultural or social needs of various groups can greatly impact effectiveness in reducing inequities (Hampton 1999).

The Weldon Cooper Center for Public Service Demographics Research Group at the University of Virginia developed the Racial Dot Map in 2013 (Figure 2.6), which features one dot per person for the entire United States, displaying the racial and ethnic demographics across the country (DRG 2017). The dot map utilizes census data from the 2010 Census and is based upon census blocks, which is the smallest area that the census collects (DRG 2017). There are five racial categories that the map focuses on: non-Hispanic white, non-Hispanic Black, non-Hispanic Asian, Hispanic or Latino, or other, which accounts for multiracial identifications (DRG 2017). The dot map can be utilized to display how integrated or segregated various areas are by race or ethnicity. Additionally, the map can be used for further analysis, such as overlaying flood pattern and distribution maps with the dot map. This can showcase what areas are primarily receiving the bulk of the flood impacts and if there are any specific demographic groups that are carrying the burden of flooding. These data could help to prove the presence of environmental inequalities or environmental racism in different areas.

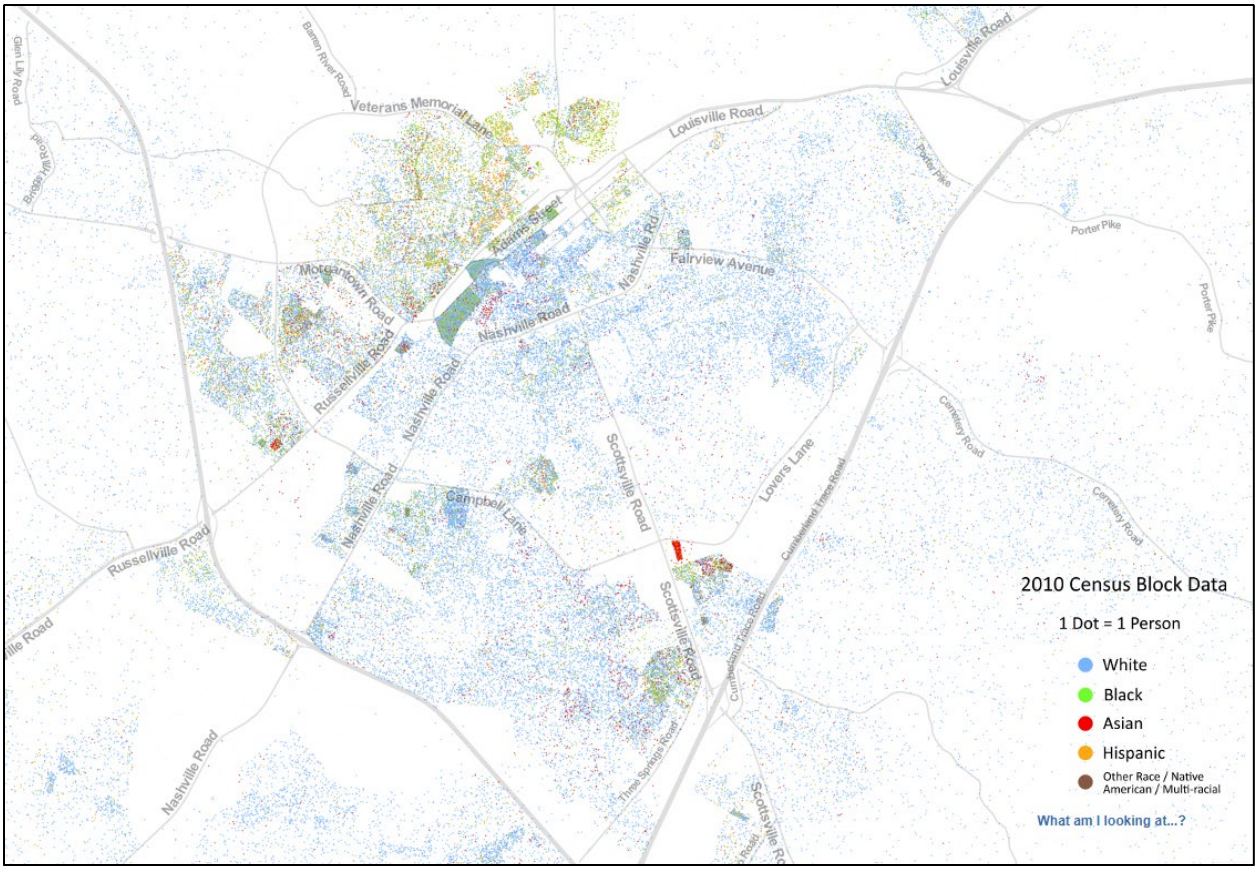


Figure 2.6 The Racial Dot Density map of Bowling Green, Kentucky (Source: DRG 2017).

2.4.1 Flood Inequity in Karst Landscapes

In 2010, the city of Nashville, Tennessee saw one of the worst flood events in the city's history when rainfall exceeded 17 inches (43 cm) within a matter of just a few days, reaching the third highest flood levels in more than 140 years of recorded history, exceed only by the flood events in 1927 and 1937 (Metropolitan Government of Nashville and Davidson County Tennessee 2021; NWS 2022). The Nashville Metro Planning and Metro Codes estimated that the flooding resulted in more than $2 billion in flood damage to private property around the city, as the Cumberland River crested a full 12 feet (4 m) above flood stage (Metropolitan Government of Nashville and Davidson County Tennessee 2021). In some areas surrounding the Cumberland River, the National Weather Service determined the flood events to be so extreme that the chances exceeded solely 100-year flood events and instead were deemed 1,000-year flood events, which included Davidson County where Nashville is situated (NWS 2021).

While the 2010 flooding in Nashville was largely riverine-based, Nashville, like much of the states of Tennessee and Kentucky, sits upon karst topography (Moore and Drumm 2018). This can make management of flood events particularly tricky, especially in scenarios as extreme as the 2010 flood. Despite the fact that this particular flood event was largely unrelated to the karst features of the city, the 2010 flood event still made very apparent the lack of preparedness and planning on the city's part to account for disadvantaged populations and evacuation. Homeless camps and tent cities inhabited by homeless populations were completely swept away in the flooding, leaving the much of the homeless with even less than they already had (Spencer 2010). Many people lost their homes and all of their possessions, leaving them at the mercy of shelters and aid relief workers. This region had not seen flooding like this during the lifetime of anyone currently living, so many of the people that were hardest hit did not have any form of flood insurance to help rebuild after losing everything (Spencer 2010). Flood-related inequities in Nashville that could cause disproportionate impacts to certain neighborhoods in the city during karst-based flood events as well were extremely emphasized by the 2010 event.

Flood events like the 2010 Nashville flood emphasize the need for research and action to address the inequalities that exists when flooding occurs, especially in karst landscapes. People lose their lives, homes, property, to events that are generally anticipated to become worse as climate change increasingly impacts the world. Karst landscapes can exacerbate flood impacts, particularly due to the fact that the topography and where the flooding stems from is typically much less understood than river or ocean flooding. The lack of understanding can result in poor management and response when flooding occurs. Additionally, insurance companies typically do not offer adequate coverage for flood damage or destruction due to karst flooding. The Kentucky Farm Bureau offers insurance policies that address karst, but the coverage mainly only extends to sinkhole formation, rather than flooding, which is particularly limiting in a state that is dominated by karst landscape (KFB 2021). Because there is a significant gap in karst flood insurance policies, people impacted by these events have to be prepared beforehand in order to be able to more easily recover. The people and communities who do not have the resources to be able to do so are placed at an even greater disadvantage and could be left with nothing after extreme events.

In the City of Bowling Green (CoBG), urban karst flooding has been a significant problem as rapid urbanization has altered the karst hydrology extensively, making stormwater and groundwater issues manifest across the sinkhole plain. The CoBG utilizes the Daugherty Manual for the current standards for stormwater basin designs and flood control (Daugherty 1976). The manual, which was written in 1976, has not been comprehensively updated in the nearly 50 years since its creation. Given advancements in technology, infrastructure design, and the field of stormwater management, a manual created in 1976 is a largely outdated standard to utilize in a rapidly changing urban environment like the CoBG. The management plan in place for the CoBG is the usage of Class V injection wells that are intended to alleviate some of the stressors caused by flooding (Nedvidek 2014; Shelley 2018). Studies conducted in the 1980s regarding urbanization in a karst landscape and the resulting hydrological problems determined that the Class V injection wells utilized in the CoBG did not successfully reduce the severity of flooding due to improper siting, design, and maintenance (Crawford 1982). The studies indicated that the wells and management practices could actually be contributing to contamination of groundwater and perpetuating sinkhole collapses (Crawford 1982).

The CoBG is one of the fastest growing cities in Kentucky, yet there exists a substantial gap in research regarding current conditions of management practices of the karst landscape around the city, as the general plans and designs of the injection wells have not been updated over the last few decades. The lack of research into new strategies that have the potential to be more successful is particularly detrimental given the apparent inequity that seems to exist in terms of the location of the flooding around the CoBG. Lower-income and marginalized communities appear to bear the brunt of the flood impacts, which could leave the communities at an even more dramatic disadvantage. In 2010, the CoBG experienced the same storm events as Nashville did, resulting in major flooding in the area. The wells and karst features around the city were unable to handle the heavy amounts of precipitation that occurred over such a short period of time and were completely inundated. The measures put into place to prevent or slow flooding proved to be ineffective, especially in such an extreme event. Understanding how to improve management strategies to better handle flood events could alleviate many of the stressors these events place upon the city, particularly in communities of lower socio-economic status who may lack the resources to rebuild and recover in the wake of flooding.

Understanding both the science behind climate change and the characteristics and features that make karst landscapes unique is vital to making and understanding plans for the future to mitigate the impacts of climate change in karst areas. Environmental equity has to be addressed moving forward into the future, as the disadvantaged populations will need aid in protecting their homes and communities. Various disciplines and factors, such as social, environmental, and economical, must be synthesized to create a more impactful assessment, while leaving space for flexibility and adaptation. A better understanding of the barriers and limitations to the adaptation of these strategies is incredibly important as well, as policies and infrastructure likely cannot be implemented effectively if there is no understanding as to what is standing in the way of these advancements. Robust strategies and plans that focus on the sustainability of the karst landscapes account for the level of uncertainty that surrounds climate change, while also including provisions for environmental equity, are necessary. Researchers around the world are already pursing the development of different strategies to try to accomplish this goal, but there needs to be a stronger emphasis on sustainability and setting actionable goals. With the growing sense of urgency associated with climate change action, methodologies need to be created or updated to account for climate change and aid in protecting karst areas against the impacts of climate change, in addition to methodologies that are intended to achieve environmental justice in order to make informed decisions about management going forward.

2.5 NFIP

The National Flood Insurance Program (NFIP) is a program managed by FEMA that is intended to help provide insurance coverage to communities around the United States in an effort to reduce the socio-economic impacts of flooding. The NFIP offers insurance policies to property owners, renters, and businesses in participating communities or property on federal land, as many homeowner or business insurance policies do not cover flood impacts to either buildings or possessions within the building. In areas with high flood risk or those within flood zones, flood insurance is a requirement for any property built within the area.

In order to become an active community in the NFIP, there are several requirements. The community requesting to join the program must develop a floodplain management ordinance that aligns with the NFIP criteria and have a Flood Insurance Rate Map (FIRM) or a Flood Hazard Boundary Map (FHBM), both of which are developed by FEMA. A FIRM is a map of delineated Special Flood Hazard Areas (SFHA), Base Flood Elevations (BFEs), and risk premium zones. A FHBM outlines the special hazard areas that related to flooding, mudflow, and erosion. The initial phase of a community participating in the NFIP is the Emergency Phase, during which communities can still receive insurance coverage, though not as extensively as active communities. Once a community is a participating community in the NFIP, the eligibility of each property is dependent upon the property's location, and whether both the building and the contents of the building meet specific insurability requirements.

The cost of utilizing the NFIP is dependent upon the level of risk to flooding and damage associated with the building being insured. This means that the higher the risk of flooding is, the higher the insurance premium is going to be. In late 2021, FEMA released a revised Flood Insurance Manual outlining the newly developed risk assessment approach, Risk Rating 2.0, an update to the previous risk assessment methodology utilized by the NFIP since the 1970s. The intention behind the development of Risk Rating 2.0 extended beyond solely bringing the risk assessment methodology utilized by FEMA into the 21st century. In the 2021 Flood Insurance Manual, the FEMA Deputy Associate Administrator for Insurance and Mitigation David Maurstad stated,

> "The goal of Risk Rating 2.0 is to deliver easy-to-understand premiums that are distributed more equitably across all policyholders based on the replacement cost value of their home and their property's unique flood risk. By addressing the current inequities, Risk Rating 2.0 puts the NFIP on the path towards sound financial footing by creating a more stable program that is accountable to taxpayers, more accurately reflects flood risk to both

> policyholders and nonpolicyholders, and helps disaster survivors recover faster after floods." (FEMA 2021, 3).

One of the key differences in the updated risk assessment methodology is that flood zones and BFEs are no longer the driving factor behind risk calculation. While flood zones and BFEs are still taken into consideration, Risk Rating 2.0 utilizes variables related to cost to rebuild, elevation, flood type, flood frequency, or distance to water source to calculate flood risk (FEMA 2021).

Overall, without a method to assess vulnerability and risk perception in an urban karst area, there lacks a sufficient means by which these communities, particularly those underserved and historically excluded groups, can develop effective flood mitigation strategies. Collectively, many tools exist for evaluating flood threat and vulnerability, as well as karst features and their impacts, but none directly focus on the issue or urban karst flood vulnerability and its impacts. There needs to be a direct examination of how flood planning can be achieved in urban karst communities using both new and existing approaches.

Chapter Three: Study Area

This study is an analysis of social vulnerabilities and flooding in karst regions, focusing primarily on the city of Bowling Green (CoBG) in Warren County, Kentucky (Figure 3.1). With the synthesis of GIS, modeling, and focus on management strategies within the study area, predictions and management plans could potentially be refined and made more reliable. The sensitive nature of karst landscapes in conjunction with growing populations that depend upon the resources these areas provide means that an understanding of the potential situations that will come with climate change is becoming increasingly necessary, especially in areas that are economically or socially depressed and lack the resources to effectively recover. Action following the predictions and analyses will be crucial in order to properly take care of both the landscapes and the people who depend upon them.

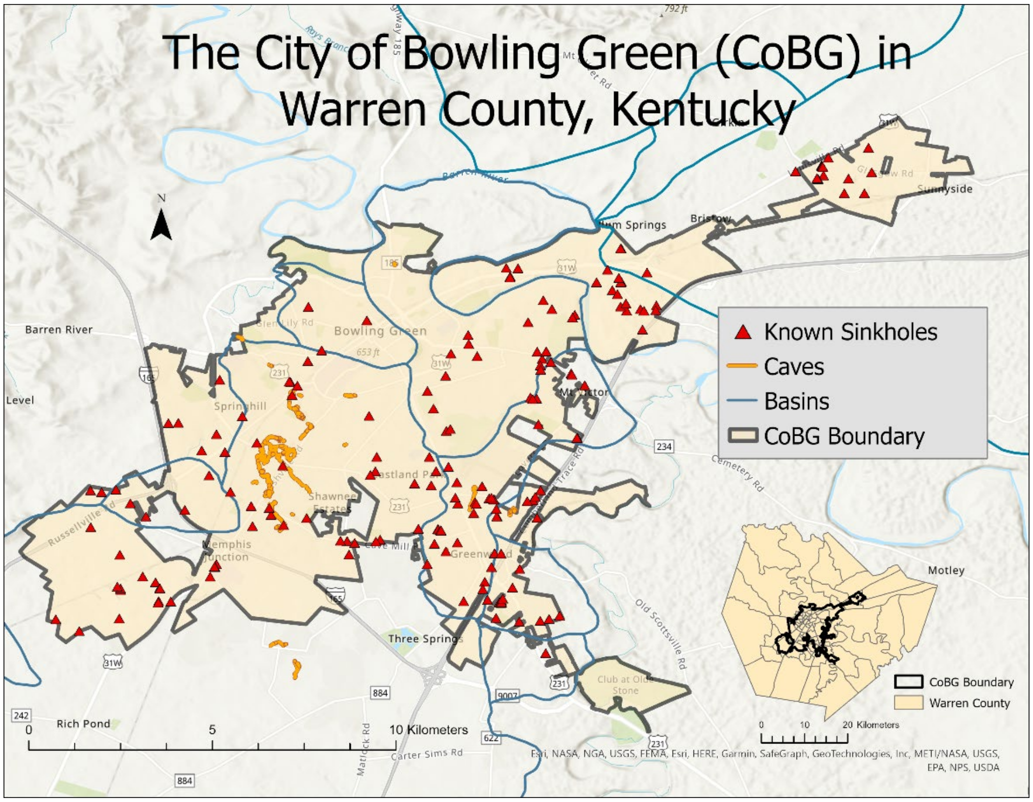


Figure 3.1 Map of the CoBG with known caves and groundwater basins. (Source: created by author).

3.1 City of Bowling Green (CoBG)

Located in south-central Kentucky, the CoBG in Warren County is the largest city in the region and third largest in the state, with a population of 70,543 in 2019 (Census Bureau 2019). The city lies at an average elevation of about 492 feet, or 150 meters, above sea level (Reeder and Crawford 1989) While this area is predominantly rural with low population densities currently, the region is rapidly growing at a rate that exceeds the national average of population growth (Southcentral Kentucky 2020). On average, there are about 1,537 people per square mile (Census Bureau 2019). Located south of Louisville, Kentucky and just north of Nashville, Tennessee, the CoBG is a common stopping place for tourists from around the United States. With the growing population of the city and the surrounding area, development has increased and grown outwards towards the borders of the city, which will become increasingly problematic as many of these new development areas are located in areas that are prone to flooding (CoBG Planning Commission 2005). Within the city, the primary land cover is considered to be "Developed," while the secondary type is "High Intensity Residential" (USGS 2010).

While about 70 percent of the CoBG is white, there is a relatively significant population of foreign-born persons at about 13 percent, according to the US Census Bureau (Census Bureau 2019). About 13 percent of the population is Black or African American alone, about 8 percent is Hispanic or Latino alone, and about 5 percent is Asian alone (Census Bureau 2019). The CoBG is a common location for resettlement in Kentucky, as the International Center of Kentucky (ICofKY) is located in the CoBG. The ICofKY works with the Department of State and the US Committee for Refugees and Immigrants to resettle immigrants, refugees, and human trafficking victims from 30 different countries around the world (ICofKY 2022).

The ratio of male population to female is relatively normal, with about 49 percent male and 51 percent female (Census Bureau 2019). About 11 percent of the CoBG is 65 years old or older, while about 21 percent is 18 years old or under (Census Bureau 2019). The percentage of persons living with a disability that are under the age of 65 is about 12 percent, while the percentage of persons without health insurance that are under the age of 65 is about 8 percent (Census Bureau 2019). According to the US Census Bureau, about 24 percent of the population is living below the poverty line (Census Bureau 2019). The average unemployment rate in Bowling Green in 2021 is about 4.4 percent (Bureau of Labor Statistics 2021). The owner-occupied housing unit rate is only slightly above a third of the population at 39 percent, though the presence of Western Kentucky University could contribute to a higher percentage of renters as university students require temporary housing (Census Bureau 2019). The average household size is about 2.4, while about 16 percent of households speak a language other than English at home (Census Bureau 2019). In the population of people aged 25 years or older, about 85 percent are high school graduates or higher, and almost 33 percent have a bachelor's degree or higher (Census Bureau 2019).

3.1.1 Environment of the CoBG

South-central Kentucky has a fairly moderate climate and experiences all four of the seasons distinctively. The CoBG generally sees about an average of 50.12 inches (1273.05 millimeters) of rain annually, the majority of which generally occurring in the spring and summer seasons from March to July (NOAA 2020). In the summertime, the average monthly temperature is about 78.1 °F (25.6 °C), though temperatures can get into the nineties or higher on extreme days (NOAA 2020). In the winter months, temperatures generally hover around 39.6 °F

(4.22°C) (NOAA 2020). In the spring of 2021, the National Oceanic and Atmospheric Administration released updated data regarding climate normals across the United States for 1991 through 2020. The state of Kentucky saw an increase in annual mean temperature, with some parts of the state warming slightly more than others, including areas in south-central Kentucky (NOAA 2021). Across the state, temperatures rose by about 0.5 to one degrees Fahrenheit over the 30-year time period (NOAA 2021). Kentucky also saw a general increase in overall precipitation during the same span of time, with about one to five inches increase per decade across the state (NOAA 2021).

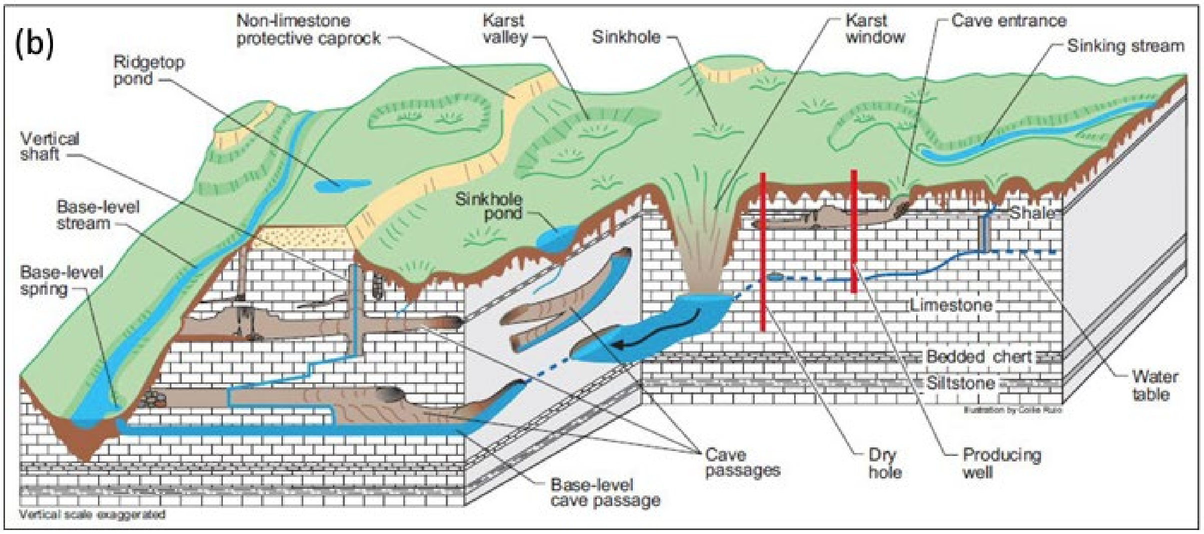


Figure 3.2 Typical surface and subsurface karst features in the Western Pennyroyal karst region of Kentucky (Source: Currens 2002).

The karst landscape of south-central Kentucky is considered to be a part of the Western Pennyroyal karst area, which is the largest segment of Kentucky's karst areas (Figure 3.2) (Currens 2002). The area is populated with doline karst (sinkholes and depressions) and an extensive karst plateau, dominated by limestone and bedrock surface (White et al. 1970). The CoBG is located above the upper Mississippian Limestones, primarily of the Ste. Genevieve and

St. Louis formations (Crawford and Groves 1984; Shelley 2018). The stratigraphic units of the area are composed of fine-grained limestone lithology that exist in varying thickness with two separate confining layers, which includes the Lost River and Corydon Ball chert (Woodson 1981). The plateau of limestone has propagated the flow of water through the landscape, forming underground passageways.

Some of the largest caves and cave systems in the world are found in this region, including Mammoth Cave and the Flint Ridge Cave System. Because of this, south-central Kentucky is one of the most famous and researched karst areas in the world. Within Warren County, there are five major surface streams: the Green River, Barren River, Gasper River, Drakes Creek, and Jennings Creek (Crawford and Hoffman 1989). The CoBG sits upon the Lost River Cave System, another extensive karst system in the region, which includes subsurface streams that ultimately flow into Jennings Creek before discharging in Barren River (Groves 1987). Lost River Cave has about 11 kilometers of mapped passageways and is part of the Lost River Groundwater Basin but is not the only cave in the basin. Robinson Cave, Sullivan Cave, and State Trooper Cave are a few of the caves that are also located in the Lost River Groundwater Basin and the system as a whole is largely underground except for several blue holes and karst windows (Crawford and Hoffman 1989; Figure 3.3). The headwaters for Lost River are located south of the city limits near the border between Warren County and Allen County and flow north toward the final discharge point, Lost River Rise (LRR), which is located in Lampkin Park within the CoBG and drains agricultural and urban runoff (Crawford and Hoffman 1989). Lost River Cave has a history of flooding, in addition to the areas near Jennings Creek and the Barren River. Within the CoBG, there are unmodified sinkholes and over 2,000 Class V Injection Wells, which includes modified sinkholes, in addition to numerous other karst features (Shelley 2018). Stormwater that reaches the various infiltration sources flows through numerous subsurface passageways before resurfacing at one of the karst springs located within the city (Shelley 2018) and can contribute to flooding when the water table rises. A few of the major ground water basins in the CoBG are Harris Spring, Double Springs, New Spring, and Graham Springs (Nedvidek 2014; Shelley 2018).

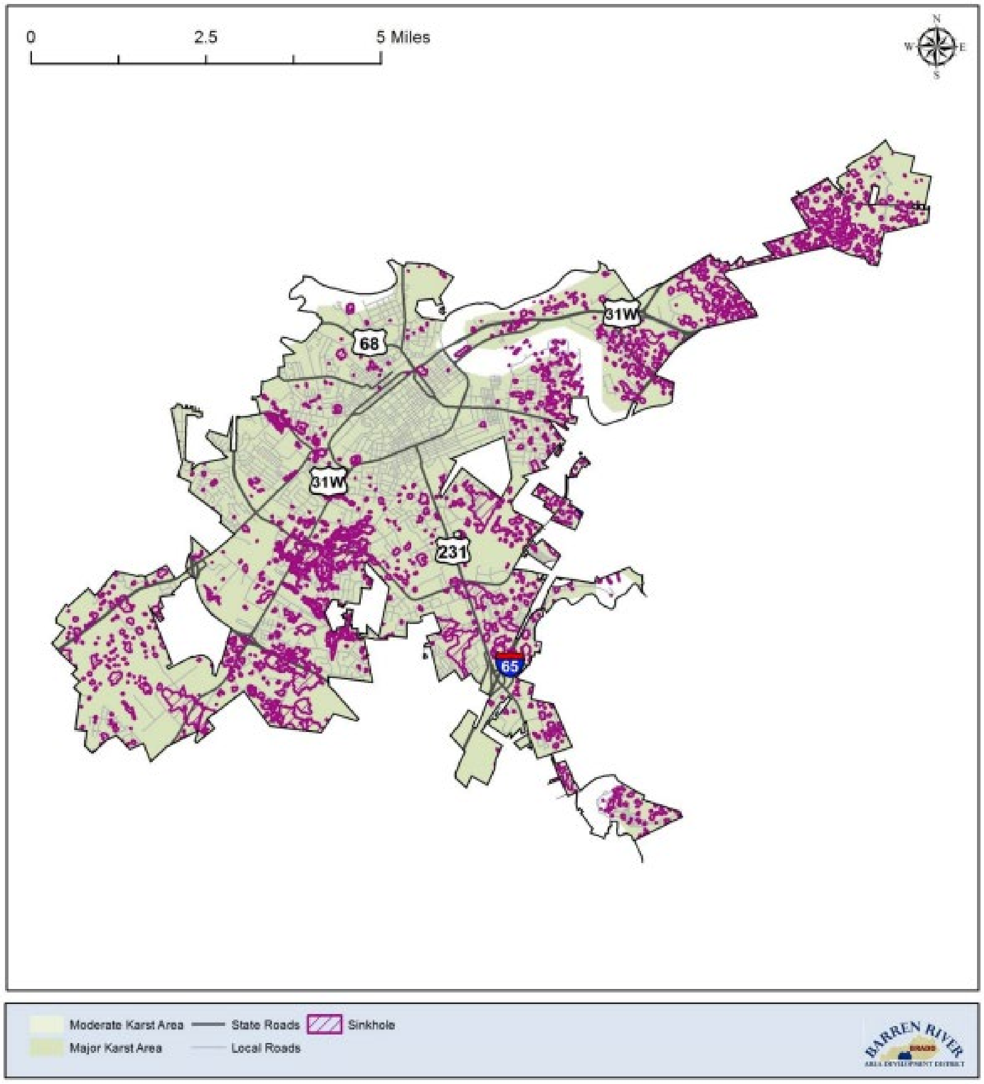


Figure 3.3 Sinkhole and karst locations in the CoBG (Source: BRADD 2011).

The unique landscape that characterizes the area makes it an important place to study the impacts of climate change. Karst landscapes in general are inherently sensitive and the growing population of the area is not anticipated to have positive effects on the landscape. This presents the need for planning and preparation of management strategies to attempt to anticipate the needs of both the land and the people as climate change impacts the world in the coming years.

3.1.2 Flooding in the CoBG

Because the CoBG sits upon karst landscape, the flooding that much of the community experiences is related to recharge and flow, rather than riverine flooding. One of the more common flood occurrences in the CoBG is sinkhole flooding. Sinkhole flooding can occur when the amount of water or runoff exceeds the discharge or storage capacity of the sinkhole, resulting in ponding of water in the sink (Sweeting 1972). The conditions of the landcover can heavily influence the amount or direction of surface runoff, which can subsequently impact the presence of flooding in a sinkhole (Feeney 1986). Impervious surfaces, such as sidewalks, streets, and parking lots, greatly alter the landcover and the paths that water can take. The amount of area available for infiltration is lowered, leading to increased runoff volume and increased amount of time for runoff to seep into the subsurface (Feeney 1986). Sinkhole flooding can also occur when surface and subsurface streams are at flood stage, thus increasing the water table and exceeding the capacity of the sinkhole (Feeney 1986). Due to the karst environment and presence of sinkhole flooding in the CoBG, there are many small pockets of land that are designated as FEMA flood zones throughout the city, rather than solely the areas that surround surface streams and rivers. The areas of low elevation in sinkholes are particularly susceptible to flooding, though flooding will not necessarily occur in every sinkhole. A CoBG official stated, “Sinkholes are not just blanket designated as flood zones. It has to have been noted and documented to have flooded before it can be designated as a flood zone, which has to happen at the state or federal level, not the local level" (Pers. Comm. 2022).

Numerous studies have been conducted in the past decades to assess flooding in karst environments throughout Kentucky and the CoBG in attempts to better understand the nature of the flooding and determine solutions for fixing or mitigating the flooding (Crawford 1982; Feeney 1986; Zhou 2007). Although the city and local government have implemented many management strategies such as drainage wells, regulation of new development plans, and the removal of many properties built in flood zones, there are still many areas of the city that experience frequent flooding.

One area of Bowling Green that has experienced persistent flood problems for decades is South Sunrise Drive, located towards the western side of the CoBG. Feeney (1986) conducted an extensive study of the South Sunrise/Media Drive sinkhole by assessing several different past flood events and analyzing the events to determine the reasons behind the flood events and the characteristics of the area. The sinkhole area had seen repeated flood events, despite the numerous drainage structures that had been installed to combat the flooding (Feeney 1986). A substantial proportion of the area surrounding South Sunrise Drive has been designated by FEMA as a flood zone; however, there are still many properties that are located within the sinkhole and flood zone. In 2010, a property on South Sunrise Drive located just outside of the FEMA designated flood zone was added to the stormwater mitigation priority list (SMPL), though the property was removed from the list in 2021. The SMPL is further described and discussed in Section 3.1.3. Properties throughout the South Sunrise area have been experiencing flood problems for more than fifty years despite numerous attempts to control the flooding, which is unfortunately not entirely uncommon for Bowling Green.

3.1.3 Regional Landscape Management

Warren County and the CoBG are serviced by the Barren River Area Development District (BRADD), which is an organization dedicated to facilitating economic growth and planning in addition to development within a multi-county region. BRADD provides a link between the local, state, federal, and private agencies associated with ten counties in south-central Kentucky (Figure 3.4): Butler, Edmonson, Hart, Logan, Warren, Barren, Metcalfe, Simpson, Allen, and Monroe (BRADD 2021). One of the main goals of BRADD is to "Provide support and assistance to the elected officials, leaders and community stakeholders of the region in achieving their missions" (BRADD 2021). As such, BRADD has developed a Regional Hazard Mitigation Plan (HMP) for each of the counties that are serviced and each includes a regional description, overview of the planning process, risk assessments for various hazards, mitigation strategies, and plan maintenance procedures. Among the risk assessments are assessments specific to both flooding and karst or sinkholes. Within the flooding risk assessments, BRADD focuses more on flooding that stems from rivers and streams, or FEMA-designated floodplains, but does include acknowledgement of the possibility of flooding due to reasons beyond overflow of bodies of water, including karst topography, flash floods, and urban floods. Within karst risk assessments, the HMP primarily assesses potential for sinkhole development throughout the BRADD region. The majority of Warren County, including the CoBG falls within a high to moderate risk of sinkhole development (BRADD 2011). For all risk assessments in the HMP, vulnerabilities are profiled by manmade, natural, systems, and populations.

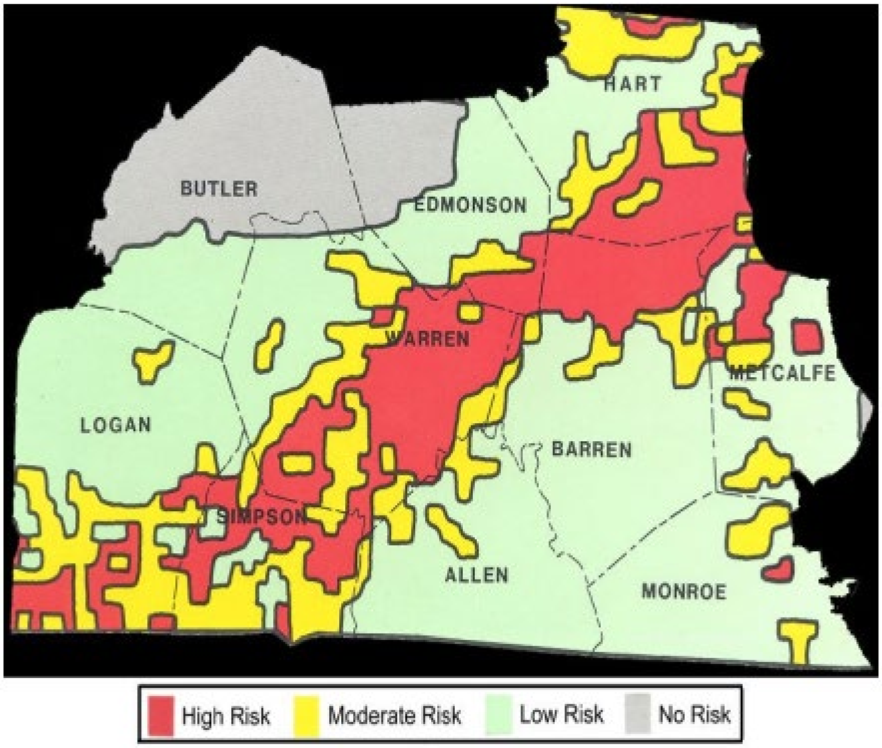


Figure 3.4 BRADD Region Sinkhole Risk (Source: BRADD 2011).

BRADD developed six broad goals for mitigation of each of the hazards with separate objectives for each, including increasing public awareness of existing hazards, increasing technical capabilities of the local jurisdictions to reduce potential losses from hazards, and reducing disruptions to essential public services and infrastructure by reducing vulnerability to critical facilities during hazard events (BRADD 2011). Each proposed plan of action is assessed before implementation with prioritization assessments based upon costs and benefits, economic effects, potential to save or benefit life, property, or essential services, consistent with plans and priorities, and appropriateness of the action proposed. Depending on the calculated level of priority for a hazard, action can be implemented anywhere between immediately or ten years away. One of the current action items listed in the HMP is to create an inventory of susceptible areas around the CoBG, such as roads and bridges prone to flooding, and implement measures to correct these issues. This item was given a priority level of ‘High,’ which equates to one to three years to implement (BRADD 2011). One of the completed action items with a ‘Very High’ priority was the development of a stormwater management plan to reduce flood impacts, such as erosion and property damage (BRADD 2011). While this plan is listed as completed in the HMP, there is still progress to be made around the CoBG to implement and improve upon this plan. This is particularly important as another listed action item is to purchase and remove repetitive home floods, which was given a low priority and a seven-to-ten-year timeline, though is listed as ‘Ongoing – currently completed’ (BRADD 2011). Given the current existence of homes around the CoBG with histories of flooding and the amount of new development underway, this action item should be revisited, and this study will assist in that effort.

In addition to BRADD, the Bowling Green Public Works Department (BGPW) is a city-run organization that is tasked with maintaining much of the infrastructure in the CoBG, such as the streets, stormwater injection wells and sinkholes, and storm sewers (BG Public Works 2022). One of the most recent projects that BGPW has begun to implement is the Stormwater Mitigation Priority List (SMPL). The SMPL is a list created and maintained by the Bowling Green Public Works Department that outlines sites around the CoBG that have known drainage issues or have received complaints of flood issues. Each site is scored based upon characteristics related to estimated cost to cure, public impact and road closures, frequency, and impact to private property. The resultant score is then used to determine the priority positioning for each site. The SMPL was created in order to address and catalogue some of the areas of the city that deal with flooding frequently or consistently that may not technically fall under the jurisdiction of BGPW.

For stormwater management, BGPW focuses on two broad categories of management: stormwater quantity management and stormwater quality management. Management of stormwater quality focuses on the cleanliness of stormwater runoff. BGPW utilizes a best management practices (BMP) manual to outline requirements for stormwater quality and to provide guidance on how to achieve the requirements (BG Public Works 2022).

Management of stormwater quantity focuses on the amount of water in an area, specifically with relation to flooding and the prevention of new flood areas. As new developments occur throughout the city, BGPW regulates structure designs with regards to how the water in an area is handled, as the karst environment of the CoBG adds an element of complexity that must be addressed when designing new developments. Essentially, the BGPW attempts to regulate the volume of water that an area produces and plan for changes in the landscape that will alter where water can go and how much water the landscape can handle in order to avoid flooding. These plans focus primarily on 100-year flood events, or one percent annual chance flood events as these flood events have the highest chance of occurring. According to the CoBG City Ordinances,

> “Any person proposing or constructing alterations, improvements or other disturbances changing the flow characteristics of stormwater shall have prior approval through permitting or plan approval by the Public Works Director or designee. This includes altering drainage onto an adjoining property or right-of-way, or into any drainage crevice, sinkhole, ditch, closed system, catch basin, dry well, or any other drainage facility whether natural or constructed.” (Code of Ordinances 2022, 21-3.01, b.)

The responsibility of the city, as outlined in the ordinances, is essentially to maintain structures and repair sinkholes within drainage easements in single- and two-family residential neighborhoods; any property that does not align with those criteria is intended to be maintained by the property owner.

Management of changes to the landscape with new developments are typically addressed by including retention or detention basins in the development plans, though the basins are not the only management strategy employed. Retention basins catch water and allow for the water to drain into the subsurface, typically using injection wells. Detention basins hold water before releasing the water more slowly through an outlet pipe. Both retention and detention basins have set standards that must be met in order to be approved before construction related to the amount of water the basins must be able to handle in the event of a one percent annual chance flood event. The CoBG began to enforce drainage standards in 1976 when David Daugherty, a local hydrologic engineer, looked at various storm events and recommend designs for stormwater retention and detention basins to prevent localized flooding (Daugherty 1976). Any structures proposed or built before 1976 would not have been designed to meet the standards that began to be implemented after the development of stormwater management in the CoBG. Because of this, there are still many properties throughout the city that do not meet the current criteria for design standards. Additionally, though drainage standards began to be implemented in the CoBG in the 1970’s after Daugherty (1976) released a manual on the topic, the official standards have not been updated in the nearly fifty years since.

The CoBG is an active participating community in the NFIP, with the first FHBM developed in 1974 and the first FIRM developed in 1980 (FEMA 2022). FEMA has updated the floodplain maps in the CoBG several times in the years since the development of the first ones, with help from the Kentucky Division of Water (DOW); however, the current floodplain map that is utilized in the CoBG was developed in 2007 and has not been updated since (FEMA 2022). The CoBG joined the Community Rating System (CRS) in 1991, which is a voluntary program available to all participating communities in the NFIP. The CRS program is designed to incentivize increased floodplain management beyond the minimum requirements of the NFIP by offering discounts on premium insurance rates (CRS 2022). The CoBG is currently a Class 7 community within the CRS, which means that the city receives a 15% premium insurance discount in SFHA and a 5% discount in non-SFHA. The classification is given based upon certain criteria that align with public information, mapping and regulations, flood damage reduction, and warning and response (CRS 2022).

Chapter Four: Methodology

The purpose of this study was to examine how the usage of an integrated GIS (Geographic Information Systems) and FVI with the inclusion of current climate change projections can aid in understanding urban karst flooding impacts to communities based on geospatial intersections of humans and environmental and socioeconomic factors. This study focused on communities with varied demographics and histories of flooding in order to: 1) better understand differences and levels of equity associated with the impacts of flood events on different groups, 2) determine policy implications for flood protection in karst areas, and 3) examine future development planning based on projected changes in severe event and flood occurrences in the study area.

Drawing upon work completed by Cutter (1996) and Wakhungu et al. (2021) regarding place-based vulnerabilities, and various studies using the FVI (Balica and Wright 2010; Balica et al. 2012; Nasiri et al. 2019; Salazar-Briones et al. 2020), this study focused on three main components in the vulnerability framework and how these components intersect: social, environmental conditions, and economic. By understanding which areas of a city are most vulnerable and the precise ways in which these areas are vulnerable, management can be focused to specifically target those areas and the susceptibilities present. The GIS flood maps and the modified FVI were used in conjunction to identify patterns, trends, and disparities in how urban karst flooding is managed and potential areas for modified management practices to account for identified vulnerabilities. Current climate change projections regarding flooding in the southcentral Kentucky region were also assessed in tandem with the GIS flood extent maps and FVI to further assess flood risk and vulnerabilities throughout the CoBG in the past, present, and potentially in the future. Additionally, anonymous semi-structured interviews were conducted with city officials and other individuals who work with flooding and flood response to capture information about the regulatory and management processes underway from an insider's perspective. This was done in order to ultimately attempt to better plan for the future by making management recommendations and assess policy implications. The general outline of the methodology is showcased in Figure 4.1.

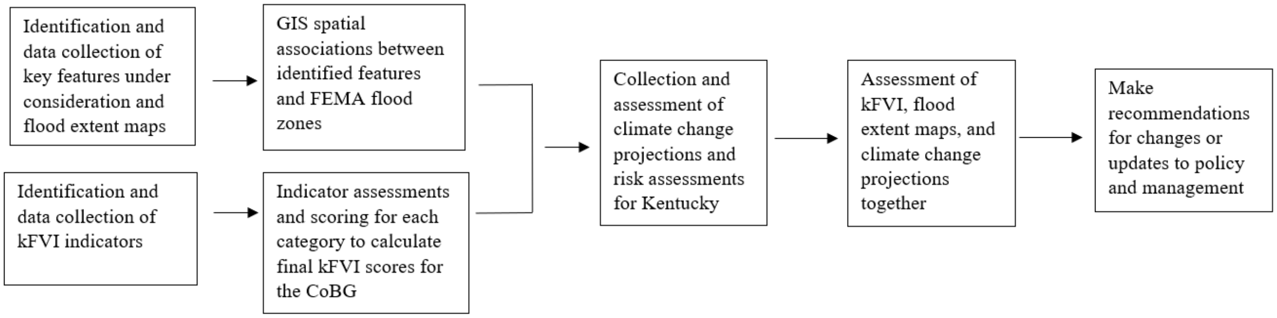


Figure 4.1: Basic outline of methodology steps (Source: Created by author).

4.1 GIS Assessments and Analyses

In order to collect all of the necessary data for the GIS component of this project, multiple data sources were utilized and further processing of acquired data was required in some cases. Sources of data used were BG RUCKAS, United States Census Bureau, and the American Community Survey (ACS) (ACS 2020; Census Bureau 2020; Troxell 2021). Demographic data were generally downloaded at the block group level in order to achieve consistency among data, though data at the tract or block level were used in the absence of data at the block group level. Because the full extent of the 2020 Decennial Census results were not published at the time of this research, demographic data were supplemented using ACS 5-year aggregate data for 2020. Because ACS data are aggregated and are an estimation, there is a more substantial margin of error associated with those data. Despite this limitation, ACS data were determined to be the most updated and applicable data for the study area at hand, rather than utilizing data from the 2010 Decennial Census that are over a decade old at the time of research. The ACS offers data solely at the block group level; data obtained from other sources were also downloaded at the block group level to achieve consistency. Once the data were downloaded, the tables were edited to ensure the data were readable in ArcGIS Pro by editing heading names and eliminating unnecessary data. Some additional data conversions were necessary once the tables were inputted into ArcGIS Pro, such as the calculation of the unemployment rate, which was calculated by dividing the ‘Unemployed Persons in Labor Force’ by ‘Total number of persons in labor force,’ then multiplying the result by 100 to find the percentage.

The National Flood Hazard Layer (NFHL) shapefile was obtained from ArcGIS Online, though the NFHL is created and maintained by FEMA. The NFHL displays several different categories of flood zones, such as special floodways, one percent annual chance flood zones, and 0.2 percent annual chance flood zones. For the purposes of this project, only the one percent annual chance flood zones were examined, since these areas generally experience the most frequent flooding, even if on a small scale or as nuisance flooding. There are many designated flood zones throughout Warren County that surround the CoBG; to attempt to alleviate any edge effects and still encompass Special Flood Hazard Areas (SFHA) that impact areas in the CoBG, a two-kilometer buffer was generated around the CoBG and all of the SFHA within the limits of the buffer and the CoBG were included in analyses. SFHA were spatially associated with various features using the Select By Location tool in ArcGIS Pro. SFHA were selected based upon their respective proximity to the chosen features from distances of: within 200 meters, 201 to 400 meters, 401 to 600 meters, and 601 to 1,000 meters, though analyses were primarily based upon associations below 600 meters in order to maintain strongest correlations. The features that were spatially associated with the SFHA were known sinkholes, caves, potential sinkholes, ACRES, NPDES, RCRA, SEMS, TRI, CoBG SMPL sites, and CoBG Hazard Mitigation Portal (HMP) points. Table 4.1 outlines and describes the features that were listed as their respective acronyms. The CoBG HMP is a feedback map application that allows “city/county officials and employees, local steering committee members, and members of the public to propose potential projects for the Hazard Mitigation Plan and/or identify areas of concern within their communities (such as a road that always floods during heavy rain)” (BRADD 2022). Additionally, the Select By Location tool was utilized in order to select the SFHA that directly intersect potential sinkholes, as there is a very large amount of potential sinkholes through the CoBG.

Table 4.1: Description of acronyms and features utilized in GIS analyses.

Acronym	Full Name	Definition
ACRES	Assessment Cleanup and Redevelopment Exchange System	ACRES stores information reported by EPA Brownfields grant recipients on Brownfields properties assessed or cleaned up with grant funding, as well as information on Targeted Brownfields Assessments (TBA) performed by EPA Regions. The Facility Registry Service (FRS) identifies and geospatially locates facilities, sites or places subject to environmental regulations or of environmental interest. This data set contains the subset of FRS facilities that link to Brownfields sites once the ACRES data has been integrated into the FRS database.
SEMS	Superfund Enterprise Management System	SEMS is a comprehensive tracking and reporting tool that records information regarding hazardous waste sites evaluated by the Superfund program. The SEMS contains sites that are either proposed to be, or are on, the National Priorities List (NPL) as well as sites that are in the screening and assessment phase for possible inclusion on the NPL.
NPDES	National Pollutant Discharge Elimination System	As authorized by the Clean Water Act, the NPDES permit program controls water pollution by regulating point sources that discharge pollutants into waters of the United States. This sub facility data shows the actual discharge/outfall locations of the pollutants into the water system.
RCRA	Resource Conservation and Recovery Act	EPA's comprehensive information system in support of the Resource Conservation and Recovery Act (RCRA) of 1976 and the Hazardous and Solid Waste Amendments (HSWA) of 1984, RCRAInfo tracks many types of information about generators, transporters, treaters, storers, and disposers of hazardous waste. This data set contains the subset of FRS integrated facilities that link to RCRAInfo hazardous waste facilities once the RCRAInfo data has been integrated into the FRS database.
TRI	Toxic Release Inventory	TRI is a publicly available EPA database reported annually by certain covered industry groups, as well as federal facilities. It contains information about more than 650 toxic chemicals that are being used, manufactured, treated, transported, or released into the environment, and includes information about waste management and pollution prevention activities.
SMPL	Stormwater Mitigation Priority List	The SMPL is a list created and maintained by the Bowling Green Public Works Department that outlines sites around the CoBG that have known drainage issues or have received complaints of flood issues. Each site is scored based upon characteristics related to estimated cost to cure, public impact and road closures, frequency, and impact to private property. The resultant score is then used to determine the priority positioning for each site.

The data chosen were selected for analysis due to the potential of each to cause or influence vulnerability to flooding, in addition to vulnerabilities associated with the aftermath of flooding. Known sinkholes, caves, and potential sinkholes are all karst features that have the potential to cause flooding in certain areas, in addition to aiding in the identification of areas that could conceivably flood in the future. The data associated with ACRES, NPDES, RCRA, SEMS, and TRI sites all have the potential to have negative impacts to communities in the event of intense flooding, infrastructure failure, or poorly managed sites. The potential for hazardous or toxic waste or pollutants being released into waterways can increase overall flood vulnerability, as water quality could be substantially degraded, impacting the health of the humans and ecosystems that rely on the water systems to support life and everyday functions.

The CoBG maintains a stormwater mitigation prioritization list for each fiscal year (FY) that is public record and easily accessible through an open records request to the City Clerk's office. The stormwater mitigation prioritization list in the CoBG officially began in 2011 and has been utilized since; essentially, the list outlines the locations of flood hazards that the city received at least one complaint about, though many of the sites on the list received multiple complaints. Each location is scored based upon its estimated cost to cure or fix, public impact and road closures, frequency of flooding, and impact to private property. Based upon the resulting scores, each location is given a priority position wherein the locations with the highest scores are the highest priority. Between 2015 and 2021, there were 71 individual sites listed on the stormwater mitigation prioritization list located throughout the CoBG. There were no sites documented for 2020, as the CoBG did not receive funding to address flood concerns due to the onset of the COVID-19 pandemic. In order to assess the locations around the CoBG that have experienced documented flood impacts, the spreadsheet was converted to be readable in ArcGIS

Pro and each location was digitized as a point feature. Many of the sites remained on the list for multiple years, due to low priority or lack of adequate funding to address the problems. Each site was assigned a single fiscal year (FY); if the site was successfully addressed, the FY in which the site was completed was listed. If the site has yet to be addressed, the FY in which the site was originally added to the list was listed. The documented flood locations were then compared with the NFHL SFHA to assess the similarity between areas that are known to currently flood and those that are FEMA designated SFHA. Point features were utilized as the precise flood extents of each of the flood hazards on the priority list have not yet been assessed. The sites are largely complaint-driven, meaning the sites are typically added to the city's mitigation list when citizens in the community file complaints regarding the flooding. Because of this, the full extent of the flooding is not always seen and recorded by the city officials personally, leading to documentation of the general centralized location where the flooding is occurring rather than the exact boundaries. This can present a limitation in analyses as many of the flood areas are larger than the single point location representing the flood extents; however, identifying the general areas in which flooding is occurring aids in determining the general distribution of flooding amongst the varied communities and demographics throughout the CoBG. The identification of locations of areas that are known to flood but may not have technical flood extents mapped can also serve to establish regions of the city that may require further examination and could be starting points for floodplain assessments.

4.2 Karst Flood Vulnerability Index (kFVI)

Due to the inherently varied and complex nature of karst regions throughout the world, a sole karst Flood Vulnerability Index (kFVI) that would be completely applicable in every karst landscape would be incredibly difficult. The original FVI developed by Balica et al. (2009) has been adapted and modified many times since its inception to assess many different climates and landscapes around the world, though there are currently no known applications of the FVI in urban karst regions. The kFVI developed in this research is intended to be a foundation for assessing flood vulnerabilities in urban karst landscapes and can be adapted to suit the needs of specific locations. Composed of three categories of vulnerabilities: social, economic, and environmental conditions, the kFVI attempts to address the following goals:

- Identify vulnerable areas to flooding, particularly through the lens of social equity
- Easily adaptable to various karst regions
- Aid in making informed management decisions

Various indicators related to the exposure, susceptibility, and resilience of a community were selected and evaluated in the CoBG in order to assess the strength and applicability of the developed index.

For the purposes of this project, the study area was assessed using both the FVI and the kFVI at the urban scale, focusing on the CoBG and known flood areas as a whole using block groups, rather than solely investigating specific areas of the city based upon the setup of the terrain or environmental features. Assessing the city and the land immediately surrounding the boundaries of the city was determined to be important for this project for several reasons. When creating management plans, land managers must be able to create plans that account for the entirety of their city; however, the physical environment does not always conform to arbitrarily constructed political boundaries. Evaluating communities in alignment with environmental features does make logical sense but doing so does not always paint a full picture of the people and communities that are impacted, which is necessary when building robust management plans.

Construction of a proper and successful management plan for a city typically requires the cooperation of various levels of governmental agencies and stakeholders, particularly in scenarios where hazards cross political boundaries. Interagency cooperation and communication can be especially important in karst environments as the high levels of connectedness between karst features can impact landscapes and communities spanning large distances and subsequently, jurisdictions. A hazardous waste spill during a flood event in one county may be quickly swept miles away before causing significant complications in a completely different county.

While the general FVI has been utilized to assess a variety of environments and regions around the world at the urban scale (Balica et al. 2009; Balica et al. 2012; Nasiri and Shahmohammadi-Kalalagh 2013; Nasiri et al. 2019; Kumar et al. 2020; Salazar-Briones et al. 2020), the kFVI was designed to examine karst areas even more closely, by focusing on various neighborhoods and communities within the urban area utilizing block groups. Application of both the original FVI and modified kFVI was completed and allowed for comparison of the effectiveness of the kFVI for capturing additional vulnerability that karst features may cause. All block groups within the boundaries of the CoBG were examined, in addition to block groups immediately surrounding the boundary of the CoBG. Including block groups that surround the outer edge of the CoBG aids in reducing edge effects, while also keeping the area under consideration consistent with previous analyses of SFHA surrounding the CoBG. Additionally, many of the block groups located on the outer perimeter of the CoBG span past the technical boundary of the city. The purpose of examination of the urban area by segments was to be able to identify areas of the city that are highly vulnerable to flooding and the specific ways in which communities are vulnerable. By identifying the levels of vulnerability associated with various segments of the city, land managers can more easily prioritize which areas to focus time, personnel, and funding towards. In smaller urban areas like the CoBG, funding and personnel tend to be lacking in abundance, making prioritization lists crucial so that resources can be allocated where they will be most beneficial.

Creating an index of this nature is inherently associated with a level of subjectivity, as some of the indicators and associated scoring metrics do not have a set standard for determining vulnerability, but are still relevant and valuable for achieving the goals of the kFVI. Additionally, some of scoring metrics chosen for the study area at hand may not be applicable in the exact form utilized in this research in other areas depending on the scale, but rather would need to be adjusted to better align with the characteristics of the study area. Attempting to create an index of this nature and utilizing the exact same scoring metrics in areas with vastly different demographics is not entirely realistic. For example, the cost of living and home value in the CoBG is relatively low compared to many other urban areas around the United States; to account for this, the home value brackets utilized to assess vulnerability are fairly low in value but may need to be increased if the kFVI is utilized to assess a different urban karst area that may be in a region with a higher cost of living, such as Nashville, Tennessee. While this detracts from the scalability of the kFVI in its ability to be applied to areas of varying spatial scales in its completed form, this allows for increased adaptability and customization to specific study areas while providing guidelines to aid location-specific alterations.

4.2.1 Social Vulnerability

Social vulnerability in this context was viewed as the disproportionate impacts a person or community's social positioning has on the ability to respond and recover after environmental events occur. Social vulnerability for this study was evaluated on the block group scale using various indicators to assess levels of potential vulnerabilities in different areas and where the vulnerabilities stem from. Specific indicators were selected and developed based upon data access, applicability, and feasibility. The indicators utilized in this research to assess social vulnerability were Population Density, Underage and Elder Populations, Population in Poverty, Limited English-Speaking Households, Disabled Populations, Population Growth, and Education Level (Table 4.2).

Data regarding social vulnerability in the CoBG were obtained from the American Community Survey (ACS) 5-year aggregate data for 2020. At the time of research, all data from the 2020 Decennial Census were not released, leading to usage of solely ACS data rather than use the 2020 or 2010 Decennial Census data to be able to consider all data and analyses within the same timeframe. This could create a margin of error associated with the assessments and analyses as the ACS data are aggregated over the span of several years and are sample data, rather than a survey of the entire population. Because of this, ACS data are not available on the block scale to avoid substantial sampling errors, as the block units are much smaller. While the 2010 Decennial Census data are provided at the block level, many of the data necessary for the indicator assessments are not offered, such as data related to income levels or education. The ACS data provides the most updated and robust set of data related to the indicators used in the kFVI. The data used in analyses were concluded to be the most appropriate options among the available data at the time of research to be representative of the CoBG.

Table 4.2: Social vulnerability indicators (Source: Created by Author).

Indicator	**Abbrev.**	**Factor**	**Unit**	**Definition**	**Functional Relationship with Vulnerability**
Population Density	PD	Exposure	Person/km²	Concentration of individuals within the specified area (block groups)	The higher number of people and density, higher vulnerability
Underage and Elder Populations	UEP	Susceptibility	%	Percentage of population under the age of 18 and over the age of 65	The older or younger a group is, the more susceptible to flood impacts they might be
Limited English-Speaking Households	LEH	Susceptibility	%	Percentage of households where limited English is spoken	Higher %, higher vulnerability as language barrier may cause lack of understanding or spread of information
Population in Poverty	Pov	Exposure	%	% of population living in poverty or at the poverty line	Higher %, higher vulnerability
Disabled Populations	DP	Susceptibility	%	% of population with any kind of disabilities	Higher %, higher vulnerability
Population Growth	PG	E	%	% of growth of population in urban areas in the last 10 years	Fast PG, higher vulnerability, hypothesis is made that fast population growth may create pressing on land subsidence
Education Level	EL	Susceptibility	Categorical data, using %	Predominant education level by %	The more educated people are, the more resilient they tend to be to flood impacts

4.2.2 Environmental Conditions Vulnerability

Environmental Conditions vulnerabilities were evaluated based upon the following indicators: Average Annual Increase in Precipitation, Concentration of Superfund or Brownfield Sites, Concentration of Hazardous Waste Sites, Concentration of Sinkholes, Potential Sinkholes, Caves, Special Flood Hazard Area (SFHA), Monitoring in Place, and Regulatory protection (Table 4.3). These indicators were chosen based upon relevance and previous research studies that have shown to have impacts on communities of lower socio-economic status or urban karst flooding (Cutter 1996; Cutter et al. 2008; van Beynen and Townsend 2005). Indicators related specifically to karst landscapes were drawn from the Karst Disturbance Index (KDI) and other karst-specific indices (van Beynen and Townsend 2005; van Beynen et al. 2012).

Data were partially drawn from existing datasets from the UnderBG Hydronet. UnderBG is a water quality monitoring website that provides live data from different streams and rivers around the CoBG, including pH, temperature, and depth (UnderBG 2021). Additional data were also drawn from the Bowling Green Response to Urban Contamination in Karst Aquifer Systems (RUCKAS), which is a guide that was developed to help communities develop response plans to various environmental hazards, including flooding. The Bowling Green RUCKAS database is comprised of data related specifically to the CoBG and necessary data for indicator assessment were collected from the database, including the locations of Superfund or Brownfield sites, locations of hazardous waste production or disposal sites, and locations of various karst features (Troxell 2021).

While the state oversees the investigation and remediation of the superfund sites, both state and local government entities can receive federal funding for brownfield sites to support assessments and cleanups. However, the documentation of brownfield sites generally is not as meticulous as superfund sites. According to the Kentucky Energy and Environment Cabinet (2019), the approximate number of brownfields around the state is known, but the locations of each one is not. The inclusion of brownfield sites in vulnerability assessments can provide valuable statistics and information but the possibility of additional sites that are currently unknown must be acknowledged.

Table 4.3: Environmental conditions indicators (Source: Created by Author).

Indicator	**Abbrev.**	**Factor**	**Unit**	**Definition**	**Functional Relationship with Vulnerability**
Average Annual Change in Precipitation	PC	Exposure	% change/year	Average annual percentage change in precipitation	higher precipitation, higher vulnerability; an increase in annual precipitation could lead to increased number or intensity of flood events
Superfund / Brownfield Sites	SBS	Susceptibility	sites/km^2	Density of EPA designated Superfund and Brownfield Sites per km^2	Proximity to Superfund or Brownfield sites can lead to higher vulnerability, particularly regarding contamination during flood events
Hazardous Waste Sites	HW	Susceptibility	sites/km^2	Density of sites that handle hazardous waste (RCRA facilities) per km^2	Proximity to hazardous waste sites can lead to higher vulnerability, particularly regarding contamination during flood events
Sinkholes	Si	Exposure	sinkholes/km^2	Density of sinkholes per km^2	Proximity to sinkholes can lead to higher vulnerability and flooding
Potential Sinkholes	PS	Exposure	% of area	Percentage of area of potential sinkholes over total land area	Proximity to potential sinkholes can lead to higher vulnerability and flooding
Caves	C	Exposure	% of area	Percentage of area of caves over total land area	Proximity to caves can lead to higher vulnerability and flooding
Special Flood Hazard Area	SFHA	Exposure	% of area	Percentage of area of SFHA over total land area	Proximity to current SFHA can lead to higher vulnerability and flooding
Monitoring in Place	MiP	Resilience	sites/km^2	Presence of water level and flood monitoring in neighborhoods	More monitoring aids in awareness of flooding and potential areas for future flooding
Regulatory Protection	RP	Resilience	n/a	Level of regulations regarding flooding, development, and protection of karst features	More regulations increase awareness and guidelines to abide by, which can lower vulnerability

4.2.3 Economic Vulnerability

Economic vulnerability can prevent or hinder a community's ability to both recover from flood impacts or take preventative measures. Indicators associated with economic vulnerability that were assessed are Land Use, Home Value, Unemployment Rates, Income (Household), Flood Insurance, and Recovery Time (Table 4.4). Property value and various economic demographics can also influence the extent of damage in terms of cost or expenses. Scoring metrics to evaluate vulnerability associated with property value were chosen based upon the expected ability of those impacted to rebuild or recover in the wake of flood impacts, rather than the cost of the damage to property. Appropriate economic factors were assessed based on previous applications of the FVI and available data for the study area. Data for economic indicators were collected from the Bowling Green RUCKAS and ACS aggregate data for 2020.

Table 4.4: Economic vulnerability indicators (Source: Created by Author).

Indicator	**Abbrev.**	**Factor**	**Unit**	**Definition**	**Functional Relationship with Vulnerability**
Land Use	LU	Exposure	Categorical data	The predominant way in which an area is utilized by humans, such as residential, commercial, by land mass	Areas with more human activity have more sources of vulnerability in addition to increased impervious surfaces
Home Value	HV	Susceptibility	US Dollars	Average value of homes in area	Lower value, higher vulnerability due to lower economic resources
Unemployment Rates	UR	Susceptibility	% of population	Percentage of persons over the age of 16 and below 65 that are unemployed	Areas with high unemployment rates tend to have less resources available to address flood impacts
Household Income	HI	Susceptibility	US Dollars	Average income of households in area	Areas with low incomes tend to have less resources available to address flood impacts
Flood Insurance	FI	Resilience	% of properties	Percentage of properties in SFHA with flood insurance	Properties lacking flood insurance have much lower resilience to flood impacts
Recovery Time (Average)	RT	Resilience	Days	Average amount of time needed by the city to recover to a functional operation after Declared Disaster flood events	The higher amount of time, the higher vulnerability

4.2.4 Scoring and Analysis

The scoring system employed in the kFVI was created specifically for simplicity while remaining effective, to be user-friendly, yet valuable enough to aid in making educated decisions. A scoring system was developed by the researcher that assesses the indicators and assigns a value to each indicator that corresponds with level of vulnerability an area has regarding that specific indicator (Table 4.5). The values range from zero to three, with each indicator having specific criteria that aligns with each value. Utilizing a range of zero to three rather than a larger scale such as zero to ten helps to maintain a broader view of vulnerabilities and have more easily identifiable brackets of vulnerability extents. The difference between a '3' and a '1' on a total scale of zero to three would be much more apparent and identifiable than the difference between a '3' and a '1' on a scale of zero to ten. When making assessments intended to influence management strategies and allocation of resources, focusing on the more drastic differences in vulnerability can provide much more beneficial insights than the minute details.

Because the general equation for the overall vulnerability for an area is (Exposure + Susceptibility – Resilience), a higher value assigned to the exposure and susceptibility indicators indicates greater vulnerability, whereas a lower value for the resilience indicators is associated with greater vulnerability. Resilience lowers a community's vulnerability to flooding and is subtracted from the overall vulnerability score. The less resilience a community has, the higher the overall vulnerability score should be. A score of '0' is associated with little to no impact on vulnerability level. A score of '1' indicates some impact to vulnerability level but is relatively minimal. A score of '2' indicates moderate impact to vulnerability level, while a score of '3' indicates high impact.

Table 4.5: kFVI scoring metrics for the three categories of vulnerability: Social, Economic, and Environmental Conditions (Source: Created by Author). ** Denotes the indicators that assessed and identified an equivalent score for all block groups in the study area. Indicators can be adjusted based upon location and scale if needed; the indicators that are recommended for adaptation are underlined.

Category	**Indicator**	**Factor**	**0**	**1**	**2**	**3**
Social	Population Density	E	Less than or equal to 500 people/km^2	500-1,000 people/km^2	1,001-2,000 people/km^2	Greater than 2,000 people/km^2
	Underage and elder populations	S	Less than 5%	5%-25%	25%-50%	Greater than 50%
	Population in Poverty	E	Less than 5%	5%-25%	25%-50%	Greater than 50%
	Limited English-Speaking Households	S	Less than 5%	5%-25%	25%-50%	Greater than 50%
	Disabled Populations	S	Less than 5%	5%-25%	25%-50%	Greater than 50%
	Annual Population Growth	E	Negative Population Growth	0%-0.5%	0.51% - 1.0%	Greater than 1%
	Education level	S	Master's or PhD	Bachelor's or Associates	High School or Equivalent	No schooling or less than High School
Economic	Land Use	E	Vacant	Public, Public Institutional, Agricultural	Commercial or Industrial	Residential or Multi-Family Residential
	Home Value	S	$300,000+	$200,000-$299,999	$100,000-$199,999	$99,999 or less
	Unemployment Rates	S	<1%	1%-5%	5%-10%	10%<
	Household Income	S	>=$200,000	$75,000-$199,999	$25,000 - $74,999	<=$24,999
	Flood Insurance**	R	Little to no flood insurance	Less than 50% of property in a SFHA with flood insurance	More than 50% of property in a SFHA with flood insurance	Widespread flood insurance
	Average Recovery Time**	R	More than three weeks	Two to three weeks	One to two weeks	One week or less

Table 4.5 (cont.): kFVI scoring metrics for the three categories of vulnerability: Social, Economic, and Environmental Conditions (Source: Created by Author). ** Denotes the indicators that assessed and identified an equivalent score for all block groups in the study area. Indicators can be adjusted based upon location and scale if needed; indicators recommended for adaptation are underlined.

Category	**Indicator**	**Factor**	**0**	**1**	**2**	**3**
Environmental Conditions	Average Annual Increase in Precipitation**	E	0% or negative	0% - 5%	5% - 10%	Greater than 10%
	Superfund / Brownfield Sites	S	1 per 20 km^2 or more, or 0	1 per 10 - 20 km^2	1 per 5 - 10 km^2	1 per 5 km^2 or less
	Hazardous Waste Sites	S	1 per 20 km^2 or more, or 0	1 per 10 - 20 km^2	1 per 5 - 10 km^2	1 per 5 km^2 or less
	Sinkholes	E	1 per 20 km^2 or more, or 0	1 per 10 - 20 km^2	1 per 5 - 10 km^2	1 per 5 km^2 or less
	Potential Sinkholes	E	Less than 5% or none	5%-10%	10%-20%	Greater than 20%
	Caves	E	Less than 1%	1 - 5%	5%-10%	Greater than 10%
	SFHA	E	Less than 1%	1 - 5%	5%-10%	Greater than 10%
	Monitoring in Place	R	1 per 20 km^2 or more, or 0	1 per 10 - 20 km^2	1 per 5 - 10 km^2	1 per 5 km^2 or less
	Regulatory protection**	R	No regulation	A few regulations, but contain loopholes or may not be strictly enforced	Ample statutes in place but require updates or revisions	Region fully protected

After assigning a vulnerability score between zero and three to each of the indicators based upon the scoring metrics outlined in Table 4.5, the scores were then summed. The summed scores for each group were then divided by the highest possible score to obtain a value between 0 and 1. A score closer to 1 indicates higher vulnerability, while a score closer to 0 indicates lower vulnerability (Table 4.6). Four levels or categories of vulnerability were created are 'Low Vulnerability,' 'Vulnerable,' 'Moderate Vulnerability,' and 'High Vulnerability.'

Table 4.6: Final scoring metrics and classification for overall vulnerability in the kFVI (Source: Created by Author).

Final Score (# of points / highest # of points possible)	Level of Vulnerability
0.0 – 0.24	Low Vulnerability
0.25-0.49	Vulnerable
0.50-0.74	Moderate Vulnerability
0.75-1.0	High Vulnerability

The following equations were used to calculate the normalized level of vulnerability for the study area and determine classification of vulnerability level:

Social Vulnerability Equation

$$kFVI_{Social} = \frac{(PD + UEP + LEH + Pov + DP + PG + EL)}{Max}$$

where,

PD= Population Density Score

UEP= Underage and Elder Population Score

LEH= Limited English-Speaking Households Score

Pov=Population in Poverty Score

DP= Disabled Populations Score

PG= Population Growth Score

EL= Education Level Score

Max= Maximum possible score for social vulnerability

Economic Vulnerability Equation

$$kFVI_{Economic} = \frac{(LU + HV + UR + HI) - FI - RT}{Max}$$

where,

LU= Land Use Score

HV= Home Value Score

UR= Unemployment Rate Score

HI= Household Income Score

FI= Flood Insurance Score

RT= Recovery Time Score

Max= Maximum possible score for economic vulnerability

Environmental Conditions Vulnerability Equation

$$kFVI_{Environmental\ Conditions} = (PC + SBS + HW + Si + PS + C + SFHA) - MiP - RP$$

where,

PC=: Average Annual Change in Precipitation Score

SBS= Superfund/Brownfield Sites Score

HW= Hazardous Waste Sites Score

Si= Known Sinkholes Score

PS= Potential Sinkholes Score

C= Caves Score

MiP= Monitoring in Progress Score

RP= Regulatory Protection Score

Max= Maximum possible score for environmental conditions vulnerability

Normalization of the indicators allowed for evaluation and calculation of final vulnerability scores by placing the indicators on a common, unitless scale. The indicators were not weighted. Social, environmental conditions, and economic vulnerability were calculated individually before calculating a final vulnerability score for the study area. For each indicator, the total across all block groups was calculated to examine which of the indicators within each category featured scores that most consistently demonstrated vulnerability.

If an indicator was determined to have relevance and value for the overall kFVI assessment but limited data was available for some of the study area block groups, a designation of 'LD' (Lack of Data) was assigned to those groups for that indicator. This allows for the indicator to still be utilized to assess the majority of the study area rather than discarding the indicator due to lack of data in some areas. A designation of 'LD' does lower the overall confidence level in the vulnerability assessment of the block groups that received 'LD' for an indicator, but can provide insight on regions of the study area that might require more attention or have been overlooked in the past. For block groups with 'LD' designations, the final score was divided by the maximum score possible without the indicator with the 'LD' designation, rather than the maximum possible score with all of the indicators.

4.3 Semi-Structured Interviews

Semi-structured interviews were conducted with various professionals, stakeholders, and community members in the CoBG and Warren County. Interviewees were chosen based upon their professional experience related to flooding in karst regions, management strategies, regulations, and policies. Interviewees selected for their professional experience in the field of flood management were purposefully chosen to gain insight from agencies that are involved with flood prevention, response, protection, and regulation enforcement. Additional interviewees were selected that have experienced flood impacts in their homes, businesses, or places of employment to gain insight regarding perceptions and experiences of community members throughout the CoBG. All interviewees completed an informed consent document approved by the Internal Review Board (IRB) prior to the interview. Each interview was audio recorded and transcribed by the researcher. The interview questions are located in Appendix D.

Chapter Five: Results and Discussion

The purpose of this research was to develop a more robust and adaptable method of assessing the vulnerability of urban karst communities to flooding, particularly with regards to contributing factors to vulnerability that extend beyond solely the physical environment to socio-economic characteristics of a community as well. Specifically, an urban karst specific FVI (kFVI) was developed to pursue these goals in order to assess the study area and identify vulnerable areas in the community to flooding, utilizing indicators associated with environmental conditions, economic, and social vulnerabilities. This study also identified patterns, trends, and disparities in how urban karst flooding is managed and potential areas for modified management practices to account for identified vulnerabilities. Results informed recommendations for modifications to current management strategies, in addition to changes and implementation suggested in future policy and practices.

5.1 GIS Assessments and Analyses

Special Flood Hazard Areas (SFHA) designated by FEMA in the NFHL were spatially associated with the following features: known sinkholes, caves, potential sinkholes, ACRES, NPDES, RCRA, SEMS, TRI, and SMPL sites. The purpose of associating the features was twofold: to identify potential reasons or contributing factors as to why an area might experience flooding and to identify potential areas with specific vulnerabilities during flood events, such as the presence of hazardous waste facilities. The associated features were chosen for the potential impacts of the features on both water quality and water quantity. Additionally, documented sites from the CoBG SMPL were associated with the current flood zones to determine if there are certain areas in the CoBG that are not designated SFHA, but that do experience persistent flooding issues.

In order to attempt to alleviate any edge effects and still encompass SFHA that impact areas in the CoBG, a two-kilometer buffer was generated around the CoBG and all of the SFHA within the limits of the buffer and the CoBG were included in analyses. Within the two-kilometer buffer surrounding the CoBG and within the city limits, there are currently 138 one-percent annual chance flood zones in the NFHL. Table 5.1 outlines the number of current NFHL one percent annual chance flood zones, or SFHA, in the CoBG within specified distances of various features.

Table 5.1: Number of current NFHL one percent annual chance flood zones in the CoBG within specified distances of various features (Source: Created by Author).

Associating Feature	Within 200 meters	Between 201-400 meters	Between 401-600 meters	Between 601-1,000 meters	Total # within 1,000 m.
Known Sinkholes	44	35	17	17	113
Potential Sinkholes	120	8	3	7	138
Caves	25	15	14	23	77
ACRES	5	1	2	10	18
SEMS	1	0	1	2	4
NPDES	33	33	24	32	122
RCRA	41	24	19	22	106
TRI	10	5	8	17	40
SMPL Sites	27	26	19	31	103
HMP Sites	13	7	4	11	35

Given that there are only eleven ACRES or SEMS sites within the CoBG, the number of SFHA within 1,000 m of these features was the lowest with only four SFHA associated with SEMS sites and only eighteen associated with ACRES sites. Almost 90 percent of the SFHA are within 1,000 m of NPDES sites and more than 75 percent within 1,000 m of RCRA sites. Just over a fourth of the SFHA are within 1,000 m of TRI sites. The association between the SFHA and the features related to hazardous waste, pollution, or other issues does not mean that these sites will definitively pose problems in the event of flooding. The sites examined have the potential to have very serious impacts on the community and are sources of possible vulnerabilities, not absolute vulnerabilities. About fifty percent of the SFHA are within 600 m of SMPL sites. There are many SMPL sites that are more than 600 m away from any SFHA, indicating areas of the city that may require further evaluation for potential new flood zones or for adjustments to current flood management. In an interview regarding flooding in the CoBG and the SMPL, a local official stated, "There are areas of Bowling Green where the city attempted to resolve flooding issues by installing wells but haven't successfully been able to fix the issues, so the sites have gone back onto the mitigation list," referring to the SMPL (Pers. Comm. 2022).

The strongest associations of features to the SFHA were found to be with known sinkholes and potential sinkholes. About one third of the SFHA are within 200 m or less of known sinkholes. Almost 87 percent of the current SFHA are within 200 m of or directly intersect potential sinkholes throughout the CoBG, with 100 percent of the SFHA within 1,000 m of at least one potential sinkhole. Over half of the SFHA are within 1,000 m of the mapped caves in the CoBG, with almost a third within only 400 m of the caves. This is consistent with some of the flooding throughout the CoBG, given that many flood events in the city are related to karst features and sinkholes; however, riverine flooding is still a problem in the city, as some of the surface streams and rivers such as the Barren River have been prone to flooding historically (Shelley 2018). A relatively low number of the SFHA were located within 1,000 m of any of the HMP sites with only about 25 percent in that category. The lower association between the HMP sites and SFHA could potentially be due to the relatively low number of current HMP sites as the mitigation portal is a relatively new development for the CoBG and BRADD. The low association could also be due to the need for the NFHL to be updated to reflect new flood areas that the HMP is attempting to identify (FEMA 2022).

The clear relationship between flooding and karst features emphasizes the need to consider the landscape when buying properties or planning new developments more heavily in urban karst environments. The National Research Defense Council (NRDC) and Columbia University's Sabin Center for Climate Change Law reviewed the various policies and regulations throughout the US related to real estate flood disclosure and gave each state a 'report card,' ranking the level of protection each state gives its residents (NRDC 2018). The state of Kentucky received a 'C' grade, denoting an 'Average' ranking, as the state at least has some level of flood disclosure requirements but has much room for improvement (NRDC 2018). One of the states that received one of the worst grades out of the entire United States was Missouri, which is a state with substantial karst landscape (NRDC 2018). Not only does the state of Missouri have no regulations in place that require any disclosure to a buyer of previous flooding or damage to a property, but the state also does not have any type of disclosure requirements beyond whether or not methamphetamine has ever been produced on the property (NRDC 2018). In a state that has such extensive karst landscape that it has been dubbed "The Cave State," the lack of any sort of flood disclosure requirements is a flagrant problem (MDC 2022). The requirement of disclosure related to flooding or any associated issues is a valuable policy for Kentucky or any state to have but there are still improvements that could be made to current regulations in many states to better protect home and property buyers. Residents and property owners are still vulnerable to flooding even when made aware of the potential for flooding in the area but lacking knowledge of even the possibility of flooding could increase vulnerability exponentially.

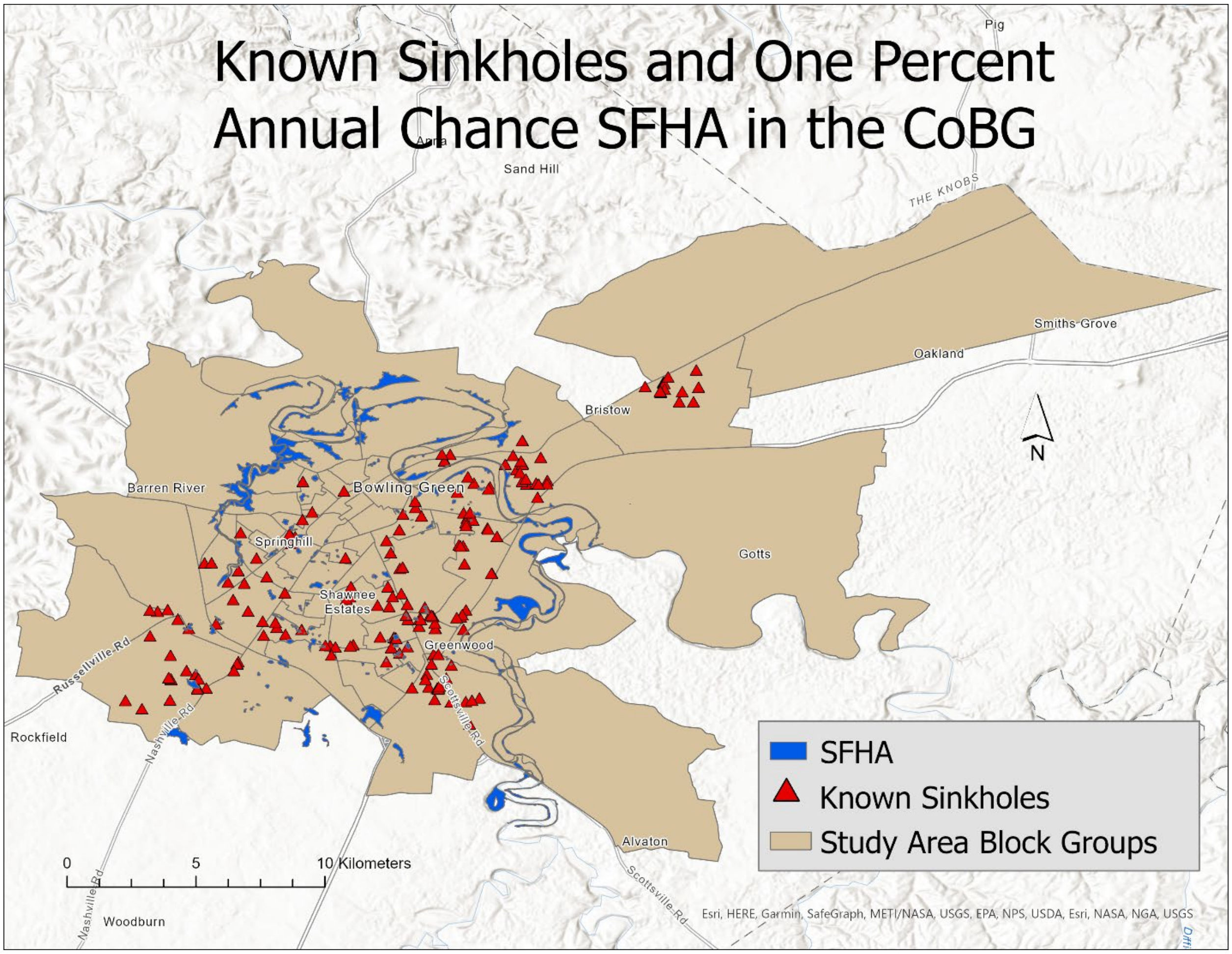


Figure 5.1: Known sinkholes and one percent annual chance SFHA in the CoBG study area block groups (Source: Created by Author).

In the CoBG, flood extents were mapped based upon aerial imagery taken after a flood event in 2021 to showcase which areas of the city experienced flooding. Flood extents were mapped within the boundaries of the CoBG and the subbasin that extend to the south of the city boundary, then associated with SFHA (Figure 5.2). In order to reduce edge effects and to remain consistent with the study area under consideration amongst the other GIS analyses in this research, only flood extents within the CoBG or within a two-kilometer buffer surrounding the city boundaries were included in analyses. The general lack of mapped flood extents for the CoBG presents a limitation in analyses because the flood extents are based upon solely one major rain event; additionally, the imagery utilized to map flood extents was taken several days after the flood event, rather than immediately succeeding the precipitation event. Flood extents mapped from the imagery may not reflect the entirety of flooded area, as water levels may have receded in the time between the precipitation event and when the images were taken. Additional data would need to be gathered to identify any patterns or draw significant conclusions, but examining the current mapped flood extents can still provide helpful insights or information.

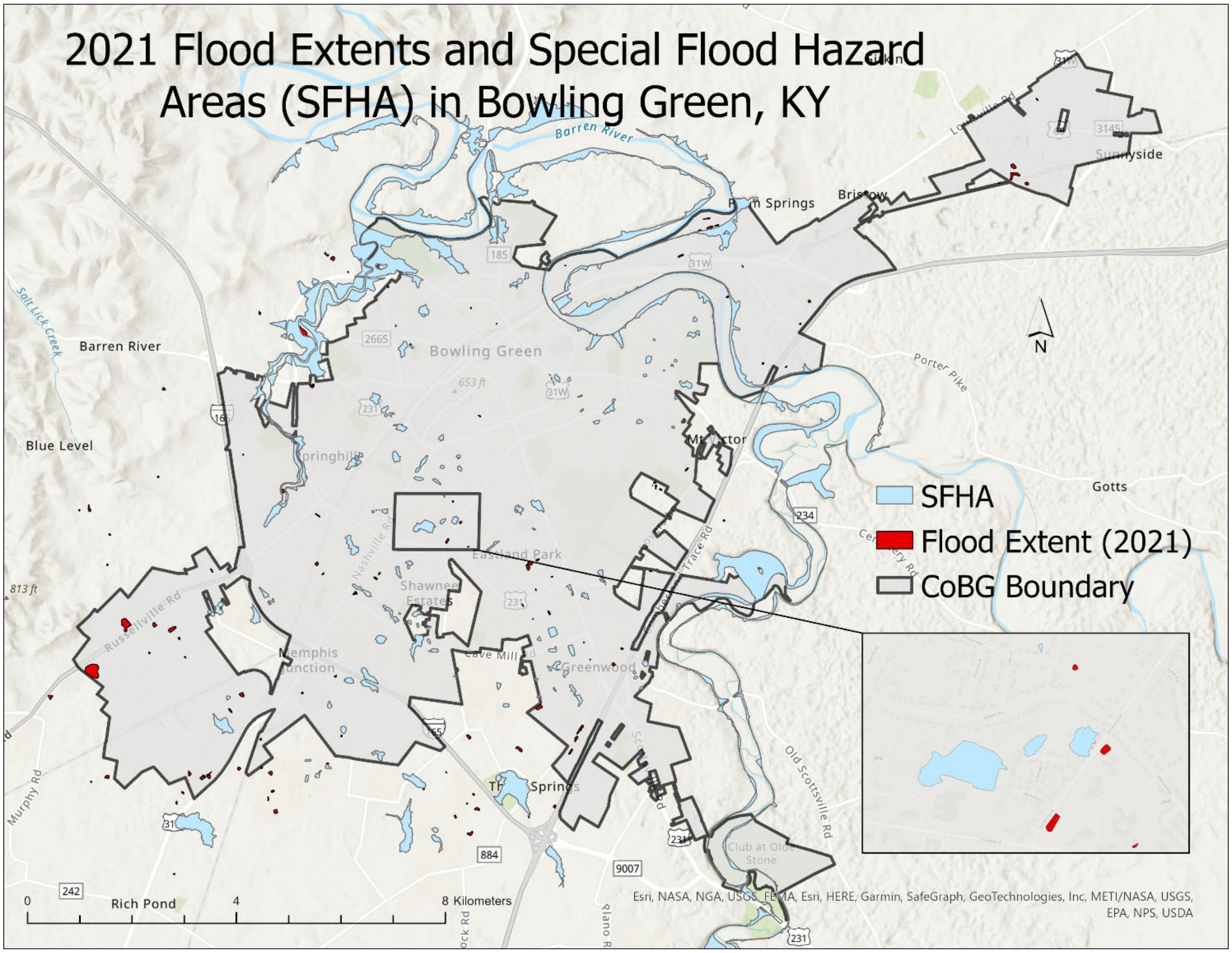


Figure 5.2: Map of 2021 flood extents and SFHA in the CoBG (Source: Created by Author).

The mapped flood extents were spatially associated with the SFHA within the CoBG and the two-kilometer buffer to examine the relationship between the features. The total area of the SFHA is much larger than the total area of the flood extents, which could contribute to the SFHA and flood extents having only 0.74 percent of their combined area in common. About 20 percent of the area of the flood extents directly intersects or is located within a SFHA and almost 30 percent of the area of the flood extents is within fifty meters of a SFHA. Only about 0.77 percent of the area of the SFHA intersects with the mapped flood extents. The intersection of the flood extents and SFHA helps to showcase areas that are designated SFHA that still experience flooding, while also identifying regions that may have begun flooding since the last time the official floodplain maps for the CoBG were updated in 2007. Referring to the current SFHA maps utilized in the CoBG, a local official stated, “When the maps were drawn, there was nowhere near as much development as we’re seeing now. When there’s lots of new developments, the land changes drastically and places that have never flooded in the past may become new flood zones” (Pers. Comm. 2022).

For both the SFHA and the flood extents, over 60 percent of the parcels that directly intersect or are within fifty meters of the SFHA or flood extents separately are residential or multi-family residential. Given that land use parcels are separated and categorized by property boundaries, the sheer number of properties that have the potential to be impacted by flooding is dominated by residential properties. When examining the total area that the different types of land use parcels occupy, agricultural land is the predominant land use located inside or within fifty meters of the SFHA or flood extents. Over 70 percent of the land use associated with the SFHA and flood extents separately is utilized for agriculture. The total area of the properties that have the potential to be impacted by flooding is vastly dominated by agricultural properties.

Aside from agriculture being a major industry in Kentucky, the potential impacts of flooding in agricultural lands are numerous, from pollution due to runoff of fertilizers, pesticides, or waste from livestock to economic losses from losing arable land or livestock (Howe and White 2003).

The identified SFHA and flood extent areas are areas of the city that already experience flood impacts that need mitigation; with the growing population, development, and potential climate change impacts, many areas of the city could potentially begin to experience much more frequent or intense flooding in the coming decades without proper planning and mitigation. Known sinkholes and potential sinkholes were the karst features that were most associated with both the SFHA and the flood extent maps. While riverine flooding occurs in the CoBG, karst-related flooding is also a frequent problem in the CoBG, despite the lack of specific inclusion of karst flooding in many flood policies and regulations (Feeney 1986). The floodplain maps of SFHA developed by FEMA have not been updated since 2007, a gap of fifteen years at the time of this research; current flood extent mapping that accurately reflects flooding in the CoBG is very limited. Much of the city has grown in both development and population in the past fifteen years and many new properties have been established in regions of the city that are dense with known karst features and potential sinkholes, such as along the Russellville Road corridor in the CoBG (Sergent 2021). Referring to the Russellville Road corridor in the CoBG, a local official stated, “There are over four-hundred acres of proposed development within this corridor, including mixed use subdivisions, industrial facilities, commercial facilities, apartments, and single-family residences” (Pers. Comm. 2022). Despite some flooding in the area, and the potential for increased flooding, many developers are still requesting approval to build new structures and developments using the same drainage requirements as decades past.

The Bowling Green Area Chamber of Commerce has been nationally recognized for past nine years in a row for attracting corporate facility investments, with continued growth and development an expectation for the coming years (BG Chamber 2022). While the increase in companies and industries has aided the local economy and increased job opportunities for the local community, the combination of higher costs for development and decreasing land availability has forced development in flood prone areas (Shelley 2018; BG Chamber 2022). A CoBG official stated in an interview, “There are areas of the city that we know beyond a shadow of a doubt that flood but there is still development occurring in these areas,” presenting potential future impacts to the inhabitants of the CoBG (Pers. Comm. 2022).

Current industrial and commercial land use properties already constitute the highest number of parcels and highest total area associated with sinkholes than any other land use in the CoBG. Any new developments in Warren County must align with the zoning ordinances of the City-County Planning Commission, though each property is reviewed on a case-by-case basis. Each development is essentially viewed as one independent entity rather than as an addition to the surrounding area, meaning that approvals of development do not always consider how the land changes may impact the land beyond the boundaries of the property. A CoBG official stated in an interview, “A lot of development gets caught up with what we can do with this specific lot with not a lot of consideration for the offsite impacts. The way that our current body of regulation is written, you really only have to account legally for the immediate offsite impacts” (Pers. Comm. 2022). Though construction in designated SFHA can be approved with a permit, flood insurance is legally required for any properties located in SFHA; however, the lack of updates to the floodplain maps for the CoBG means that construction could occur in areas that should now be designated as SFHA but may not have been prone to flooding when the floodplain maps were last assessed. Without a SFHA designation, renters or owners of the newly developed properties would not be required to purchase flood insurance for their homes.

Table 5.2: Percentage of population of the identified demographics associated with SFHA, sinkholes, caves, and 2021 Flood Extents (Source: Created by Author).

Demographic	SFHA	Sinkholes	Caves	2021 Flood Extents
Disabled Populations	27.02%	29.90%	25.00%	30.00%
Education Level (High School or Equivalent, or Less)	55.98%	55.21%	54.53%	60.18%
Annual Household Income (Less than $75,000)	63.05%	65.65%	67.83%	68.27%
Poverty (Below Poverty Line, Household)	18.74%	16.07%	23.97%	18.66%
Unemployment Rate	5.24%	5.06%	6.00%	5.80%

Demographic data related to disabled populations, level of education, annual household income, poverty, and unemployment rates were associated with the SFHA, known sinkholes, caves, and 2021 flood extents in the CoBG to identify any potential environmental inequities (Table 5.2). The demographic characteristics associated with the flood and karst features were chosen because previous research studies have identified these factors as common sources of vulnerability and susceptibility to flooding (Cutter 1996; Cutter et al. 2008). At 17.5 percent of the population, the state of Kentucky has the third highest rate of disabled populations compared to the rest of U.S. states, while the national disability rate is 12.7 percent of the population (ACS 2020). The percentage of disabled populations in the CoBG associated with the flood and karst features ranges from twenty-five percent to thirty percent, which far exceeds the national or state disability rates. Over half of the population associated with the flooding and karst features in the CoBG has a highest level of educational attainment of a high school diploma or equivalent, or less. Between sixty and seventy percent of the population associated with the flood and karst features have an annual household income of less than $75,000. The poverty rates span between 16.07 percent to 23.97 percent, all exceeding the national poverty rate of 11.4 percent and the Kentucky poverty rate of 14.4 percent (CRS 2022). The unemployment rates of the populations associated with the karst features and flooding in the CoBG also exceeded both the national and state unemployment rates of 3.5 percent and 3.7 percent, respectively (BLS 2022).

While the percentage of the population associated with the flood and karst features in the CoBG showcase potential sources of vulnerability to flooding that are generally much higher than the state and national rates, the rates are not significantly higher than the demographics of the CoBG as a whole. The consistency of the identified populations with the CoBG could potentially be due to spatial limitations associated with the datasets available; current demographic data that accurately represents the region are not available in a format smaller than the block group level. Many of the flood and karst features cover a relatively small area of the block groups that are spatially associated with the features; the population that is closely associated with the features would be much smaller than the population of the block group. The lack of data on a smaller scale makes the confident identification of specific environmental injustices that are consistent throughout the CoBG difficult, though assessing the block groups individually could aid in identifying specific areas of the city that may experience disproportionate flood impacts that could then be further examined to identify potential trends in demographics.

The growing population and economy, changing landscape, climate change predictions, the presence of regularly occurring flooding, and numerous other characteristics of the CoBG are all factors that contribute to the necessity of assessing the vulnerabilities to flooding that the community already presents. The nature of urban karst in general can heavily impact the ways in which flooding can be mitigated that deviate from the typical practices utilized when managing types of flooding such as coastal or riverine. Alleviating problems that already exist combined with planning for the future is an inherently difficult task to undertake; coupled with a lack of knowledge about the characteristics of the community, economic development, or physical environment, flood management could quickly become a seemingly impossible undertaking. Collecting as much relevant information as possible related to the community under consideration could help to alleviate the notion of impossibility and promote successful management.

Verifying the relationship between karst features and their subsequent impact on flood vulnerability can help in understanding where flooding stems from, which could then help to identify potential areas where flooding may occur in the future. Karst landscapes are very complex in nature and have profound impacts on the behavior and patterns of water, necessitating more structured and holistic methods by which to further analyze the relationship between flooding, karst features, and the communities that inhabit the land. Implementing a flood vulnerability index such as the kFVI to assess the community for types of vulnerabilities within the social, environmental, or economic categories that can more effectively inform strategies employed to address current and future flooding, particularly when utilized in conjunction with GIS assessments and analyses of the physical environment and flooding.

5.2 kFVI

Assessing the vulnerability of a community to flooding is an inherently complex and complicated process, as there are many different directions and methods to utilize. The final kFVI designed and implemented in this research was an adaptation of many of the current FVIs employed in various environments around the world. The kFVI is a developed method for assessing vulnerability to flooding specifically in urban karst communities and is not intended to be a flawless system for all communities that experience flooding; rather, the kFVI is designed to be a starting point that can be adapted to align with the community under consideration. Communities located in karst environments can experience flooding that can be difficult to manage, largely due to the high levels of connectivity and sensitivity of the karst features; however, understanding the vulnerabilities that are present can aid in making management decisions and employing strategies that best address the problems a community is facing. Additionally, assessing vulnerabilities associated with social, environmental, and economic conditions of an area in a more zoomed-in approach can paint a more detailed picture by providing information on the individual characteristics of each area of vulnerability. The more relevant and useful information available, the more likely it is that informed management decisions can be made with success.

Within the study area, 63 block groups were assessed that were completely or partially within the boundaries of the CoBG or within a two kilometer radius surrounding the city in order to reduce edge effects in assessments. The results were first examined for each of the three categories, social, environmental conditions, and economic vulnerability, then compiled together to create a final kFVI assessment for each of the block groups and the CoBG. The environmental conditions indicators were additionally separated for a secondary assessment to determine the impact of karst-specific indicators on levels and locations of environmental vulnerability. Further instructions and discussion of the indicators and scoring metrics utilized was included to aid future implementations of the kFVI in other urban karst regions.

5.3 Application of the kFVI

In order to determine the indicators and scoring metrics in the application of the CoBG, many research studies utilizing the FVI and other vulnerability indices were examined to understand consistent indicators and how scoring metrics were determined in order to reduce subjectivity and arbitrariness of the kFVI (Table 5.3). The kFVI is intended to be adapted and implemented in other regions, but some scoring metrics were noted, as the indicators may need to be adjusted based upon the community at hand.

Table 5.3: List of indicators, data sources, and references to previous studies from which the indicators utilized in the kFVI were adapted (Source: Created by Author).

Category	**Indicator**	**Data Source**	**Unit**	**Indicator/Scoring Adaptation Reference**
Social	Population Density	US Census Bureau: ACS 5 Year Aggregate 2020	People/km²	Balica and Wright 2010; Sebald 2010; Son et al. 2011; Dunning and Durden 2013; Nasiri and Kalalagh 2013; Nasiri et al. 2019; Salazar-Briones et al. 2020; UNESCO-IHE 2022
	Underage and Elder Populations	US Census Bureau: ACS 5 Year Aggregate 2020	% of population	Connor and Hiroki 2005; Fekete 2009; Cutter et al. 2013; Dunning and Durden 2013; Salazar-Briones et al. 2020; UNESCO-IHE 2022
	Population in Poverty	US Census Bureau: ACS 5 Year Aggregate 2020	% of population	Balica and Wright 2010; Cutter et al. 2013; Dunning and Durden 2013; Salazar-Briones et al. 2020; UNESCO-IHE 2022
	Limited English-Speaking Households	US Census Bureau: ACS 5 Year Aggregate 2020	% of population	Fekete 2009; Cutter et al. 2013; Dunning and Durden 2013
	Disabled Populations	US Census Bureau: ACS 5 Year Aggregate 2020	% of population	Fekete 2009; Balica and Wright 2010; Balica et al. 2012; Can et al. 2013; Nasiri and Kalalagh 2013

	Annual Population Growth	US Census Bureau 2010 and 2020 Decennial Censuses	% of population	Sebald 2010; Balica and Wright 2010; Son et al. 2011; Balica et al. 2012; Nasiri and Kalalagh 2013; UNESCO-IHE 2022
	Predominant Education level	US Census Bureau: ACS 5 Year Aggregate 2020	Categorical data, using % of population	Fekete 2009; Sebald 2010; Cutter et al. 2013; Can et al. 2013; Dunning and Durden 2013; Salazar-Briones et al. 2020; UNESCO-IHE 2022
Economic	Land Use	BG RUCKAS	Categorical data	Fekete 2009; Balica and Wright 2010; Sebald 2010; Cutter et al. 2013; Can et al. 2013; Nasiri and Kalalagh 2013; Nasiri et al. 2019; UNESCO-IHE 2022
	Predominant Home Value	US Census Bureau: ACS 5 Year Aggregate 2020	US Dollars	Fekete 2009; Son et al. 2011; Cutter et al. 2013; Dunning and Durden 2013; Nasiri et al. 2019
	Unemployment Rates	US Census Bureau: ACS 5 Year Aggregate 2020	% of population	Fekete 2009; Balica and Wright 2010; Sebald 2010; Cutter et al. 2013; Dunning and Durden 2013; Nasiri and Kalalagh 2013; Salazar-Briones et al. 2020; UNESCO-IHE 2022
	Predominant Household Income	US Census Bureau: ACS 5 Year Aggregate 2020	US Dollars	Fekete 2009; Cutter et al. 2013; Can et al. 2013; Dunning and Durden 2013; UNESCO-IHE 2022
	Flood Insurance**	FEMA	% of properties	Balica and Wright 2010; Nasiri and Kalalagh 2013; UNESCO-IHE 2022
	Average Recovery Time**	FEMA (Declared Disasters)	Avg. # of Days in a Declared Disaster Incident Period	Balica and Wright 2010; Balica et al. 2012; UNESCO-IHE 2022
Environmental Conditions	Average Annual Increase in Precipitation**	Environmental Protection Agency (EPA); USGCRP (2017)	% increase/year	Connor and Hiroki 2005; Son et al. 2011; Can et al. 2013; Nasiri and Kalalagh 2013; Nasiri et al. 2019; UNESCO-IHE 2022
	Superfund / Brownfield Sites	BG RUCKAS	sites/km2	McMaster et al. 1997; Neumann et al. 1998; Wheeler 2004; Mohai et al. 2009
	Hazardous Waste Sites	BG RUCKAS	sites/km2	McMaster et al. 1997; Neumann et al. 1998; Wheeler 2004; Mohai et al. 2009
	Sinkholes	BG RUCKAS	sinkholes/km2	van Beynen and Townsend 2005
	Potential Sinkholes	BG RUCKAS	% of area	van Beynen and Townsend 2005
	Caves	BG RUCKAS	% of area	van Beynen and Townsend 2005

	Special Flood Hazard Areas	FEMA, National Flood Hazard Layer (NFHL)	% of area	Connor and Hiroki 2005; Balica and Wright 2010; Son et al. 2011; Balica et al. 2012; Nasiri and Kalalagh 2013; Nasiri et al. 2019; Salazar-Briones et al. 2020
	Monitoring in Place	WKU CHNGES	sites/km2	Son et al. 2011; van Beynen et al. 2012
	Regulatory Protection**	Policies and Regulations review by author	n/a	Connor and Hiroki 2005; van Beynen and Townsend 2005; Son et al. 2011; van Beynen et al. 2012

Assessing a community based upon social, economic, and environmental conditions vulnerabilities to flooding can aid in understanding how to best implement management practices. Various iterations of the FVI and other vulnerability indices were assessed and the resulting indicators and scoring metrics utilized in the kFVI were applied to the study area.

- Social vulnerability indicators and scoring metrics justifications:
    - Population density, Underage and Elder Populations, Population in Poverty, Annual Population Growth, Disabled Populations, and Education Level: derived directly from the UNESCO-IHE (2022) and Balica and Wright (2010) FVI framework, which are generally regarded to be the standards for iterations of the FVI, in addition to the validation associated with the use of the indicators and scoring by other researchers (Table 5.3).
    - Limited English-Speaking Households: derived from previous researchers (Table 5.3) based upon the understanding that the greater amount of the population with language barriers or limited English, the higher vulnerability can be, as a language barrier may cause lack of understanding or spread of information.

The social vulnerability indicator that was identified as potentially needing to be adjusted for different study areas was Population Density. The average population density per block group in the CoBG is about 1,000 people per square kilometer. Using the average of 1,000 people/km^2 as the middle value, scoring for population density was split equally into the four possible scores with half of the possible scores ranging above 1,000 and half below 1,000. Given that a higher population density is associated with higher vulnerability, a score of '0' was determined by a population density of less than or equal to 500 people/km^2 and a score of '3' was determined by a population density of more than 2,000 people/km^2. In other areas of the country, population densities could be very different. Higher population densities are still associated with higher vulnerability but 1,000/km^2 may not be a realistic or accurate representation of a different community, so the calculation of the average density divided into four scores can aid in the inclusion of population density when applying the kFVI in a different area.

Indicators with scoring metrics determined by percentage of the population were determined with a goal of having consistent metrics between indicators to aid in comparisons while maintaining scalability. The scoring metrics were primarily based upon work by previous researchers, by examining national and state averages, and by assessment of the natural breaks in the percentages to maintain logical divisions as well. Many of the indictors using population percentages featured relatively similar natural breaks and divisions at the five percent, 25 percent, and 50 percent values. For example, average poverty rates by state in the U.S. range from about five percent to about 25 percent in general. At the block group level, percentages and rates can be more extreme than at the state level because the scale is much smaller so an examination of the natural divisions for the study area at hand is important to include. At the block group level, a poverty rate lower than five percent would be very low, a poverty rate over 25 is higher but still relatively moderate; there are some areas with extremely high poverty levels, so a score of ‘3’ indicating the highest vulnerability was associated with poverty levels higher than 50 percent of the population.

- Economic vulnerability indicators and scoring metrics justifications:
    - Land Use, Unemployment Rates, Household Income, Flood Insurance, Average Recovery Time: derived directly from the UNESCO-IHE (2022) and Balica and Wright (2010) FVI framework, which are generally regarded to be the standards for iterations of the FVI, in addition to the validation associated with the use of the indicators and scoring by other researchers.
    - Predominant Home Value: derived from previous researchers (Table 5.3); for the purposes of this research, homes with low value or low household incomes were viewed as more vulnerable than those with high value or income because the goal was to examine vulnerabilities to communities of lower socio-economic status or marginalized communities. Lower-income homeowners with lower home values have been found to be more likely to suffer total flood damages that exceed the value of their home (Moore 2017).
- The economic indicators identified for potential adaptations based upon the study area were Home Value and Household Income. Land Use scoring metrics were chosen based upon metrics utilized by previous researchers and the potential for immediate impacts to the lives of the people in the community. The CoBG has a relatively low average cost of living compared to some other localities in the U.S., so the average home value and household income may be lower in the CoBG than in an area like Nashville, Tennessee. The divisions of the scoring metrics for the two indicators were based upon the natural breaks and the average home value or household incomes in the CoBG. The average

home value or household income of the area can be utilized as the middle value of the range of scores, with half of the possible scores ranging above the median home value and the other half ranging above. For example, an area with an average home value of $200,000 could have scoring divisions of less than $100,000, $100,000 to $199,999, $200,000 to $299,999, and $300,000 or more.

- Environmental vulnerability indicators and scoring metrics
    - Average Annual Increase in Precipitation: indicator derived from previous researchers (Table 5.3); scoring metrics were adapted based upon reports released by the USGCRP (2017) associated with precipitation changes across the United States, which were broken up into the ranges utilized in the kFVI.
    - Superfund / Brownfield Sites, Hazardous Waste Sites: derived directly from previous researchers (Table 5.3) with relation to environmental equity and general potential for contamination and hazards in the event of flooding.
    - Sinkholes, Potential Sinkholes, Caves, Special Flood Hazard Areas: adapted from indicators utilized in the Karst Disturbance Index (KDI). Sinkholes, caves, and flood zones have the ability to influence flood impacts to the inhabitants of the area, placing areas with higher land area or densities of the features at potentially higher levels of vulnerability to flooding.
    - Monitoring in Place: adaptation based upon the idea that water level and precipitation monitoring in a neighborhood can help land managers to have real-time data showing where flooding is occurring and the level of flooding, which can help with emergency services and evacuations, if necessary. Additionally,

land managers will have more data available regarding flood events, which can aid future mitigation.

- Regulatory Protection: indicator and scoring derived directly from the KDI and based upon the amount of protection the community has been given (van Beynen and Townsend 2005).

The scoring metrics associated with environmental conditions vulnerability were largely determined to be scalable to other karst regions but could still be adapted to align more closely to a specific study area if necessary. The densities of the features such as hazardous waste facilities or sinkholes could be adapted by adjusting the number of sites per square kilometer or the associated area. Any of the scoring metrics and indicators utilized in the kFVI can be adjusted to a different study area but many could be utilized in the current format and still aid in understanding flood vulnerabilities of a community outside of the CoBG. There have been many iterations of the FVI but none have included karst environments or karst-specific indicators, despite the presence of karst features in many regions around the world.

5.3.1 Social Vulnerability

The final indicators utilized to assess social vulnerability were Population Density, Underage and Elder Populations, Population in Poverty, Limited English-Speaking Households, Disabled Populations, Annual Population Growth, and Education Level. Amongst the sixty-three block groups examined, only one block group received a classification of High Vulnerability for social vulnerability. Of the 63 block groups assessed, 19 block groups were classified as Moderate Vulnerability, 36 as Vulnerable, and the final seven groups as Low Vulnerability.

Given the total population of 97,907 people amongst the 63 block groups under consideration, about 31.6 percent of the population lives within High to Moderate classification for social vulnerability, about 56.8 percent within Vulnerable, and about 11.7 percent with Low Vulnerability (Table 5.4).

Table 5.4: Total number of people and percentage of the population in the study area by calculated social vulnerability classification (Source: Created by Author)..

	Low Vulnerability	**Vulnerable**	**Moderate Vulnerability**	**High Vulnerability**
Number of People	11,437	55,569	29,267	1,634
Percentage of Population	11.7%	56.8%	29.9%	1.7%

Block Group 212270110012, located towards the west end near the Springhill area and Russellville Road in the CoBG, received the highest final social vulnerability score with a score of 0.76, indicating a classification of High Vulnerability (Table 5.5). The high population density and population growth, in addition to the low education levels of this area resulted in scores of '3,' and scores of '2' for underage and elder populations, population in poverty, and disabled populations. Block Group 212270114021, located just beyond the eastern border of the city limits near Cemetery Road and Drakes Creek, received the lowest final social vulnerability score of 0.14. This block group received scores of '0' for every indicator except for Underage and Elder Populations, for which this block group received a '3.'

Table 5.5: Study area block groups with the top five highest calculated social vulnerability scores (Source: Created by Author).

Geographic Area Name	GEOID	PD	UEP	LEH	PP	DP	PG	EL	S	Final Score	Classification
Block Group 2, Census Tract 110.01	212270110012	3	2	1	2	2	3	3	0	0.7619	High Vulnerability
Block Group 2, Census Tract 103	212270103002	3	2	1	2	2	3	2	0	0.7143	Moderate Vulnerability
Block Group 3, Census Tract 103	212270103003	3	1	1	3	2	3	2	0	0.7143	Moderate Vulnerability
Block Group 1, Census Tract 105	212270105001	3	2	1	3	1	3	2	0	0.7143	Moderate Vulnerability
Block Group 3, Census Tract 102	212270102003	2	2	1	2	2	3	2	0	0.6667	Moderate Vulnerability

Block Groups 212270108053, 212270114011, and 212270114013 tied for the next lowest scores, with each receiving a score of 0.19 (Table 5.6). Each of these block groups are located completely within or majority within the boundaries of the CoBG and are all located towards the eastern end of the city. These block groups each received a ‘2’ for Underage and Elder Populations, and a ‘1’ for Disabled Populations and Education Level, with the remaining indicators each receiving ‘0’. The areas with the lowest social vulnerability scores were generally found to be located in the eastern and southern regions of the city. The areas with the highest social vulnerability scores were generally found to be located in the western and central regions of the city, particularly across the train tracks on the northwestern side.

Table 5.6: Study area block groups with the top five lowest calculated social vulnerability scores (Source: Created by Author).

Geographic Area Name	GEOID	PD	UEP	LEH	PP	DP	PG	EL	S	Final Score	Classification
Block Group 1, Census Tract 114.02	212270114021	0	3	0	0	0	0	0	0	0.1429	Low Vulnerability
Block Group 3, Census Tract 108.05	212270108053	0	2	0	0	1	0	1	0	0.1905	Low Vulnerability
Block Group 1, Census Tract 114.01	212270114011	0	2	0	0	1	0	1	0	0.1905	Low Vulnerability
Block Group 3, Census Tract 114.01	212270114013	0	2	0	0	1	0	1	0	0.1905	Low Vulnerability
Block Group 3, Census Tract 109	212270109003	1	2	0	0	1	0	1	0	0.2381	Low Vulnerability

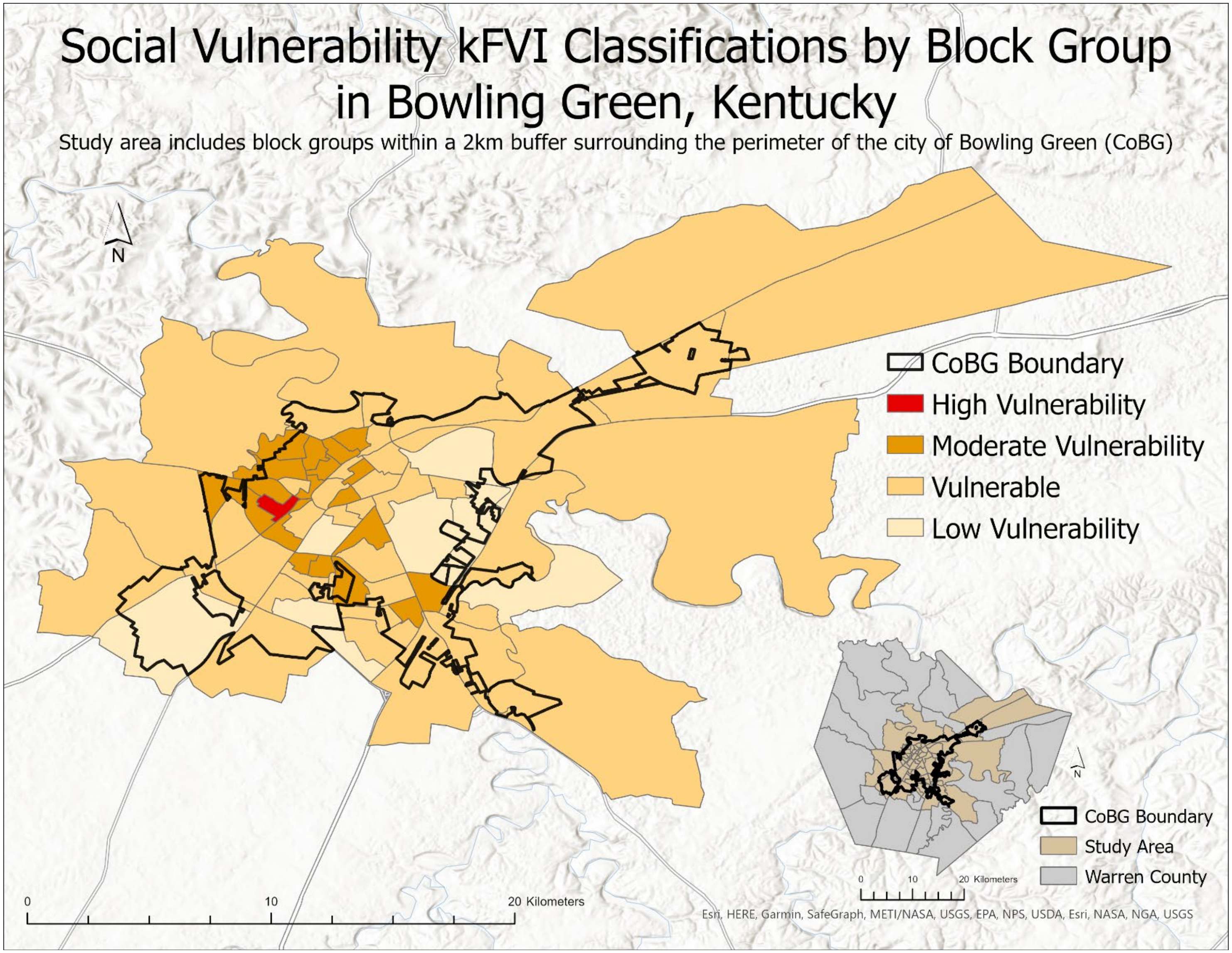


Figure 5.3: Map of Social Vulnerability distribution based upon kFVI scores for the CoBG (Source: Created by Author).

Table 5.7: There were 63 block groups were assessed within the study area for each of the social vulnerability indicators and scored from 0-3; the table breaks down how many of the block groups were scored for each indicator (Source: Created by Author). **Denotes indicators that the same score was given to all block groups in the study area, rather than individual scores for each.

Social Indicator	Score of '0'	Score of '1'	Score of '2'	Score of '3'
PD	24	13	16	10
UEP	0	7	48	7
LEH	43	19	1	0
PP	9	30	18	6
DP	2	25	31	5
PG	37	5	5	16
EL	3	25	30	5
S**	63	0	0	0

One of the social indicators with some of the most consistently high scores was Underage and Elder Populations, demonstrating higher vulnerability throughout the CoBG related to that specific indicator. The final Underage and Elder Populations scores featured primarily scores of '2' or '3,' with only one block group of the 63 under consideration receiving a score of '0' and only seven block groups receiving a score of '1.' Block groups receiving a score of a '2' or '3' feature high percentages of Underage and Elder Populations, which can elevate a community's vulnerability to flooding as a person's age can impact ability or desire to evacuate an area quickly in a time of emergency (Fekete 2009; Balica et al. 2012). While the CoBG does have high percentages of elder populations in some areas, the underage population in the CoBG contributes more heavily to the higher scores in this indicator. The strong concentration of underage populations in the CoBG could be due to the fact that Bowling Green is the fastest growing city in the state of Kentucky, in addition to the presence of Western Kentucky University (Southcentral Kentucky 2020). The high influx of new residents in the CoBG and the young adults graduating from the local university could contribute to the substantial proportion of residents under the age of 18, as new families join the community or choose to settle down in the CoBG. Additionally, Bowling Green is a common location for refugee and immigrant resettlements, as the International Center of Kentucky is located in the CoBG (ICofKY 2022). The ICofKY frequently resettles families in the CoBG, as the organization offers daycare for young children and aids families in enrolling children that are old enough in school amongst other services. The presence of the IcofKY and the resettlement of families in the CoBG could also contribute to the high concentrations of underage populations.

The indicator with the consistently lowest scores was Limited English-Speaking Households, with the vast majority of block groups having less than five percent of the households claiming limited English. Out of the 63 block groups assessed, none scored a ‘3,’ and only one scored a ‘2.’ Three of the 63 block groups have over 20 percent of households claiming limited English, which is still well over then national average of an estimated 4.3 percent and the estimated average for Kentucky at 1.3 percent. Although much of the CoBG does not have many households with limited English, there are still certain areas of the city that feature high concentrations of households with limited English. Identifying these neighborhoods is important because the language barrier can present a number of issues. Residents without proficient English-speaking abilities may disregard flood warnings, lack understanding of insurance policies, or may be overlooked when educational opportunities are created related to flooding or the karst environment. Lacking an understanding of the language that the vast majority of the United States employs can hinder a resident’s ability to understand the policies and regulations that are in place; this obstacle can prevent knowledge and awareness of resources that are available, ways in which homes and properties may be vulnerable, or even simply the knowledge of what falls under the government's jurisdiction to address versus what is the responsibility of the property owner.

5.3.2 Economic Vulnerability

The final indicators utilized in the kFVI to assess economic vulnerability in the study area were Land Use, Home Value, Unemployment Rate, Household Income, Flood Insurance, and Recovery Time. Of the 63 block groups under consideration, three were classified as High Vulnerability, 27 as Moderate Vulnerability, 23 as Vulnerable, and the final ten block groups as Low Vulnerability. With a total population in the study area of 97,907 people, about 44.9 percent of the population lives in an area of High or Moderate economic vulnerability, about 37.3 percent within Vulnerable, and about 17.8 percent of the population is within an area with Low Vulnerability (Table 5.8).

Table 5.8: Total number of people and percentage of the population in the study area by calculated economic vulnerability classification (Source: Created by Author).

	Low Vulnerability	**Vulnerable**	**Moderate Vulnerability**	**High Vulnerability**
Number of People	17,410	36,565	39,531	4,401
Percentage of Population	17.8%	37.3%	40.4%	4.5%

The block group with the highest evaluated economic vulnerability was Block Group 211270107021 located in the south-central region of the city near the Greenwood area and Scottsville Road. With a final score of 0.83, this area is classified as High Vulnerability (Table 5.9). As a predominantly multi-family residential area with low home values, high unemployment rates, and low household incomes, this area of the CoBG is economically very vulnerable to impacts of flooding. Though the predominant land use in this area is residential, the second highest usage of land in this block group is commercial; much of this area is concentrated housing and businesses creating large amounts of impervious surfaces and human activity.

Table 5.9: Study area block groups with the top five highest calculated economic vulnerability scores. Seven groups included due to equivalent scores (Source: Created by Author).

Geographic Area Name	GEOID	LU	HV	UR	HI	FI	RT	Total Score	Final Score	Classification
Block Group 1, Census Tract 107.02	212270107021	3	3	3	3	1	1	10	0.8333	High Vulnerability
Block Group 3, Census Tract 102	212270102003	2	3	3	3	1	1	9	0.7500	High Vulnerability
Block Group 1, Census Tract 112	212270112001	3	3	3	2	1	1	9	0.7500	High Vulnerability
Block Group 2, Census Tract 103	212270103002	3	3	2	2	1	1	8	0.6667	Moderate Vulnerability
Block Group 1, Census Tract 105	212270105001	3	3	1	3	1	1	8	0.6667	Moderate Vulnerability
Block Group 2, Census Tract 110.01	212270110012	3	3	2	2	1	1	8	0.6667	Moderate Vulnerability
Block Group 3, Census Tract 110.01	212270110013	3	2	3	2	1	1	8	0.6667	Moderate Vulnerability

The region of the study area that received the lowest overall score for economic vulnerability was Block Group 211270114021, which received the lowest overall score for social vulnerability as well. This block group received scores of '1' for only Land Use and Household Income in the susceptibility and exposure indicators while also receiving scores of '1' for the two resilience indicators, thereby receiving a final score of '0' (Table 5.10). This does not mean that this block group does not necessarily have any economic vulnerability to flooding, but the likelihood of the inhabitants of this area being able to take preventative measures or recover is much higher than inhabitants of other neighborhoods.

Table 5.10: Study area block groups with the top five lowest calculated economic vulnerability scores (Source: Created by Author).

Geographic Area Name	GEOID	LU	HV	UR	HI	FI	RT	Total Score	Final Score	Classification
Block Group 1, Census Tract 114.02	212270114021	1	0	0	1	1	1	0	0.0000	Low Vulnerability
Block Group 1, Census Tract 114.01	212270114011	1	0	0	2	1	1	1	0.0833	Low Vulnerability
Block Group 2, Census Tract 114.01	212270114012	1	0	1	1	1	1	1	0.0833	Low Vulnerability
Block Group 4, Census Tract 115	212270115004	1	0	1	1	1	1	1	0.0833	Low Vulnerability
Block Group 3, Census Tract 116	212270116003	1	0	0	2	1	1	1	0.0833	Low Vulnerability

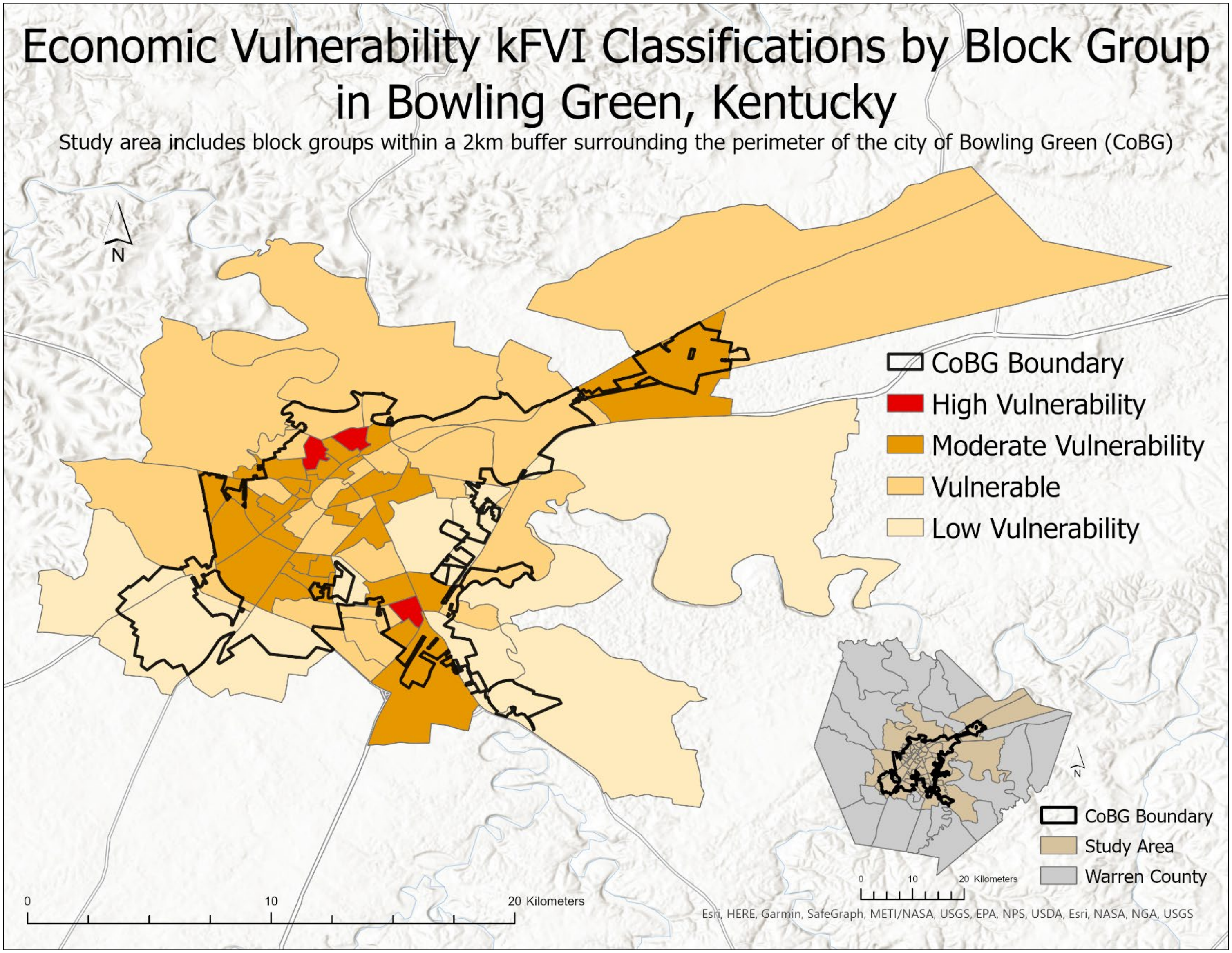


Figure 5.4: Map of Economic Vulnerability distribution based upon kFVI scores for the CoBG (Source: Created by Author).

Table 5.11: 63 block groups were assessed within the study area for each of the economic vulnerability indicators and scored from 0-3; the table breaks down how many of the block groups were scored for each indicator (Source: Created by Author). **Denotes indicators that the same score was given to all block groups in the study area, rather than individual scores for each.

Economic Indicator	Score of '0'	Score of '1'	Score of '2'	Score of '3'
LU	0	28	6	29
HV	12	7	26	18
UR	15	25	16	7
HI	0	15	36	12
FI**	0	63	0	0
RT**	0	63	0	0

The indicator 'Flood Insurance' was assessed for the entirety of Warren County, rather than at the block group scale due to the lack of data available related to flood insurance policies in the CoBG. The United States Congress has mandated that all buildings located within a SFHA must have flood insurance (FEMA 2022); however, FEMA estimated in May of 2022 that the penetration rate or percentage of buildings within a SFHA in Warren County was only about 30.5 percent, or 0.5 percent for the whole community (FEMA, Pers. Comm. 2022). While this statistic is representative of Warren County as a whole and the statistics within the CoBG may be different, county-level data were the smallest scale available to best be able to assess the flood insurance indicator for the study area. Given that less than 50% of buildings in a SFHA have flood insurance, each of the block groups was given the same score of '1' for the flood insurance indicator, indicating low levels of resilience related to this indicator (Table 5.11).

One of the economic vulnerability indicators with consistently high scores was Land Use. Many of the block groups assessed were predominantly composed of Residential, Multi-Family Residential, Commercial, or Industrial land use parcels. Areas with higher levels of human activity tend to be associated with more sources of vulnerability (Salazar-Briones et al. 2020). Residential areas can have vulnerabilities associated with impacts to the economy as community members suffer economic losses when their homes and property are damaged or destroyed in flood events and are forced to either rebuild or abandon their homes. In areas with lower incomes and home values, community members may not have the financial resources to be able to recover from flood impacts. In commercial and industrial areas, floods can disrupt necessary or everyday operations and services, which can be damaging to economic activity in the region. Additionally, residential, commercial, and industrial areas can be associated with rapid landscape changes and large concentrations of impervious surfaces such as parking lots, sidewalks, or driveways. The addition of impervious surfaces can drastically alter the paths and locations of absorption for water and ultimately modify areas of flooding.

Household Income and Home Value are both important factors to examine when assessing economic vulnerability to flooding. From an economic standpoint, lower home values tend to be associated with lower damage estimates because the homes are worth less. When homes are valued a lower price, the cost of damages and repairs generally would not be as high compared to homes with high value. Homes with higher household incomes would likely have more disposable income or savings available to repair damage or take preventative measures against flooding; however, for the purposes of this research, homes with low value or low household incomes were viewed as more vulnerable than those with high value or income because the goal was to examine vulnerabilities to communities of lower socio-economic status or marginalized communities. Lower home values are typically associated with lower income levels; people of lower socio-economic status will generally buy or rent homes that are less expensive and therefore align more closely with incomes and budgets (Capozza et al. 2002). While cost of repairs or preventative measures may not be high, many members of the community may not have the resources available to be able to afford the costs of flooding. Even just one inch of floodwater in a home could potentially cause up to $25,000 in damage (FEMA 2022). Additionally, in a report released by the National Research Defense Council (NRDC) regarding the NFIP, the NRDC found that homes in the NFIP with lower value were more likely to suffer flood damages that exceeded the property's value; according to the NRDC, this indicates that lower-income homeowners may be more likely to suffer total flood damages that exceed the value of their home (Moore 2017).

The Household Income indicator consistently identified higher levels of vulnerability throughout the study area, as none of the block groups received a score of '0.' 12 of the 63 block groups received scores of '3,' with a predominant household income for those areas at less than $25,000 a year; 36 of the block groups received scores of '2,' with predominant household incomes of $25,000 to $74,999. In one group, more than 70 percent of homes have an annual household income of less than $25,000. The Home Value indicator also identified many areas of the CoBG with lower home values with 18 of the groups scoring a '3' and 26 groups scoring a '2.' In over a quarter of the block groups, more than half of the homes are valued at less than $100,000 in value.

In general, the unemployment rates for the CoBG are similar to the national rate for unemployment of about 3.6 percent as of May of 2022 (BLS 2022); however, seven of the 63 block groups had unemployment rates of over 10 percent, the highest of which reaching almost 23 percent. Another 16 of the block groups had unemployment rates above the national average in the five to ten percent range.

Due to a lack of substantial data regarding recovery times to flooding in the CoBG, the study area groups were all given the same score and assessment for the Recovery Time indicator. For the purposes of this study, recovery time was assessed by examining Declared Disaster flood events that occurred throughout the past thirty years since 1992. Since 1992, there have been six federally declared disasters in Warren County, with one in 1997, 1998, 2004, 2009, 2010, and 2021. Official incident periods for each range from three days to 31 days. On average, the recovery time for the city to return to normal operations after a declared disaster event is just under 21 days, or about three weeks. As a resilience indicator, Recovery Time for each of the block groups was scored as a ‘1,’ indicating relatively low resilience associated with the amount of time needed for the city to return to normal functioning after a major flood event.

5.3.3 Environmental Conditions

The final indicators utilized in the kFVI to assess environmental conditions vulnerability in the study area were Average Annual Increase in Precipitation, Superfund or Brownfield Sites, Hazardous Waste Sites, Sinkholes, Potential Sinkholes, Caves, Special Flood Hazard Area (SFHA), Monitoring in Place, and Regulatory Protection. Of the 63 block groups under consideration, none received a classification of High Vulnerability and only two groups were classified as Moderate Vulnerability. Of the block groups, 23 were classified as Vulnerable and the final 38 groups scored Low Vulnerability. With a total population in the study area of 97,907 people, only about 4.3 percent of the population lives in an area with a Moderate Vulnerability classification, 37.0 percent reside in a Vulnerable classification area, and about 57.8 percent live in a Low Vulnerability classification area (Table 5.12).

Table 5.12: Total number of people and percentage of the population in the study area by calculated economic vulnerability classification (Source: Created by Author).

	Low Vulnerability	Vulnerable	Moderate Vulnerability	High Vulnerability
Number of People	56,626	37,057	4,224	0
Percentage of Population	57.8%	37.9%	4.3%	0%

For overall environmental vulnerability, two block groups tied for the highest score with a final score of 0.52, or a Moderate Vulnerability classification (Table 5.13). One of the two block groups with the highest scores was Block Group 212270107021, which scored the highest in economic vulnerability as well. This block group has a land area of less than one square kilometer but features four current SFHA that cover a little over five percent of the land, giving the group a score of '2' for the SFHA indicator. Given the close proximity and concentration of hazardous waste sites, known sinkholes, potential sinkholes in this area, the group scored '3' for each of the related indicators. Potential sinkholes that cover almost a third of the area, or about 33 percent. While Greenwood Cave is located in this block group, the cave spans less than one percent of the area. The presence of Greenwood Cave in this area could impact flooding but would require more detailed examination to determine. The second block group that tied for the highest score was Block Group 212270113003. This block group is much larger than Block Group 212270107021 with a land area of about eight square kilometers but still received a relatively high score due to the high concentration of sinkholes and hazardous waste sites. Block Group 212270113003 was one of the only groups that received a '2' for the presence of Superfund or Brownfield sites in the area. Potential sinkholes cover about 15 percent of the area, which is in the top third of all groups in the study area.

Table 5.13: Study area block groups with the top five highest calculated environmental conditions vulnerability scores. Six groups included due to equivalent scores (Source: Created by Author).

Geographic Area Name	GEOID	PC	SBS	HW	S	PS	C	SFHA	MiP	RP	Total Score	Final Score	Classification
Block Group 1, Census Tract 107.02	212270107021	1	0	3	3	3	0	2	0	1	11	0.52	Moderate Vulnerability
Block Group 3, Census Tract 113	212270113003	1	2	3	3	2	0	1	0	1	11	0.52	Moderate Vulnerability
Block Group 1, Census Tract 103	212270103001	1	3	3	3	0	0	0	0	1	9	0.43	Vulnerable
Block Group 1, Census Tract 107.01	212270107011	1	0	3	3	3	0	0	0	1	9	0.43	Vulnerable
Block Group 2, Census Tract 107.01	212270107012	1	0	3	3	2	0	1	0	1	9	0.43	Vulnerable
Block Group 1, Census Tract 108.01	212270108011	1	0	3	3	2	0	1	0	1	9	0.43	Vulnerable

There was a four-way tie for lowest overall environmental conditions vulnerability between the block groups 212270104001, 212270105002, 212270109001, and 212270111004. These groups each scored a final environmental conditions vulnerability of 0.0, or a Low Vulnerability classification. A final score of 0 does not mean these areas do not have vulnerability to flooding. These areas all received scores above '0' for some of the exposure or susceptibility indicators; however, the groups also had high enough resilience scores that brought the overall vulnerability calculation lower (Table 5.14). All four of the groups with a final score of zero received a '3' for the indicator Monitoring in Place as each group contains at least one monitoring site per 5 km^2 or less. The presence of flooding or precipitation monitoring helps to identify problems sooner and respond more quickly, thereby increasing resilience to flooding.

Table 5.14: Study area block groups with the top five lowest calculated environmental conditions vulnerability scores (Source: Created by Author).

Geographic Area Name	GEOID	PC	SBS	HW	S	PS	C	SFHA	MiP	RP	Total Score	Final Score	Classification
Block Group 1, Census Tract 104	212270104001	1	0	3	0	0	0	0	3	1	0	0.00	Low Vulnerability
Block Group 2, Census Tract 105	212270105002	1	0	3	0	0	0	0	3	1	0	0.00	Low Vulnerability
Block Group 1, Census Tract 109	212270109001	1	3	0	0	0	0	0	3	1	0	0.00	Low Vulnerability
Block Group 4, Census Tract 111	212270111004	1	0	0	2	1	0	0	3	1	0	0.00	Low Vulnerability
Block Group 1, Census Tract 105	212270105001	1	0	3	0	0	0	1	3	1	1	0.05	Low Vulnerability

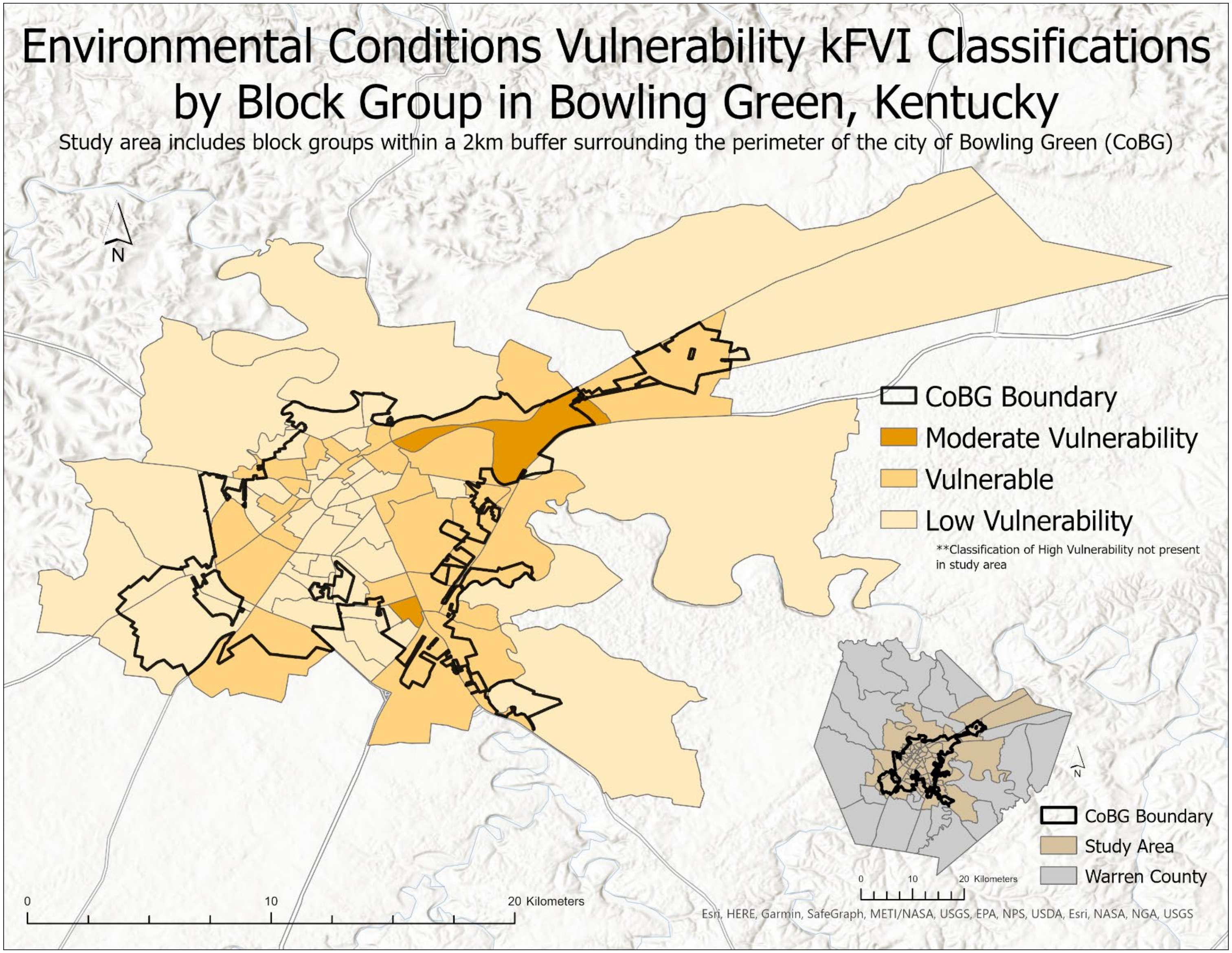


Figure 5.5: Map of Environmental Conditions Vulnerability distribution based upon kFVI scores for the CoBG (Source: Created by Author).

Table 5.15: 63 block groups were assessed within the study area for each of the environmental conditions vulnerability indicators and scored from 0-3; the table breaks down how many of the block groups were scored for each indicator (Source: Created by Author). **Denotes indicators that the same score was given to all block groups in the study area, rather than individual scores for each.

Indicator	**Score of '0'**	**Score of '1'**	**Score of '2'**	**Score of '3'**	**LD**
PC**	0	63	0	0	--
SBS	55	1	2	5	--
HW	19	3	3	38	--
S	24	1	3	28	7
PS	26	13	10	14	--
C	60	3	0	0	--
SFHA	28	21	10	4	--
MiP	38	1	1	23	--
RP**	0	63	0	0	--

For the indicator Average Annual Increase in Precipitation, each of the study area groups were assessed and given the same score because the regions of the CoBG have all seen the same average annual percentage increase in precipitation. Across the United States, annual precipitation has increased an average of about four percent between 1901 to 2015 (USGCRP 2017). The state of Kentucky is only slightly above the national average with an annual precipitation increase of about five percent (EPA 2016b). Some regions of the United States have been experiencing more annual changes reaching 15 percent increases, or decreases in some regions (USGCRP 2017). As annual increases in Kentucky are milder in nature yet still contribute to continued vulnerability, the study area groups each scored a '1' for the Average Annual Increase in Precipitation indicator (Table 5.15). The score was also based upon the divisions utilized in the Climate Science Special Report (CSSR) that displayed the differences and annual changes in precipitation across the United States (USGCRP 2017). Climate change is projected to exacerbate these changes further in the coming decades, altering the level of vulnerability the CoBG may have to flooding in the future.

One of the indicators that showcased relatively low vulnerability throughout the study area was Concentration of Superfund or Brownfield Sites. In the CoBG, there is only one Superfund site and ten Brownfield sites. The relatively low concentration of sites of this nature contributes to a lower vulnerability for many of the block groups. Alternatively, the high density of hazardous waste sites associated with the Resource Conservation and Recovery Act (RCRA) produced many block groups with higher scores for the indicator Concentration of Superfund or Brownfield Sites. With 232 RCRA sites throughout the study area, many of the block groups have more than one site within their boundaries as the sites are absent in only 16 of the 63 block groups. One block group in the study area hosts five RCRA sites in less than one square kilometer.

The inclusion and consideration of features associated with human-originated environmental hazards like hazardous waste sites or Superfund sites relates more to vulnerability during or after flooding as a secondary impact and environmental equity. The location of these types of features can cause complications if the hazardous materials or other pollutants were to enter the water during or after a flood. The people in the immediate vicinity of the sites would bear the brunt of the repercussions if water quality was diminished, leading to potential environmental inequities to those neighborhoods. Drinking water, nearby creeks or streams that the children may play in, or water used for cooking or bathing, could be contaminated in the aftermath of flooding. In a review of two decades worth of environmental justice studies in the United States, Mohai et al. (2009) found hundreds of studies demonstrating that, in general, “ethnic minorities, indigenous persons, people of color, and low-income communities confront a higher burden of environmental exposure from air, water, and soil pollution from industrialization, militarization, and consumer practices” (405). The potential for flooding to result in the degradation of water quality if the hazardous or polluted sites were compromised leads to an overall higher level of vulnerability for the groups nearby.

The concentration of caves throughout the study area is relatively low, as many of the caves in the CoBG are fairly spread across its area. Many of the block groups did not score very high on vulnerability related to caves based upon the scoring metrics utilized; however, the individual characteristics of each of the caves could have impacts on flooding or vulnerability throughout the study area that can be difficult to measure or predict. The area of the caves in the study area was equivalent to about 0.03 percent of the total area of the study area block groups, though the caves are still an important part of the landscape and are valuable to consider when assessing flood vulnerability. The presence of or lack of caves in an area does not necessarily indicate that an area definitively will or will not flood; the specific attributes of each cave can impact flooding and closer examinations of each would be necessary to assess more precise levels of vulnerability. Vulnerability assessments are intended to provide a general evaluation of vulnerability, but are not indicative of exact probability.

At the time of research, there were 190 known sinkholes throughout the CoBG. There were seven block groups that were marked as 'LD' or 'Lack of Data' due to the fact that the groups were beyond the technical boundary lines of the city and did not have mapped known sinkholes at the time of research. One block group featured 13 known sinkholes in a span of only 1.5 km^2, while 23 block groups with data contained no known sinkholes. On average, there were about 3.33 sinkholes per block group or one sinkhole every 2.17 km^2 and 28 block groups scored '3' with an average of one sinkhole per 5 km^2 or less. Only three groups scored '2' and only one group scored '1.' The remaining 24 groups scored '0' with either an average of one sinkhole per 20 km^2 or more, or no known sinkholes.

The mapped potential sinkholes in the study area were much more abundant than the current known sinkholes in the region; the area of the potential sinkholes is equivalent to about twenty percent of the area of the entire study area. Four block groups did not have any mapped potential sinkholes, giving the study area an average of 12.6 percent potential sinkhole land coverage per block group. Fourteen groups scored ‘3’ with potential sinkholes covering more than 20 percent of the area. In one group, the potential sinkholes cover about 76 percent of the area. Ten groups scored ‘2’ with ten to 20 percent of the land covered by potential sinkholes, 13 groups scored ‘1,’ and the final 26 groups scored a ‘0’ with less than five percent or none of the land featuring potential sinkholes.

For the indicator Regulatory Protection, all of the study area block groups were given the same score as each should fall under the same regulations and legislation. Scoring the regulatory protections of the study area can be more subjective or arbitrary than some of the other indicators but was included in the vulnerability assessments in order to evaluate the effectiveness of current regulations or identify areas of improvement. The regulatory protection of the study area was evaluated and each of the block groups were given a score of ‘1,’ as regulatory protection is a resilience indicator. A score of ‘1’ for this indicator is associated with a scoring metric of “A few regulations but contain loopholes or may not be strictly enforced.” There are some regulations in the study area so the level of resilience associated with this indicator was determined to be above a ‘0;’ however, the groups were given a score of ‘1’ rather than a ‘2’ because the regulations in place were determined to contain loopholes or are not always strictly enforced. Additionally, the study area would require increased regulations in order to be considered fully protected.

Even with solid regulations and protections in place, enforcement is largely still necessary for the regulations to be successful. A local official for the CoBG stated in an interview, “Our subdivision regulations require that if a developer is going to install a stormwater injection well to drain a basin, they have to flow test it to show us that it can drain at the rate that it is required to drain at for that basin. It seems like for quite some time that responsibility was just not fulfilled” (Pers. Comm. 2022). In the CoBG and Warren County, there are many SFHA that contain properties or buildings that would be legally required to purchase flood insurance; however, FEMA estimated in May of 2022 the penetration rate of the NFIP flood insurance in Warren County was only about 30.5 percent of properties in SFHA, meaning only an estimated 30.5 percent of the buildings located in SFHA in Warren County have flood insurance (FEMA 2022). The lack of flood insurance coverage in areas that are technically required to have some form of insurance demonstrates a lack of enforcement of NFIP regulations in the CoBG.

In the CoBG, the first FHBM was developed in 1974, the city first began to enforce drainage standards in 1976, and the first FIRM was developed in 1980. Any properties established before the 1970s or 1980s would not have been built to the current standards and could potentially have been placed directly in areas that are now known as flood zones. Because these structures were built before the current standards were put in place, the local government does not currently have any rights to alter these properties unless bought outright by the city. According to the current city ordinances for the CoBG, the responsibility of the city is to maintain structures and repair sinkholes within drainage easements in single- and two-family residential neighborhoods. Any structures beyond single- and two-family residential neighborhoods are supposed to be maintained by the property owner, whether the property is not in a drainage easement or is in a multi-family residential or commercial area. A local official for the CoBG stated, “There were many flood complaints that our ordinances just didn’t cover for numerous reasons like budget or liability, and were outside of what we were specifically required to maintain" thus prompting the start of the SMPL in an attempt to provide some resources and expertise to the areas that fall beyond the technical responsibilities of the local government but still experience flood impacts (Pers. Comm. 2022). Beyond purchasing flood insurance for the property or gaining a spot on the SMPL, residents and property owners located in the areas that predate or do not fall under the umbrella of the current city ordinances do not have much protection that might alleviate the impacts of flooding.

In the United States, there is no federal law that requires the disclosure of the flood risk or history of flooding to prospective buyers. Only 29 states have any sort of flood disclosure requirements, leaving the residents of the other 21 states in an even more vulnerable position (NRDC 2018). In Kentucky, state law requires that the seller must disclose if the property is located within a SHFA and the zone designation, or if the property has ever had problems with flooding (NRDC 2018). The Kentucky Real Estate Commission developed a form titled 'Seller's Disclose of Property Condition' in response to the revised Kentucky statutes to address all the disclosure requirements for sellers (Kentucky Revised Statutes 2000). In Warren County and the CoBG, the City-County Planning Commission developed subdivision regulations that include the completion of the 'Subdivision Plat Review & Submission Checklist' (CCPC 2019). One of the components of the checklist is to disclose the location and elevation of any 100-year floodplain, FEMA flood elevation certificate, FEMA FIRM map number, the minimum finished flood elevation (FFE) of the lot, and any maintenance notes for drainage or stormwater; however, if the properties are new developments, the buildings would not technically have a history of flooding; this means that sellers would not be required to disclose any historical flood issues as any flooding that might have occurred on the plot of land in the past would have predated the construction of the building.

In Bowling Green and Warren County, one of the main documents used by the local government for stormwater management standards is the Stormwater Management Manual written by Daugherty (1976). The development of the manual prompted enforcement of drainage standards in the CoBG in the 1970s, a change that had positive impacts on the city as flooding and development guidelines began to be held to a higher standard; however, the Daugherty manual is still utilized today as the benchmark for stormwater management standards in the CoBG despite the fact that the manual was written nearly 50 years ago. While the computing power and mathematics involved have improved in the past decades, the general standards outlined in the Daugherty manual have remained much the same. Given the advancements of technology, knowledge in the field of stormwater management and karst landscapes, and predications associated with climate change, the standards utilized to regulate stormwater management and flooding need to be updated more regularly than once in a 50-year period.

The Code of Federal Regulations (CFR) released by various federal government agencies and organizations forms the basis for many floodplain management regulations throughout the U.S. (GovInfo 2021). In the state of Kentucky, the commonwealth and the NFIP further define the minimum floodplain standards for development but allow for local communities to set higher standards that exceed the minimum requirements (EEC KY 2022). The floodplain management standards set forth by the commonwealth and the CFR do not generally differ greatly from the standards of the NFIP, making the NFIP standards a relatively consistent minimum for most communities throughout Kentucky. The presence of an overarching and common set of standards primarily defined by a centralized source like the NFIP can help to ensure that more communities have baseline floodplain management regulations that are easily defined and outlined, but could also lead to the implementation of requirements that are not sufficient for every community, as some communities may require stricter regulations to effectively manage flooding and development. In cities or counties with less resources available, enforcement of even the minimum standards could lack, particularly as many of the predominantly rural counties in Kentucky lack any sort of Planning and Zoning Commission.

5.3.4 Final kFVI Score

After calculating the levels of vulnerability associated with each of the three categories of the kFVI, the final vulnerability score was calculated for each of the study area block groups between the three categories (Table 5.16). Of the 63 block groups examined in the study area, none received a final classification of High Vulnerability. Six block groups scored a Moderate Vulnerability classification, and 45 groups scored a Vulnerable classification. The final 12 block groups resulted in a Low Vulnerability classification. With a population of 97,907 people throughout the study area, about 8.5 percent of the population resides within a Moderate Vulnerability area, about 74.9 percent reside within a Vulnerable area, and 16.6 percent reside within a Low Vulnerability area.

Table 5.16: Total number of people and percentage of the population in the study area by calculated final overall vulnerability classification (Source: Created by Author).

	Low Vulnerability	**Vulnerable**	**Moderate Vulnerability**	**High Vulnerability**
Number of People	16,236	73,319	8,352	0
Percentage of Population	16.58%	74.89%	8.53%	0%

The block group with the highest calculated overall flood vulnerability was Block Group 212270107021 (Table 5.17). With a final score of 0.61, the group was given a classification of Moderate Vulnerability. This group scored the highest for both economic and environmental conditions vulnerability and was in the top quarter for social vulnerability as well. The second highest score for overall vulnerability was Block Group 212270110012. With a final score of 0.57, the group was a close second for overall vulnerability and given a classification of Moderate Vulnerability as well. Block Group 212270110012 scored the highest for social vulnerability, tied for fourth highest economic vulnerability, and was in the top third for environmental conditions vulnerability.

Table 5.17: Study area block groups with the top six highest calculated overall vulnerability scores. Top six included due to equivalent scores for fourth highest final score (Source: Created by Author).

Geographic Area Name	GEOID	Social	Economic	Environmental Conditions	Final Score	Classification
Block Group 1, Census Tract 107.02	212270107021	12	10	11	0.61	Moderate Vulnerability
Block Group 2, Census Tract 110.01	212270110012	16	8	7	0.57	Moderate Vulnerability
Block Group 1, Census Tract 112	212270112001	11	9	8	0.52	Moderate Vulnerability
Block Group 1, Census Tract 103	212270103001	12	6	9	0.50	Moderate Vulnerability
Block Group 1, Census Tract 107.01	212270107011	11	7	9	0.50	Moderate Vulnerability
Block Group 5, Census Tract 109	212270109005	13	7	7	0.50	Moderate Vulnerability

The block group with the lowest calculated overall flood vulnerability score was Block Group 212270114021 (Table 5.18). With a final score of 0.09, the group received a final classification of Low Vulnerability. This group scored the lowest for both social and economic vulnerability as well and tied for third lowest in environmental conditions vulnerability. The second lowest score for overall vulnerability was Block Group 212270111004. With a final score of 0.17, the group was given a final classification of Low Vulnerability. This group tied with several other groups for lowest environmental conditions vulnerability, tied for third lowest economic vulnerability, and was in the lowest fourth of block groups for social vulnerability.

Table 5.18: Study area block groups with the top seven lowest calculated overall vulnerability scores. Seven groups included due to equivalent scores (Source: Created by Author).

Geographic Area Name	GEOID	Social	Economic	Environmental Conditions	Final Score	Classification
Block Group 1, Census Tract 114.02	212270114021	3	0	2	0.09	Low Vulnerability
Block Group 4, Census Tract 111	212270111004	7	2	0	0.17	Low Vulnerability
Block Group 4, Census Tract 115	212270115004	6	1	3	0.19	Low Vulnerability
Block Group 3, Census Tract 107.02	212270107023	6	4	1	0.20	Low Vulnerability
Block Group 1, Census Tract 113	212270113001	7	3	1	0.20	Low Vulnerability
Block Group 1, Census Tract 114.01	212270114011	4	1	6	0.20	Low Vulnerability
Block Group 3, Census Tract 116	212270116003	6	1	4	0.20	Low Vulnerability

The levels of vulnerability that each of the block groups displayed for each category were relatively consistent across all three categories, meaning that many of the highest scoring groups for social vulnerability scored high for economic or environmental conditions as well. Many of the lowest scoring groups for each category were consistently identified as having low vulnerability amongst all three categories. Socially or economically vulnerable groups were frequently found to be higher in environmental vulnerability as well. The association between populations of lower socio-economic status and environmental vulnerability indicators showcases a disparity in environmental equity. Block groups with higher rates of underage and elder populations, poverty rates, disabilities, lower levels of education, unemployment rates, limited English-speaking abilities, and lower household incomes and home values were consistently associated with higher densities of hazardous waste facilities, sinkholes, potential sinkholes, SFHA, and overall higher levels of environmental-based vulnerability to flooding.

Two of the block groups with some of the highest environmental vulnerability scores, 212270113003 and 212270113001, both received high scores for density and proximity to both Superfund or brownfield sites and hazardous waste facilities. More than 70 percent of the population in block group 212270113003, and over half of the population in block group 212270113001, has a household income of less than $75,000 a year. The CoBG has a strong immigrant population in addition to many neighborhoods with heavy concentrations of specific races or ethnicities that were located in areas of the city that scored higher in the kFVI. Researchers have found that in many areas across the U.S., hazardous waste facilities and sources of eventual Superfund or brownfield sites have disproportionately been sited in existing communities of color (Pastor et al. 2001; Saha and Mohai 2005; Pellow and Roberts 2009). In a study spanning over 50 years, researchers found that predominantly white communities had greater success at controlling the surrounding land use than other communities, particularly related to locations of new hazardous waste facilities (Saha and Mohai 2005). The ‘Not In My Back Yard’ or ‘NIMBY’ mentality can have impacts on flooding when land use is more heavily controlled in certain areas, thus pushing developers towards neighborhoods that may not be as vocal in raising concerns over certain land use changes (Saha and Mohai 2005). Particularly in urban karst regions, land use changes can have profound impacts on floodplains as the paths water can take are permanently altered (NCBI 2019).

In the U.S., researchers have found that populations of lower socioeconomic status are generally less likely engage in political participation than those of higher socioeconomic status (Hoang 2019; Logan et al. 2012). Given that the CoBG is a resettlement site for immigrants and has many neighborhoods with strong concentrations of minority populations or are of lower socioeconomic status, flood mitigation and management strategies need to include consideration of the neighborhoods and populations that are being impacted. Floodplain management does not have to be solely infrastructure or regulations based, but can include educating the public on flood related topics and policies specific to the area, advertising or increasing opportunities for public participation in discussions regarding flooding in the area.

The "chicken or the egg" debate regarding whether the siting of hazardous waste facilities and flooding from land use changes came first, or if the minority and lower socioeconomic groups were already present, is an important conversation to consider from an environmental justice standpoint; however, the result of the debate does not change the reality of disadvantages the communities experience with regards to flood vulnerability. Some areas may need more aid than other groups to avoid drastically uneven flood impacts across the community, which could be through financial means, improved infrastructure, or simply education about flooding and related policies so that the people impacted are more knowledgeable about the nature of karst flooding and the rights that are afforded to community members. To alleviate the disproportionate impacts of flooding on any community members, regardless of race or class, incorporating the knowledge of the demographics of the people impacted by flooding and the landscapes type upon which they live into management decisions is important.

The presence of environmental injustices is not contingent upon the injustices occurring purposefully, meaning that certain demographic groups may experience environmental injustices that were not created intentionally due to conscious or unconscious biases; the resulting disadvantages are still injustices regardless of origin, cause, or motivation. Environmental injustices are also not restricted to only specific demographic groups as many sources of vulnerability intersect; for example, disabled populations or elderly residents are disproportionately likely to be less financially advantaged, making preparation and recovery from flooding much more difficult (Walker and Burningham 2011). In the CoBG, many of the groups with higher social vulnerability scores due to higher densities of disabled or elder populations in particular were also associated with higher environmental conditions vulnerability. In an interdisciplinary study of risk and vulnerability based upon economics, environmental science, disaster management, and several other disciplines, researchers stated, “A household might be able to mitigate or cope with a risk or set of risks in a given period, but the process can result in limited ability to manage risk in subsequent periods - especially when assets are degraded” (Alwang et al. 2001). Even if a household has enough resources to recover from a flood event, the future ability to continue to mitigate and recover is diminished, particularly when households are facing disadvantages beyond solely the financial (Alwang et al. 2001).

The socioeconomic disparity between the populations that are environmentally vulnerable to flooding in this research further emphasizes the need for the kFVI to be adapted and expanded further in the CoBG and other urban karst regions. By calculating and examining social and economic vulnerabilities in addition to the physical environment vulnerabilities, flood related education can be focused more heavily in the identified areas to help inhabitants to know what resources are available to aid in flood mitigation and recovery or different policies and regulations that might impact the community. Flood mitigation projects located in the identified regions could be reorganized by including the kFVI metrics and indicators in prioritization calculations.

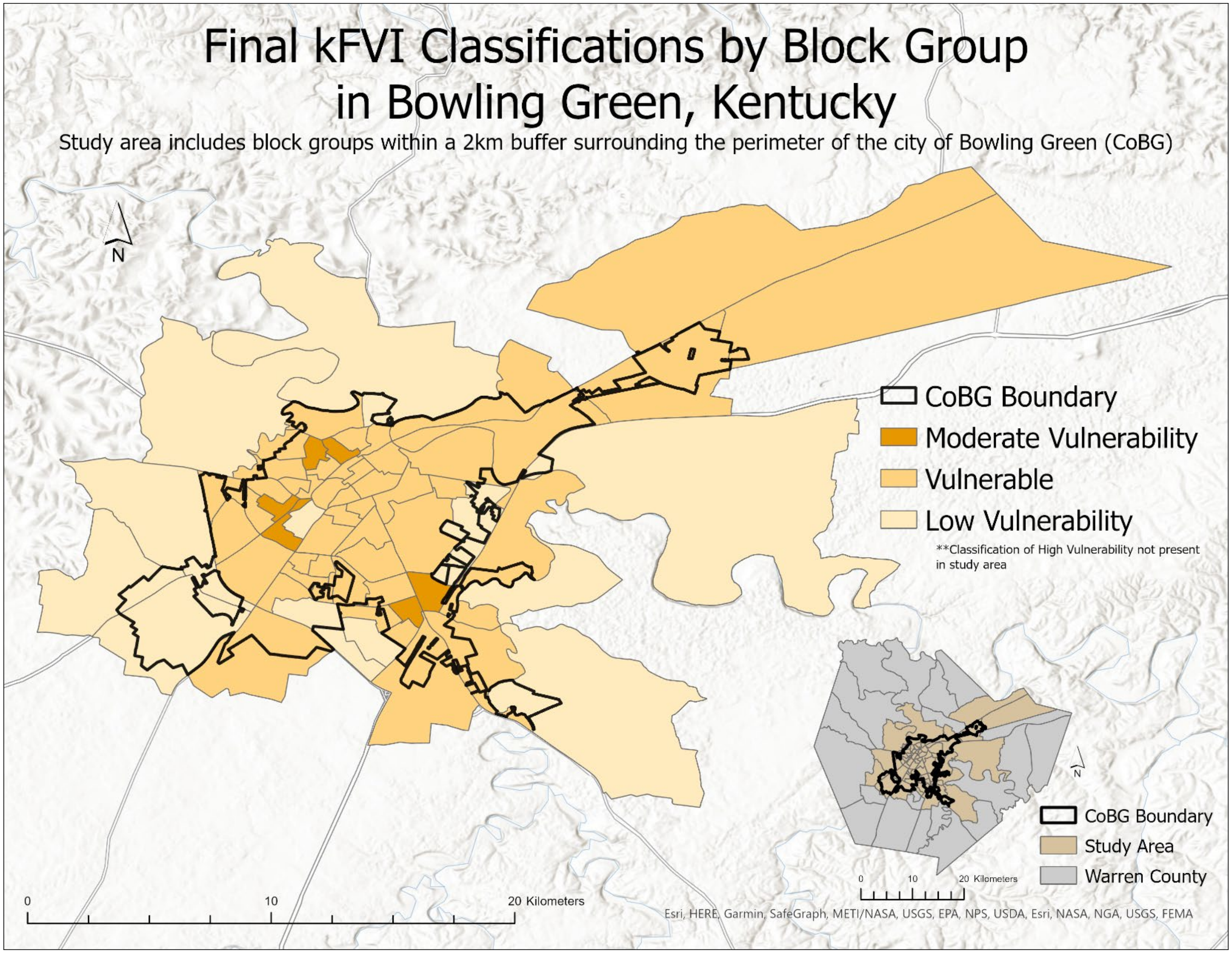


Figure 5.6: Map of final calculated overall vulnerability distribution based upon kFVI scores for the CoBG (Source: Created by Author).

5.3.5 kFVI Limitations

Due to lack of available data, issues associated with spatial scales, or time constraints, some indicators that may have been applicable to the study area were excluded from the final iteration of the kFVI. Within the social vulnerability category, some indicators that were considered but were ultimately excluded from final assessments included occupancy rates or types, estimated population located within the boundaries of known flood zones, past experience with flooding, and awareness and preparedness. Considered but excluded indicators related to economic vulnerability were inequality rates, investment in counter measures, and urban planning; for environmental conditions, indicators included future planned land use, enforcement of regulations, quality of infrastructure, stormwater drainage, and infilling or dumping in caves or sinkholes. There is a wide variety of characteristics or sources of flood vulnerability in karst environments that extend beyond solely the metrics utilized in the kFVI that could greatly enhance the ability of the kFVI to be further focused on karst landscapes. Karst springs in particular can have impacts on flood vulnerability in several ways, in that not only can the springs potentially cause flooding if precipitation exceeds the drainage capacity of the spring, but can also contribute to degradation of water quality in the aftermath of flooding if the springs are connected through various other karst features (Zhou 2007; Sinreich et al. 2014). In addition to springs, another indicator that could be utilized for the kFVI in the future is depth to water. Some areas may be densely concentrated with sinkholes, yet never experience flooding because the depth to water from the surface is high. Sinkholes can raise overall vulnerability to flooding because the potential for flooding is increased, but the presence of sinkholes does not automatically indicate that flooding will occur. The inclusion of additional indicators and metrics of assessing vulnerability related to karst could greatly aid in increasing levels of confidence in vulnerability classifications. The indicators utilized in the final kFVI assessments are by no means exhaustive but are designed to be a baseline or starting point for vulnerability assessments in urban karst communities.

When applying the kFVI to the CoBG, a social indicator ‘Shelters’ was originally utilized to assess the resilience of the CoBG associated with shelters available for community members displaced from their homes in the event of flooding. The indicator was ultimately excluded from the final iteration of the kFVI after attempts to determine the most appropriate scoring metrics for shelter-based resiliency but could potentially be implemented in future assessments utilizing the kFVI. Due to the removal of the indicator, the social vulnerability assessment was comprised of exposure and susceptibility indicators and did not include any resilience indicators. Future applications of the kFVI should include assessments of community resilience to flooding. A shelters indicator could be associated with emergency service access, or simply the level of access community members may have to shelters related to public transportation or distance to walk. Shelters could also be assessed based upon a number of metrics that could more accurately represent a community while maintaining scalability, such as percentage of the population the shelters can accommodate. Indicators such as Shelters that may have been ultimately excluded from the kFVI could still be utilized in future applications of the kFVI to aid in providing additional assessments of vulnerability and resilience.

With the exception of the environmental conditions indicator assessing the average annual increase in precipitation, none of the indicators utilized in the final kFVI were chosen explicitly to assess flood vulnerability associated with climate change. Climate change indicators were largely excluded from the kFVI due to the lack of certainty correlated with many of the metrics that could be used to assess climate change-associated vulnerability. While past data can be useful to attempt to predict potential climate change impacts, such as average annual precipitation and increases, scoring different areas based upon events that might occur in the future could create an unreliable narrative and negatively impact management decisions if the predictions are ultimately found to be inaccurate. Some regions may experience more flooding while other regions may experience more droughts, or encounter neither scenario at all.

Creating a risk assessment that heavily includes metrics that are uncertain could result in higher likelihood of incorrect vulnerability classifications for the areas under consideration, such as identifying lower risk in an area that eventually experiences heavy flooding in the future. To attempt to decrease the likelihood of incorrect vulnerability classifications, block groups were utilized for the kFVI assessments in this research because block groups were the smallest geographic unit possible given the availability of applicable data. Smaller geographic units are less likely to encounter ecological fallacy than larger geographic units, such as zip code areas or at the county level, that may showcase relationships between features that may not remain consistent at a smaller geographic scale. Additionally, the inclusion of a higher number of relevant indicators helps to reduce the impact of any one indicator on the overall vulnerability score, which is beneficial when metrics may be associated with a level of uncertainty as the weight of each indicator on the final score is simultaneously lowered.

Each of the flood vulnerability indicators will inherently have some margin of error but are associated with lower levels of uncertainty because the basis of the scoring metrics is not grounded in predictions but rather in events or demographics that have already transpired or are representations of current conditions. Climate change projections should be included in decision making and flood vulnerability assessments, but the associated doubts should also be recognized; the inclusion of uncertainties in final assessments could be accomplished in a variety of ways, including by adjusting the weight the projections have on identified vulnerability levels or by building flexibility into management plans to account for the potential variations in outcomes. Incorporating anticipated climate change impacts into management strategies in conjunction with the kFVI could help to create more robust and sustainable planning.

5.3.6 Comparing the kFVI and the FVI

The kFVI was designed to be an adaptation of the existing FVI, to assess flood vulnerabilities in urban karst regions specifically. In order to understand and quantify the impacts of including karst-specific indicators in the FVI, the environmental conditions category was further assessed in the CoBG beyond the assessment utilized for the final kFVI scoring. First, the CoBG was assessed employing only the environmental conditions indicators that were associated with the general iterations of the FVI. The CoBG was then assessed a second time utilizing only the environmental conditions indicators that are directly related to or influenced by the karst environment and utilized by the kFVI. The environmental vulnerabilities assessment of the CoBG, separated by karst-related indicators and non-karst-related indicators, showcased a substantial difference in the locations of vulnerability.

The assessment of the CoBG utilizing the general FVI environmental conditions vulnerability included evaluation of the indicators Annual Change in Precipitation, Superfund and Brownfield Sites, Hazardous Waste Sites, and Monitoring in Place, as these indicators are not specific to karst environments. The FVI indicators identified higher vulnerability in neighborhoods closer to the northern region of the city (Figure 5.7). The neighborhoods have over 70 percent of the Superfund and Brownfield sites in the CoBG, high concentrations of RCRA and TRI sites, and almost no monitoring sites, but feature some of the most socioeconomically disadvantaged residents of the CoBG. The Bowling Green Housing Authority and homes under government housing programs are located in the identified block groups, and over 43 percent of the households in the identified block groups have an annual income of less than $25,000 per year. Over 87 percent of the households in the identified block groups make less than $75,000 per year. Assessing the regions of the city that are heavily associated with environmental vulnerabilities such as hazardous waste facilities and Superfund sites can help to identify regions of environmental inequities that are based less in the physical environment and more that are caused specifically by humans.

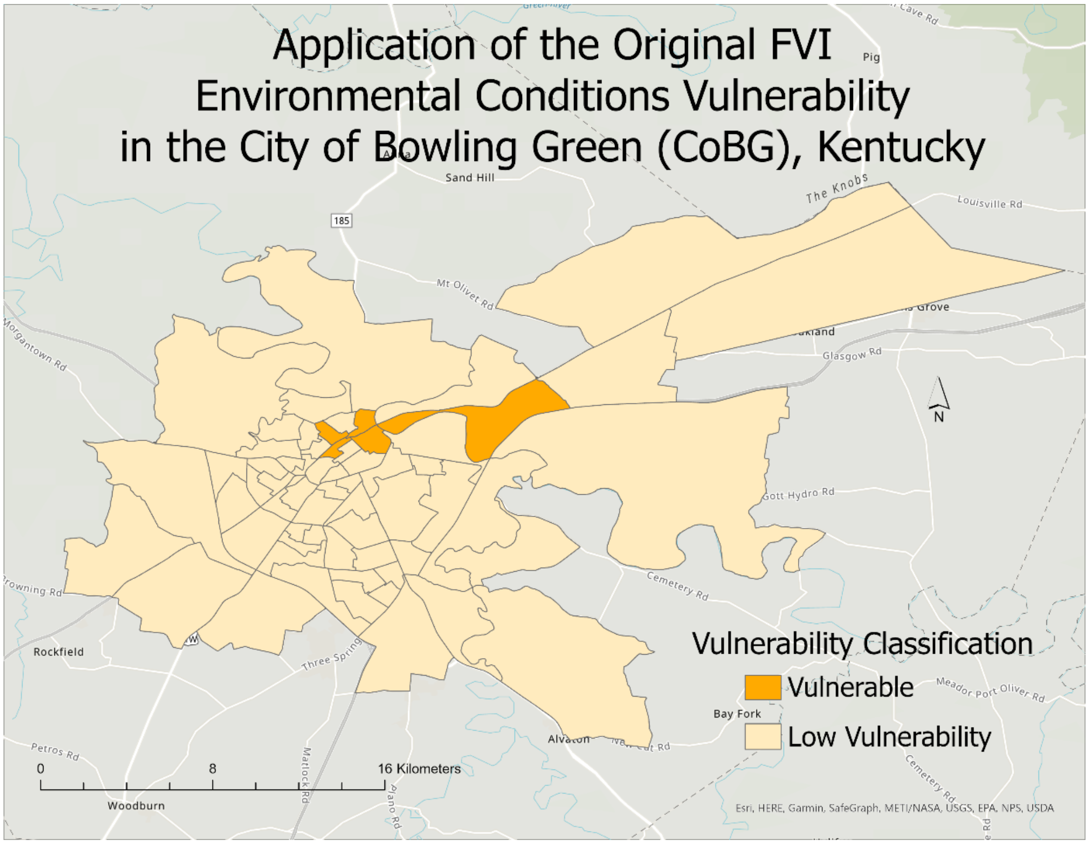


Figure 5.7: Application of the FVI Environmental Conditions vulnerability indicators (Source: Created by Author).

The assessment of the CoBG utilizing the modified kFVI environmental conditions vulnerability included evaluation of the indicators Sinkholes, Potential Sinkholes, Caves, Special Flood Hazard Areas (SFHA), and Regulatory Protection. The SFHA and Regulatory Protection indicators were included in the karst-specific assessment as both indicators are heavily correlated with karst in the CoBG; many of the flood zones in the CoBG are karst-based or sinkhole related, leading to the necessity of consideration of karst in flood management regulations as well. The evaluation of karst-specific vulnerabilities with the kFVI yielded higher overall scores related to environmental vulnerability than the indicators unrelated to karst within the FVI.

The areas of the city that were identified as having higher vulnerability were largely in the southcentral region of the city that feature dense concentrations of sinkholes, caves, and known flood zones (Figure 5.8). Figure 5.8 showcases the entirety of the study area of the kFVI assessment with a box around the block groups, of which Figure 5.9 provides a closer examination. Lost River Cave, Sullivan Cave, State Trooper Cave, Creason Cave, Cold River Cave, Greenwood Cave, and Robinson Cave are all located in the block groups identified with higher vulnerability. The presence of caves in an area can have impacts on flood vulnerability related to both potentially causing flooding and the potential for water contamination in the event of flooding. Many of the SFHA in the groups with higher vulnerability were heavily associated with both known and potential sinkholes, in addition to the locations of the caves in the area (Figure 5.9).

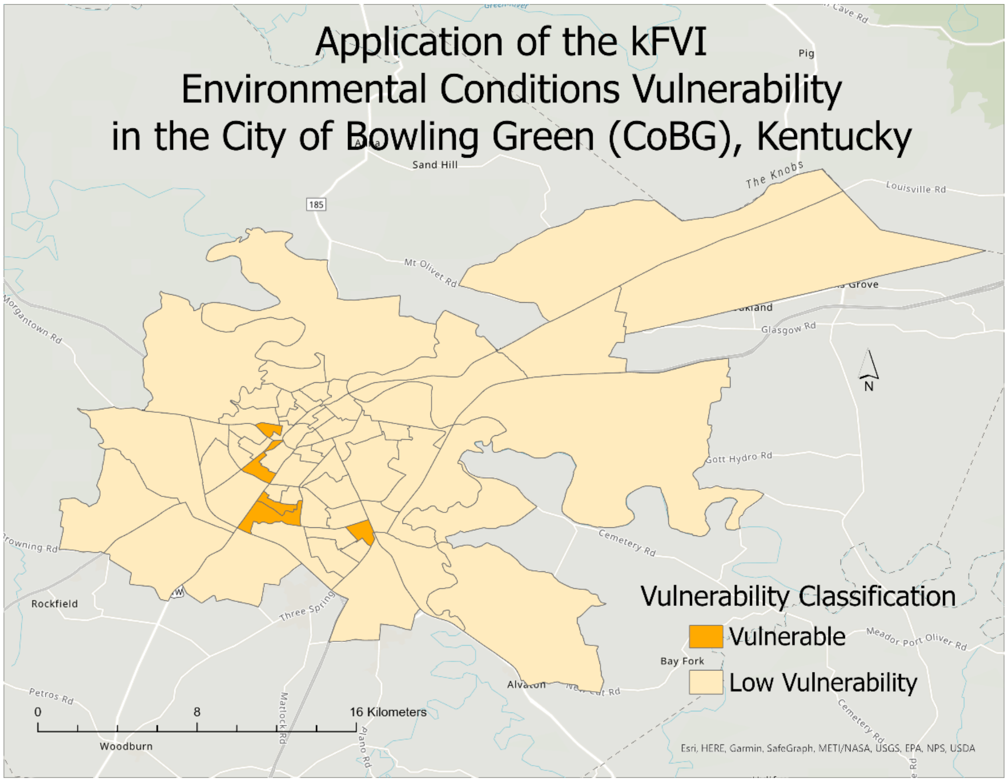


Figure 5.8: Application of the kFVI Environmental Conditions vulnerability indicators (Source: Created by Author).

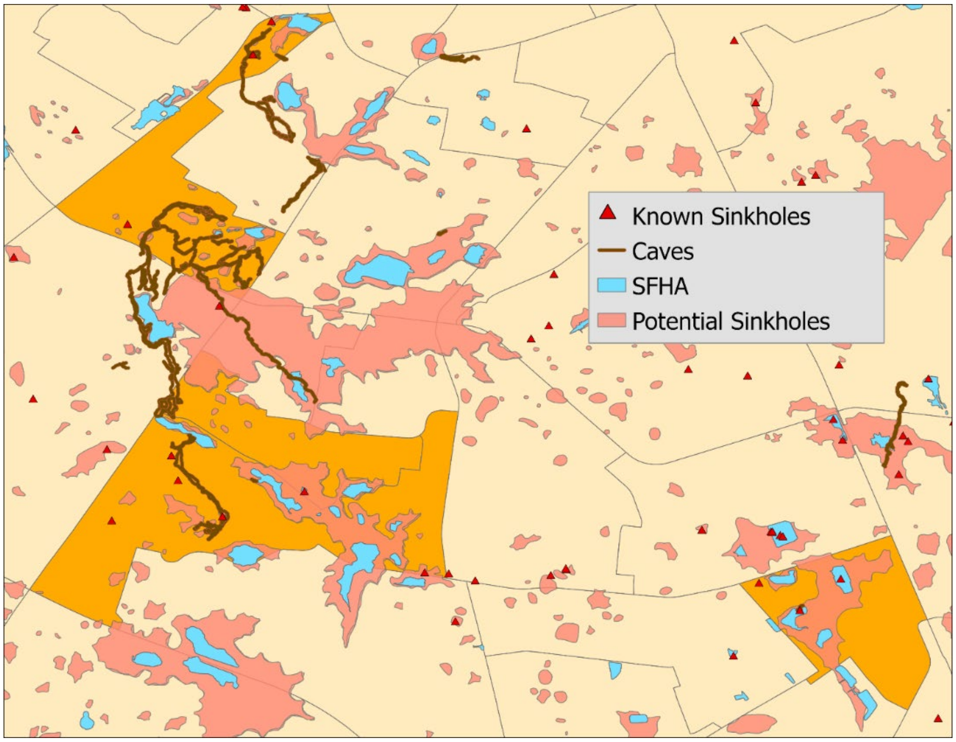


Figure 5.9: Zoomed in look at identified areas of higher kFVI Environmental Conditions vulnerability overlain by known sinkholes, caves, SFHA, and potential sinkholes (Source: Created by Author).

The differences in the outcomes of the kFVI and the general FVI without karst indicators emphasizes the limitations associated with only having one category to place environmental-based vulnerabilities into, as the karst indicators have a very different impact on vulnerability than the non-karst indicators. The FVI utilized by researchers in the past typically includes two separate physical and environmental categories of vulnerability (Balica and Wright 2010; UNESCO-IHE 2022; Kumar et al. 2021); however, there is a lack of consistent clarity on the difference between the two categories and many researchers have combined the two or altered the titles (Balica et al. 2012; Salazar-Briones et al. 2020), which has resulted in overlap of the categories and the indicators utilized. There have been additional discrepancies regarding indicators that fall within other categories of vulnerability as well, particularly with economic vulnerability; for example, an indicator measuring closeness or contact with a river has been placed within the economic category (Balica and Wright 2010), but has also been assessed within the environmental category by other researchers (Nasiri and Kalalagh 2013).

In addition to the focus on karst landscapes, the kFVI differs from other variations of the FVI by utilizing a smaller scale to examine vulnerability in the urban area. Many variations of the FVI assess study areas at three different spatial scales: river basin scale (R), sub-catchment scale (S), and urban scale (U) (Balica and Wright 2010; UNESCO-IHE 2022). The kFVI adjusted the urban scale study area to be further broken down into the Census block group scale as the smallest unit available at the time of research. The intention behind narrowing the focus of the index assessment was to help emphasize the varying degrees of vulnerability throughout a single urban area that can greatly alter management strategies. In the CoBG alone, there are areas with high concentrations of karst features or hazardous waste facilities, while others have very little. There are areas that are very heavily concentrated with people of color or immigrant families and other areas are predominantly inhabited by white, wealthy, elderly populations. No city is completely homogenous or uniform, necessitating the assessment of the characteristics of the area on a smaller, more personal scale. Assessing an urban area on a larger scale can help when comparing cities to one another but limits the ability of land managers to make informed decisions for the local community, because the broader urban scale does not provide enough spatial detail to accurately reflect the unique qualities of the individual neighborhoods within the various communities.

The differences in locations of environmental conditions flood vulnerabilities based upon karst-related indicators versus non-karst indicators demonstrates the need for karst indicators in flood vulnerability assessments. The karst landscape can have profound impacts on patterns and sources of flooding, which was further showcased in the preliminary GIS assessments and analyses of known flood zones and karst features in the CoBG. Current SFHA in the CoBG were heavily correlated with sinkholes, potential sinkholes, and caves. Lost River Cave and the surrounding area in the CoBG in particular has experienced flood problems for years, is closely associated with several extensive SFHA, and is located in the block groups with higher flood vulnerability identified by the kFVI karst indicators. Utilizing GIS assessments of karst features and flood zones can help to identify features that are strongly associated with flooding, which can then raise the level of confidence in vulnerability classifications when the features are included as indicators for flood vulnerability assessments. Given that the GIS assessments of the CoBG demonstrated a strong relationship between karst features and known flood zones, karst-specific indicators can be utilized in kFVI assessments with a higher degree of confidence. Many of the previous iterations of the FVI have included indicators designed to identify sources of flooding in the physical environment similar to the karst indicators utilized in the kFVI but are specific to other regions or types of landscapes and flooding, such as coastline and sea level rise (Balica et al. 2012), number of rivers or proximity to a river (Nasiri et al. 2019), or number of cyclones (Kumar et al. 2021). The usage of physical environment-based flood metrics in previous iterations of the FVI showcases the applicability and necessity of karst-specific flood indicators.

5.4 Flood Vulnerability and Equity in the CoBG

The associations between populations that have been historically marginalized, or are of lower socioeconomic status and higher overall or environmentally-related flood vulnerability, does not mean that those populations are the only inhabitants of the CoBG that are impacted by flooding; however, the human-environment intersections throughout the CoBG have led to potentially disproportionate impacts of flooding on many of the populations that have historically been marginalized or generally lack the economic resources to be able to address flood impacts to homes and businesses. In the CoBG, block groups with higher rates of underage and elder populations, poverty rates, disabilities, lower levels of education, unemployment rates, limited English-speaking abilities, and lower household incomes and home values were consistently associated with higher densities of hazardous waste facilities, sinkholes, potential sinkholes, SFHA, and overall higher levels of environmental-based vulnerability to flooding. Many of the groups with higher identified environmental vulnerability in the CoBG were associated with higher percentages of people of color, or ‘minority majorities.’ In block group 212270107021 with the highest overall identified flood vulnerability, in addition to the highest environmental conditions and economic vulnerability, over 60 percent of the population are people of color (Figure 5.10). In the same group, nearly half of the households have an average income of less than $25,000 a year, 85 percent average less than $75,000 a year, and zero households averaged over $200,000. The vast majority of residences in the area are multi-family residential, as the area is dominated by apartment buildings. Block group 212270103001, located just over the north side of the train tracks, had the second highest environmental conditions score, was in the top third of economic vulnerability, tied for fifth highest social vulnerability score, and had the fourth highest overall score; the group is also located in a neighborhood that is over 65 percent people of color (Figure 5.11). In block Group 212270103001, almost 30 percent of households have an average income of less than $25,000 a year, and over 90 percent average less than $75,000 a year. None of the households average more than $200,000 a year.

Figure 5.10: Apartment buildings located in block group 212270107021 (Source: Created by Author).

Figure 5.11: Homes on Woodford Avenue in block group 212270103001 that have experienced flooding in the past and were placed on the SMPL in 2014 (Source: Created by Author).

In a study spanning more than 50 years, Saha and Mohai (2005) examined the locations of hazardous waste facilities and the demographics of the people in the immediate vicinity and found that neighborhoods composed of working-class, and people of color were vastly disproportionately impacted than other neighborhoods. Based upon findings from the kFVI, the conclusions made by Saha and Mohai (2005) were largely consistent in the CoBG as well. Block group 212270112001, located directly north of the train tracks and the university campus, had some of the highest scores associated with all three categories of vulnerability for the third highest overall score (Figure 5.12). Located in the group is the Lee Pointe Apartment complex, home to many of the immigrant and refugee families that are helped by the International Center of Kentucky. Over 20 percent of the households in the area claimed little to no English-speaking ability. The area also features several project sites that were included on the SMPL in 2021. Many of the regions of Bowling Green with higher vulnerability scores are also associated with the concentrations of immigrant populations, indicating a potential source of environmental inequity. The area is also associated with neighborhoods comprised of government assisted housing through the Housing Authority of Bowling Green (HABG 2022). Similarly, block group 212270102002 is also home to substantial government assisted housing neighborhoods and was also associated with consistently high levels of economic and environmental vulnerabilities, highlighting further potential environmental inequities related to the low-income populations and immigrants in the CoBG (Figure 5.13). Both groups were heavily associated with hazardous waste sites in particular, but also featured high vulnerability associated with Superfund or Brownfield sites and sinkholes.

Figure 5.12: A neighborhood on N. Lee Dr. in block group 212270112001 (Source: Created by Author).

Figure 5.13: Bowling Green Housing Authority residences in block group 212270102002 (Source: Created by Author).

Associating environmental vulnerabilities related to flooding with socioeconomic demographics is essential, because factors like poverty, language barriers, or historic marginalization can be threat multipliers that increase flood vulnerability tremendously. Other factors, such as climate change, can be additional threat multipliers that exacerbate the already strained resources and resiliencies of the community. In the coming decades, climate change has the potential to impact many of the everyday activities and functions of communities around the world in a number of ways, including through flooding (IPCC 2018). In the state of Kentucky, annual precipitation has increased in the past decades by about five percent (EPA 2016b) and extreme rain events and precipitation change are projected to continue to increase by five to ten percent (Risk Factor 2022). The Environmental Protection Agency (EPA) estimates that precipitation in Kentucky will continue to increase over the next fifty years but rising temperatures will also increase the severity of droughts in the state (EPA 2016b); essentially, greater precipitation might produce an increased number or intensity of flood events while rising temperatures might produce an increased number or intensity of droughts in Kentucky. Climate change-related indicators could be a way of further adapting and refining the kFVI to more holistically assess a karst-based community, particularly as climate change projections and vulnerability assessments have already identified potential areas of risk even within the CoBG.

The First Street Foundation, an organization that focuses on climate change and risks associated with various hazards, evaluated future flood risk for the CoBG and reported that flooding would be the greatest risk for community members in the CoBG over the next thirty years compared to other hazards, such as fires (Risk Factor 2022). Utilized in some climate change predictions and planning, the National Risk Index (NRI) developed by FEMA is a tool designed to develop a baseline relative risk measurement across the U.S. in order to evaluate areas of vulnerability due to various hazards or simply because of lack of resiliency (NRI 2022). In Warren County, the NRI evaluated the expected annual loss rate as 'Relatively Moderate,' as the expected loss rate for the county exceeds both the state and national average (NRI 2022). The expected annual loss rate is based upon vulnerability related to building values, population, population dollar equivalence, and agriculture value, and the relative likelihood of various hazards occurring in a year that could contribute to annual losses (NRI 2022). When compared with the rest of the U.S., 82.9 percent of counties have a lower expected annual loss than Warren County and 95.8 percent of counties in Kentucky have a lower expected annual loss (NRI 2022). In Warren County, census tracts 010200 and 010701 were both ranked as 'Relatively High' for social vulnerability, which both correspond to regions of the study area that were identified by the kFVI as having higher social and environmental vulnerability than the majority of the study area. Tract 010200 received a social vulnerability score that is higher than 99.6 percent of all census tracts in Kentucky and 97.8 percent of all census tracts in the U.S., demonstrating a level of social vulnerability to hazards that could impact management strategies utilized in the area (NRI 2022).

The NRI was used by the Climate and Economic Justice Screening Tool developed by the Council on Environmental Quality (CEQ) under direction from President Biden (CEQ 2022). The tool evaluates census tracts across the U.S. using a variety of categories, including climate change, to identify potentially disadvantaged communities (CEQ 2022). The tool identified specific characteristics of Warren County that did consistently receive high scores and are potential sources of climate-related vulnerability; many of the tracts were in the 80th to 90th percentile for expected population loss rate, which is the expected rate of fatalities and injuries resulting from natural hazards each year (CEQ 2022). Additionally, many of the tracts scored higher than the bottom threshold of eighty percent when assessed for higher education non-enrollment, or the percentage of the population in the area that is over the age of fifteen, but is not enrolled in college, university, or graduate school (CEQ 2022). Identifying areas of vulnerability related to social demographics of this nature when building a strategic plan is important because the demographics of the community can heavily impact levels of resilience and ability to respond (USC 2022). Calculating risk for an area by examining the vulnerability through an economic lens can be misleading as well because some areas may be economically depressed; estimated building losses may be much lower than those in affluent areas because the value of the buildings would likely be lower.

Many climate change projections or flood risk assessments lack any sort of affiliation with karst, despite the presence of karst landscapes in almost a quarter of the land around the globe (Ford and Williams 2007). Various tools or assessments related to natural hazards include flooding as a general category of study but tend to focus more on types of flooding like riverine or coastal that may be spatially related to karst landscapes in location but are not specifically caused by the karst features (NRI 2022; Risk Factor 2022). The gap in research regarding karst flooding and climate change together establishes a need for flood risk and vulnerability assessments in karst regions to determine baseline levels or sources of vulnerability and identify regions with particular susceptibilities to a changing climate. With more available data, an understanding of current vulnerabilities, and projected impacts of climate change, land managers and decision-makers in karst regions could attempt to better anticipate the ways in which the environment may be affected in the coming decades and have an increased chance of identifying successful strategies for mitigation and recovery.

5.5 Recommendations

There are many areas throughout urban karst communities and the CoBG that experience flood hazards and complications, with each community presenting slightly different vulnerabilities that are important to incorporate and consider when determining methods to alleviate flooding; however, there are some strategies that can be utilized to make the process of vulnerability or flood evaluation and response more cohesive and successful that can be utilized to address the entirety of the area. The changing of policies and regulations or implementation of new management strategies can take time, particularly when adjustments require government approval; the suggestions made as a result of this research are not expected to come to fruition immediately if implemented but are rather recommendations of strategies that could aid the CoBG or other urban karst environments in assessing or addressing flooding issues in the future. Based upon the findings of this research, the main recommendations for urban karst communities are the following:

- Adapt and implement the kFVI to identify flood vulnerabilities and assess environmental equity.
- Incorporate climate change projections into mitigation strategies.
- Create and maintain a centralized database related to flood hazards, mitigation, risk, and vulnerability, in addition to relevant flood information for the general public to access and utilize.
- Implement programs designed to decrease the impacts of flooding on the community, such as buy-out programs or stormwater utility fees.
- The policies and regulations that dictate the rules and actions of a community should be living documents that are regularly updated.

The first recommendation for urban karst communities or regions that experience flooding is to utilize or develop a vulnerability index. The purpose behind developing the kFVI was to adapt the standard FVI and make it more specific for assessments of karst regions so that the index could be used by land managers or officials to make informed decisions. There are many different types of vulnerability that could be utilized to assess flood risk; the indicators applied in the initial form of the kFVI for the purposes of this research could be expanded upon or alternated with various other metrics of assessing vulnerability that may align better with a different study area. There are many different variations of karst landscapes and features around the world in many different environments, creating distinct vulnerabilities specific to each area. The kFVI is recommended to be used to aid in assessing vulnerability in urban karst regions but may benefit from including indicators that are chosen specifically for the study area under consideration.

The kFVI developed for this research does not explicitly include climate change as a vulnerability indicator, though an assessment of potential impacts and inclusion of climate change in development of mitigation strategies is recommended for the CoBG and urban karst communities. The current Hazard Mitigation Plan (HMP) for Bowling Green and Warren County does not include any mention of climate change. Despite some uncertainty surrounding climate change modelling in terms of the precise impacts that might occur in a region, a consideration of climate change promotes building more robust strategies that account for changes in precipitation or environment. Methods in which climate change can be built into mitigation strategies in a more sustainable way include: homes with frequent inundation problems could be bought out, elevated, or updated to increase flood proofing measures, drainage easements or wells could be expanded or increased in number, development regulations could be updated to be stricter and more heavily enforced, infrastructure and wells could be redesigned and updated to address current problems, or the area surrounding new developments could be included in assessments to better understand potential impacts of new structures on flooding before permits are granted.

Regional climate risk assessments are useful and need to be considered when building management plans for the future but cannot always be regarded as having perfect accuracy. Not only can regional differences heavily influence the outcomes and manifestations of climate change impacts, but any predictions made regarding the future of the world's climate are simply that: predictions. Modern technology has advanced incredibly far in the past decades, making climate modelling more reliable than ever before, but still cannot be regarded as flawless. Regardless of whether predicted climate change impacts prove to be accurate in the future or not, the strategies that could be employed to incorporate the potential issues are all still strategies and changes that could be made in order to support the regions that already experience flood impacts.

In order to assist the application of the kFVI and assessments of climate change impacts in a community, one of the conceptually simplest changes that could be made is to create a centralized database that includes all of the data pertinent to assessing flood vulnerability. Having data scattered throughout multiple platforms and sources makes it very difficult to assess vulnerability and is not helpful when attempting to make management decisions based upon the data available. This can be especially important when multiple groups even within one organization are attempting to evaluate or address the same issues. Tracking down necessary data can take extensive amounts of time that may not be available or possible at the time that the data is needed; creating a database ahead of time that is routinely updated as new data becomes available could make a significant difference in assessment outcomes. The promotion of collecting and maintaining relevant data in a shared environment can help to foster effective communication and decision making.

The creation of a centralized database for local communities can also aid in prioritizing different projects or flood issues, particularly with adherence to floodplain management standards. The Code of Federal Regulations (CFR) for floodplain regulations in the United States are written and published by the federal government and are largely dictated by adherence to NFIP regulations and the ability of a community to obtain flood insurance when related specifically to SFHA and water surface elevations (GovInfo 2021). A city official stated in an interview, “The ability to participate in the NFIP is the primary driver of floodplain regulation at the local level. That is why we have local floodplain ordinances” (Pers. Comm. 2022); however, according to the 2021 Annual Edition Title 44 CFR 60.3,

> “If the Federal Insurance Administrator has not provided sufficient data to furnish a basis for these regulations in a particular community, the community shall obtain, review and reasonably utilize

data available from other Federal, State or other sources pending receipt of data from the Federal Insurance Administrator" (139).

Essentially, if the Flood Insurance Administrator has not created or updated SFHA or provided sufficient data for a community to be able to adhere to the regulations outlined in the floodplain management regulations, then the local community is expected to complete these tasks instead and conduct proceedings as if the identified areas are SFHA or are provided water surface elevations. The deference of the federal government to the local managers to assess and collect data for the community related to additional flood zones or increased flood extents, identify floodways or high hazard areas, update water surface elevation data, and regulate developments and permits based upon the resulting data could be a difficult expectation to place upon the local communities. While some communities may have the resources available to do so, some communities may encounter complications with enforcement or allocation of resources to be able to regularly accomplish the tasks required. The general lack of not only regulatory protection but also enforcement of the regulations already put into place reemphasizes the need for assessments like the kFVI, in addition to the creation and maintenance of a centralized database that is routinely updated so that the local community has more readily available and current data. When state and federal regulators neglect to provide communities with the information and resources required to adhere to the standards set forth by organizations beyond the local government, the responsibility falls upon the local communities to restructure planning and mitigation regardless of the number of local resources available.

The benefits of a centralized database or information portal could extend beyond solely supporting the people who are managing the area or making decisions by benefitting the community members as well. The ability to access pertinent information related to flooding throughout the community could help residents to make more informed decisions. Potential homeowners need to know if a home has had issues with flooding in the past or if a home is located in or near a flood zone. Land developers need to know if the area under consideration is pockmarked with sinkholes or potentially unstable land so that construction designs can be formulated accordingly. There are numerous ways in which the citizens of a community would be benefitted by knowledge of hazards or sources of vulnerability in the surrounding environment; however, if certain types of data are beneficial to land managers or city officials but would not be advantageous or legal to share in entirety with the general public, separate databases or portals could be created. A password-protected database could be utilized by city officials and land managers while a separate database could be viewed by the public.

Potential home or property owners could stand to benefit considerably from having access to current and relevant information related to flooding. Throughout the U.S., many states do not have any form of real estate flood disclosure requirements, leaving home or property buyers at risk of purchasing a property that may have problems with flooding (NRDC 2018). From 1978 to 2015, the NFIP identified more than 30,000 severe repetitive loss properties (SRLP) across the United States that have flooded repeatedly, and in many cases, been rebuilt repeatedly (Moore 2017). In the 21 states without flood disclosure laws, the owner of an SRLP would not be legally required to disclose information regarding the repeat flooding of the home; in the 29 states with flood disclosure laws, some of the policies are written so loosely or ambiguously that the owner still may not have legally be required disclose flood information related to the property (NRDC 2018). A public database that contains information regarding a property's history with flood insurance, damage claims, past receipt of federal disaster aid, and other relevant information could aid property buyers tremendously.

Real estate flood disclosure laws by nature are designed to protect property buyers from making adverse investments and do not afford much aid to property sellers. By disclosing flood information, sellers might see the property value lessen or have a more difficult time selling the property. In order to provide aid to the property sellers and not solely the buyers, buyout programs could be implemented to purchase properties that routinely flood or are located in known flood zones. In the CoBG, the buyout of properties that repeatedly flood or are in flood zones has been utilized in the past but this practice is contingent upon the availability of funding to be utilized for this purpose or the ability to apply for grants. In smaller cities like the CoBG, limited resources can reduce the ability of local officials to implement programs like a buyout program. One suggestion made in a report by the National Resources Defense Council (NRDC) was for FEMA and the NFIP to provide homeowners with the option of relocation through a buyout program within the NFIP, rather than continuing to dole out aid to rebuild or repair homes that repeatedly flood (2017).

There are approximately 227,000 properties throughout the state of Kentucky that are located within one-percent annual chance flood zones (BRADD 2022). Over the past 25 years with the exception of 2017 and 2001, Warren County and the CoBG have had multiple flood-related FEMA declarations resulting in a 400 percent chance of experiencing flooding each year (BRADD 2022). According to a local official regarding a residential home in the CoBG, “Over the past ten to fifteen years, there were about three instances where the water had flooded to the finished floor elevation of that home” (Pers. Comm. 2022). The properties within the CoBG and Warren County that have been identified as SRLPs or repetitive loss properties are all single-family residential homes, making the properties obvious choices for participation in a buy-out program (BRADD 2022). Given that the NFIP paid more than $5.5 billion between 1978 and

2015 to rebuild SRLPs around the U.S., a buyout program could potentially reduce the amount of unnecessary federal spending on repeatedly repairing homes and redirect funding towards eliminating the problems across the United States (Moore 2017). Residents and homeowners that participate in the program would no longer have to handle the stress and financial strains that flood damage can cause. A program built into the NFIP could also aid communities with limited resources available to dedicate towards a buyout program.

An opportunity to increase monetary resources for a community that could potentially be utilized to help fund a buyout program would be the implementation of a stormwater utility fee (SUF). Due to a relative lack of literature or research related to stormwater utility fees, Zhao et al. (2019) examined various communities across the U.S. that have implemented SUFs and concluded that the lack of stable and dedicated funding for many municipalities has been a central challenge when attempting to implement effective stormwater management programs. Based on their evaluations of SUFs, the researchers stated, “stormwater utility fees are a more efficient and environmentally sustainable source of revenue that allows for long-range planning of capital improvements and operations, but their high political visibility and legal obstacles can affect their effective implementation” (Zhao et al. 2019, 1). Attempting to gain support or approval for an additional expense on a bill, regardless of the amount, has proven to be difficult for many communities across the U.S. (Zhao et al. 2019). Warren County currently has a stormwater utility fee (SUF) that is included in the monthly water and sewer bill residents receive; the residential fee is a flat rate of $4 per month and the non-residential fee is $10 per month (WCWD 2022). The CoBG does not currently have any sort of equivalent fee. The Census Bureau estimated in 2020 around 30,000 households in the CoBG; a monthly SUF of only $4 could bring in over $1 million annually based upon residential fees alone (ACS 2020).

An SUF could provide additional funding for construction, operation, or maintenance of stormwater programs, regulatory compliance, the buyout of properties in flood zones or with repeated flood issues, the repurposing of flood areas for drainage easements or other methods of flood control, or various other endeavors that could benefit the local community. A CoBG official stated, "Money from a stormwater utility fee would give us a lot more leeway to do out-of-easement work, to go and hunt down properties we know haven't been developed because of drainage issues. There are lots of vacant properties that receive proposals to build on but have been vacant because the property floods every six months. Extra funding would allow us to go out and put in drainage or just purchase the lot ourselves" (Pers. Comm. 2022). An increase in funding for the local government by over a million dollars annually could aid in more successful management of flood issues and stormwater management, while contributing to overall sustainable community development.

Another recommendation is that policies and regulations utilized by governing bodies should be living documents. The literature that dictates the rules and actions of a community need to be updated regularly, rather than once every few decades. Altering or updating existing laws and regulations can be exceedingly difficult or laborious in the U.S., especially for smaller communities with more limited resources. In some communities with fewer personnel, the officials that are tasked to handle flood mitigation might also be tasked with creating or updating flood-related policies and regulations for the community. A CoBG official stated in an interview, "It's difficult to get something together in the wake of the flood while also trying to respond to the flood itself. Six months after a flood, people tend to lose interest and it makes it harder to make policy changes" (Pers. Comm. 2022). Updating regulations or standards regularly or in the periods between major events could increase efficiency of resources and potentially aid in alleviating flood impacts. The Stormwater Management Manual utilized by the CoBG to dictate drainage standards and stormwater management in the city has not been comprehensively updated since 1976 (Daugherty 1976). The risk assessment methodology utilized by FEMA for the NFIP was updated in 2021 for the first time in almost 50 years since the early 1970s (FEMA 2021). The 1948 Federal Water Pollution Control Act was not significantly amended until 1972, a period of 25 years, when sweeping amendments made the original act into what is known today at the Clean Water Act (EPA 2022). Over the last 50 years since the development of the Clean Water Act, four major amendments to the act have occurred; the most recent major amendment occurred in 2014 but the latest amendment before those changes occurred in 1987, a gap of 27 years (CRS 2016). Various rules have been established under provisions of the Clean Water Act throughout the years since the conception of the act, but none have specified any regulations related to groundwater protection or management (Troxell 2021). The establishment of new laws and regulations or updating existing ones can be a lengthy process in the U.S.; however, continuously updating and strengthening management plans could help to alleviate some of the gaps in existing policies and aid in the pursuit of protecting both the physical environment and the community.

Chapter Six: Conclusions

This research resulted in a GIS analysis of current FEMA-designated flood zones in the CoBG associated with karst features, sites of potential sources of contamination to water, and mapped flood extents. Known sinkholes and potential sinkholes were determined to have the strongest association with flood prone areas in the CoBG, excluding riverine flooding, though many new developments have been situated in areas dense with both known and potential sinkholes. The GIS analyses identified flood-prone areas and the need for updated floodplain maps in the CoBG and surrounding areas, as new developments and the growth of the population has altered the landscape over the past 15 years.

The development and application of the kFVI in the CoBG identified regions of the city with higher flood vulnerability related to social, environmental, and economic factors. The assessment of the CoBG utilizing the kFVI revealed that higher rates of underage and elder populations, poverty rates, disabilities, lower levels of education, unemployment rates, limited English-speaking abilities, and lower household incomes and home values were consistently associated with higher densities of hazardous waste facilities, sinkholes, potential sinkholes, SFHA, and overall higher levels of environmental-based vulnerability to flooding. The kFVI assessment additionally highlighted the need for improved regulatory protection and enforcement at the local, state, and federal level. Many of the policies and regulations that are utilized as floodplain management standards at all levels of the government are outdated and generally written too ambiguously to provide sufficient flood protection. Utilizing a wholistic approach that incorporates the characteristics of a region beyond solely economic-based factors or the physical environment can help flood mitigation benefit the entire community. Directing resources or determining risk based upon the dollar value of property or a human life is not conducive to successful management with an overarching goal of protecting and promoting human life. By calculating and examining social, environmental, and economic in conjunction, flood related education can be focused more heavily in the identified areas to help inhabitants to know what resources are available to aid in flood mitigation and recovery or different policies and regulations that might impact the community. Flood mitigation projects located in the identified regions could be reorganized by including the kFVI metrics and indicators in prioritization calculations.

Despite some uncertainty surrounding climate change modeling in terms of the precise impacts that might occur in a region, a consideration of climate change promotes building more robust strategies that account for changes in precipitation or environment. Methods in which climate change can be built into mitigation strategies in a more sustainable way include: homes with frequent inundation problems could be bought out, elevated, or updated to increase flood proofing measures, drainage easements or wells could be expanded or increased in number, development regulations could be updated to be stricter and more heavily enforced, infrastructure and wells could be redesigned and updated to address current problems, or the area surrounding new developments could be included in assessments to better understand potential impacts of new structures on flooding before permits are granted.

The final objective of this study was to make recommendations for the CoBG and urban karst communities to aid flood management strategies and urban development regulations. Based upon the findings of this research, recommendations were made and include a focus on using the kFVI to assess flood vulnerability, then develop tracking databases for flood event mitigation and associated programs designed to decrease the impact of flooding through education and proper risk and FEMA designation. Collectively, policies must be improved to consider flood impacts, both current and future, using a data-driven approach that considers the urban karst landscape along with best practices for stormwater management.

Further application of this research could contribute to the adaptation and refinement of the kFVI in various urban karst regions and validation of the methodology utilized. This research could also be expanded upon with the development of data on a smaller scale in order to more closely examine the demographics and characteristics associated with the karst and flood features to investigate the levels or patterns of environmental equity of the study area. The continued incorporation of climate change projections and impacts with updates to predictions could aid in planning and decision making. Further identification of flood mitigation strategies and recommendations that could aid land managers is the next step in advancing flood management and environmental equity in urban karst regions.

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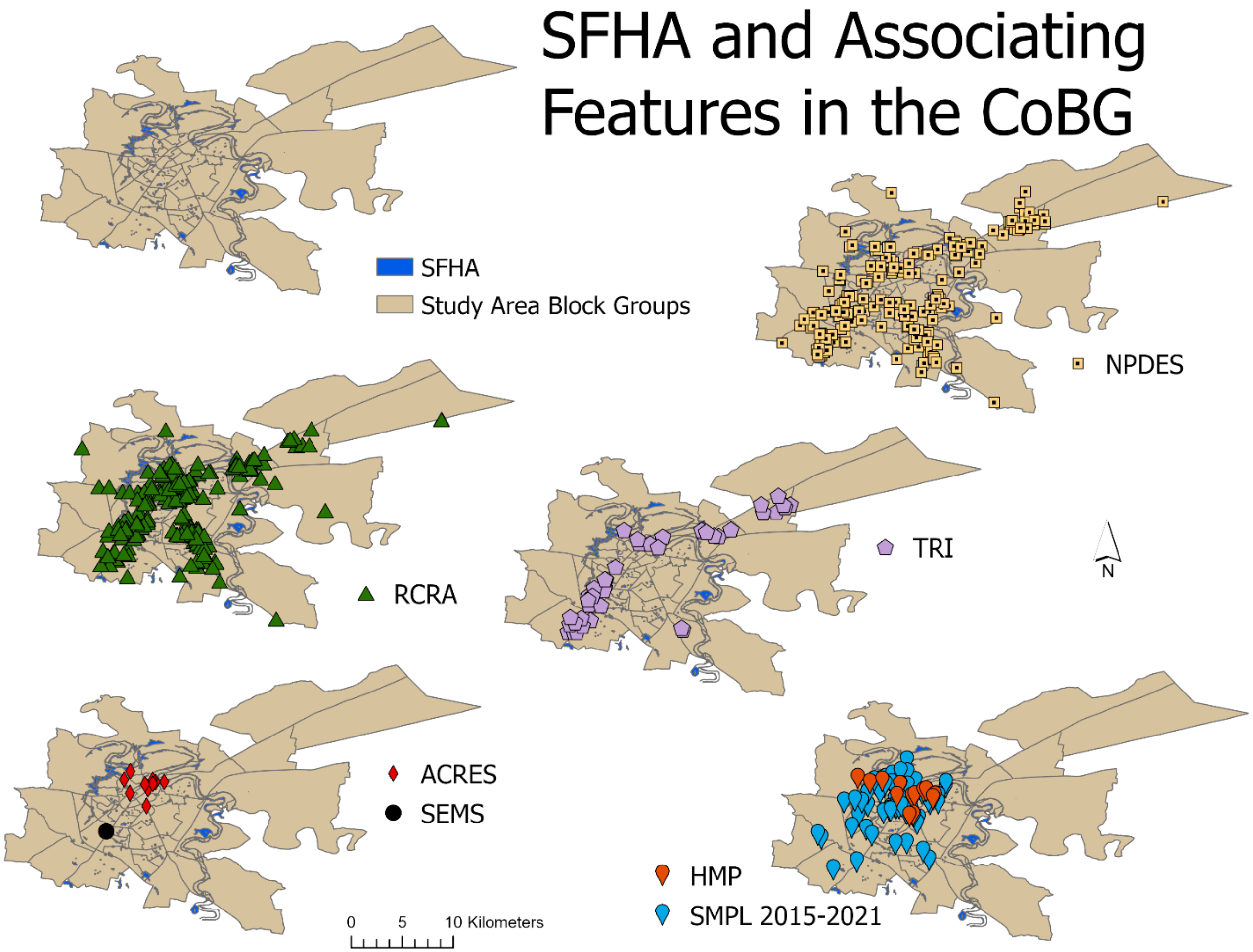
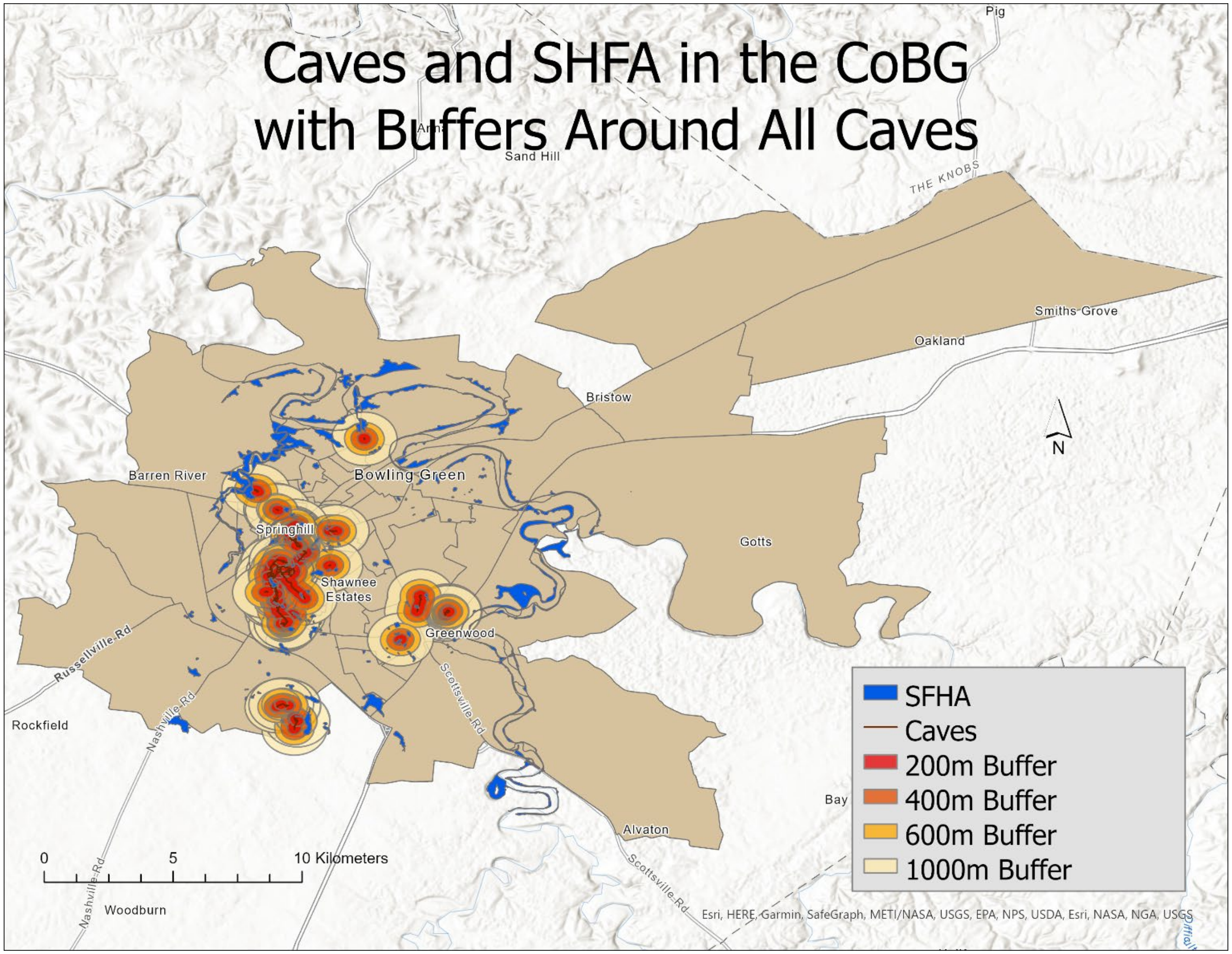
Appendix A: Associating Features and SFHA in the CoBG

This appendix contains a map of Special Flood Hazard Areas (SFHA) associated with NPDES, TRI, RCRA, ACRES, SEMS, HMP, and SMPL sites in the CoBG.



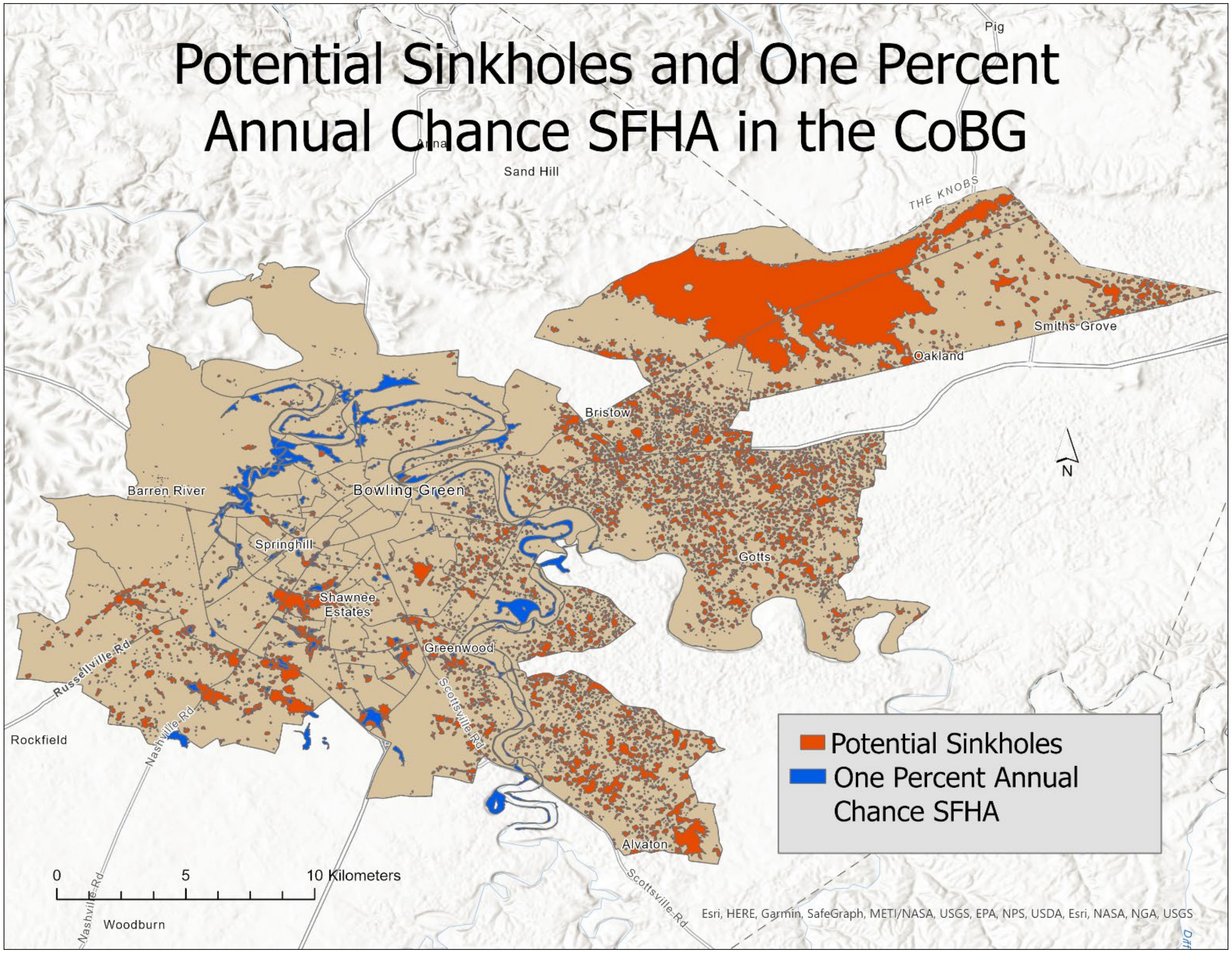
Appendix B: Caves and SFHA in the CoBG

This appendix contains a map of Special Flood Hazard Areas (SFHA) associated with caves in the CoBG, with buffers surrounding the caves at distances of 200 meters, 400 meters, 600 meters, and 1,000 meters.



Appendix C: Potential Sinkholes and SFHA in the CoBG

This appendix contains a map of Special Flood Hazard Areas (SFHA) associated with potential sinkholes in the CoBG.



Appendix D: Semi-Structured Interview Questions

1. What are some management strategies that you believe would work best to help manage flooding in urban karst communities? (and what are some that don't)
2. Do you think there are frequent or intense flood impacts around urban karst communities, such as flooded roads, damage to businesses or schools?
3. Who is responsible for fixing these issues?
4. How do karst groundwater systems contribute to flooding?
5. Do you think that flooding occurs disproportionately in Bowling Green?
6. Do you have any concerns regarding flooding (or drought) in the future with climate change?

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Type of document: ['Thesis']

Title: An Integrated GIS and Flood Vulnerability Index Approach to Evaluating Risk and Environmental Equity in Urban Karst Communities

Keywords (3-5 keywords not included in the title that uniquely describe content): flooding, karst, equity

Committee Chair: Dr. Jason Polk

Additional Committee Members: Dr. Leslie North, Nick Lawhon, Dr. Jun Yan

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