“A Hazard Vulnerability Assessment and Climatology for the State of Ohio from 1960-2016”

An Honors Thesis

by

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Abstract

Hazard mitigation has been an increasing field of importance, especially for those who work in public safety. Therefore, it is crucial to understand the risks associated with natural hazards that are frequently observed. The goal for this project is to create an original methodology for determining natural hazard vulnerability by combining methods for determining environmental and social vulnerability mentioned in the literature. The information learned from the literature was then applied to data extracted from the Spatial Hazards Events and Losses Dataset (SHELDUS) from the University of South Carolina. These data will then be used to analyze different trends of hazard occurrences within the dataset and to also determine where the area(s) of greatest vulnerability existed within the state of Ohio from 1960-2016. The data will also be aggregated into 30-year climatological periods; 1960-1989, 1970-1999, 1980-2009, 1987-2016 to identify any existing trends within the dataset in regard to vulnerability. Visuals that did not exhibit spatial trends were tested using the Moran's I test to determine how randomly the data were distributed. For those that were tested, all except one showed a random distribution, meaning no one region had the highest vulnerability to a specific hazard. While there appeared to be spatial trends within the individual hazards and their occurrences, the main finding was that only one county in the state of Ohio showed consistent vulnerability, Cuyahoga County, receiving the highest score possible.

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I.) Introduction

The creation and implementation of hazard mitigation tactics have become increasingly significant in today's society. To be prepared for any natural or manmade disaster, extensive cooperative organization and planning is completed to create Emergency Operations Procedures (EOPs) and Standard Operating Procedures (SOPs) for several scenarios that could occur. Simultaneously, creating partnerships and establishing collaborative plans and procedures are just as significant as the initial response plans themselves; without strong partnerships and relationships, the response and recovery processes of any disaster will prove to be arduous for emergency response personnel. The first step in creating these plans is to determine the history of previous occurrences and establish the possibility of similar incidents occurring in the future.

The purpose of this research is to determine the frequencies of several hazards that occur within the state of Ohio over a 57-year time period (1960-2016). Based on the frequency of each hazard for each county, a quantitative score is computed to determine vulnerability based on the number of past hazards. Data for these hazards were obtained via the Spatial Hazard Events and Losses Database (SHELDUS). In addition, a secondary method for evaluating the vulnerability for each county was created based on demographic information obtained from previous United States Census reports. A more in-depth explanation of the methodology used in this research is included in the "Data and Methods" section of this paper, Section III. It is hypothesized that the northeastern counties of Ohio have a higher vulnerability due to the elevated occurrences of natural hazards. It is also hypothesized that the southwestern counties of Ohio have a higher vulnerability due to the demographics of the region rather than the previous natural hazard experiences, the opposite of the first proposed hypothesis.

II.) Literature Review

A.) Natural Disasters in Ohio

During the period analyzed in this study (1960-2016), several natural disasters have occurred within the state of Ohio including: The 1974 Super Outbreak where an F5 tornado moved through the town of Xenia, Ohio, sparking a movement to include tornado drills in all schools (Risk Management Solutions, 2004), the winter storms of 1993, 2010, and 2016; remnants of tropical systems, the most memorable being Ivan from the 2004 Atlantic Hurricane season, and a derecho that occurred in the summer of 2012. The Xenia tornado inspired a National Tornado Safety week, which normally occurs in the month of March despite the actual event occurring in April, to spread tornado awareness (Risk Management Solutions, 2004). This also serves a purpose to school officials to be reminded of their responsibilities and the proper protocol that must be followed should an actual tornado be within close spatial proximity to their institution. From the National Weather Service (NWS) report, Xenia suffered 34 fatalities and 1,600 injuries within the town itself, population of approximately 25,000 (Risk Management Solutions 2004). In addition, this tornado alone damaged an estimated 1,300 buildings and slightly damaged an additional 2,000 buildings while causing an estimated loss of over $130 million in damages. The Xenia tornado would be remembered as the deadliest tornado of the 1974 Super Outbreak (Risk Management Solutions 2004).

One of the most memorable winter storms that affected the state of Ohio, more specifically the eastern third of the state, would be remembered as the winter storm of 1993, otherwise known as the "Superstorm of March 1993" (U.S. Department of Commerce 1994). Not only did this storm produce blizzard conditions near the Appalachians and high amounts of snow to areas surrounding the southern Appalachian Mountains, but it also produced several tornadoes in the southeastern United States (U.S. Department of Commerce 1994). In the response to the storm a "Winter Weather Awareness week" was initialized. The purpose of this awareness program was similar to the "Tornado Awareness week" to educate the public regarding the dangers that occur from a winter storm and how to be safe before, during, and after the storm (U.S. Department of Commerce 1994).

The Eastern region NWS offices were affected by the snow and blizzard conditions were highly praised for their large lead-time of winter weather watches, warnings, and blizzard warnings throughout areas near the Appalachian Mountains. In addition, nearly 100 NWS offices initiated some semblance of short-term and long-term preparedness initiatives to help educate the public of the dangers of the impending storm. The initiatives implemented in the form of long-term preparedness include: Intergovernmental drills, contact with emergency management officials, local officials, and major media outlets; NWS internal drills, spotter training, which helped verify reports and was critical during the March 1993 Superstorm, station duty manuals, and through mailings and brochures. The initiatives for short-term preparedness include: Pre-event planning sessions, internal coordination, and pre-event meetings (U.S. Department of Commerce 1994).

The remnants of Hurricane Ivan, 2004, were most memorable to those in the eastern and southeastern counties of Ohio as this caused major flooding in these areas. The Federal Emergency Management Agency (FEMA) declared 21 counties within the state of Ohio, almost a quarter of the state of 88 counties, as disaster areas. Many areas affected by Ivan were still recovering from the remnants of Hurricane Frances, which also brought high rainfall amounts and major flooding to several areas in eastern and southeastern counties of Ohio a few weeks prior to Ivan. Several stream gauges reported record peak streamflow and recurrence intervals on the order of 500-year flood or greater (U.S. Department of the Interior 2008).

The derecho of June 2012, affected nearly the entire state of Ohio and prompted several severe thunderstorm and tornado watches and warnings. The event began as a small thunderstorm complex, originating in southeastern Illinois that re-developed into a large bow echo that would travel a vast distance, reaching the east coast of the United States by midnight, the same day, at speeds of around 60 mph. Most damaging wind reports were around 60 mph, however there were local reports exceeding 80 mph with isolated areas experiencing wind gusts over 100 mph. The derecho of 2012 would cause 13 fatalities, many resulting from falling trees and leaving 4 million customers without power. Even after the derecho event ended, several heat-related fatalities occurred in areas that lost power as a result of the derecho as a majority of areas were in the middle of a prolonged heat wave (Sepic et al. 2014).

Previous events mentioned the probability of occurring and knowing this days in advance to prepare, however, this derecho was not anticipated as far in advance. Warm-season derechos are difficult to forecast because the numerous small-scale phenomena and forcing that create them present a great challenge for the models to forecast.

However, the day of the incident, short-term models predicted the possibility of a large and intense line of thunderstorms along the path eventually followed by the derecho. Due to the lack of lead-time, key partners and decision makers had significantly less time to prepare for what would be a high damaging wind event. From the NWS perspective, however, lead-time on issuing warnings was excellent, greater than 30 minutes, and additional warnings would be issued when necessary. Most NWS offices were insistent on issuing large-sized polygons due to the widespread nature of the event and the rapid storm motion, causing many areas to become highly vulnerable (Sepic et al. 2014).

B.) Vulnerability

The concept of vulnerability is complex, and many factors affect how vulnerable a group of individuals or a community is should a natural disaster impact their area. However, throughout the literature, there is no unanimous definition of the term vulnerability. This issue was discussed in Fuchs et al. (2012) by stating that several disciplines use the term vulnerability and therefore each discipline has its own definition for the term. However, Fuchs et al. (2012) does continue the discussion by stating an extremely important fact that to improve any and all efforts of reducing hazard exposure and building disaster-resilient communities, there must be an intersection among the disciplines. This research will provide a coherence of both vulnerability from the environmental and societal disciplines to create a method of combining the fields to show where an area's true vulnerability exists. The differences between the two methods of exploring vulnerability will be explored, but this research will serve as a method of bringing together scientists from both sides to aid in the discussion of reducing vulnerability.

Other studies that examine vulnerability are Turner II et al. (2003), Cutter et al. (2003), Chakraborty et al. (2005), and Hardy (2017) with each proposing their own meanings of the term vulnerability. Turner II et al. (2003), vulnerability is defined as the degree to which a system, or subsystem, or system component is likely to experience harm due to hazards, whether it be a change or a stress or stressor. Cutter et al. (2003) generally define vulnerability as the potential for loss, but continue on by discussing that losses vary spatially, temporally, and among different social groups. This is discussed further in subsection 1.

Chakraborty et al. (2005) discusses vulnerability extensively by introducing it as a human-induced situation that results from public policy and resource availability or distribution with higher levels of vulnerability being correlated with higher levels of poverty and those that are excluded from the norms of society. The authors also present a statement that is ubiquitous throughout the literature: the hazards literature has identified many components of vulnerability but have not presented many clear measures of vulnerability (Chakraborty et al., 2005). The goal of this research presented here is to create an index that assists in determining these measures as that will greatly aid the accounting of the ever-changing factors encompassing vulnerability.

1.) Social Vulnerability

Generally, Cutter et al. (2003) defined vulnerability to environmental hazards as the potential for loss. Although this is rather a general definition compared to those in the studies previously mentioned, Cutter et al.'s introduces three key factors that drive vulnerability research. These factors include the identification of conditions causing an area to be vulnerable, the assumption that vulnerability is a measure of resilience to hazards, and the integration of potential exposure and societal resilience with a focus on particular places or regions (Cutter et al., 2003).

Cutter et al. continues by discussing the components of vulnerability that are created via social factors. The components of social vulnerability often are ignored mainly due to the difficulty in quantifying the variables. Cutter et al. conclude by stating that since social vulnerabilities cannot be quantified easily, they are normally excluded from after-disaster effects and loss estimation reports. Social vulnerability factors are usually identified by characteristics that relate to people, such as age, race, gender, income, housing, and employment. Another idea introduced by Cutter et al. is that social vulnerability partially results from social inequalities, meaning that social factors influence exposure of diverse groups to harm and govern the ability for these groups to respond and recover from hazards effectively (Cutter et al., 2003).

Hardy (2017) was also noted for stating similar characteristics of social vulnerability to Cutter et al. (2003). However, Hardy (2017) presented a method of categorizing social vulnerability based on five distinct variables. These include gender, ethnicity, age, home ownership, and income (Hardy, 2017). The main difference between the two studies is within the first study, one of the variables includes employment status while the second study does not.

2.) Environmental Vulnerability

Compared to social vulnerability, environmental vulnerability is significantly easier to quantify and is also discussed within Hardy (2017). Hardy examined vulnerability within 42 communities of northeastern Ohio; when examining the environmental vulnerability of these communities, the author chose to observe the 100-year floodplain exclusively. Other factors that are correlated with environmental vulnerability include flooding history, erosion, debris, and water quality. The main factor of environmental vulnerability that was observed within this research was the history of hazards within the region.

For this research, the method of calculating environmental vulnerability will be different than the method used in Hardy (2017). Determining the environmental vulnerability for a county, rather than a community, in Ohio will be determined by the climatologies of each hazard that are examined within the study (tornadoes, severe thunderstorms, snow storms, and flooding). Based on the frequencies of each hazard, a score will be given to each county which is determined by the number of overall occurrences within the period of the study. A more detailed explanation of the methodology for this research will be presented in Section III.

3.) Reducing Vulnerability

a.) Hazard Vulnerability Assessments

After exploring vulnerability and determining the several characteristics that encompass the aspects of both environmental and social vulnerability, it is important to discuss methods of how to reduce vulnerability to limit the losses of life and property. One method of reducing vulnerability is by completing a hazard vulnerability analysis (HVA). This type of assessment is primarily used to compare different types of hazards and to aid in identifying the hazards that have the highest probability of occurring and for determining the risks that would have the highest chances of affecting the environment (Fifolt et al., 2016). For this research, the method of determining the environmental vulnerability is similar to that of an HVA in that previous hazards will be used to determine the likelihood of similar hazards in the future.

A significant reason to use HVA is that it encourages critical thinking to solve problems and to help create an emergency operations plan (EOP); an EOP is a set guideline used to help define the scope of the problem and how emergency response personnel can effectively respond to a disaster. Also, within the EOP is the decision-making process such as the chain-of-command authority, equipment and supplies needed, facilities that will be utilized, and what resources will be needed. Several HVAs are used combine several aspects of the emergency management cycle. For instance, some plans combine hazard identification, impacts to the community, and recommendations on how to effectively respond to the hazard. The common plans that contain all of the information mentioned are the Kaiser Permanente model and the Threat and Hazard Identification and Risk Assessment (THIRA) (Fifolt et al., 2016).

b.) Integrated Warning Teams

Another option for reducing vulnerability is to create an Integrated Warning Team (IWT). An IWT comprises individuals from several different areas, such as private and public sector, emergency management, local and city officials, weather forecasters, and representatives from the media. The main goal of an IWT is to cooperate and communicate clearly and consistently each other's needs to best protect life and property.

By having clear and consistent messaging, more citizens in an affected area can be more aware of their surroundings and can be more proactive in their preparations rather than reactive; creating an area that is more resilient as a result (Morris et al. 2008).

For the IWT, it is important to simulate various scenarios, similar to those in Morris et al. (2008), to ensure the IWT is confident in the language and the style in which all information would be presented, the time necessary to respond to any emergencies that may occur during the event is sufficient, and any problems or roadblocks that may occur during the simulation are addressed then and not while a life-threatening situation is occurring. Morris et al. (2008) continues stating that addressing the responsibilities of all who may be involved with the IWT and ensure these are also communicated to the respective partners involved and impacted by decisions within the IWT, which are aggregated by area represented within the IWT.

4.) Perception of Risk

The media and NWS offices may communicate that a life-threatening event may occur on a particular day or that if citizens do not evacuate, many fatalities will result. This all comes down to the individual's perception of the risk presented. Albeit there may be some factors, on an individual basis, that prevent someone from evacuating an area that could be affected by a significant natural hazard. Kunreuther (2002) addresses this issue stating that studies, pertaining to hazard risk perception, have shown that a person with little knowledge and greatest fear regarding the hazard, from personal experience, were perceived as the deadliest. Another takeaway from Kunreuther (2002) is that the figures presented to the public regarding the risk involved were not communicated effectively, the assumptions that the figures were based on were not clearly stated, and a huge disparity as to why experts disagreed with each other about the presentation of the figures.

Risk has normally been estimated via a monetary value and the most common method of calculating this cost is through an exceedance probability (EP) curve. The EP curve combines uncertainty associated with the probability of the hazard and the amount of possible damage that could occur. An example of an EP curve is displayed in Figure 1. Damage is not the only variable that can be plotted with the EP curve; fatalities, injuries, illnesses, and other units can be used for this type of analysis. However, to obtain more concise results of what the analysis may present, specialists and planners must know what to do and know how to interpret the results that the analysis presents (Kunreuther, 2002).

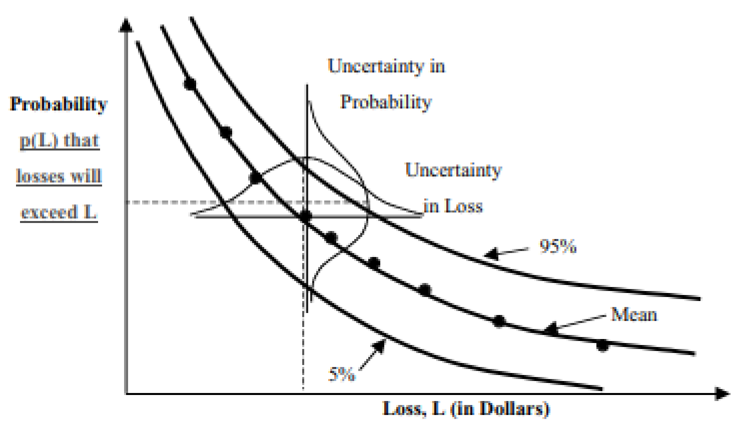


Figure 1. Example of an EP curve. From Kunreuther (2002).

Montz and Tobin (2010) support the findings and statements presented in Kunreuther (2002), by stating that the perception and interpretation of the risk is an important component of vulnerability. Personal experience can be a large influence in many decisions made prior to a significant hazard or disaster impacting an area, but this perception varies for every individual and is therefore based on cognitive and situational differences. A range of variables have also been examined, mainly associated with Hurricane Wilma in 2005, and have been determined to be positively correlated with higher preparedness.

C.) Resilience

Stated in Klein et al. (2003), the Oxford English Dictionary defines the term resilience as the act of rebounding or springing back; elasticity. Although resilience will not be examined in this research, it is important to explain why it is significant when discussing vulnerability. Klein et al. (2003) mentions two types of resilience, reactive and proactive. Reactive resilience strengthens the status quo within society and allows the current system to be resistant to change, whereas proactive resilience allows society to accept the inevitability of change and to attempt to create a system that is adaptable to changes in society and its environment. Within most major cities, the financial capabilities and expertise are present to assist in the planning process. Therefore, the city as well as the country and the rest of the world are able to assist these larger areas in their efforts to mitigate the effects of any natural disaster and are also able to assist with recovery (Klein et al., 2003).

One of the methods of determining resilience in communities or regions is use of a resilience scorecard. This scorecard allows planners to create an assessment to determine how much incorporation of vulnerabilities is necessary within the local emergency plans. Berke et al. (2015) states that a resilience scorecard should have two main purposes. The first purpose is to determine how well the plans reduce vulnerability and whether or not they are inclusive to differing areas of a community, or different districts. The authors continue their discussion of this first purpose by stating that focusing on districts with different needs, resources, and challenges is a core element of any comprehensive plan. By taking this step, the planners are able to develop different goals for their respective district(s) based on the resources required (Berke et al., 2015). The second purpose proposed by Berke et al. (2015) is that the scorecard should create comparisons between the level of inclusion and the level of vulnerability to hazards by specific planning districts. By comparing the level of incorporation with the level of vulnerability, the scorecard can then identify issues that are unique to specific planning districts as well as help create solutions to these vulnerability issues that may arise during the planning process (Berke et al., 2015).

Several factors are necessary to measure the amount of resilience in a community or region. Lindell and Prater (2003) include some factors they deem significant in their study including: Having enough homes and shelters of different sizes to accommodate smaller- and larger-sized families, accommodate those with living assistance or who need regular medical attention, a temporary shelter area in the event temporary housing is unavailable or if the needs of those for temporary housing cannot be met, support programs for a community's public and private housing, financial assistance, as well as recovery resources, such as flashlights, generators, and ice. Having these resources during times after a natural hazard or disaster occurred is significant in reducing the loss of life and increasing resiliency within the communities in and surrounding the impacted areas (Lindell & Prater, 2003).

D.) Hazards

Throughout this research, four hazards were analyzed to determine the vulnerabilities of each county throughout the state of Ohio. The hazards examined were tornadoes, severe thunderstorms, snowstorms, and flooding events. All hazards except flooding were under classification "b" from Regmi et al. (2013) as atmospheric events, such as climate change, geomagnetic storms, winds (including hurricanes, tornadoes, and straight winds), drought, freeze, and lightning. Flooding was classified under category "a," a geophysical event, and is being associated with large rainstorms, snowmelt, and storm surges (Regmi et al., 2013.).

Tornadoes are the primary focus, compared to the other hazards mentioned previously, of this research because of the amount of damage that can be created. Because of the extremely low pressure, high winds, and rotation associated with this natural phenomenon, winds are able carry debris that have may have been attributed to smaller, weaker structures and use this as a secondary method of causing damage (Boruff et al., 2003). These small pieces of debris can damage larger structures and can be carried far distances as a result (Boruff et al., 2003). Normally, tornadoes are localized and associated with thunderstorms or when hurricanes make landfall. Although several atmospheric processes are required for conditions to be conducive, these conditions and processes do not fully explain or identify the variability, both spatially and temporally, of tornado touchdowns (Boruff et al., 2003).

Over the years, the lead-time for tornado warnings have increased and have helped reduce the number of fatalities that result from tornadoes. There have been additional factors that have attributed to this reduction as well, including improved shelter services for those populations that are at greatest risk, the structural composition of housing has improved, and vehicle-occupied deaths during tornadoes have also decreased despite an increase in vehicle registrations (Boruff et al., 2003). However, an increase in false alarm tornado warnings has led to less credibility and, therefore, a lesser risk perception (Boruff et al., 2003).

Consistent with previous research, Ripberger et al. (2015) found that an individual's perception about warning system accuracy is influenced by the ratio of errors to non-errors produced by the system responsible for producing and issuing the warnings that are disseminated to the public. However, Ripenberger et al. (2015) also found that local experience played a role in risk perception as well. Local experience usually results from an individual's most recent experience rather than all of their previous experiences when formulating perceptions about the accuracy of the warning system. Therefore, a combination of factors attribute to perception, including those mentioned previously in II.B.4, so it is important to account for many factors when determining effectiveness of any warning product that may be disseminated to the public.

III.) Methodology

A.) SHELDUS

As stated in the literature review, there are a few methods of calculating the vulnerabilities for each county in the state of Ohio. From the Spatial Hazard Events and

Losses Database (SHELDUS), aggregated county-level data were obtained in the form of a comma separated values (CSV) file that can be imported into mapping software. Within this database, several variables may be examined, such as county name, FIPS code, hazard that occurred for each event, the year and month the event occurred, property damage (at the rate for which the event was reported), property damage adjusted to 2016's values, property damage per capita, injuries and injuries per capita, and fatalities and fatalities per capita. Not all variables within the dataset were used for analysis as they were not pertinent to this research. Many hazards were also addressed in this dataset that include: Avalanches, coastal occurrences, drought, flooding, fog, hail, heat, tropical storms and hurricanes, landslides, lightning, severe thunderstorms, tornadoes, winds, and winter weather.

It was then determined that a total of 47,204 events had occurred within the state of Ohio from 1960-2016. The data were then divided into 30-year intervals to create climatological periods of record that can be created for comparison and analysis purposes. Thirty-year periods are a popular convention amongst meteorologists and climatologists when discussing a number of events in large time period. The time periods of this study were divided into the following: 1960-1989, 1970-1999, 1980-2009, and 1987-2016. Once this data sorting was complete, the author then chose to create a separate sheet detailing the number of hazard occurrences per county per 30-year period of the study, which would then be used for analysis both statistically and via mapping software. While having this vast amount of data, the author also wanted to determine the greatest damaging event that took place throughout the period of this study and determine if there were any commonalities spatially or per hazard. The goal of this method was to determine whether or not trends existed within the data both spatially or temporally.

B.) United States Census Data

Prior to completing this data sorting, the author collected data from the United States Census, from the 2010 population survey. From this source, data regarding the population and demographic information such as ethnicity, race, age and sex, and household data were included, however, for this study the author was only interested in the population data

(U.S. Department of Commerce, 2018). These data would be used to determine events per capita, each hazard per capita, and would also be used when determining the vulnerability factor, created by the author and explained further in the results section. Essentially, this vulnerability factor would be used to identify hot spots that either resulted from previous hazard occurrences or the high level of vulnerability of the population.

Data from the 2000 population census was deemed irrelevant as the scope of this research encompasses the current vulnerabilities of the state of Ohio, rather than observed vulnerabilities and how they have changed over time. The next subsection of the methodology will detail the two methods that will, collectively, combine to create a vulnerability score, similar to the purpose of an HVA, mentioned in Fifolt et al. (2016), and the resilience scorecard, mentioned in Berke et al. (2015). The methodology used is similar to these studies but have no influence in creating the methodology herein.

For the purpose of this research, the method of determining vulnerability used to was meant to examine vulnerability at the county-level for the state of Ohio. The first method entails a natural hazard frequency displayed via mapping software. Once the data have been imported into mapping software, a score was given for each county based on the total occurrences observed over the fifty-seven-year period. The score was based on where the county's respective value was placed within the breaks of the data, determined by the mapping software. The total hazards per capita was also used as a method to parse out potential outliers and better highlight the counties that have high hazard occurrences with high populations (Franklin County, where the capital city of Columbus resides). The data were divided into five scores to create a scale from 1, having the least occurrences, to 5, having the most occurrences.

IV.) Results

Each thirty-year period is analyzed and includes the results of each hazard, both quantitatively (as in the total occurrences during the thirty-year period), and spatially (via results produced by mapping software).

A.) 1960-1989

Throughout the first thirty period, displayed in Figures 2 and 3, damaging winds were the most frequently observed hazard, followed by severe thunderstorms and then lightning. Spatially, these results are displayed in Figures 4-11. As predicted, a majority of events that occurred throughout the state were damaging wind events followed by severe thunderstorms.

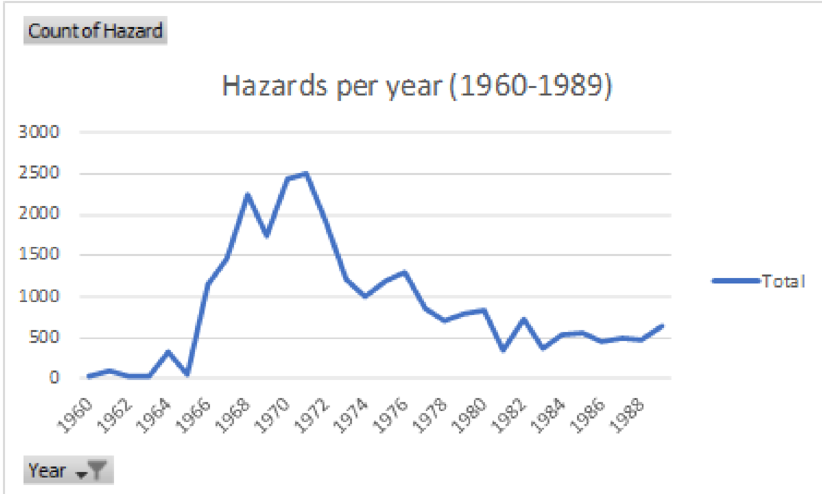


Figure 2. Temporal trends of overall Ohio hazard occurrences from 1960-1989.

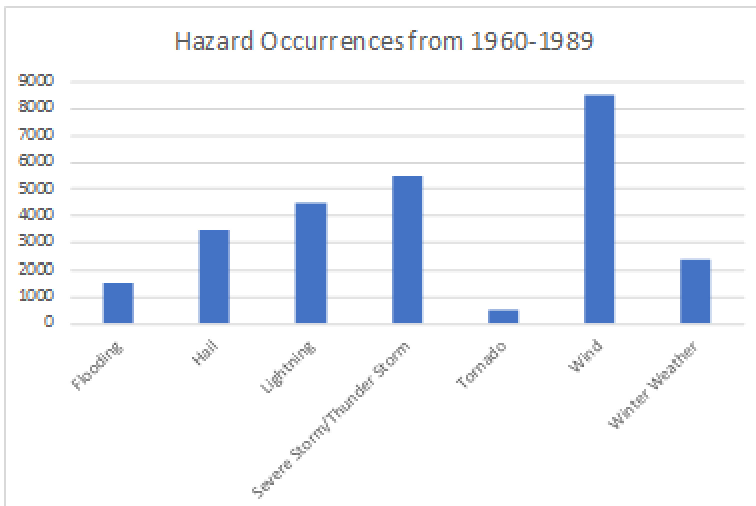
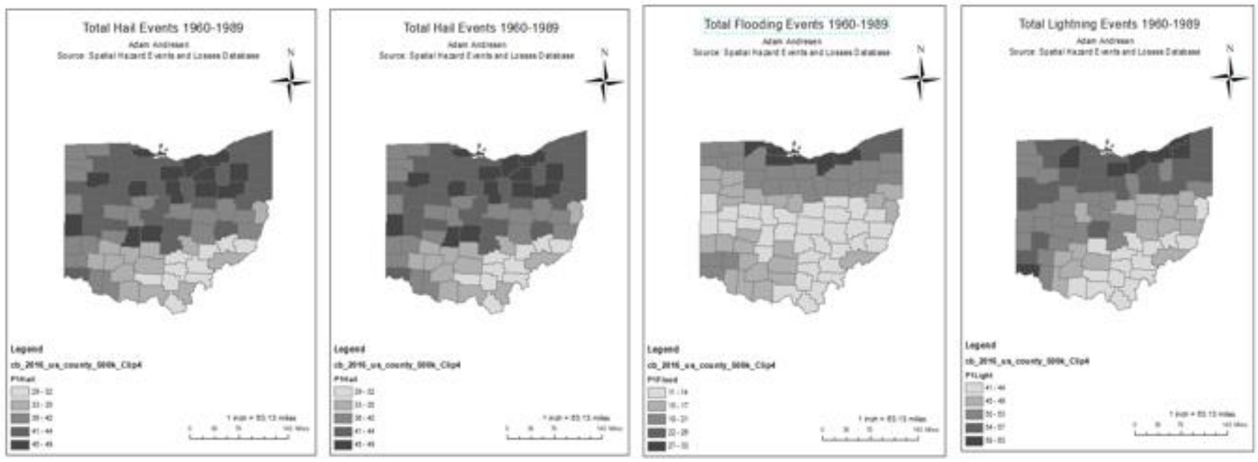
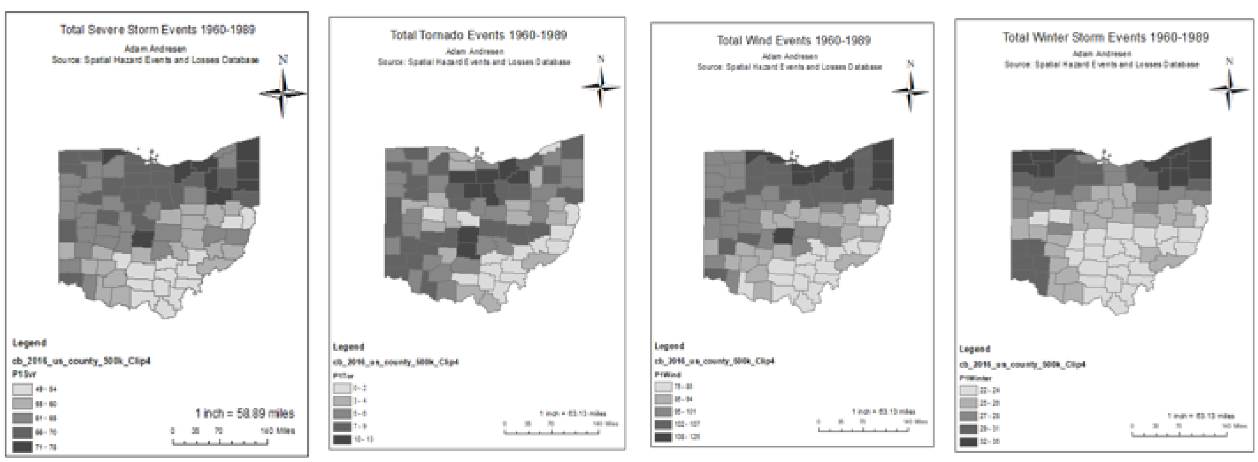


Figure 3. Analysis of the Ohio hazards and their respective occurrences from 1960-1989.



Figures 4-7. Total Ohio hazard, hail, flooding, and lightning occurrences by county from 1960-1989.



Figures 8-11. Severe thunderstorm, tornado, damaging wind, and winter storm occurrences from 1960-1989.

Figure 4 denotes the spatial distribution of the hazard occurrences within the state. The counties with the highest number of occurrences were mainly in the northern and western counties. Figure 5 depicts the total flooding events that occurred. As to be expected, the counties with the highest numbers are located near major bodies of water (e.g., Great Lakes, Ohio River). The extreme southwestern counties also show a higher number of occurrences because several other smaller rivers' and streams' discharges flow into the Ohio River, which explains how those feel the effects of high precipitation events that occur on the eastern side of the state.

Figure 6 shows the hail events and an overwhelming majority of counties in the northern half of the state show the greatest number of occurrences. In particular, Cuyahoga, Franklin, and Hamilton counties (which is where the major cities Cleveland, Columbus, and Cincinnati are located, respectively), there are a larger number of events. Figure 7 shows the distribution of lightning events that occurred throughout the first thirty-year period. Similar to flooding events, the major cities in Ohio, and their respective counties, display a higher number of occurrences.

Figure 8 shows the number of severe storm events by county during the first thirty-year period. Again, similar to the previous two hazards, the major cities have the most reported hazard occurrences. The northeastern and the northwestern counties show the highest number of occurrences, with the southwestern area showing the next highest, and the southeastern counties having the least number of occurrences. Figure 9 displays the total tornado events by county for the first thirty-year period. The tornado events that did occur are not evenly distributed nor do they show any spatial trends.

A Moran's I test was completed to assess the randomness of the spatial randomness of the data. Values ranged from -1 to 1. Values close to -1 were shown to have greater dispersion, values closer to 1 had greater clustering and values closer 0 greater randomness associated with the distribution. This first test for the tornadoes during the first thirty-year period was found to have a value of 0.367, showing close to perfect randomness. Figure 10 displays the damaging wind events that have occurred within the first thirty-year period. Similar to other hazards, the counties where the largest populations exist reported the highest number of events and the northeastern and northwestern counties are where the greatest number of events occur spatially. Figure 11 shows the winter storm events that occurred during the first thirty-year period. As to be expected, the counties that are nearest to the lakes have the highest number of occurrences, due to lake-effect snowfall. The southwestern counties show a higher number of occurrences, though not the highest compared to the counties near the lakes.

B.) 1970-1999

Throughout the second thirty period, displayed in Figure 12 and 13, damaging winds were the most frequently observed hazard, followed by severe thunderstorms and then lightning. Spatially, these results are displayed in Figures 14-21. In the beginning of the second thirty-year period, referring to Figure 12, there was a large number of hazard events. However, after the first three years, a much lower number of hazards occurred per year and continued through periodic increases and decreases over time. After the first three years, the highest observed hazards count occurred in 1976. Figure 13 breaks down the types of hazards that occurred. As with the first thirty-year period, damaging wind events had the most frequent occurrence, followed by severe thunderstorms.

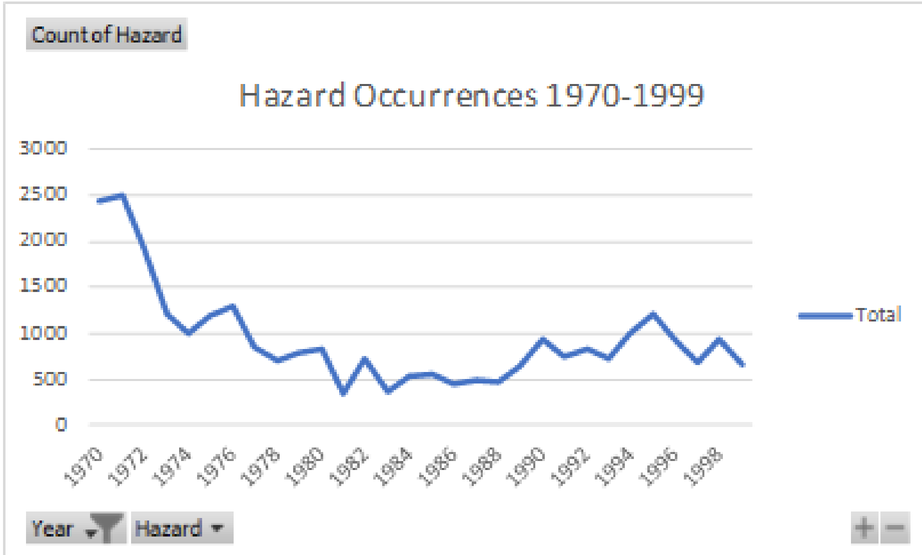


Figure 12. Temporal trend of Ohio hazard occurrences from 1970-1999.

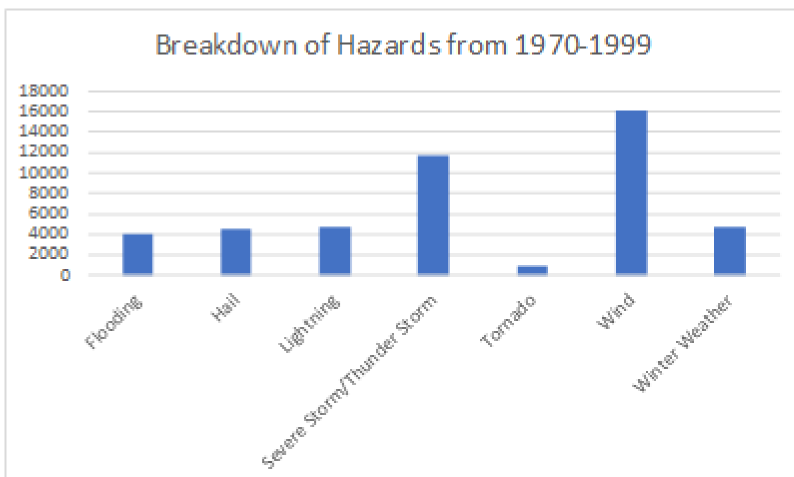
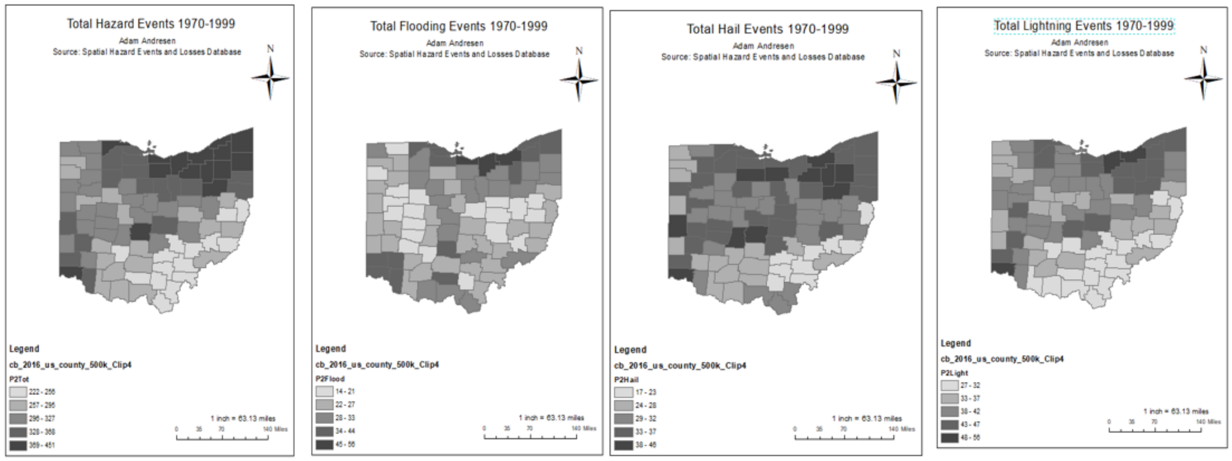
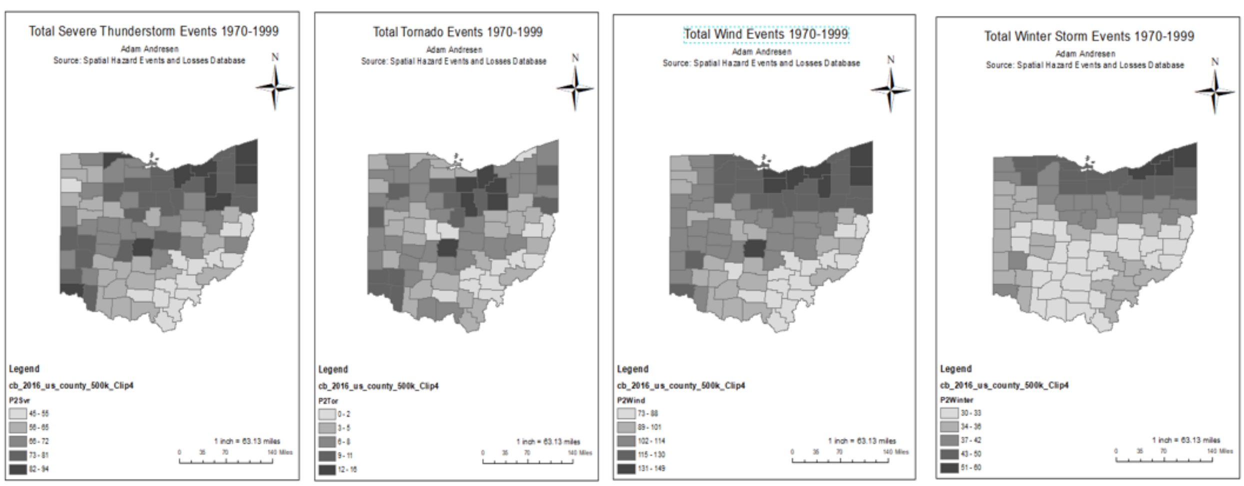


Figure 13. Analysis of Ohio hazard occurrences from 1970-1999.



Figures 14-17. Total hazards, flooding, hail, and lightning occurrences from 1970-1999.



Figures 18-21. Severe thunderstorm, tornado, damaging wind, and winter storm occurrences from 1970-1999.

Figure 14 shows the total hazard occurrences for the second thirty-year period. Compared to the first period, the two are relatively similar in regard to the areas where the most occurrences happened. The northeast and northwest Ohio counties had the largest frequencies, followed by the southwestern, and then the southeastern counties having the lowest frequency. Figure 15 shows the flooding events that occurred during the second thirty-year period. The second period shows more counties experiencing a higher number of flooding events than the previous period. However, the highest occurrences are located near the main bodies of water that run through the state of Ohio. Figure 16 displays the hail occurrences as well as displaying a close resemblance to the first period. The areas with the highest occurrences are still the same and the northern half of the state experiencing the most events. Figure 17 shows the lightning events that occurred during the second period. As with Figure 16, this closely resembles the map for lightning events from the first period. In addition, the areas with the highest occurrences were also similar to the first period.

Figure 18 shows the number of severe thunderstorm events that occurred during the second period. As stated regarding Figures 16 and 17, there was a close resemblance between the maps for the first and second periods for severe thunderstorm events. The areas with highest occurrences remained the same while the southeastern counties had the lowest number of occurrences. Figure 19 displays the number of tornado events that occurred during the second thirty-year period. As with the first period's tornado events, there was also a level of randomness to the spatial distribution. After completing a Moran's I test, the value came to be around 0.372, again showing a high level of randomness. While the hot spots shown from the first period remained in the second period, damaging wind events were also increasing during the second period, as displayed in Figure 20. More counties had an increase in the number of occurrences, while the southeastern portion of the state experienced the least amount. Figure 21 displays the number of winter storms that occurred during the second thirty-year period. There was a decrease in the northwestern and southwestern counties while some southeastern counties showed an increase in the number of occurrences.

C.) 1980-2009

Throughout the third thirty-year period, displayed in Figures 22 and 23, damaging winds were once again the most frequently observed hazard, followed by severe thunderstorms and then winter weather. Spatially, these results are displayed in Figures 24-31. This period was different from the second period in regard to the trends of hazards as more hazards were observed towards the latter part of the period, compared to the beginning. Figure 23 analyzes the types of hazards that occurred. With the third period, all of the hazards examined a decrease in the number of events. It should also be noted that the scales for Figures 2 and 22 are the same, while Figure 12 had to be adjusted to fit the larger number of reports during this time period.

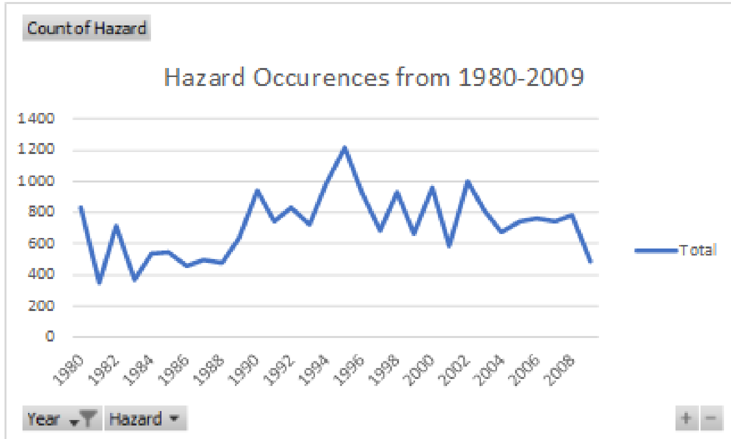


Figure 22. Temporal trend of hazard occurrences from 1980-2009.

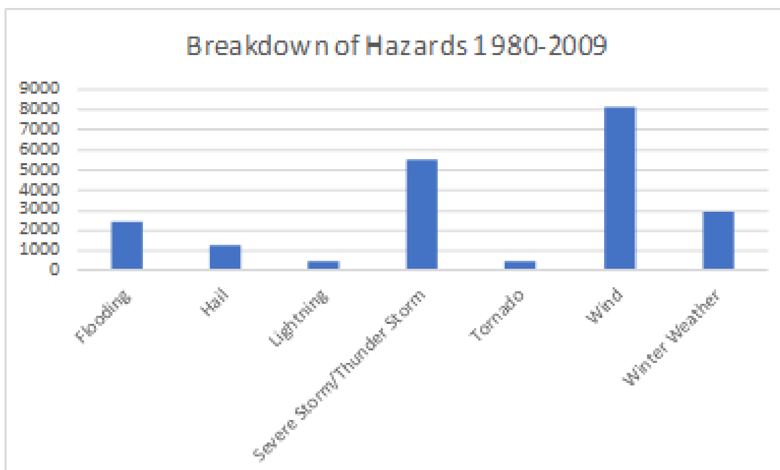
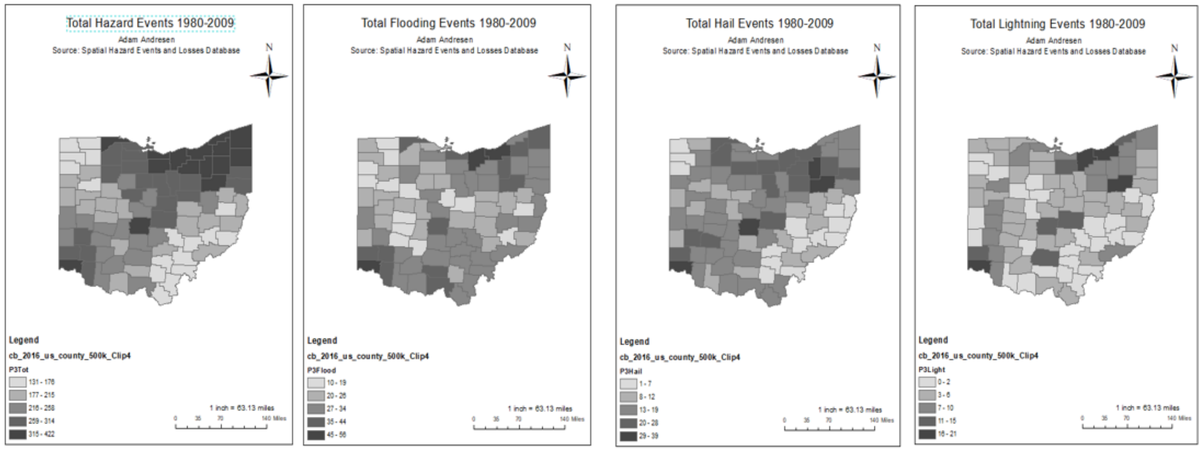
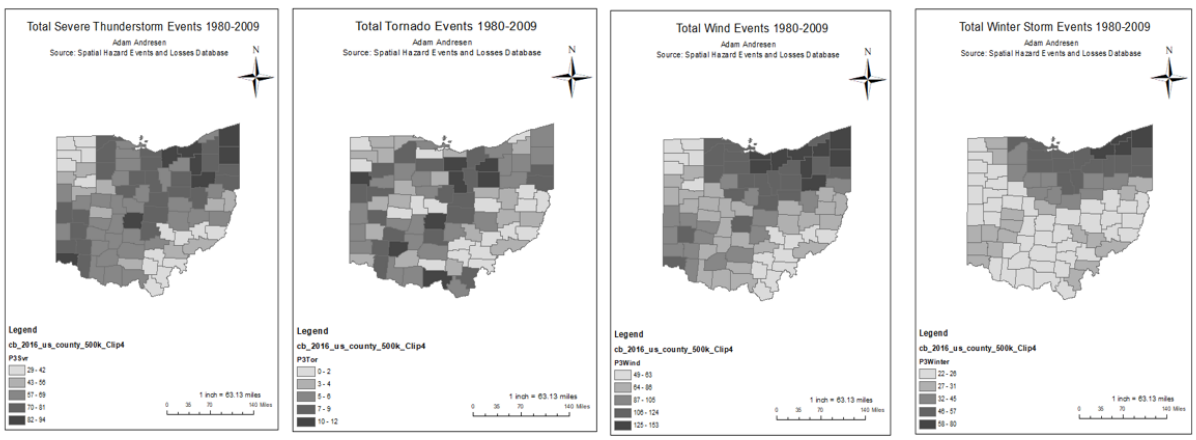


Figure 23. Analysis of hazard occurrences from 1980-2009.



Figures 24-27. Total hazards, flooding, hail, and lightning occurrences from 1980-2009.



Figures 28-31. Total severe thunderstorm, tornado, damaging wind, and winter storm occurrences from 1980-2009.

Figure 24 shows the total hazard occurrences by county during the third period. Compared to the second year, the spatial distribution is more clustered than the previous period. The northeastern counties still observe a high number of events, but the southwestern counties have observed a large number of events as well. Figure 25 shows the number of flooding events that occurred during the third thirty-year period. A number of counties observed an increase in occurrences, especially those that are near a major body of water. Figure 26 represents the number of hail events that occurred during the third period. Some counties in central Ohio showed an increase in the number of events, while some of the counties in east central Ohio observed a decrease in the number of events. Figure 27 displays the lightning events that occurred in the third period and showed an overall decrease in the number of events that occurred throughout the state, compared to the second period.

Figure 28 represents the number of severe thunderstorm events that occurred during the third period. Compared to the second period, the northeastern counties of the state continued to have the highest number of occurrences. The southwestern counties, however, observed a decrease in the number of events. Figure 29 shows the number of tornado events that occurred during the third period. A Moran's I test was calculated, with the same regards in as the first and second tornado occurrences, and was found to have a value of 0.260, showing these events to be even closer to perfect randomness compared to the previous two thirty-year periods. Spatially, the visuals between the second and third periods show similarities. Figure 30 displays the number of damaging wind events that occurred by county during the thirty-year period. Comparing from the second period to the third period, the spatial distribution of events was similar. Some southwestern counties of the state observed a decrease in the number of events while some counties in the northwestern part of the state observed an increase in the number of events. Figure 31 shows the number of winter storm events that have occurred in the third thirty-year period. Compared to the previous period, more of the counties located closer to Lake Erie, and the surrounding counties observed a higher number of winter storm occurrences. However, the northwestern counties observed a lower number of occurrences than the previous period.

D.) 1987-2016

Throughout the fourth thirty period, displayed in Figure 32 and 33, damaging winds were once again the most frequently observed hazard. Severe thunderstorms occurrences were higher than previous periods. The reasoning for this will be explained in the Discussion section. Spatially, these results are displayed in Figures 34-41. This period was different from the second period in regard to the trends of hazards as a fairly steady trend throughout the period until the end where a small decreasing trend occurred. Figure 33 breaks down the types of hazards that occurred. With the fourth period, all of the hazards examined here observed an increase in the number of events except for lightning and tornadoes. These hazards observed a decrease and a neutral change, respectively.

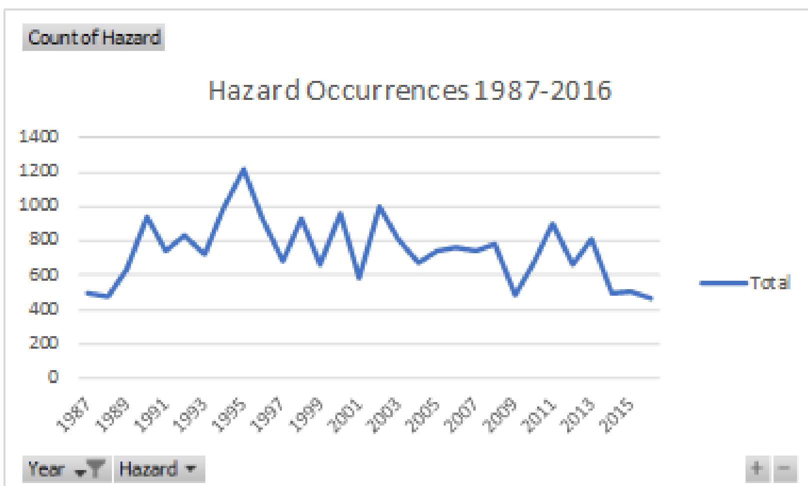


Figure 32. Total Ohio hazard occurrences from 1987-2016.

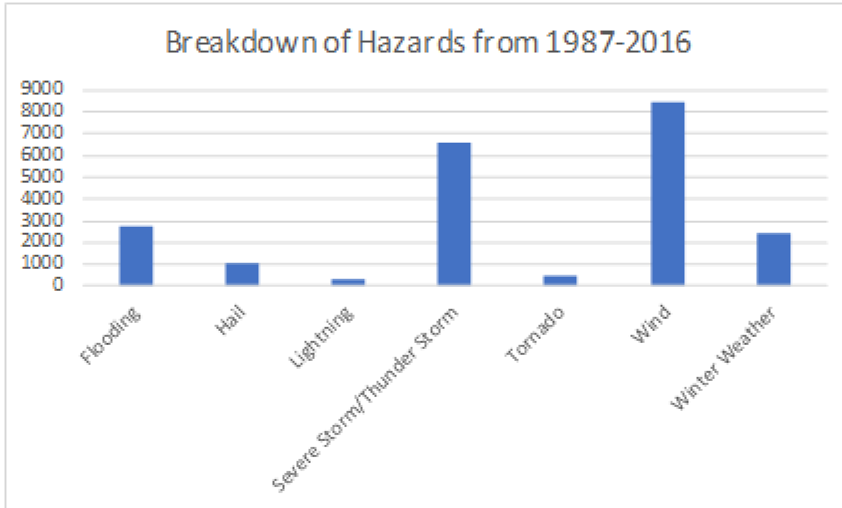
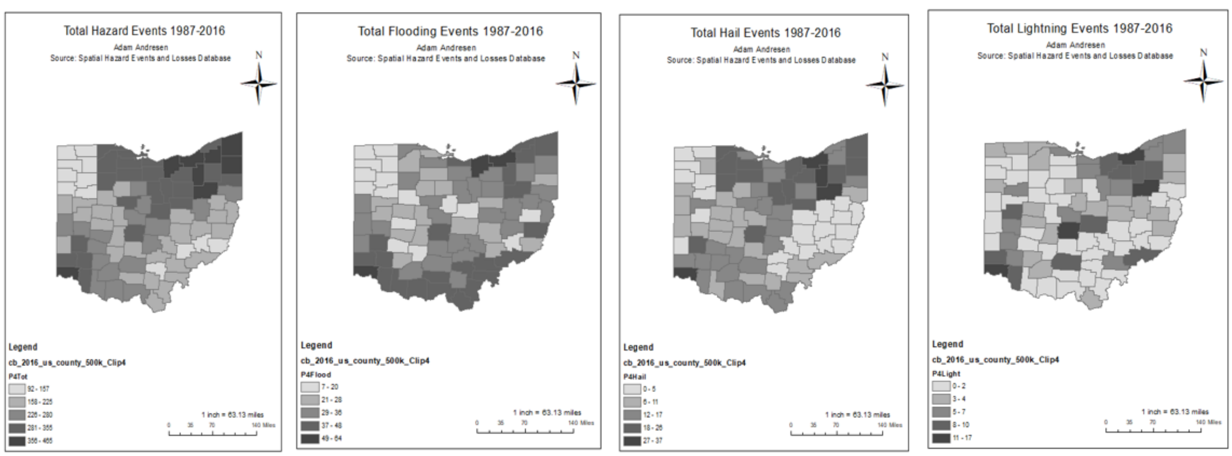
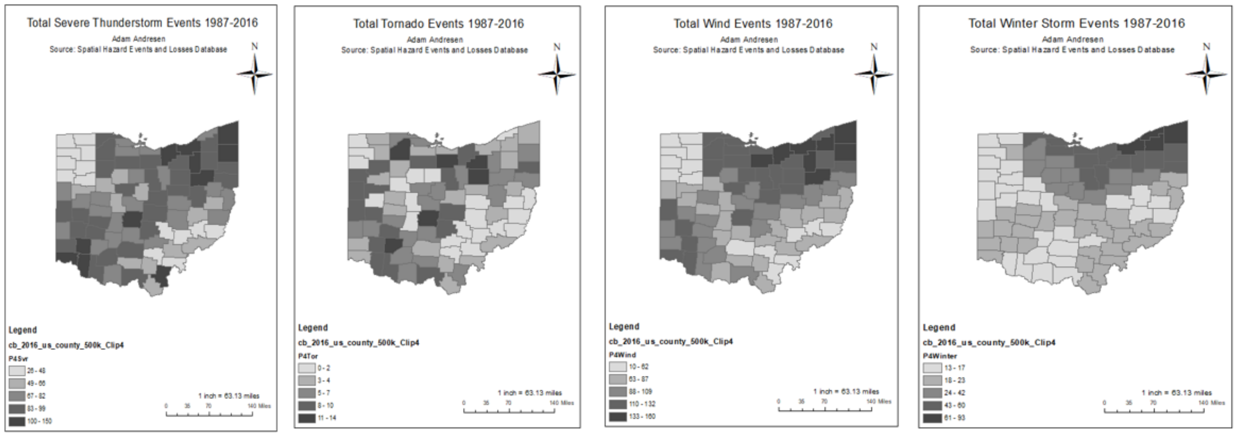


Figure 33. Breakdown of Ohio hazard occurrences from 1987-2016.



Figures 34-37. Total Ohio hazards, flooding, hail, and lightning occurrences from 1987-2016.

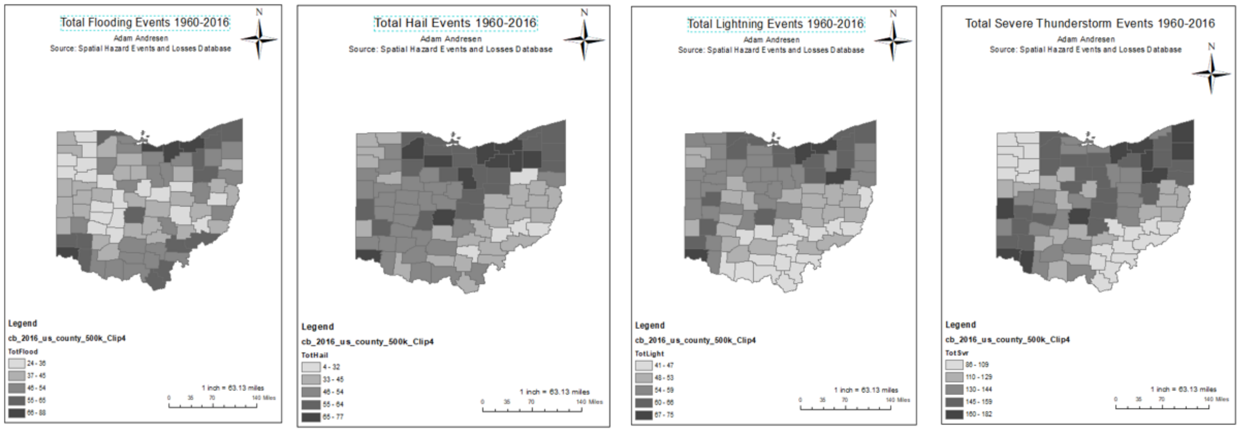


Figures 38-41. Total Ohio severe thunderstorm, tornado, damaging wind, and winter storm occurrences from 1987-2016.

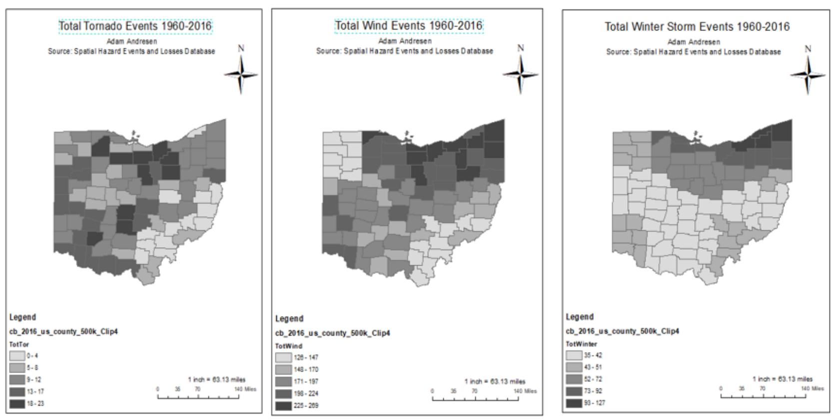
Since the figures are from a similar time period to that of the previous period of this study, a majority of the figures resemble each other to an extent, as was the case with Figures 34 (total hazards), 35 (Flooding), 36 (Hail), 37 (Lightning), 38 (Severe Thunderstorms), 39 (Tornadoes), and 40 (Damaging winds), and 41 (Winter storms). Figure 39, although similar to other maps previously shown, does show the same areas of high occurrences. Because of the random nature of the occurrences, a Moran's I test was once again completed for this period's tornado occurrences and was found to have a value of 0.284, meaning the distribution is random.

E.) Total Occurrences

Within this subsection, the total occurrences for each hazard are displayed and the total occurrences per county are displayed in Figures 42-48.



Figures 42-45. Total Ohio flooding, hail, lightning, and severe thunderstorm occurrences from 1960-2016.



Figures 46-48. Total tornado, damaging wind, and winter storm events from 1960-2016.

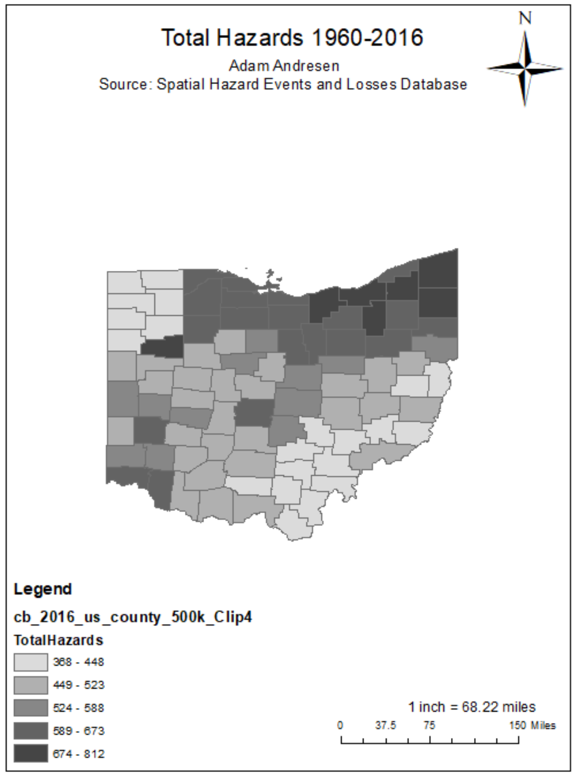


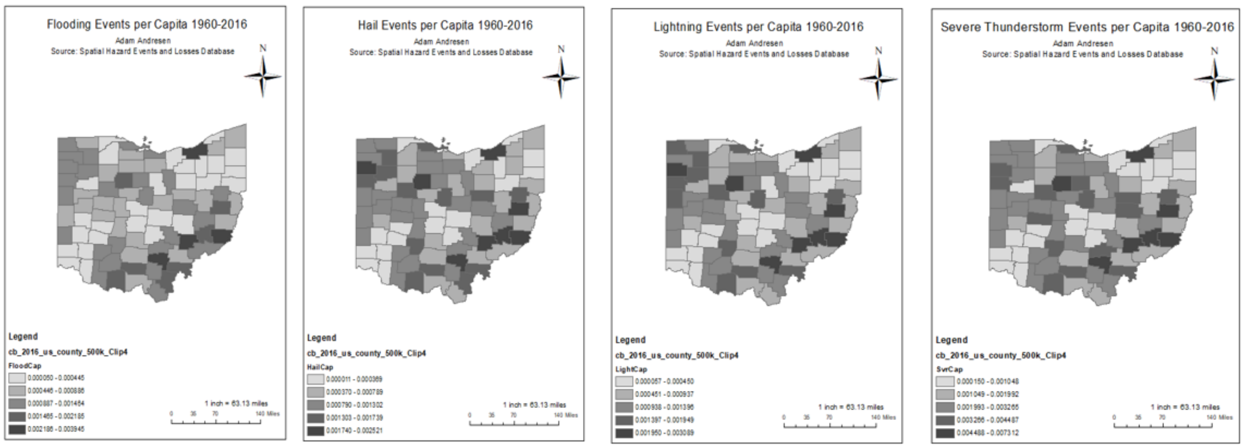
Figure 49. Total hazard occurrences from 1960-2016.

Based on the shade of gray that was assigned to each county, referring to Figure 49, a score was given to each county to help determine its vulnerability to hazards. This was one of two factors used when determining the overall vulnerability for each county.

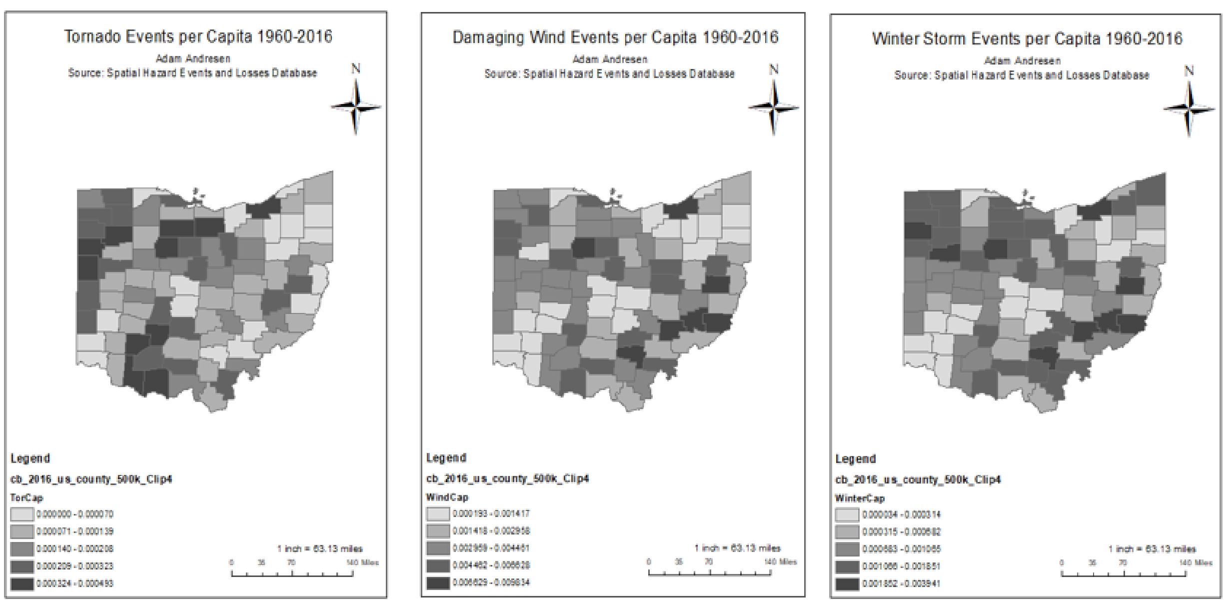
F.) Total Events per Capita

Data from the 2010 U.S. Census were used in examining the number of events that occurred for each county per capita. The population data would act as a weight for each county so the counties with higher populations and greater urban development would be equal to those that are mainly rural and have significantly lower populations.

This was done by computing the number of events and dividing it by the population, as of the current census. The spatial results are displayed in figures 50-56.



Figures 50-53. Ohio Flooding, hail, lightning, and severe thunderstorm events per capita from 1960-2016.



Figures 54-56. Ohio Tornado, damaging wind, and winter storm events per capita from 1960-2016.

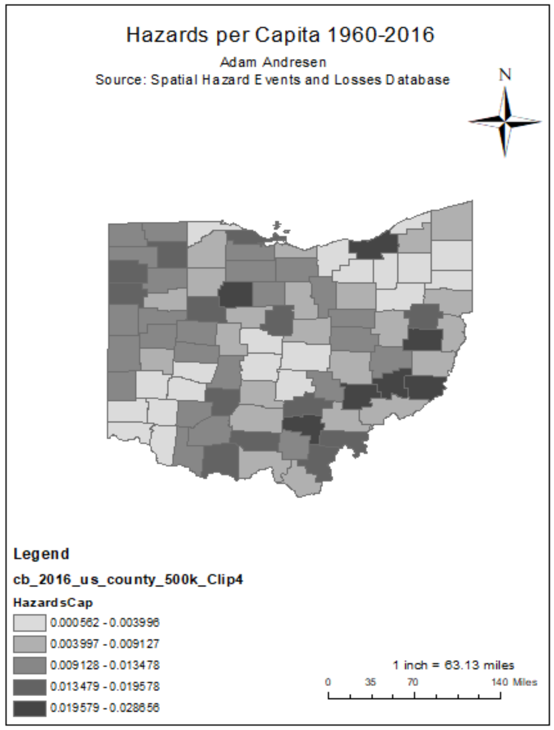


Figure 57. Total Ohio hazard events per capita from 1960-2016.

Again, the shading of gray assigned in Figure 57 contributes to the second part of the methodology. When examining this set of figures, all of the major metropolitan and urban areas of the state that usually had the highest frequencies of hazards are now at either the lowest or second lowest level. One county, Knox County, displayed the highest categories for all hazards and the total hazards per capita, but was never assigned to the highest category of occurrences for any hazard of any period.

G.) Fatalities

It is expected that a significant number of fatalities will occur because of hazards. But the main purpose of analyzing the number of fatalities that resulted from natural hazards is to examine what type of trend is being observed. Figure 58 depicts the number of fatalities per year as a result of natural hazards.

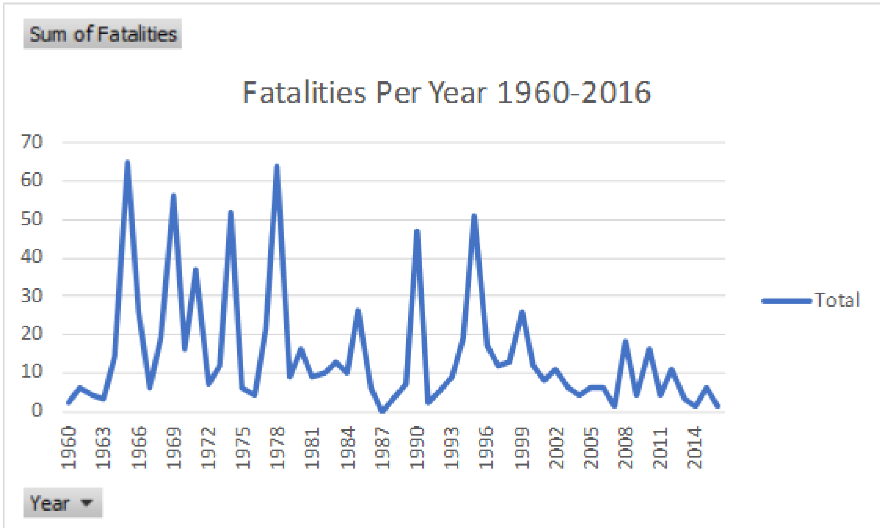


Figure 58. Trend of fatalities per year from 1960-2016 because of natural hazards and their impacts.

A decreasing trend can be observed as time progresses. There are a few possibilities as to why this may be so and will be mentioned in the Discussion section. In addition to the decreasing trend, the cyclical pattern also persists throughout the period of study, meaning that the number of years with anomalously high fatalities is low and the years with anomalously low numbers of fatalities is low, as well.

H.) Determining Vulnerability

Using the results determined in Figures 49 and 57, a vulnerability score from 2-10 was given to each county in the state. The score was calculated by sorting the data by greatest to least for each variable and assigning the values based on the values for each county. The findings are displayed below in Figure 59.

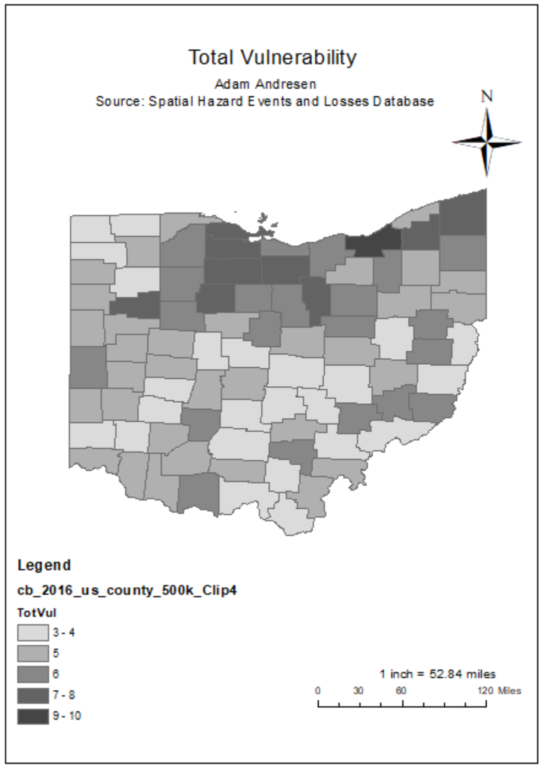


Figure 59. Total Ohio county vulnerability based on the methodology described for this study. A score of 2-3 means least vulnerable and 10 means most vulnerable.

Around a quarter of the counties were categorized as "least vulnerable," while only one county was designated "most vulnerable." Cuyahoga County was designated the most vulnerable county in Ohio due to the high number of hazard occurrences and the high value of hazards per capita. Cuyahoga County is where the city of Cleveland resides. Due to the distribution of the spatial context, another Moran's I test was completed to determine how close the data were to be perfectly random. After completing the test, the value was found to be 0.210, which is closer to perfect randomness than any of the tornado maps shown. This shows that no area shows the greatest vulnerability but may contain individual counties or communities that may exhibit high vulnerability.

V.) Discussion

A.) Hazards and trends

When examining the trends of hazards both spatially and temporally, the results were to be expected. However, there were a few anomalous results that need to be mentioned. From 1968-1972, there was a spike in the number of reports that occurred. The spike was the result of a bow echo/back-building MCS that occurred 4-5 July 1969, otherwise known as the Independence Day storm. Widespread damage was reported with flash flooding and was responsible for causing 41 fatalities across Michigan, Ohio, and Lake Erie (Corfidi, 2003).

Other significant weather events that took place during this time but did not seem to affect the results include: The 1974 Super Outbreak where an F5 tornado struck the town of Xenia, the Superstorm of 1993 that brought significant snowfall amounts to the eastern counties, several tropical cyclones and remnants of those systems from 2003-2005 which caused flooding in the eastern and southeastern counties, and the derecho that affected nearly the whole state in 2012. More details regarding the events were previously discussed in the beginning of the literature review, Section II.

B.) Hazards per Capita

Using Census data proved to be useful for this research. Not only were most of the major metropolitan areas less significant in terms of their vulnerability but using population data highlighted those areas that experience a greater number of hazards in less populated areas; this is shown within the winter storms per capita visual, Figure 55. When examining the occurrences throughout each thirty-year period, the northeastern counties experienced the most events in all four periods. However, when examining the number of events per capita, this statement is not valid.

After completing Moran's I tests for each hazard per capita and total hazards per capita, it was determined that all but one hazard, lightning, showed nearly perfect randomness in their distributions (values were all approximately near -0.003). This means that there are no trends for regions within the state to observe a particular hazard. Therefore, all counties must be prepared for any of the seven hazards examined as they are unpredictable with regards to their spatial occurrence, based on the results herein.

The findings of the flooding events and events per capita corroborate Hardy (2017) in terms of their findings with environmental and social vulnerability. Hardy examined vulnerabilities at the community level, but this research provides a secondary alert for city planners and emergency managers that Cleveland is a highly vulnerable city and precautions must be taken to reduce the risks associated with natural hazards. Additionally, further investigation into the social vulnerabilities within and around the city will further enhance the mitigation and preparedness processes (Hardy 2017).

C.) Vulnerability Index

The vulnerability index created serves as a guide to emergency managers and planners, so they may be able to better prepare their respective areas for future hazards, similar to that of Berke et al. (2015). This index can also serve as the start of a conversation on how plans can be improved, what partnerships should be established, and what resources are necessary to have an effective response to any disaster. As previously mentioned, Cuyahoga County is the most vulnerable county, receiving the highest score possible (10), followed by Ottawa County receiving a score of 8, and Wyandot, Ashland, Huron, Seneca, Sandusky, Allen, Geauga, and Ashtabula counties receiving scores of 7. Although many counties received lower scores of 3 and 4, planning for hazards should not be ignored or delayed. This should remain a priority as these events are still possible and have the chance to have more intense impacts as a result.

By doing this research, the first step identified in Regmi et al. (2013) is completed. This first step was to understand the major hazards associated with an area and to evaluate the hazards in terms of their likelihood that a problem may occur and the damages that could arise. Prioritizing hazards based on the records of the historical events, impacts of the most recent events, current scientific knowledge, and the sensing of the environmental changes is another method of identifying the major hazards in an area. This was also completed in this research. The next step, as described previously, is to develop the appropriate approach to hazard mitigation, and to be prepared for emergency situations (Regmi et al., 2013).

D.) Statistical tests

To determine the significance of the findings herein, each map that had a Moran's I test completed had the p-value calculated to determine the statistical significance of the finding. The null hypothesis in this case was that the data had a greater clustering than spatial randomness associated with the data, Moran's I test value was greater than or equal to 0.5. These findings are listed in Table 1.

Table 1. Maps that were examined for spatial randomness, their Moran's I test value, and the p-value associated with the finding.

Map	Moran's	p-value
Total Vulnerability	0.21914	0.00660
Total Winter Storms	0.09504	0.04950
Total Damaging Winds	0.65681	0
Total Tornadoes	0.38968	<0.00001
Total Severe Thunderstorms	0.57640	0
Total Lightning	0.55168	0
Total Hail	0.50082	0
Total Flooding	0.40644	<0.00001
Total Hazards	0.56021	0
P1 tornadoes	0.36742	0.00001
P2 tornadoes	0.37225	<0.00001
P3 tornadoes	0.25960	0.00162
P4 tornadoes	0.28423	0.00059
Flooding per capita	0.25638	0.00136
Hail per capita	0.15945	0.04672
Lightning per capita	0.21872	0.00710
Severe Thunderstorm per capita	0.18746	0.01997
Tornado per capita	0.22373	0.00612
Damaging Winds per capita	0.16931	0.03460
Winter Storms per capita	0.13215	0.08986
Total hazards per capita	0.17939	0.02564

It was found that 95.24% of the maps tested for spatial randomness showed statistical significance at $p<0.05$. At the $p<0.01$ significance, 71.43% of maps showed statistical significance. At the $p<0.001$ significance, 47.62% of the maps showed statistical significance. In most cases, especially the $p<0.05$ and the $p<0.01$ values, the null hypothesis was rejected. The findings presented tells us that there is no spatial clustering of this data. Therefore, there are no regions within the state of Ohio that are more prone to one specific hazard over another.

VI.) Conclusions

As the cost of damages increases because of natural hazards, it is imperative that the necessary precautions are taken to reduce the amount of damages caused by hazards. This issue all originates with the issue of the lack of a definition of vulnerability. Although several definitions have been proposed throughout the literature, some have been mentioned in the literature review of this paper; the definitions mentioned all encompass different areas involving vulnerability and therefore must be re-examined to further study vulnerability in the future. A concise definition of vulnerability should mention the risks associated with the hazard, the perceptions the local population may have regarding a hazard, the amount of damages possible with a given hazard, and how the intensity or frequency of a hazard deviates from the normal impacts.

As stated in the Discussion section, the results of the Moran's I test show that there is little distribution of the data and that this finding was significant at the $p<0.05$ level. Therefore, all counties within the state of Ohio should be prepared for any hazard mentioned herein. Lack of preparation could lead to devastating results and possibly more injuries and fatalities as a result. Therefore, understanding the impacts and possible scenarios that may arise from each hazard is important throughout the mitigation, preparedness, and recovery stage of the emergency management cycle.

The research presented herein may serve as a foundation for future research in regard to creating a new vulnerability method by combining historical data and demographic data. Additional research must be completed to determine what demographics enhance vulnerabilities and reduce vulnerabilities. With this additional research, it might be possible to create a model, via mapping software, to determine vulnerability using other data available. In addition, should this research be repeated in other states, the results will also prove to be prudent to those associated with emergency management and planning. Then, communities that are vulnerable to certain hazards can mitigate the effects of the specific hazards, prepare for the event, respond in an efficient manner, and recover from the event and learn from the mistakes that were made so they are not repeated in the future.

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