Applying Geographic Information System (GIS) for Analyzing Changes in Tornado Intensity in Minnesota Using 1970 to 2010 Tornado Data

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Keywords: Geographic Information System (GIS), Fujita Scale (F-Scale), Enhanced Fujita Scale, Old Fujita Scale, Tornadoes, Linear regression, Slope, Hot Spot Analysis (Getis-Ord Gi*), Regression Analysis, Coefficient of Determination (R^2)

Abstract

Tornadoes have caused human and property damage in Minnesota. Geographic Information System (GIS) can be an important tool for understanding and analyzing the intensity of tornadoes. Using tornado data from 1970 to 2010, this study explored if tornado intensity has changed in Minnesota and if change in tornado intensity was related to population characteristics. Linear regression was used to analyze relationships and the Esri ArcGIS Hot Spot Analysis (Getis-Ord Gi*) tool was utilized to analyze and locate hot spots of change. To understand if there was a relationship between land cover and tornado intensity, the counties of Minnesota were classified as Forested, Agricultural or Twin Cities Metropolitan.

Introduction

This study analyzed change in tornado intensity in Minnesota and analyzed the correlation between change in tornado intensity and population. The hypothesis was that a correlation between population and change in tornado intensity occurred, partly because in populated areas more people are available to spot tornadoes.

Minnesota led the nation in 2010 with a total number of 122 tornadoes by August (Huttner, 2010). This included a series of tornadoes which tore through Wadena, Minnesota on Thursday, June 17. These tornadoes killed at least three people, injured dozens, flatted homes and toppled power lines (AOL News, 2010). In southern Minnesota's Freeborn County, a series of tornadoes hit 40 to 60 rural properties and killed one person at a farm west of Albert Lea (AOL News, 2010).

Fujita Scale

Tornado intensity is measured by the damage it causes. Tetsuya Theodore Fujita developed the Fujita Tornado Intensity Scale for this purpose (Rosenberg, 2011). In 2007, an enhanced Fujita scale was introduced. In the original and enhanced scales, tornadoes are rated using a six-step scale of 0-5 (Table 1, Figure 1) (Oswald, 2008).

The original Fujita scale has a number of weaknesses that may have led to inaccurate measurements of tornado wind speed. Some of the other disadvantages of the old Fujita scale include “lack of damage indicators, no account for construction quality and variability and no definitive correlation between damage and wind speed” (48 News, 2011).

The new improved Fujita scale is not perfect. However, this enhanced

Dinku, Addisu. 2012. Applying Geographic Information System (GIS) for Analyzing Changes in Tornado Intensity in Minnesota Using 1970 to 2010 Tornado Data. Volume 14, Papers in Resource Analysis. 11 pp. Saint Mary’s University of Minnesota Central Services Press. Winona, MN. Retrieved (date) from http://www.gis.smumn.edu

version is more precise in the way it measures wind speed and this precision in measurement provides researchers more data points on the ‘degrees of damage’ (Oswald, 2008).

According to Rosenberg (2011), although the Fujita scale has been proven to be a reliable measurement of the strength of a tornado, it is not without its flaws. The main issue is that it can only be used after the tornado has occurred.

The Fujita scale uses damage to measure the intensity of the tornado so in an area with little or no infrastructure, the Fujita scale cannot be used (Rosenberg, 2011). Also, according to ThinkQuest (n.d.), the major weakness of the Fujita scale is “it is based on the damage a tornado does and not on the wind speed of a tornado.” Despite the disadvantages, the Fujita scale is still in use because nothing better exists (ThinkQuest, n.d.).

Table1. Enhanced Fujita scale and original Fujita scale ratings and associated wind speed (Weather Underground, 2012).

Enhanced Fujita Scale	Old Fujita scale
EF-0 (65-85 mph)	F0 (65-73 mph)
EF-1 (86-110 mph)	F1 (73-112 mph)
EF-2 (111-135 mph)	F2 (113-157 mph)
EF-3 (136-165 mph)	F3 (158-206 mph)
EF-4 (166-200 mph)	F4 (207-260 mph)
EF-5 (>200 mph)	F5 (261-318 mph)
EF No rating	F6-F12 (319 mph to speed of sound)

Location of Tornado Occurrences

According to Fujita (n.d.), agricultural areas are where the majority of tornadoes occur as moisture levels and temperatures found in agricultural areas are suitable for the formation of tornadoes (Fujita, n.d.). However, tornadoes can also occur in urban areas. For example, a tornado hit just south of downtown Minneapolis on Wednesday, August 19, 2009 and caused property damage on Portland Ave S and at the Minneapolis Convention Center (MyFoxTwinCities, 2009).

Figure 1. The figure illustrates the Enhanced Fujita Scale with an example of damage (Weather Underground, 2012).

When do Tornadoes Occur

For all years over time in Minnesta three-fourths of all tornadoes occurred in the months of May (15%), June (37%), and July (25%) (Minnesota Climatology Working Group, 2010). Tornadoes can occur any time; however, late spring and early summer, between 2PM and 9PM is the most dangerous period (Minnesota Climatology Working Group, 2010).The instability associated with spring and summer warming feeds thunderstorm which can culminate in tornadoes (Minnesota Climatology Working Group).

Managing Tornado Disasters

Identifying locations where tornado intensity is changing could improve allocation of resources used to mitigate tornado damage. Improved building standards for new construction and land use planning are actions communities could undertake to avoid or reduce damages (Yamaguchi, 2005). For example, the design and construction of different types of structures including more stringent building codes can help (Yamaguchi, 2005). Land use maps, zoning maps, structure inventories, building code details and structure valuations are some GIS data layers that could enable community officials to inform the public and enact appropriate regulations (Yamaguchi, 2005).

Tornado Reporting

According to Sky-Fire.tv (1997), the argument that cities attract more tornadoes than rural areas is biased upon the fact that most tornado data are coming from highly populated areas. Two of the reasons for this might be that in highly populated areas there are more people to spot tornadoes and, unlike rural areas, there are more structures to be hit (Sky-Fire.tv, 1997).

Stanga (2009), who studied "The Effects of Population and Storm Reports in Minnesota from 1985-2005" determined that highly populated areas have more reports of tornadoes. According to Masters (2008) and Wurman (2010), there is a correlation between population growth and an increase in tornado reporting but Wurman (2010) also adds technological advances as a factor that plays a role in more tornadoes being reported.

Methods

Software Used

The software programs used for the research were Esri ArcMap10 and Microsoft Office Excel 2007.

Tornadoes Data

Tornado data were obtained from Tornado History Project (Lietz, 2012), and the data used for the research covers the years 1970 to 2010. The tornado data variables analyzed were Fujita Scale (F-Scale) values by county and year.

Based on information found on the Tornado History Project website, the original Fujita scale was used prior to 2007 and the enhanced Fujita scale was used since.

The original tornado data from the Tornado History Project (Lietz, 2012) included additional information such as injuries and deaths; however, the variable nature of injuries and deaths due to tornadoes deemed these variables too difficult to use to determine trend over time. Instead the F-Scale was chosen for the study as the variable that shows change in severity over time. Tornado data were organized using an Excel spreadsheet and separate tables was created for each county in Minnesota (Table 2).

Table 2. Tornado data and the population data organized in an Excel spreadsheet using the example of Douglas County.

Date	Year	F-Scale	Population
June 19	1971	0	23, 146
May 11	1985	0	28, 606
July 17	1991	1	28, 674

Population Data

The population data for each year from 1970 to 2010 for each county were obtained from the US Census Bureau. This information was added to each county's tornado data table.

Regression Analysis

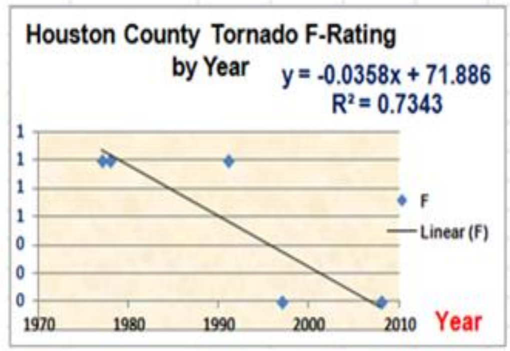
Linear regression was used for this project. Linear regression uses a straight line to model the relationship between two variables (ReliaSoft, 2008). The equation of a linear regression line is Y = a + bX, where "a" is the intercept, "b" is the slope, 'X' is the independent variable, and 'Y' is the dependent variable (Yale University, 1997).

The slope shows the direction and size of the trend. A positive slope indicates that the F-Scale of tornadoes in that county has generally been increasing over time. A negative slope indicates that the F-Scale of tornadoes has been decreasing over time. The further the slope number moves away from 0, the steeper the slope and the more substantial the change.

For a relationship between two variables (x, y), "if the observed data perfectly match the model y = ax + b, then the coefficient of determination $R^2 = 1.00$" (Boslaugh and Watters, 2008). According to McCune (2010), "Nevertheless, the existence of a recognizable correlation between two variables does not imply a causative relationship between the variables. The correlation might be a reflection of outside variables that affect both variables under study."

In this study, linear regression was performed using an Excel spreadsheet to analyze the relationship between the following variables for each county: 1) Year of tornado occurrence vs. F-Scale, and 2) Population vs. F-Scale (Figure 2). Tables with the resulting R-Squared and slope values were imported into ArcMap and mapped using a shapefile of Minnesota counties (Table 3) (Esri, n.d.).

Counties with less than 5 tornado occurrences were excluded from the research; these counties include Cook, Kanabec, Lac Qui Parle, Le Sueur, Lincoln, Mahnomen, Red Lake and Wabasha. In the resulting figures, these appear as having no data.



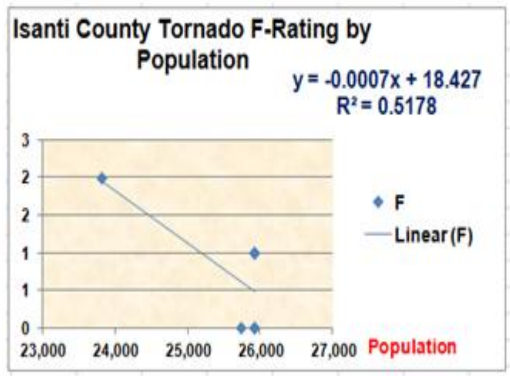


Figure 2. Sample linear regression analysis for Houston and Isanti County using an Excel spreadsheet.

Table 3. The slope and the R-Squared values were organized as follows to allow for use in ArcMap. This sample data is for F-Scale vs. Year. This table represents only an excerpt of the data.

County	Slope	R-Squared
Aitkin	-0.0177	0.0572
Anoka	-0.032	0.063
Becker	-0.002	0.004

Hot Spot Anaysis (Getis-Ord Gi)*

Are there clusters of counties where tornado intensity has increased over time in Minnesota? To answer this question the ArcGIS Hot Spot Analysis (Getis-Ord Gi*) tool was utilized. According to Esri (2010), "The Hot Spot Analysis tool calculates the Getis-Ord Gi* statistic for each feature in a dataset and it works by looking at each feature within the context of neighboring features." The Z-scores and the p-values are two outputs of Hot Spot Analysis that help to locate high and low value clusters spatially (Esri, 2010).

If a feature has a high value does it automatically mean that it is a statically significant hot spot? According to Esri (2010), a feature needs to have a high value and be surrounded by other features with high values to be qualified as a statistically significant hot spot.

According to Esri (2010), the Z-score is the returned value of the Gi* statistic for each feature in the dataset. A positive and larger Z-score indicates a more intense clustering of high values (hot spot), and a negative and smaller Z-score indicates a more intense clustering of low values (cold spot) (Esri, 2010).

Figure 3 shows the Hot Spot Analysis input field interface used to specify parameters needed to run the Hot Spot Analysis. The input feature class was the feature class for which the General G statistic was calculated; the Minnesota county shapefile was used for this purpose. For the input field, the R-Squared and slope values of F-Scale vs. Year and F-Scale vs. Population plots were analyzed, one at a time.

For the Conceptualization input, POLYGON_CONTIGUITY (FIRST_ORDER) was selected. With this method only neighboring polygon features that share a boundary influenced computations for the target polygon feature (Esri, 2010). This method was used because compare to the other options it provided a better result of the Hot Spot Analysis. When running the Hot Spot Analysis, one can expect a cluster of counties with a positive slope to have a greater positive change in tornado intensity and a cluster of counties with a negative slope to have a greater negative change in tornado intensity.

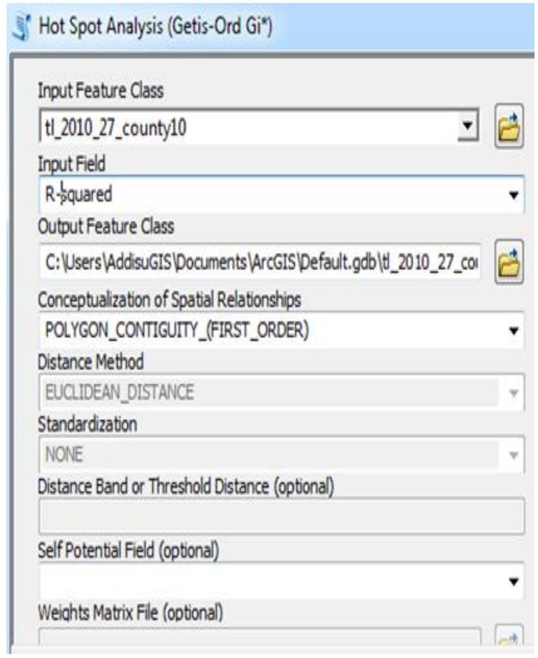


Figure 3. The Hot Spot Analysis tool interface.

Land Cover Data

To analyze the relationship between land cover and change in tornado intensity in Minnesota, the state of Minnesota was divided into Agricultural, Forested, and Twin Cities Metropolitan areas. A map from the Minnesota Geospatial Information Office (n.d.) was used to classify Minnesota counties (Figure 4); however, this map did not identify land cover for Beltrami, Clearwater, and Olmsted counties. The land cover information found for Beltrami and Clearwater Counties indicated that Beltrami and Clearwater counties could be considered Forested areas. Olmsted County was considered an agricultural area.

Roseau and Morrison counties fell into both the state forest and agricultural classifications. As Figure 4 depicts, the state forest part of the two counties are very minor, so for the sake of simplicity, Roseau and Morrison counties were categorized as agricultural areas.

Figure 4. Minnesota Land Use Data Sets map used to classify Minnesota counties based on change to land use (Minnesota Geospatial Information Office, n.d.).

Results

Figure 5 displays the correlation between year and tornado intensity. R-Squared values range from 0 to 0.85.

Figure 6 depicts change in tornado intensity in Minnesota counties (slope of Year vs. F-Scale linear regression model). The majority of counties were found to have a negative slope, indicating a trend towards less intense tornadoes; however all slope values in general were small indicating little change.

Figure 7 shows results of the Hot Spot Analysis identifying areas where the correlation between year and tornado intensity were the strongest (red) and weakest (blue).

Figure 8 depicts the results of the Hot Spot Analysis using the slope of the year vs. F-Scale linear regression model. Areas of greater positive change in tornado intensity appear red while areas of greater negative change in intensity appear light blue.

Figure 9 displays the correlation between population and tornado intensity. R-Squared values range from 0 to 0.81 again illustrating a high variability in results.

Figure 10 depicts population influence on change in tornado intensity in Minnesota counties (slope of Population vs. F-Scale linear regression model). The majority of counties were found to have a negative slope indicating a trend towards less intense tornadoes; however, slope values were overall quite small indicating little change.

Figure 11 shows results of the Hot Spot Analysis identifying areas where the correlation between population and tornado intensity were the strongest (red) and weakest (yellow).

Figure 12 depicts the results of the Hot Spot Analysis using the slope of the Population vs. F-Scale linear regression model. Areas of greater positive change in tornado intensity as population increases appear in red, while areas of greater negative change in tornado intensity appear in yellow.

Table 4 and Table 5 show the correlation between tornado intensity and land cover is weak. Agricultural and Forested land covers have a negative slope indicating a trend towards less intense tornadoes, but Metro land cover had a positive slope. However, slope values were overall quite small indicating little change in tornado intensity regardless of land cover.

Table 4. The table summarizes the relationship between tornado intensity and land cover using the R-Squared and slope values of the F-Scale vs. Year analysis.

	Agricultural	**Forested**	**Metro**
R-Squared	0.0153	0.0288	0.001
Slope	-0.00005	-0.0116	0.0005

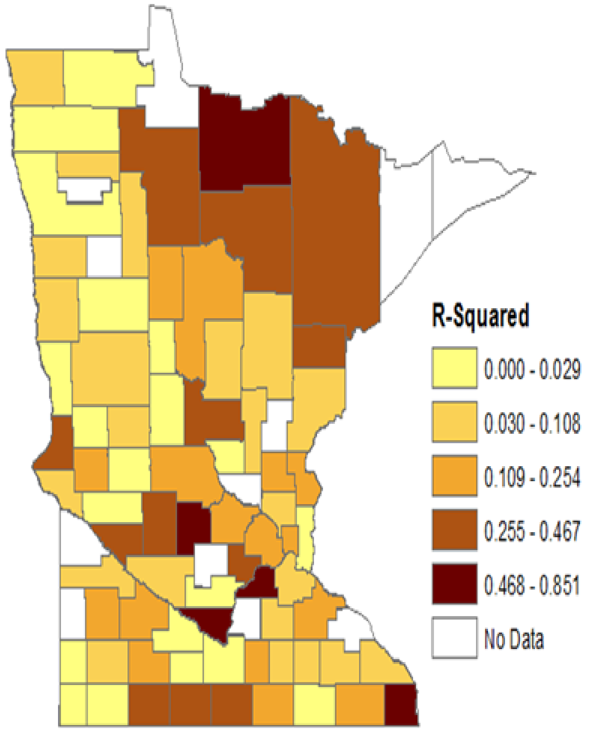


Figure 5. R-Squared value of the F-Scale vs. Year plot.

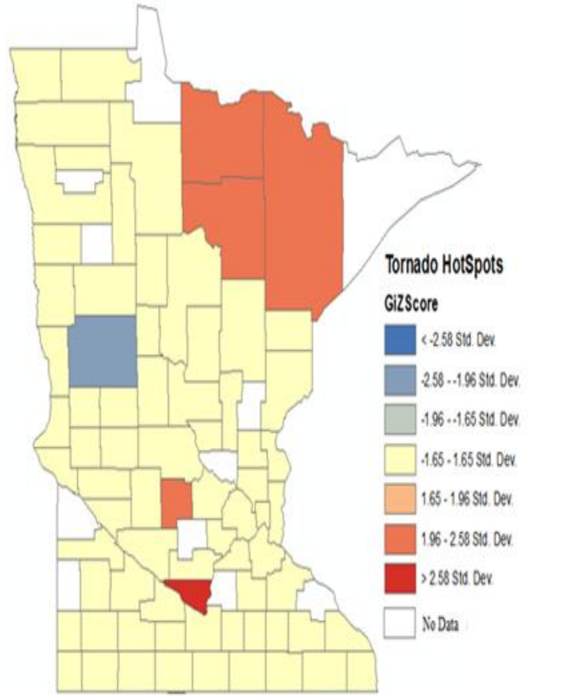


Figure 7. County-based Minnesota map with Hot Spot Areas of correlation using the R-Squared value of the F-Scale vs. Year plot.

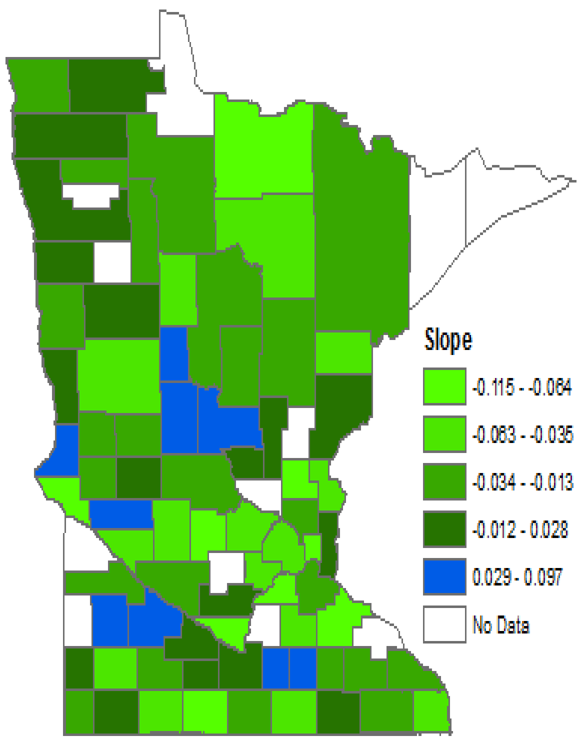


Figure 6. Slope values of the F-Scale vs. Year plot. Green shows a negative slope and blue shows a positive slope.

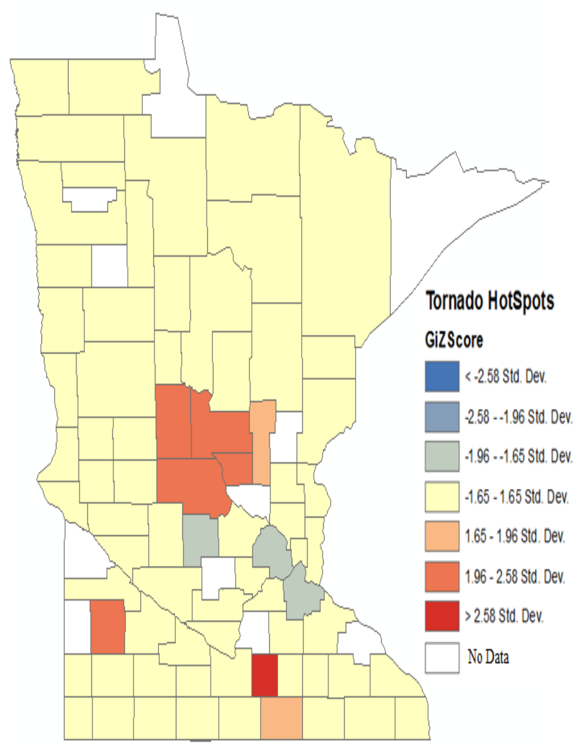


Figure 8. County-based Minnesota map with Hot Spot areas of tornado intensity change using slope.

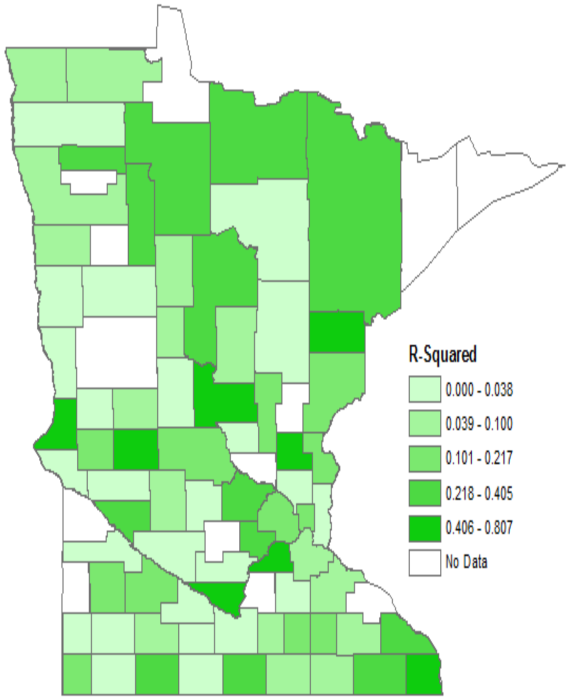


Figure 9. R-Squared value of the F-Scale vs. Population plot.

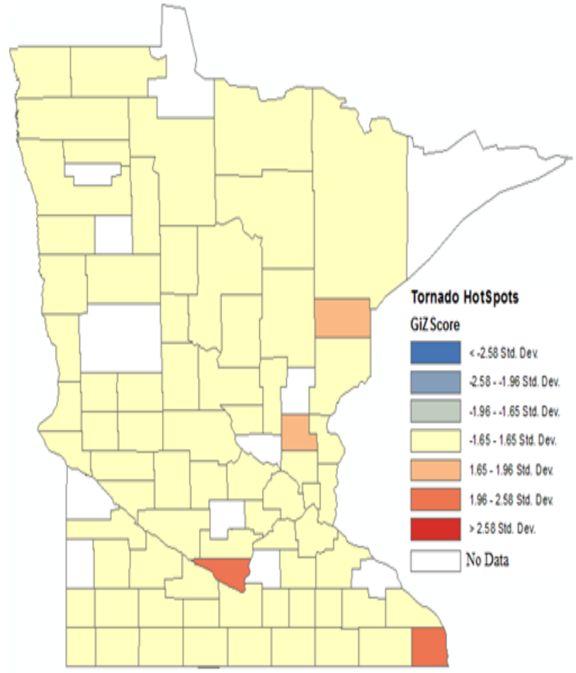


Figure 11. Hot Spot Analysis of tornado intensity in Minnesota by using the R-Squared value of the F-Scale vs. Population plot.

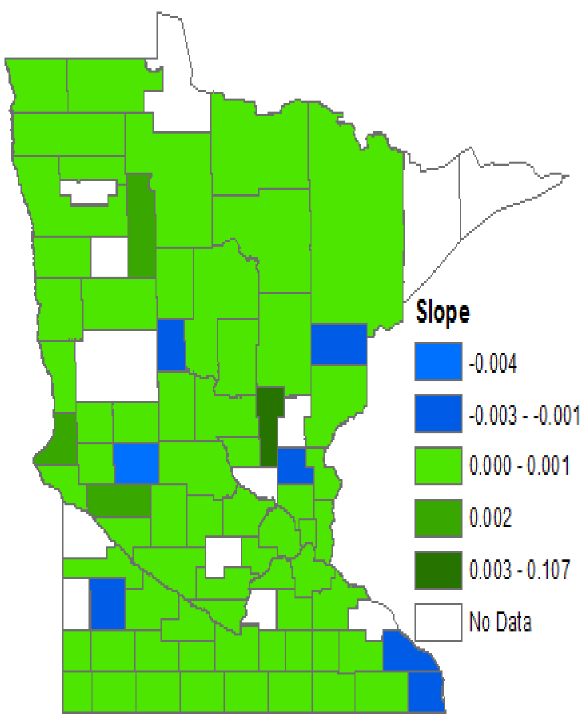


Figure 10. Slope value of the F-Scale vs. Population plot. Green shows a positive slope, and Blue shows a negative slope.

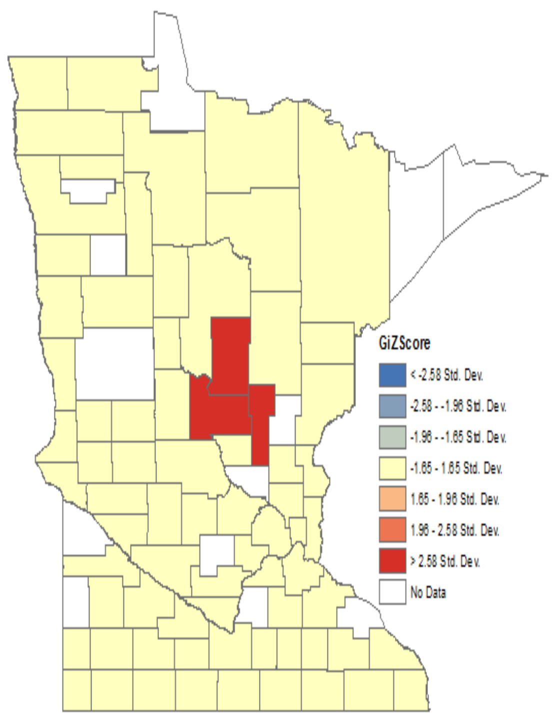


Figure 12. Hot Spot Analysis using the slope value of the F-Scale vs. Population plot.

Table 5. The table summarizes the relationship between tornado intensity and land cover for the F-Scale vs. Population variables.

	Agricultural	Forested	Metro
R-Squared	0.0006	0.0107	0.0251
Slope	-0.000001	-0.000002	0.00001

The average F-Scale was calculated for the three different land cover areas by adding the total F-Scale values for each land cover and dividing it by the total number of tornadoes. The result shows Agricultural areas have an average F-Scale value of 0.70, Forested areas have an average F-Scale value of 0.72 and Twin Cities Metro Areas have an average F-Scale value of 0.093.

Discussions

Figure 6 and Figure 7 show tornado intensity has increased in counties such as Koochiching, Itasca, St. Louis, Nicollet, Waseca, Lyon, Stearns, Benton, Todd, Morrison, Freeborn Counties. Counties such as Otter Tail and Morrison depict a decrease in tornado intensity.

Figure 10 and Figure 11 show Hot Spot areas of change in tornado intensities are in the counties of Houston, Nicollet, Isanti, Carlton, Aitkin, Crow Wing, Morrison, Benton, and Mille Lacs. All these counties except Houston County show an increase in population. However, other counties that are not shown in Figure 10 and Figure 11 as possible Hot Spot areas also show an increase in population.

Limitations

In the United States, population counts are decennial, so population values for each year in between census years are estimates. This could be one limitation of this study.

The method used for the study was use of theArcGIS Hot Spot Analysis tool and Linear Regression. Applying other methods of analysis might produce different results.

The research covers only 1970 to 2010 tornado data and changes in tornado detection over time might influence the results of this study. For example, if advances in weather radar or more spotters are able to detect more small F-0 tornadoes, this could skew the results towards showing a decreasing trend in tornado intensity.

Future Studies

It would be interesting to study tornado intensity in Minnesota by including pre-1970 and post 2010 tornado data. It might also be beneficial to analyze change in tornado intensity by dividing the state by eco-region or by using a different land cover classification.

Conclusion

The finding of the research is by no means a conclusive one, but it can be a good starting point. Understanding changes in tornado intensity and the relationship to population helps to manage tornado disasters and GIS can be a great tool for analysis.

Acknowledgments

I would like thank the following Saint Mary’s University Department Resources Analysis faculty and staff for creating a positive learning environment: Ms. Greta Bernatz, Dr. David McConville, Mr. John Ebert, and Mr. Patrick Thorsell. Also, I would like to thank my families and my friends for their support.

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