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SPATIAL ANALYSIS OF TORNADOES IN THE US

Shishir Kumar Das[1], Mohammad Moniruzzaman[2], Eshmi Rai[3] Mosharef Hossain[4]

[1]*Graduate Assistant, Department of Environmental science; Southeast Missouri State University, Cape Girardeau, MO, USA*
Email: shishir.semo@gmail.com

[2]*Master in Development Studies; Dhaka University, Dhaka, Bangladesh*
Email: monirnstu0321@gmail.com

[3]*Environmental Science, Department of Biology; Southeast Missouri State University; Cape Girardeau, USA*
Email: esmiraee01@gmail.com

[4] *Master of Environmental Science; Southeast Missouri State University, USA*
Email: mosharefhossain379@gmail.com

ABSTRACT

Tornadoes are among the most devastating meteorological hazards, causing significant destruction and losses each year across the United States. This study aims to identify the regions and states that are particularly vulnerable to tornado threats, while also providing deeper insights into the geographic patterns that influence tornado activity. By leveraging geoprocessing tools, historical data was analyzed to visualize various aspects, including tornado density, seasonality, and the regions most impacted in terms of fatalities, injuries, and property damage. The analysis reveals that certain states, notably Texas, Alabama, and Oklahoma, emerge as hotspots with heightened exposure to tornado risks. Texas, in particular, stands out due to its high frequency of tornado occurrences and substantial property losses, underscoring its vulnerability. Additionally, the study highlights that these states experience significant variations in tornado activity, which are often influenced by seasonal patterns. The findings contribute to a more comprehensive understanding of tornado distribution, enabling better risk assessment and potentially informing more effective disaster preparedness strategies to mitigate future impacts in these high-risk areas.

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Corresponding Author:

Shishir Kumar Das

Graduate Assistant, Department of Environmental science; Southeast Missouri State University, Cape Girardeau, MO, USA

email: shishir.semo@gmail.com

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Tornado Risk Analysis, Spatial Analysis, Geoprocessing Tools, Disaster Preparedness, Tornado Impact on Infrastructure

1 Introduction

Tornadoes are among the most destructive meteorological events in the United States, posing significant threats to life, property, and infrastructure (Ashley et al., 2014). These hazards not only lead to loss of human lives but also inflict severe economic damages on communities. Historical records reveal that tornadoes have caused billions of dollars in property damage annually, emphasizing the critical need for in-depth studies to better understand and mitigate these risks (Brooks & Doswell, 2001). According to the National Oceanic and Atmospheric Administration (NOAA, 2021), the United States experiences more tornadoes than any other country, with an average of over 1,200 tornadoes reported each year. These events are particularly concentrated in the central and southeastern parts of the country, where unique climatic conditions often converge to create ideal environments for tornado formation. The increasing frequency and intensity of tornadoes in recent years call for an urgent need to re-evaluate high-risk areas to support disaster preparedness and resilience efforts (Coleman et al., 2024). The primary focus of this study is to identify regions in the United States that are historically prone to tornado activity by analyzing tornado frequency, intensity, and distribution patterns. Existing literature highlights that tornado occurrences are not uniformly distributed across the nation; instead, they follow specific geographic and seasonal trends (Corey & Senkbeil, 2023; Cusack, 2014). Previous studies have identified Texas, Alabama, and Oklahoma as particularly vulnerable states, where tornadoes have historically caused significant destruction (Corey et al., 2024). Leveraging historical tornado data from 1950 to 2022, this project utilizes geospatial analysis to investigate the density and distribution of tornadoes. By mapping tornado hotspots, this research seeks to provide a clearer understanding of the underlying factors contributing to tornado risk in different regions, which can inform targeted mitigation strategies.

Geoprocessing tools play a critical role in examining historical data and visualizing spatial patterns related to tornado activity. For instance, spatial analysis methods such as kernel density estimation and hotspot analysis have been used in previous studies to identify tornado-prone zones (Dixon et al., 2011; Foglietti et al., 2020). By applying these techniques, this study identifies high-risk areas where tornadoes are most likely to occur, providing valuable insights for disaster management agencies (Badhon et al., 2023; Istiak & Hwang, 2024). The utilization of Geographic Information System (GIS) tools not only enhances the precision of risk assessments but also helps in visualizing infrastructure vulnerabilities, particularly in areas intersected by major highways and interstates. Such mapping is essential as infrastructure disruptions due to tornadoes can have cascading effects on emergency response and recovery efforts (Farney & Dixon, 2014; Frazier et al., 2019; Fricker & Friesenhahn, 2022). Another dimension explored in this study is the seasonality of tornado occurrences. Research indicates that tornado activity tends to peak during specific months, particularly in the late spring and early summer (Fuhrmann et al., 2014; Kelnosky et al., 2018; Markert et al., 2019). Understanding these seasonal trends is crucial for enhancing preparedness efforts and reducing the impact of tornadoes on communities. Historical data suggests that while tornadoes can occur throughout the year, there are pronounced peaks in the central and southeastern regions during May and June (Long et al., 2018). By analyzing these seasonal patterns, this research aims to improve forecasting models, thereby allowing communities and policymakers to implement more effective disaster preparedness strategies(Istiak et al., 2023; Saika et al., 2024; Uddin et al., 2024). Furthermore, this study extends its analysis to assess the impact of tornadoes on critical infrastructure such as highways and interstates. Previous studies have documented that tornadoes can cause extensive damage to transportation networks, disrupting the movement of goods and emergency services (Fan & Pang, 2019; Foglietti et al., 2020; Fuhrmann et al., 2014). The research includes maps that illustrate how tornadoes have historically affected these vital infrastructures, highlighting areas where future interventions may be necessary. By visually communicating the spatial distribution of tornado risks, the findings emphasize the need for proactive measures to protect vulnerable communities. This research aligns with the growing body of literature emphasizing the importance of integrating geospatial analysis with disaster risk reduction strategies (Farney & Dixon, 2014).

2 Literature Review

The United States experiences a wide range of natural hazards, including meteorological, hydrological, and geophysical events. Among these, tornadoes are particularly severe, often causing extensive property damage, significant injuries, and substantial economic losses (Anderson et al., 2022; Ashley et al., 2014; Daneshvaran & Morden, 2007). According to research, tornadoes are responsible for some of the most devastating natural disasters in the country, with effects that ripple across various demographic and socioeconomic groups (Foglietti et al., 2020; Kelnosky et al., 2018; Senkbeil et al., 2022). The frequency and intensity of tornadoes in recent years highlight the need for a deeper understanding of their impact on communities, especially as climate change appears to exacerbate weather extremes (Farney & Dixon, 2014; Long et al., 2018). The complex nature of tornadoes and their unpredictable behavior make them a significant challenge for disaster preparedness and mitigation efforts (Hatzis et al., 2018).

A tornado is scientifically defined as a violently rotating column of air that extends from a thunderstorm to the ground, typically associated with a funnel cloud and sometimes producing a loud, roaring noise (NOAA, 2014). Tornadoes are among the most destructive atmospheric phenomena, capable of leveling buildings and uprooting trees within seconds (Masoomi & van de Lindt, 2017; Pîrloagă et al., 2021). Various atmospheric conditions such as wind shear, instability, and moisture contribute to the formation of tornadoes, particularly in regions where these factors converge, like the central United States (Coleman & Dixon, 2014; Fuhrmann et al., 2014). Research has shown that the southeastern states, including Alabama and Mississippi, are increasingly experiencing tornadoes outside the traditional "Tornado Alley," indicating shifting patterns likely driven by changing climate conditions (Masoomi & van de Lindt, 2017; Pîrloagă et al., 2021). This shift underscores the need for updated risk assessments to adapt to evolving tornado activity.

The socioeconomic impact of tornadoes is profound, disproportionately affecting vulnerable populations who may lack the resources needed for adequate recovery (Corey & Senkbeil, 2023; Moore, 2019). Studies suggest that low-income communities are at a heightened risk due to inadequate housing structures and limited access to emergency services, which exacerbates the damage and recovery times following tornado events (Fan & Pang, 2019; Hatzis et al., 2018). Additionally, tornadoes can lead to significant mental health issues among survivors, as the trauma from such events often results in long-term psychological distress (Ashley et al., 2014; Moore, 2019). Given the varied impacts of tornadoes on different demographic groups, it is crucial to develop tailored disaster management strategies that prioritize the most vulnerable communities (Markert et al., 2019; Masoomi & van de Lindt, 2017).

Geospatial analysis has been instrumental in enhancing our understanding of tornado risk distribution and frequency across the United States. Tools like Geographic Information Systems (GIS) allow researchers to map tornado occurrences and identify hotspots, particularly in regions like Texas, Oklahoma, and Kansas (Daneshvaran & Morden, 2007; Fricker & Friesenhahn, 2022). These analyses not only reveal patterns in tornado density but also highlight critical infrastructure vulnerabilities, such as the intersection of tornado paths with major highways and populated areas (Kelnosky et al., 2018; Long et al., 2018). Additionally, understanding seasonal variations is essential, as research indicates that tornado activity peaks during late spring and early summer, though outlier events are increasingly observed in other months due to climatic shifts (Foglietti et al., 2020). By leveraging historical data and geospatial tools, this research aims to contribute to more effective disaster preparedness strategies, potentially reducing the human and economic toll of future tornadoes.

Although tornadoes have been identified in many places of the world, however, they are largely concentrated in the United States and most severe in the Midwest, Southeast, and Southwest regions of the U.S. Over the period from 1950 to 2022, 68,701 tornadoes are officially reported in the U.S., claiming about 6,135 deaths and 97,454 injuries (SPC, 2024). Considering the brief literature review, this research aims to achieve the following objectives:

- Conduct a comprehensive analysis of historical tornado data to determine frequency, distribution, and intensity.
- Analyze tornado occurrence by states to identify which areas have experienced the highest tornado activity.
- Analyze the seasonal patterns in tornado occurrences to identify peak activity periods.

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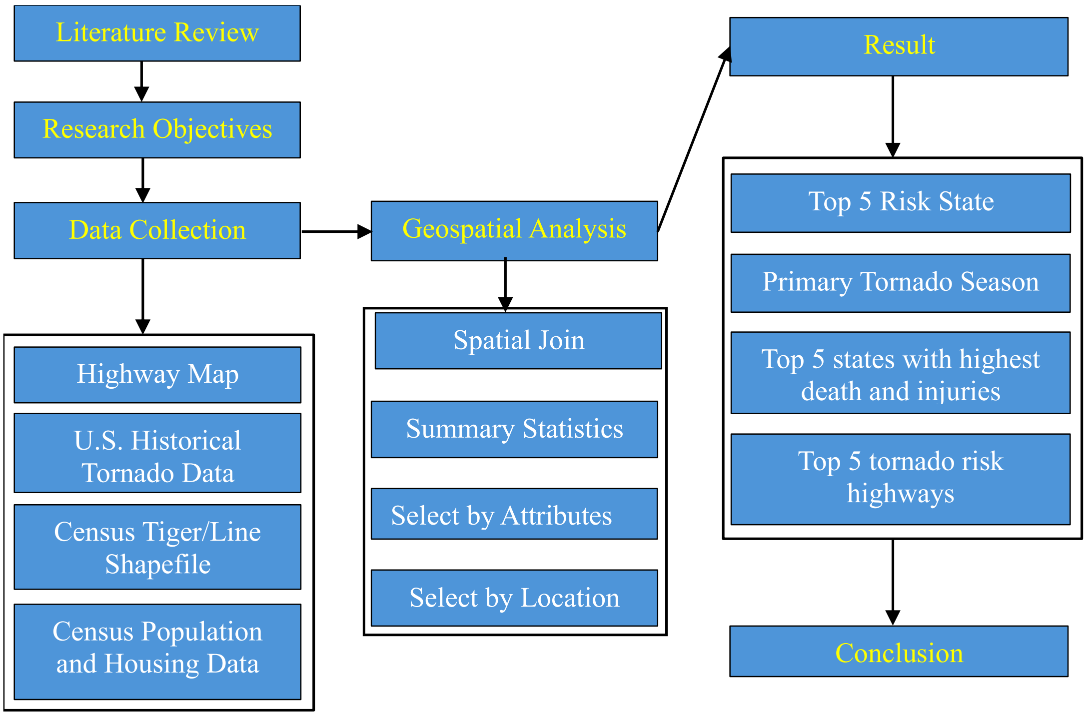
- Identify the top 5 states with highest tornado-induced fatalities, injuries, and property loss by analyzing comprehensive data on these factors.
- Identify the impact of tornadoes on interstates and major roads by state to improve understanding of their effects.

3 Methodology & Process

The following graphic illustrates the workflow, methodology, and processes of the research. Based on the research objectives, this study collected GIS data, U.S. historical tornado data, Census Tiger/Line shapefiles, and census 2020 population data. The historical tornado data, developed and administered by the Storm Prediction Center, includes tornado point data from 1950 to 2022. The Census Tiger/Line shapefile and population data for U.S. states are created and maintained by the Bureau of the Census. These datasets are imported into ArcGIS Pro to facilitate a wide range of spatial analyses using various geoprocessing tools, such as Spatial Join, Select by Location, and Summary Statistics.

Figure 1: Methodological Flowchart



Source: Prepared by authors, 2024

4 Results:

4.1 Top 5 tornado-risk states in USA

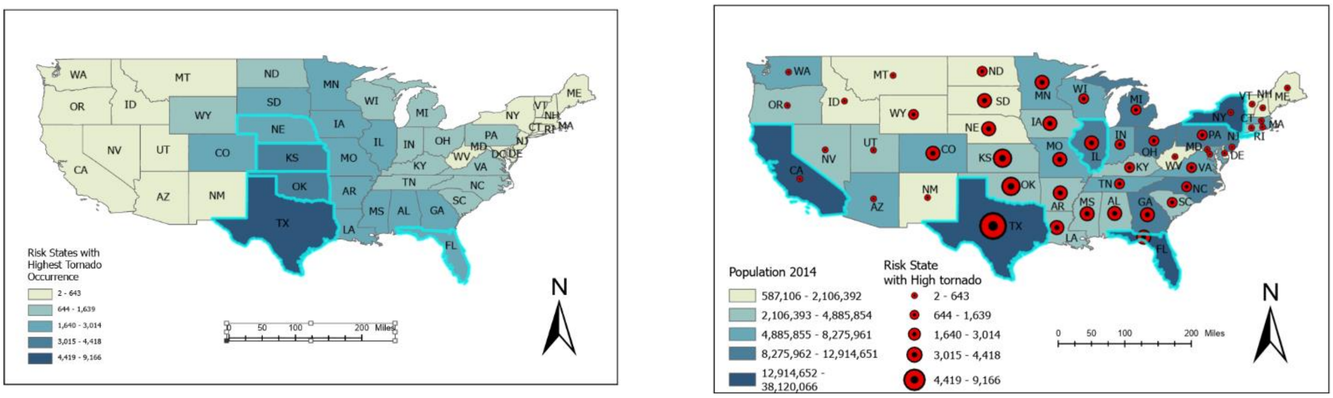
Criteria: Based upon the number of occurrences of tornadoes from 1950 to 2022

Geoprocessing Tool Used: Spatial Join

Top 5 Risk States: Texas (9,166), Kansas (4,418), Oklahoma (4165), Nebraska (3014), and Florida1982

Procedure and Results: To identify states with the highest rate of tornadoes, for analysis there is performed a spatial join operation with two datasets: states and tornadoes occurrences. This allowed us to determine the number of tornadoes that occurred within each state from 1950 to 2022. (Refer to the left map below). The central U.S. region, often called "Tornado Alley," shows a high concentration of tornado occurrences, especially in states like Texas, Oklahoma, and Kansas. There is created an additional map to compare tornado occurrences and 2014 population distribution across the U.S., as shown in the right-side below. The map shows that while Texas has both a high population and high tornado occurrences, other highly populated states like California, New York, and Florida experience relatively few tornadoes. Meanwhile, states like Oklahoma, Kansas, and Nebraska show significant tornado counts

Figure 2: Map of risk states with highest tornado occurrence Vs population 2014



Source: Prepared by authors, 2024

despite having moderate populations compared to highly populated states. This indicates that some regions with moderate populations can still experience frequent tornadoes due to their geographic and climatic conditions.

4.2 *Top 5 Tornado Months in the USA*

Criteria: Based on the number of tornado occurrences from 1950 to 2022

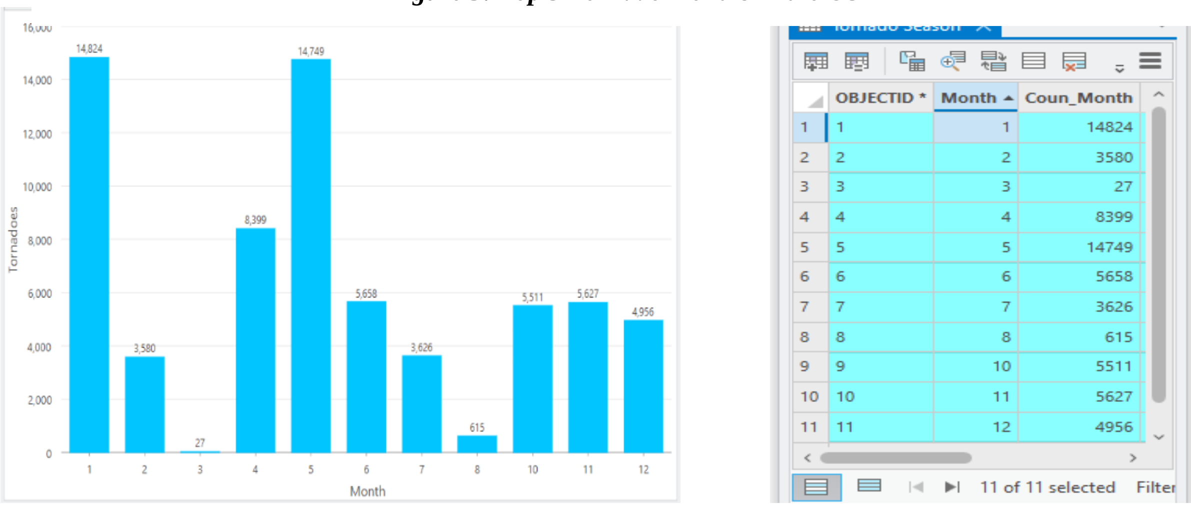
Geoprocessing Tool Used: Summarize

Top 5 Tornado Months: Jan (14,824), April (8,399), May(14,749), June(5,658), and Oct(5,627)

Procedure and Results:

To identify which months, have the highest rates of tornadoes, here used the "**Dissolve**" tool on the attribute table of the US tornadoes database to aggregate the data by month. Then applied the "**Summary Statistics**" tool, which generated a new table containing a record of tornado occurrences for each month along with relevant statistics

Figure 3: Top 5 Tornado months in the USA



	OBJECTID *	Month	Coun_Month
1	1	1	14824
2	2	2	3580
3	3	3	27
4	4	4	8399
5	5	5	14749
6	6	6	5658
7	7	7	3626
8	8	8	615
9	9	10	5511
10	10	11	5627
11	11	12	4956

Source: Prepared by authors, 2024

4.3 *Analyzing top 5 States with Tornado induced Injuries, Fatalities, and Property Damage:*

Criteria: Based upon the number of occurrences of tornadoes from 1950 to 2022

Geoprocessing Tool Used: Selection by Attribute, Spatial Join, and Summary Statistics

Top 5 states for tornado fatalities: Alabama (668), Texas (593), Mississippi (476), Oklahoma (439), and Tennessee (407)

Top 5 states for tornado injuries: Texas (9,475), Alabama (8,669), Mississippi (6,446), Oklahoma (5,999), and Arkansas (5,420)

Top 5 states for tornado injuries: Texas ($2,189,746,433), Tennessee ($1,662,404,251), Ohio ($613,606,991), Iowa ($576,905,776), and Louisiana ($570491875.196)

Procedure and Results: To identify and visualize the top 5 states for tornado-induced fatalities, Injuries, and property loss from 1950 to 2022, for the analysis here

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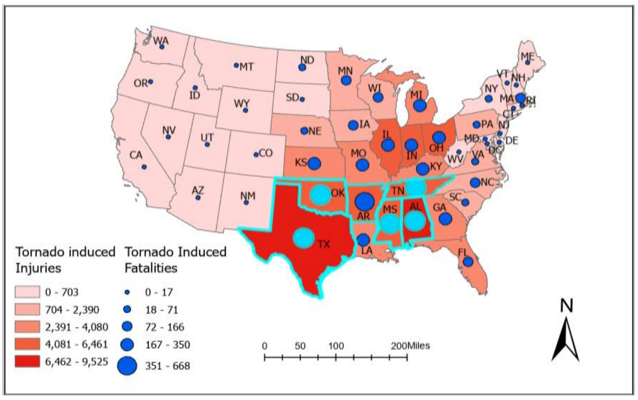
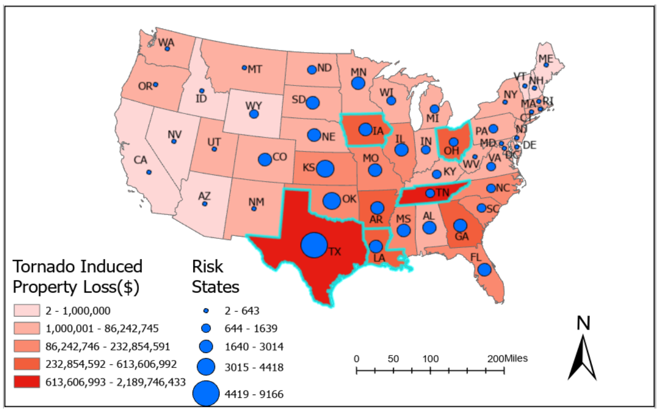
used the **Summary Statistics** tool to aggregate fatalities and injuries by state. Next, performed a **Spatial Join** to combine these statistics with the states layer. Finally, symbolized the joined layer to visually represent tornado-induced fatalities and injuries on the map.

Figure 4: Map of top 5 States with Tornado induced Injuries, Fatalities, and Property Damage





Source: Prepared by authors, 2024

4.4 Tornadoes-Prone Areas:

Criteria: Based upon the number of occurrences of tornadoes from 1950 to 2022

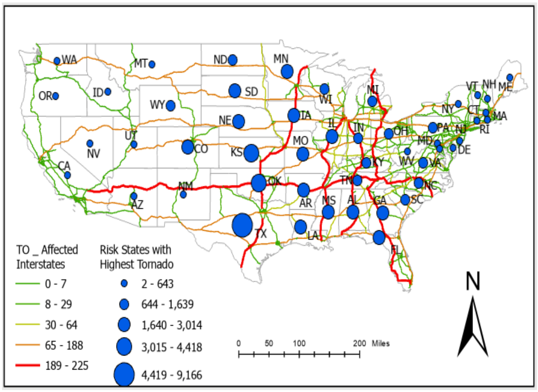
Geoprocessing Tool Used: Dissolve, Summary Statistics, Select by Attributes, and Spatial Join

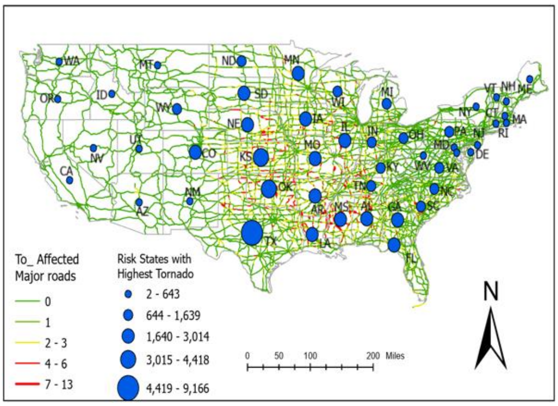
Top 5 interstates route number along with tornadoes occurrences: I40 (225), I75 (204), I65 (197), I35 (191), and I55 (189)

Top 5 major roads route number along with tornadoes occurrences: Arterial highways types: U231, U34, U49,U283, and U49

Procedure and Results: To identify and visualize the top 5 highways affected by tornado occurrences from 1950 to 2022, in these studies performed spatial join operations between two datasets: Tornadoes and Interstates/Major Roads. Then conducted another spatial join between the States and Tornadoes datasets. Afterward, sorted the resulting table by the 'Join_Count' value to identify the top 5 states most impacted by tornadoes

Figure 5: Map of top 5 states with tornado affected interstates and major roads





Source: Prepared by authors, 2024

5 Conclusion

This analysis offers an in-depth look at tornado risk across the U.S., shedding light on how tornado occurrences vary by location, season, and impact. Using geospatial tools like Spatial Join, Summary Statistics, and Dissolve, the study pinpoints regions and months with the highest tornado activity and identifies areas with significant tornado-related fatalities, injuries, property damage, and most affected highways. The results highlight the complex nature of tornado risk, driven by a mix of geographic and climatic factors that create unique patterns of tornado frequency and severity in different states. The analysis also highlights the disparities in tornado risk, where some states experience high tornado counts but relatively low human and economic impacts, while others face severe consequences even with fewer occurrences. By comparing tornado activity to population distribution and economic losses, the study provides a nuanced understanding of how tornado risk affects communities in different ways, emphasizing the need for targeted preparedness measures in both high-frequency and high-impact states. This comprehensive spatial analysis highlights how tornado risks differ by frequency, human impact, property damage, influenced by geographic location and tornado characteristics. First, Texas consistently appears among the top states for tornado occurrences, fatalities, injuries, property loss, most-affected highways, marking it as a high-risk state across all categories. Second, central U.S. States like Oklahoma and Kansas have high tornado counts, but Southern states, particularly Alabama and Mississippi, are more impacted by fatalities and injuries. Third, tornado occurrences in the U.S. are highly seasonal, with May and January emerging as the top months for tornado activity, each with over 14,000 recorded occurrences from 1950 to 2022. Finally, property loss is substantial not only in "Tornado Alley" but also in states like Tennessee and Ohio, underscoring that even states with fewer tornadoes can suffer significant economic impacts.

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