

Spatiotemporal analyses of Extreme Precipitation and Flooding in Tennessee

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Abstract

Flash floods and extreme precipitation are among the most destructive natural hazards because of their capacity to cause rapid loss of life, infrastructure disruption, and severe property damage. Across the United States, studies using diverse methodological approaches have reported increasing trends in heavy precipitation, flooding, and related hydrologic impacts. Because hydrologic hazards vary across both space and time, spatiotemporal frameworks are essential for identifying where hazard patterns are intensifying, declining, or emerging. This study develops and applies a replicable Geospatial Framework for historical extreme precipitation, riverine flood, and flash flood analysis using Tennessee counties as a case study. This study demonstrates the use of Space-Time Cubes, a uniquely appropriate time-series geospatial tool to analyze historical heavy precipitation events (1-, 2-, and 5-year return periods), flood and flash flood events, to assess trends, identify emerging hotspots and cold spots, and visualize changes across space and time. Results show that heavy precipitation events (for all return periods) are increasing in several counties across Tennessee, with Middle Tennessee emerging as a consistent hotspot. Flood and flash flood event trends were more spatially mixed (both increases and decreases) across the state; however, associated property damages increased, especially in Middle Tennessee. Beyond Tennessee, the framework developed in this study is transferable to other national and international contexts where historical hazard records are available. The results provide evidence useful for state-, regional-, and county-level hazard mitigation planning, and support broader efforts to improve preparedness for intensifying hydrologic hazards.

1. Introduction

Globally, flooding is one of the most disastrous natural hazards, resulting in high annual loss of life and damage to infrastructure [1–3]. The United States National Weather Service (NWS) defines flash floods as floods that can form within minutes to hours of excessive rainfall, generally in less than 6 hours, and are often associated with localized rainfall and high relief. In contrast, floods are the “inundation of a normally dry area” by the overflow of water in an existing waterway such as a river, stream, or drainage ditch [4]. In the United States, the NWS reported 28,826 flash flood events between October 1, 2007, and October 1, 2015, averaging 3,603 yearly events [5]. Floods and flash floods are associated with excessive rainfall and extreme climate events [6, 7]. Additionally, the highly variable nature of floods and flash floods makes identifying flood-prone areas and predicting their occurrences challenging [1, 8]. In the face of extreme weather variability and climate change, it is imperative to evaluate heavy precipitation, flood, and flash flood events from both spatial and temporal perspectives. Assessing flash flood trends in space and time gives insight into spatiotemporal trends that identify emerging hotspots and cold spots- an important first step in developing plans to mitigate such disasters.

Flash flood analysis at the global scale does not sufficiently show the changes in magnitude and frequency that could serve as an appropriate basis for local scale predictions [6, 9]. Regional scale studies (county and watershed scales) can provide more actionable information related to trends in frequency and magnitude of such events [6, 9]. Hence, there is a need to focus on regional-level research to identify patterns that can support predictions and development of mitigation strategies.

Recent research increasingly demonstrates that hydrologic hazards exhibit spatiotemporal variability, with risk intensifying in specific locations. Studies across the United States show that extreme precipitation and flooding are becoming more spatially concentrated and temporally dynamic, necessitating research approaches that capture these patterns. County-level Emerging Hot Spot Analysis was applied to an ensemble of natural hazards simultaneously to assess their collective spatial and temporal trends across the United States [10]. That study found clear evidence of shifting and intensifying hazard clusters at the county level [10]. A similar study used a high-resolution imagery simulation framework to identify increasing flood frequency and spatial extent across US climatic regions [11]. A

recent study of the seasonal timing of over 14,000 storm events in the Southeastern USA (SEUS) from 1996 to 2017 determined that flood frequency is generally higher in spring and summer, while duration and intensity are higher in autumn and winter [7]. Comparable patterns are observed in other regions of the United States, where shifts in seasonal flood timing and increases in extreme precipitation have been attributed to both climate variability and anthropogenic forcing [12–14].

Studies worldwide further reinforce spatiotemporal clustering and regional dynamics in hydrologic hazards. In China, a study used spatial autocorrelation and kernel density models to map high-risk clusters along the southeastern coastal provinces and reported temporal intensification of flood frequency and severity in vulnerable basins [15]. Similarly, [16] found increasing flash flood occurrence concentrated in specific seasons and regions, highlighting the combined influence of climatic and environmental drivers using distributed hydrological models and geographic information science (GIS). Evidence from Australia indicates that intensification of short-duration rainfall can increase flood severity even when event frequency trends are mixed [17]. Collectively, these studies highlight that hydrologic hazards often display localized concentration, temporal shifts, and non-linear relationships between drivers and impacts. Geospatial analytical frameworks that include space-time cubes and hotspot analysis are critical approaches relevant for the local scale (county) analysis applied in this research. The focus of this research is, therefore, to develop an analytical framework to evaluate flood, flash flood, and heavy precipitation records to identify trends and hotspots, and illustrate it with a dataset of such events in Tennessee counties. Tennessee was selected, in part, due to record-breaking rainfall and associated flash flooding that occurred in the state in 2021 and more recently in 2024; these were devastating events that may be part of an overall spatiotemporal trend. In Waverly, Tennessee (TN), a record 20.73-inch 24-hour rain event on August 21, 2021 caused a flash flood that resulted in 22 fatalities and over \$100 million in property damages [18, 19]. This event set a new 24-hour rainfall record for TN [18]. In northeast Tennessee, Hurricane Helene caused devastating flooding in September 2024 with record- or near-record gauge heights along the Pigeon, French Broad, Nolichucky, Doe, and Elk rivers. At least 17 casualties in northeast Tennessee were attributable to the flood, parts of multiple interstates were washed away, and multiple bridges were destroyed or severely damaged [20]. This research, therefore, evaluates a 32-year record of heavy precipitation and a 27-year record of historical flood and flash flood occurrences for TN counties with the aim to:

1. Develop a replicable workflow to analyze trends in flood, flash flood, and heavy precipitation event data across geographic areas; and
2. Apply the workflow to identify spatiotemporal trends and hotspots in flood, flash flood, and heavy precipitation events in Tennessee counties.

The results of the case study are part of a larger study to evaluate hazards in Tennessee counties and were included in the 2023 Tennessee State Hazard Mitigation Plan Update [21]. Findings will be useful in mitigation planning at both the state and county levels and we anticipate that the workflow will be replicable in other states and countries.

2. Data and Methodology

2.1. Study Region

The state of Tennessee (TN), located in the SEUS, has 95 counties, and is often divided into west, middle, and east regional blocks. The western region has low relief, forming part of the Mississippi Alluvial Plain, and is dominated by fluvial geomorphic processes. The Nashville Basin and Cumberland Plateau form the middle region, dominated by the Mississippian limestone, Ordovician limestones in the center, and Pennsylvanian sandstone [22]. East Tennessee is dominated by the tectonically formed and eroded NE-SW trending Appalachian Mountains [23, 24], forming the Valley and Ridge and Blue Ridge physiographic provinces. The margins of the Cumberland Plateau and the East Tennessee

Valley and Ridge province have prominent karst features due to the rich presence of limestone [22]. In this region, sinkholes, disappearing streams, and caves with active karst landform formations are prominent features that have a major influence on surface water flow and groundwater recharge.

Tennessee experiences a humid subtropical climate (Köppen Cfa), with higher elevations along the Appalachian Mountains in the east and the Cumberland Plateau experiencing the oceanic/highland climate type (Köppen Cfb - Marine West Coast climate) [25]. Temperature and rainfall also vary across the region, with an average annual temperature of 17°C (62°F) in the extreme southwest and 7°C (44°F) in the highest peaks in the east. Average annual rainfall ranges from 127–153 cm (50–60 inches) in West Tennessee, 132–140 cm (52–55 inches) in Middle Tennessee with over 153 cm (60 inches) in the hilly Highland Rim, and 102–140 cm (40–55 inches) in East Tennessee with locally greater amounts exceeding 254cm (100 inches) at higher elevations [25].

2.2. Data Preparation

2.2.1. Heavy Precipitation

We defined heavy precipitation as a 24-hour accumulation that exceeded the frequency duration thresholds for 1-, 2-, and 5-year recurrence intervals. To construct the dataset, rainfall frequency duration estimates for a 24-hour rainfall event for the three recurrence intervals were extracted from the NOAA Rainfall Atlas 14 volume 2 version 3 (available at https://hdsc.nws.noaa.gov/pfds/pfds_map_cont.html?bkmrk=tn) [26] for the centroid of each TN county. Daily (24-hour) rainfall accumulation data from 1991–2022 were obtained from the PRISM dataset (<https://prism.oregonstate.edu/explorer/>) using the interpolated grid cell values from the county centroid [27]. We counted the number of days with rainfall exceeding frequency duration estimates for the 24-hour 1-year event and tallied the daily events by county by year to create an annual time series dataset of the number of times heavy precipitation occurred in each county each year. We repeated this workflow for the 2-year and 5-year recurrence interval 24-hour threshold, creating three heavy precipitation event datasets defined by the three recurrence intervals; these were used as inputs in ArcGIS Pro to build a heavy precipitation events Space-Time Cube for the analysis using an annual time step and counties as the spatial unit (Fig. 1).

2.2.2. Flash floods and Floods

From 1996 to 2022 in Tennessee, 2849 flash flood events and 943 flood events were recorded in the National Oceanic and Atmospheric Administration (NOAA) storm events database (<https://www.ncdc.noaa.gov/stormevents/>) [28]. For both flash flood and flood events, we created time series datasets for: 1) the number of events per county per year; and 2) the sum of property damage per county per year in USD. From these datasets, we built Space-Time Cubes in ArcGIS Pro for the analysis using an annual time step and counties as the spatial unit.

2.3. Spatiotemporal Analysis

The Space-Time Cube for heavy rainfall contained three attributes corresponding to the 1-year, 2-year, and 5-year recurrence intervals. The Space-Time Cubes for flash floods and floods contained two attributes: 1) number of events (per year per county) and 2) USD damages to property (per year per county) (Fig. 2). Trend Analysis and Emerging Hotspot Analysis were conducted in ArcGIS Pro for all three hazards. Though localized, heavy precipitation, floods, and flash floods may extend across county boundaries; we accounted for this by defining a 37 km fixed distance neighborhood for each county, which corresponded to queen contiguity (first-order neighbors). This value was determined by developing queen contiguity spatial weights in GeoDa software version 1.20.0.22 (https://geodacenter.github.io/download_windows.html) for TN counties.

2.4. Data Visualization

Trend analysis and emerging hotspot analysis results for flash floods, floods, and heavy precipitation were displayed in 2D and 3D in ArcGIS Pro 3.1. Figure 2 shows the workflow used for this study. Note that in a separate and subsequent analysis, TN counties were segmented into East, Middle, and West Tennessee regions (Fig. 2), Space-Time Cubes were built for each region, and an independent emerging hotspot analysis on flash floods was performed for each of the three Tennessee regions. We performed separate regional analyses to evaluate the impacts of the historic flash flood event in Waverly, Middle Tennessee and Tennessee's rectangular shape, which results in many counties bordering other states and can lead to boundary effects, which may mask trends and patterns in peripheral counties. The process is illustrated in Fig. 2 in the right-hand branches.

3. Results

3.1. Heavy Precipitation

3.1.1. Trends in Heavy Precipitation

Trends analysis revealed significant ($\geq 90\%$ confidence level) uptrends in 1-year heavy precipitation in 19 counties - five counties in West TN, nine counties in Middle TN, and four counties in East TN; a downtrend was recorded in Weakley County in northwest TN (Fig. 3a, d).

Uptrends in 2-year heavy precipitation events were identified in 17 counties across the state (Fig. 3b). In particular, Humphreys County in Middle TN recorded twelve 2-year heavy precipitation events from 1997 to 2022 with six of them in the past five years (2017 to 2022), and Wilson County, also in middle TN, recorded six 2-year heavy precipitation events from 2009 to 2022 with no recorded events from 1990 to 2008 (Fig. 3e). Downtrends in 2-year heavy precipitation events were identified in Giles and Bedford counties in southern middle TN at a 90% confidence level. Six events were recorded in Giles County from 1990 to 2012 with no events in subsequent years (2013–2022) (Fig. 3e). Similarly, eight events were recorded in Bedford County from 1990 to 2010 with no events in the subsequent years (2011–2022).

The 5-year heavy precipitation analysis revealed uptrends in seven counties (Davidson, Madison, DeKalb, Jackson, Scott, Campbell, and Hancock) (Fig. 3c). Six 5-year heavy precipitation events were recorded in Madison County in West TN between 2002 to 2022, with three of those events occurring between 2017 and 2022. Davidson County recorded two 5-year heavy precipitation events in 2010 and one event each year in 2017, 2019, and 2021 (Fig. 3f). None of the counties recorded downtrends in the 5-year heavy precipitation return periods.

3.1.2. Emerging Hotspots in Heavy Precipitation

The emerging hotspots analysis of 1-year heavy precipitation events identified sporadic hotspots in Hickman, Van Buren, Grundy, Sequatchie, and Marion counties in Middle and East TN (Fig. 4). For 2-year heavy precipitation events, Hickman and Overton counties were identified as sporadic hotspots and Putnam County as an intensifying hotspot (Fig. 4). For 5-year heavy precipitation events, DeKalb and Putman counties were identified as consecutive hotspots and nine other counties in Middle TN were identified as sporadic hotspots (Fig. 4). Emerging heavy precipitation hotspots are concentrated in Middle TN in the Nashville Basin, along the Sequatchie Valley, and western edges of the Cumberland Plateau.

3.2. Flash Flooding

3.2.1. Trends in Flash Flooding

Trend analysis revealed an uptrend in flash flood events in Shelby and Tipton counties in West TN at 90% or greater confidence level (Fig. 5a). Downtrends were identified in 12 counties distributed across the state at a 90% or greater confidence level. To visualize the underlying data, a 3D map of events (Fig. 5) is a useful tool to understand uptrend and downtrend designations, and to identify counties where a lack of trend may indicate a consistently high number of annual events rather than no events. For example, Shelby County (southwest-most corner of Tennessee) is observed to have a high number of flash flood events over the years, increasing over time from 1996 through 2022 (Fig. 5e). In contrast, Lawrence County (south-central Tennessee) shows no significant trend, but the 3D visualization shows that flash floods continue to occur, only that their frequency has not changed significantly over time.

Property damage assessments are a metric used to quantify impacts of flash flooding events. Uptrends in flash flood-induced property damages were identified in four counties in Middle Tennessee (Davidson, Maury, Jackson, and Grundy), and East Tennessee (Hawkins and Sevier), all at a 90% or greater confidence level and downtrends were identified in Haywood and Fayette, both in West Tennessee (Fig. 5b).

3.2.2. Flash Flood Hotspots

The emerging hotspots analysis of flash flood events identified Blount and Anderson counties as new flash flood hotspots, and multiple counties in Middle Tennessee as sporadic hotspots, with Lewis County identified as a consecutive hotspot for flash floods (Fig. 5c, g). For flash flood-induced damages, two Middle Tennessee counties (Houston and Humphreys) and Benton County in West TN were identified as consecutive hotspots for flash-flood-related damages (Fig. 5d, h).

3.2.3. Independent Regional Analysis

The regional analysis of West, Middle and East Tennessee further identified Knox, Bradley, and Unicoi counties as the new flash flood hotspots, Anderson County as a sporadic hotspot, and Blount and Hamilton counties as consecutive hotspots (Fig. 6). West and Middle TN had few changes: Shelby County and Houston County, sporadic hotspots in the initial analysis, were no longer significant hotspots in the independent West TN and Middle TN analyses, respectively (Figs. 5c, 5d, 6a and 6b). Further, the regional analysis on flash flood-induced damages resulted in no change in Middle and East TN, but in West TN, Benton was no longer a consecutive hotspot (See Figs. 5d and 6b)

3.3. Floods

3.3.1. Trends in Floods

Trend analysis revealed significant ($\geq 90\%$ confidence) uptrends in twelve counties in Middle TN and three counties in East TN, while downtrends were identified in Lake County (northwest TN) and Bradley County (southeast TN) (Fig. 7). The 3D display of the flood events (Fig. 7d) shows increasing events over time in Middle and parts of East Tennessee, with a few other counties showing no trends but with a consistently high tally of flood events across the bins (for example, Shelby County in southwest TN and Sevier County in East TN).

Uptrends in flood-induced property damages were identified in five counties in East TN (Cumberland, Knox, Blount, Greene, and Sullivan) at a 90% or greater confidence level; downtrends were identified in Lake, Obion, Dyer, Tipton, and McNairy counties in West Tennessee (Fig. 7b). These results demonstrate that flood events are trending up in Middle TN, while flood-induced property damages are trending up in East TN.

3.3.2. Emerging Flood Hotspots

New flood hotspots were identified in Marshall and Bedford counties, and sporadic flood hotspots were identified in Williamson and Maury counties, all in Middle TN (Fig. 7c). No significant hotspots were identified in flood-induced property damage and are therefore not shown here.

4. Discussion

This study provides a comprehensive assessment of hazardous hydrologic events in Tennessee to inform hazard mitigation planning and preparedness. Using spatiotemporal analysis and geo-visualization, we identified trends, hotspots, and cold spots for heavy precipitation, flash flood, and flood events in Tennessee counties for the past 27 to 30 years. Simultaneously, the study presents a replicable workflow to evaluate similar research questions in other geographies and adds to the hydrologic hazard literature establishing the non-linear and spatially heterogeneous relationships between event frequency, intensity, and impacts globally.

4.1. Transferability of Spatiotemporal Hazard Hotspot Analysis

Tennessee serves as a case study demonstrating the applicability of spatiotemporal analysis using Space-Time Cubes and Emerging Hotspot Analysis for identifying hazard dynamics at policy-relevant scales. The identification of emerging hotspots in Middle Tennessee, alongside the decoupling of event frequency and damages, illustrates how these methods can reveal patterns that are not apparent through traditional trend analysis alone. This has direct implications for hazard mitigation planning, as it emphasizes the need to prioritize areas experiencing increasing event intensity and impact rather than frequency alone. Importantly, the transferability of this framework extends beyond Tennessee, similar methodological approaches can be applied to other regions experiencing climate-driven hydrologic change, urban expansion, or shifting exposure patterns.

4.2. Events vs. Damages in Tennessee Counties

Flash flood analyses indicate that, although counties with declining event trends outnumber those with increasing trends, USD property damages are increasing, particularly in Middle Tennessee. Notably, counties that exhibited upward trends in annual flash flood events did not show corresponding upward trends in property damage. For example, Shelby County has experienced an increasing trend in flash flood occurrence, averaging approximately four events per year since 2011 (Figs. 6 and 8). However, damages associated with these events have not exhibited a similar upward trend, likely because the county has already incurred consistently high property losses, with at least USD 3 million in damages occurring approximately every five years from multiple events within those periods. Furthermore, the NOAA storm events data shows that Shelby County incurred USD 29 million in property damages in 2010 from 24 flash flood events while incurring USD 51 million in 2014 from 4 events and USD 1.6 million in 2019 from 6 events. These related property damages have no significant uptrend or downtrend, though the impact of these floods is great in Shelby County. The storm events database reported that two of the flash floods in 2010 and one in 2014 (both in Shelby County) were caused by 'very heavy rainfall'. This description is consistent with the heavy precipitation records for Shelby County, which show two 1-year and one 2-year heavy precipitation events in 2014 and one 1-year heavy precipitation event in 2010.

A 3D visual inspection of the flash flood events (Fig. 5e) shows that Middle TN counties have experienced more events in recent years. This could be explained by land use and land cover changes as a result of increased development in Middle Tennessee and Shelby County in West Tennessee, coupled with increasing heavy precipitation events in Middle Tennessee. This implies that climate change and variability could be playing a role in the Middle Tennessee flash flood hotspot. Counties experiencing downtrends in flash flood events may be employing effective flash flood hazard mitigation strategies that make them more resilient to flash flooding, considering that heavy precipitation is trending

up. Further investigation will be required to ascertain the reasons for the downtrends, though this is beyond the scope of this study.

Middle Tennessee is a region with increasing trends in flood events that require attention from flood mitigation stakeholders. Land use in Davidson and Rutherford counties is more developed with more impervious surfaces which increases stormwater runoff and contributes to flooding [19]. Flood damage generally did not correspond to related flood events across the state, except for Greene County in East Tennessee, where both flood events and flood damages are trending up (Fig. 7a, b). These impacts may indicate either that the county experienced particularly severe flood events or that additional mitigation strategies are needed to strengthen its resilience to flooding hazards. New significant hotspots were identified in Marshall and Bedford counties in Middle TN (Fig. 7c), although neither of these counties had significant uptrends or downtrends for flood events and damages, respectively. In 2004, 2010, 2017, and 2022, Marshall County (Middle TN) recorded flood events, while there were no prior-year records of flood events in the data used for this analysis. The record of these events is not long enough to be classified as a trend but is consistent enough to be a new hotspot.

In Middle TN, fewer flash floods caused increased trends in property damage; this indicates that these events, though few, were intense. Similarly, flooding in East TN had no significant up trends, but damage was increasing. Heavy rainfall is a contributing factor because the heavy precipitation data shows that Cumberland County, for instance, experienced three 1-year, three 2-year, and one 5-year heavy precipitation events in 2020 and one 1-year and one 2-year heavy precipitation events in 2021. These recent heavy precipitation events suggest flood intensity is increasing though the number of floods has not significantly increased.

4.3. Interaction Effects and the Influence of Geology, Geomorphology and the Built Environment.

We used 1-year, 2-year, and 5-year return period heavy precipitation events for the precipitation hazard analysis to capture a range of significant events with higher expected occurrence rates. Heavy precipitation events with return periods greater than 5-years were also captured under the selected return periods, because their rainfall totals exceeded the 24-hr rainfall accumulation threshold for all shorter return periods. We didn't directly include longer return period events in the analyses because their expected number during the period of analysis was small.

The number of counties experiencing uptrends in heavy precipitation in Tennessee significantly outnumber the number of downtrends, suggesting that the recent heavy precipitation events are increasing around the state. For example, the catastrophic rainfall event in Humphreys County in 2021 that became the state's new record 24-hour rainfall was caused by a single heavy precipitation event classed as a > 1000-year event [29]. The intensity of the rainfall (20.73 inches over 24 hours) significantly affected the intensity of the resultant flash flood event that claimed 22 lives and caused \$100 million in property damage. Humphreys County is in the Western Highland Rim, a physiographic region characterized by hilly terrain, dissected by streams [30]. Hilly relief is a contributing factor to the severity of floods such as this one, because steep slopes and higher stream gradients reduce infiltration and increase runoff [31]. News reports from Fox Weather stated that the flood waters came in very fast and forcefully [19], which emphasizes the influence of hilly relief on the flash flood. The built environment, specifically a channelized creek under a railroad track, was also a major contributor to the flooding in 2021. Large woody debris (mainly tree debris) created a temporary dam at a railroad bridge where water was held back for a short period before failure, releasing flood waters towards the communities where the greatest damage and loss of life occurred.

Flood trends are also increasing, with an average range of one to five events per year per county, Increasing Flood event trends are concentrated in Middle Tennessee, along with three counties in East Tennessee (Fig. 7a), in the

carbonate bedrock. Carbonate regions in Tennessee can be relatively impermeable due to recrystallization of calcite in pore space, leading to increased surface runoff. Karst hydrologic features such as sinkholes could be a contributing factor to the intensity of flood inundation in Tennessee because sinkholes act both as drainage points for runoff and choke points, by constricting flow which can lead to increased flood inundation. However, the specific effect of the carbonates on the flash floods is complex and depends on a number of factors, including the mineral composition of the carbonates, subsurface hydrology, land uses, antecedent discharge, and the nature of the precipitation event.

4.4. Data Interpretation, Boundary Effects and Limitations

It is important to recognize that results are not predictive but instead describe trends in past events through space and time, which is essential for hazard mitigation planning. Several counties were identified to have uptrends and downtrends, but most counties showed no significant uptrends or downtrends. The absence of a significant trend in any county does not necessarily indicate the absence of events; it indicates no significant increase or decrease in events or damage (in the case of flash floods and floods) to be identified as an uptrend or downtrend.

Tennessee's long and narrow shape results in many border counties, which can enhance boundary effects in spatial analyses. Further, independently examining each of the three regional divisions in Tennessee (East, Middle, and West) helped tease out hotspots obscured by the number of events (flash floods) in middle Tennessee (Figs. 5 and 6). In the independent regional analysis, new hotspots and sporadic hotspots were identified in East Tennessee. In West Tennessee, Benton County, which was a consecutive hotspot in the contiguous states analysis (Figs. 5, 6 and 7), no longer constituted a hotspot in the independent analysis. An explanation for this could be the effect of events recorded in the neighboring contiguous counties. This outcome suggests that although independent regional analysis was necessary to identify new hotspots in East Tennessee, a contiguous analysis of the entire state remains important.

In addition to boundary effects, the analysis identified a temporal boundary issue, whereby observed trends can vary depending on the selected start and end dates of the study period. For example, extending a trend analysis from 1990–2022 to include an additional year (e.g., 2023) may alter the identified trends. While such changes are expected because the incorporation of new data can influence analytical outcomes, they highlight the need for regular updates to trend assessments to support reliable policy and planning decisions. This recommendation aligns closely with the hazard mitigation planning cycle in the United States, where state hazard mitigation plans are typically required to be reviewed and updated every five years.

The NOAA data used for the analysis does not specify the spatial extent of the flash floods. This limitation makes it difficult to draw insights into the impact of flash flooding patterns in space and time to tie them directly to climate variability or increases in extreme events that are expected due to climate change. This is because the study used the count of events which is not equal to severity of intensity. USD damages to properties were used as a proxy for the intensity of the floods to assess the impact of events.

Storm events that last more than 24 hours may be missed in this analysis because rainfall totals are split over multiple days. The PRISM rainfall data used in this analysis are reported for a 24-hour period beginning and ending at 12:00 Greenwich Mean Time (GMT). Therefore, an event starting before 12:00 GMT and ending after 12:00 GMT on the following day, producing sufficient rainfall to be counted as a 1-year event, could be omitted simply due to the timing of the rainfall which split accumulation over two days. Under this eventuality, the study findings are more conservative.

4.5. The Broader Context

Studies across the United States have shown that hazard clusters evolve over time, with localized hotspots intensifying even when overall trends remain mixed [10]. Similarly, research in the southeastern United States indicates that increases in short-duration extreme precipitation can lead to more intense hydrologic impacts without a

corresponding rise in event counts [14]. This aligns closely with the Tennessee results, where increasing property damages in Middle and East Tennessee occur despite mixed or declining trends in flood and flash flood frequency. Comparable findings have been reported globally, including in Australia, where intensifying rainfall has produced more severe flood-generating events even under variable frequency trends [17], and in China, where flood and flash flood hazards exhibit persistent and emerging spatial clusters shaped by hydroclimatic and landscape factors [15]. The patterns we observed in Tennessee are consistent with a growing body of international literature demonstrating that hydrologic hazards exhibit non-linear and spatially heterogeneous relationships between event frequency, intensity, and impacts.

5. Conclusions

This study presents a replicable methodological framework for assessing the spatiotemporal dynamics of hydrologic hazards using historical hazard records. The framework is applicable to local, national, and international contexts where consistent records of hazard events and associated losses are available. By integrating trend analysis, space-time cube analysis, emerging hotspot analysis, and 3D time-series visualization, the study demonstrates how hydrologic hazard patterns can be evaluated across both space and time to support hazard mitigation planning. The framework was applied to evaluate spatiotemporal trends and hotspots in heavy precipitation, floods, and flash floods in Tennessee counties. Results indicate that several counties in Tennessee are experiencing an upward trend in heavy precipitation, with most events occurring between 2010 and 2022 while limited counties in Middle and West Tennessee exhibited decreasing trends. Middle Tennessee emerged as the key region for new heavy precipitation hotspots, highlighting the need for hazard mitigation efforts.

Flash floods are increasing in Shelby and Tipton counties in West Tennessee, while 12 counties had decreasing flash flood trends statewide. However, flash flood related property damage increased in Middle and East Tennessee, where six hotspot counties were identified. An independent regional analysis revealed hidden flash flood hotspots, especially in East Tennessee. Overall, Middle and East Tennessee emerged as key problem areas for flash floods. Floods are trending up in Middle Tennessee and East Tennessee, while related USD property damages are also trending up in Middle Tennessee and trending down in West Tennessee. Counties in central Middle Tennessee are hotspot areas for flooding.

The 3D time series visualizations were critical in understanding the behavior of events and damages in the case of floods and flash floods when assessing spatiotemporal trends and hotspots. The 3D time series provides a snapshot of all time steps (27 years in the case of floods and flash floods) on all spatial units (TN counties) which allows for quick comprehension of the phenomenon.

Spatiotemporal approaches provide unique insights into meteorological hazard assessment in space and time. This research contributes to the literature on changing hydroclimatic extremes by showing how heavy precipitation, floods and flash floods are evolving within a climatically sensitive interior southeastern state. Methodologically, applying space-time cubes and emerging hotspot analysis to multiple hydrologic hazards at the county scale provides a stronger approach to identifying trends and their statistical significance over space and time. By linking changing hazard patterns to increasing or decreasing property damage, this study pushes beyond pattern description and contributes to hazard mitigation planning. These results will be relevant for Tennessee at both state and county hazard mitigation planning levels and contribute to the global literature on hydrologic hazards.

Statements and Declarations

CRedit Authorship Contribution Statement

Emmanuel A. Afriyie: conceptualization, data curation, formal analysis, methodology, validation, visualization, writing - original draft. **Ingrid Luffman:** Conceptualization, methodology, supervision, writing - review and editing. **T. Andrew Joyner:** Conceptualization, methodology, project administration, writing - review and editing. **William C. Tollefson:** Conceptualization, methodology, project administration, writing - review and editing.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Ethics Statement

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

Competing Interests

The authors declare that they have no competing interests.

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Figures

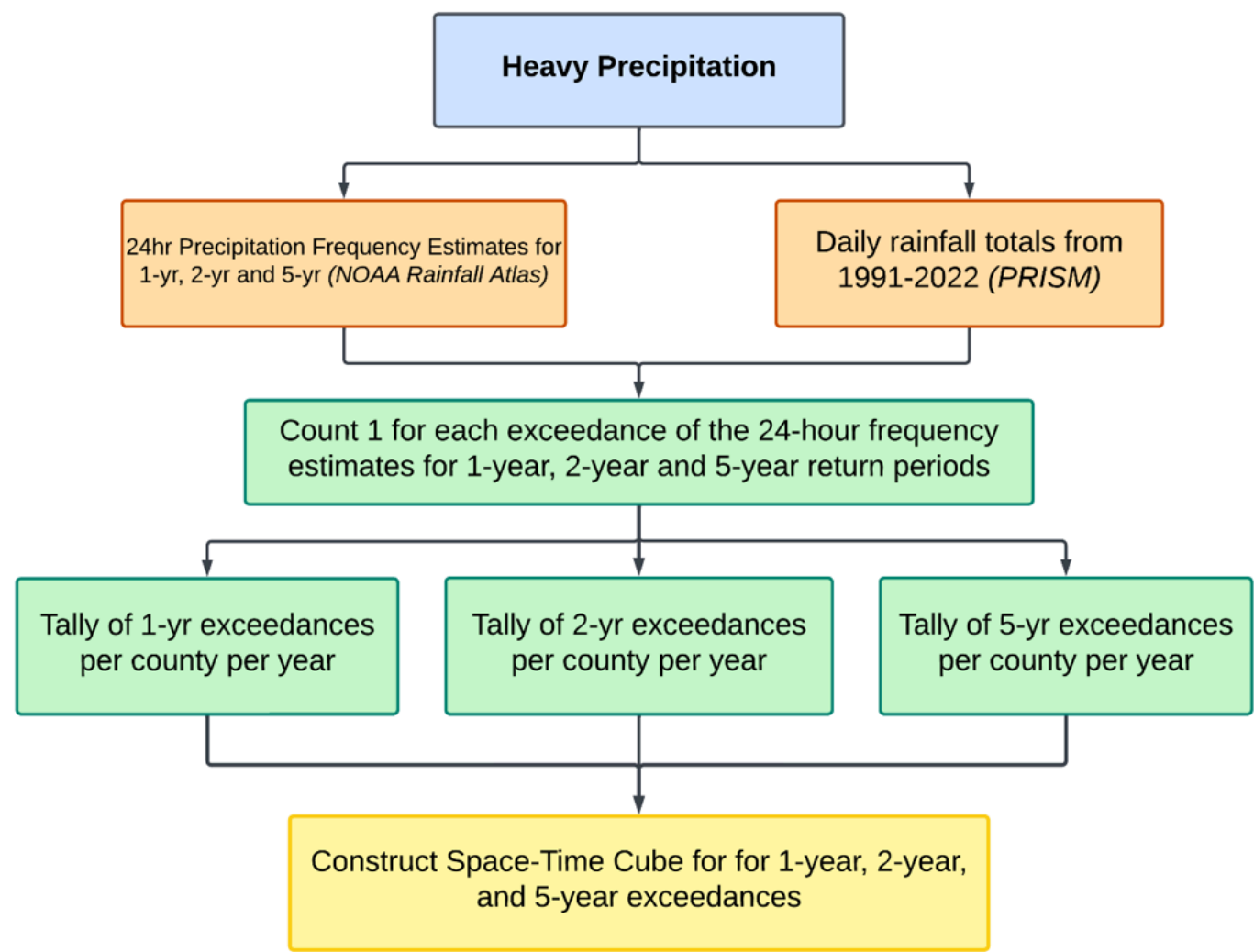


Figure 1

Data preparation workflow for heavy precipitation in MS Excel and ArcGIS Pro

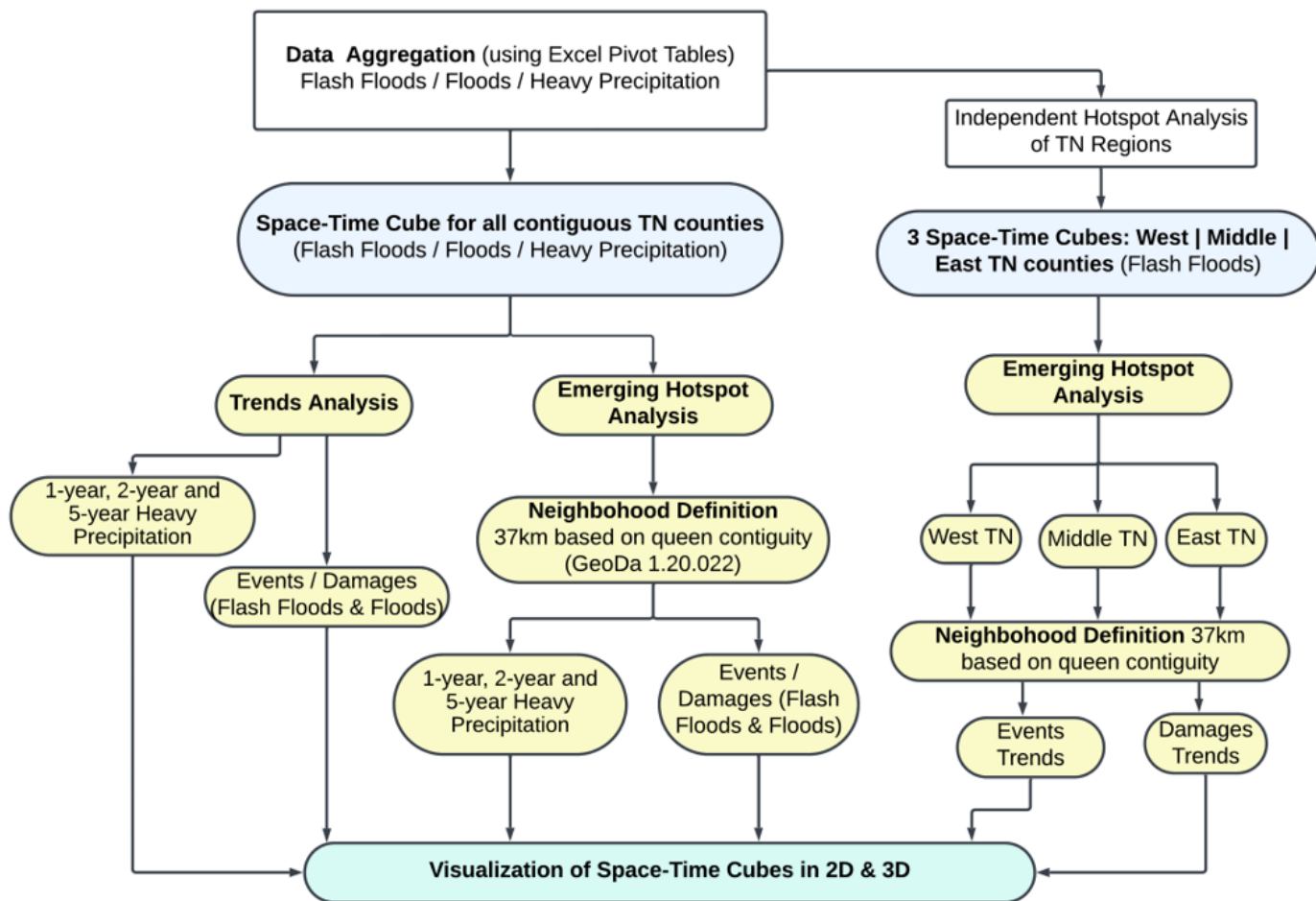


Figure 2

Workflow for spatiotemporal analysis, including trend analysis, emerging hotspots analysis, neighborhood definition and data visualization.

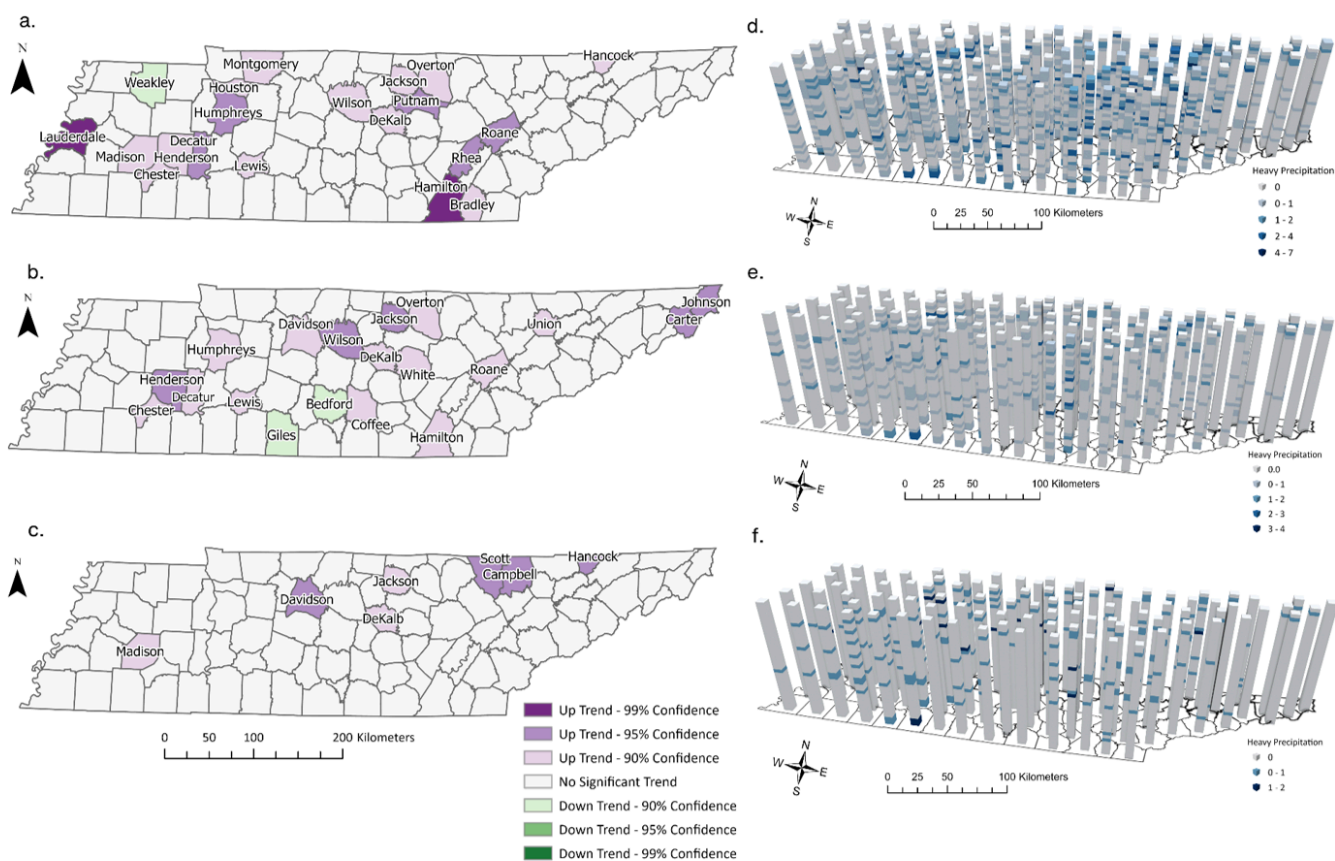


Figure 3

1-, 2- and 5-year return heavy precipitation trends (a, b, c) and corresponding 3D events time series (d, e, f) showing annual events in TN counties, where each floor represents one year such that 1997 is the lowest floor and 2022 is the top floor

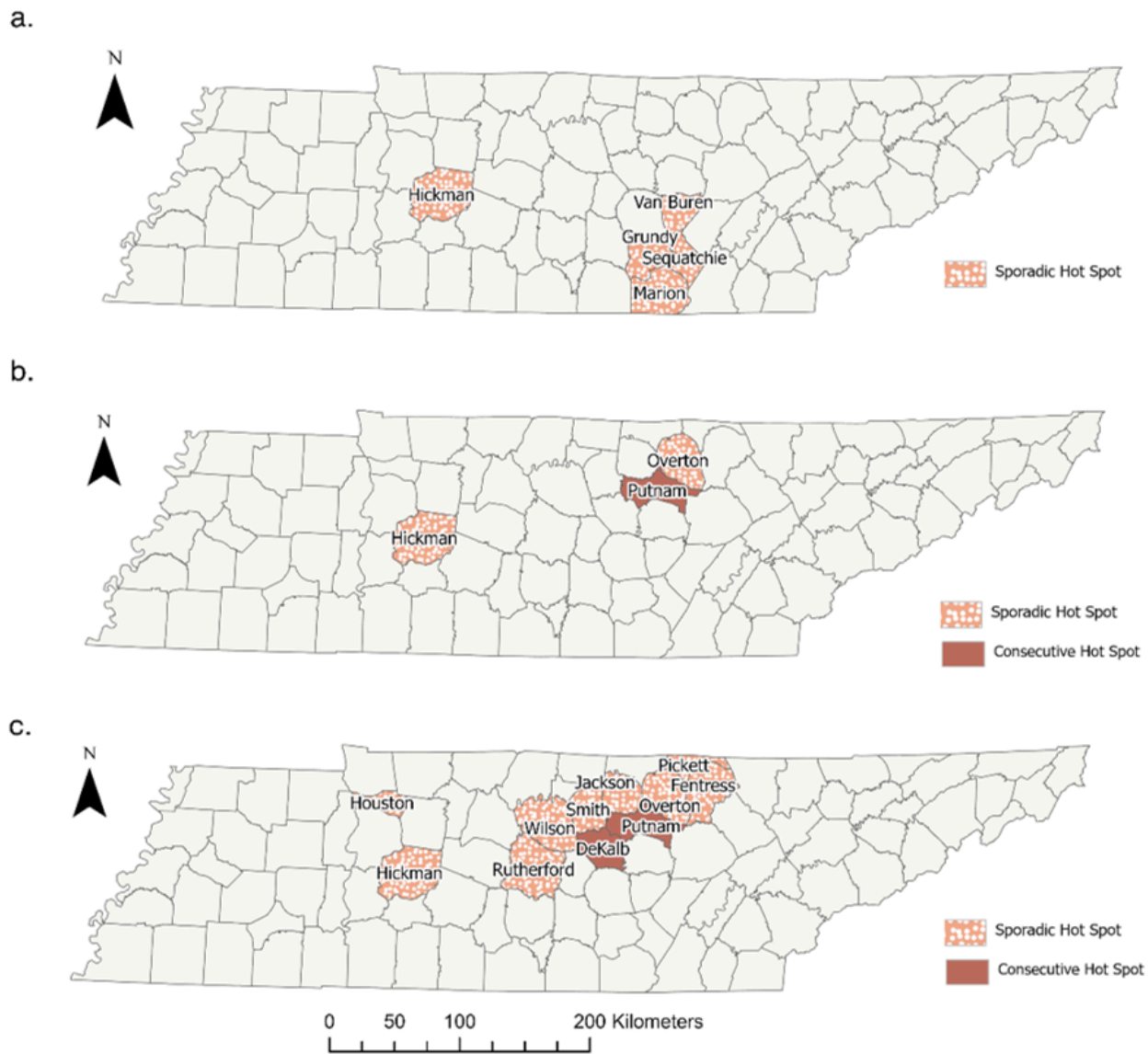


Figure 4

Emerging hotspots for heavy precipitation in a) 1-, b) 2-, and c) 5-year return periods

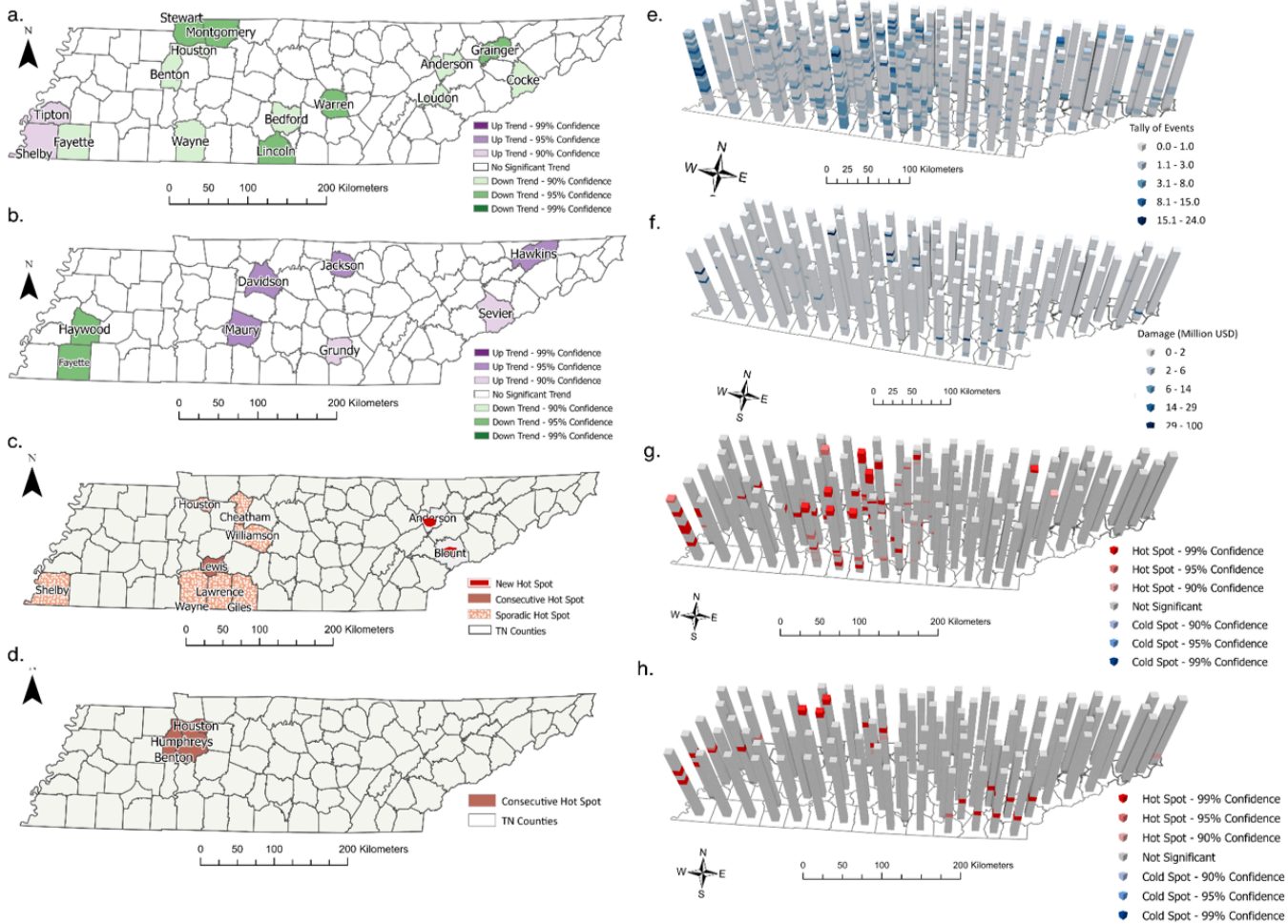
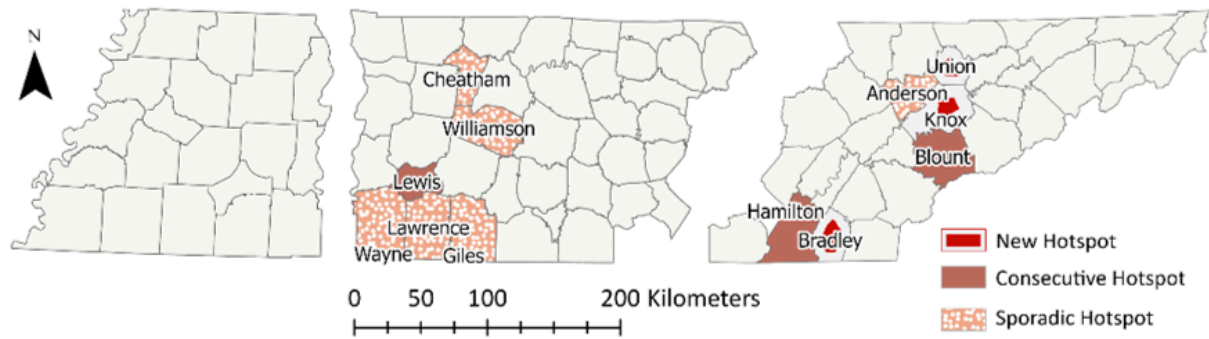


Figure 5

(a) Increasing and decreasing trends in flash flood events; (b) damage in Tennessee. Emerging hotspots for flash flood events and damage (c, d); and 3D time series visualization of corresponding events and hotspots (e, f, g, h)

a.



b.

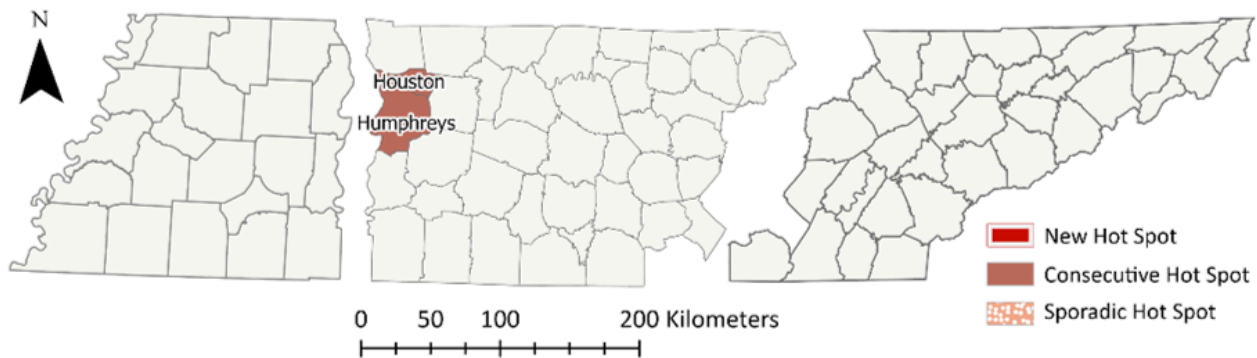


Figure 6

Independent flash flood events (a) and USD damages (b) emerging hotspots analysis of West, Middle, and East Tennessee regions shows new hotspots in East Tennessee with marginal changes in West and Middle TN

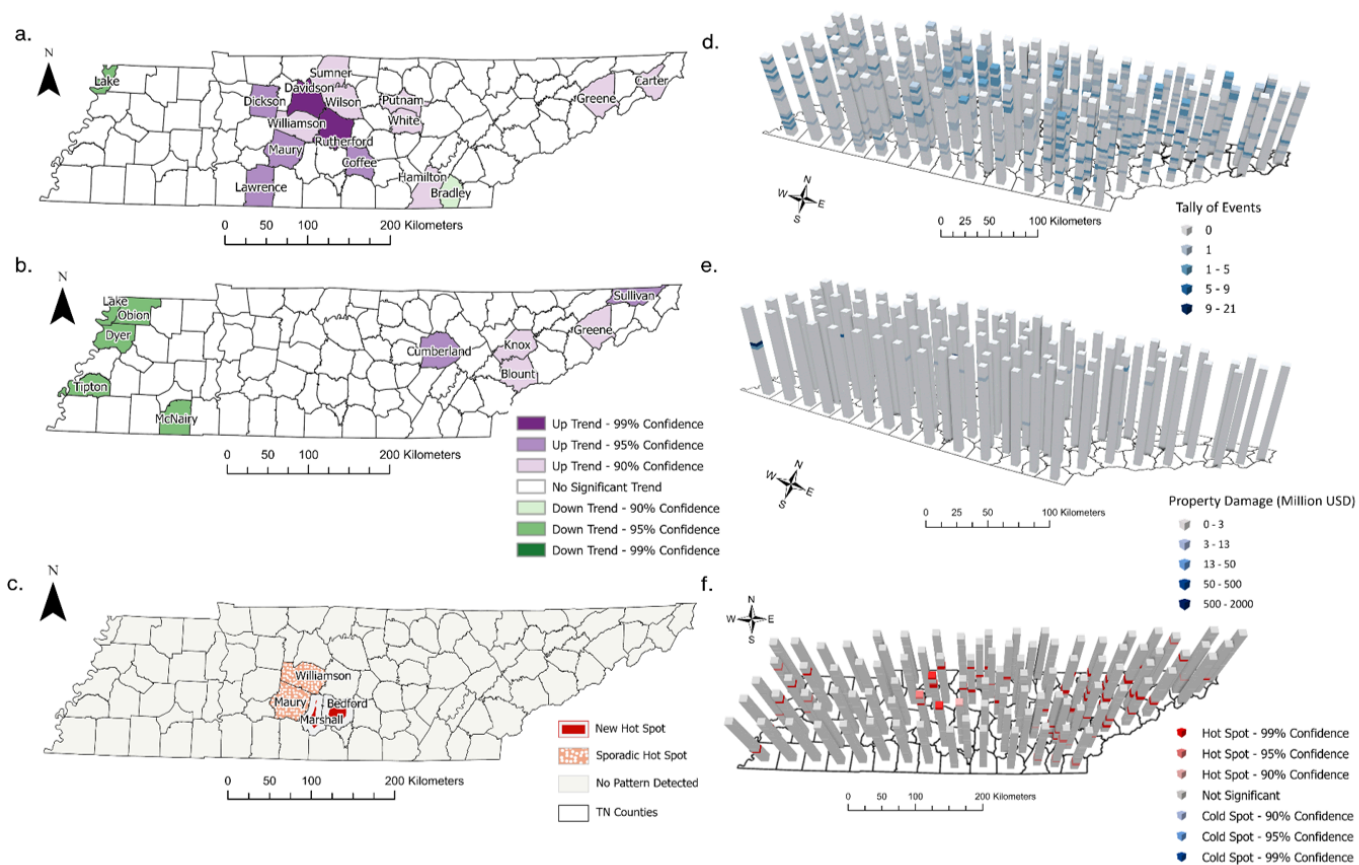


Figure 7

Trends in flood events (a) and property damage (b) in Tennessee. Emerging hotspots for flash flood events (c). 3D time series visualization of events, damages, and hotspots (d, e, f).