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Article

Fatalities Caused by Hydrometeorological Disasters in Texas

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Abstract: Texas ranks first in number of natural hazard fatalities in the United States (U.S.). Based on data culled from the National Climatic Data Center databases from 1959 to 2016, the number of hydrometeorological fatalities in Texas have increased over the 58-year study period, but the per capita fatalities have significantly decreased. Spatial review found that flooding is the predominant hydrometeorological disaster in a majority of the Texas counties located in "Flash Flood Alley" and accounts for 43% of all hydrometeorological fatalities in the state. Flooding fatalities are highest on "Transportation Routes" followed by heat fatalities in "Permanent Residences". Seasonal and monthly stratification identifies Spring and Summer as the deadliest seasons, with the month of May registering the highest number of total fatalities dominated by flooding and tornado fatalities. Demographic trends of hydrometeorological disaster fatalities indicated that approximately twice as many male fatalities occurred during the study period than female fatalities, but with decreasing gender disparity over time. Adults are the highest fatality risk group overall, children most at risk to die in flooding, and the elderly at greatest risk of heat-related death.

Keywords: natural hazards, weather disasters, hydrometeorological fatalities, flooding, tornadoes, extreme temperatures

1. Introduction

Hydrometeorological disasters can result in tremendous damage to infrastructure, significant loss to the economy, and, very often, loss of life. In terms of the human loss, natural disasters resulted in approximately 1.7 million fatalities between 1980 and 2016. More than 49% of these fatalities were due to geophysical events (earthquake tsunami, volcanic activity), 26% were due to meteorological events (tropical storm, extratropical storm, convective storm, local storm), 14% were due to hydrological events (flood, landslides), and 11% were due to climatological events (extreme temperature, drought, forest fire). Forty percent (40%) of the 16,500 disaster events that caused fatalities were hydrological, followed by meteorological (39%), climatological (12%), and geophysical (9%) [1]

Although several studies addressed multiple disasters [2,3], most of the natural disaster researches focused on a particular type of disaster (e.g. floods, hurricanes, lightning, earthquakes) or disaster event (e.g. Hurricane Harvey, Northridge Earth-quake). Flooding is an exemplary disaster type that has been extensively investigated globally, nationally, and, in the USA., at the state and regional levels. Global assessments show high numbers of fatalities due to coastal flood events [4-7]. On a national level, flood-related fatalities have been reviewed for several countries including the U.S. [8], India [9], Pakistan [10], and Australia [11].

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The most lethal natural disaster in United States history occurred in Galveston Island, Texas in 1900 in which an estimated 6,000-12,000 people died as a result of the "Great Galveston Hurricane". From January 1960 to December 2016, Texas had the highest number of fatalities in the nation in which natural disasters killed an average of 40 people per year [12]. During this period, Texas accounted for 7.4% of all U.S. fatalities (32,289) followed by Illinois, California, Pennsylvania, and Louisiana with 5.6% 5.2%, 5.1%, and 4.3%, respectively. Flood, Heat, and Tornado accounted for 60% of all fatalities in Texas during this period. Texas also ranks highest in fatalities per capita (0.15). During this period two Texas counties ranked in the top ten across all states for the occurrence of disaster events: Harris County (1,088 events) and Tarrant County (1,009 events). Dallas County, Texas ranked eighth in the number of fatalities in the U.S.

The rigor and depth of literature available on flooding is merited since it is the second most expensive disaster in the U.S. behind hurricane and tropical storm damage. Flooding also accounts for 13% of all U.S. fatalities from 1960-2015 and the ranks first in Texas for hydrometeorological fatalities. Flooding occurs along coastal regions due to storm surges as inland natural rainfall catchments drive the large quantity and runoff energy. An example of this inland geography is "Flash Flood Alley" in central Texas, which parallels the Balcones Escarpment extending from Cooke and Grayson counties which is south of the Oklahoma/Texas border, in a southwesterly arc through central Texas and towards Val Verde County. This flood-prone region encompasses 27 counties and the highly urbanized areas of Dal-las, Austin, and San Antonio. Extensive research has been conducted to investigate the quantitative and qualitative aspect of flooding in the state of Texas [12, 13].

Hurricanes are especially dangerous natural disasters that have the greatest impact along the coastal regions and are lethal due to the potential for combined effects of high winds, storm surges, and flooding. Most fatalities by hurricanes are associated with the wide spread flooding caused by heavy rainfall over a short time period. In 2005, Hurricane Katrina struck the Louisiana coast causing $96 billion in damages and 1,833 fatalities. Two-thirds of the fatalities were directly related to more than fifty breaches of the levee and floodwall systems [14]. Most recently in August 2017, Hurricane Harvey made the landfall near Port Aransas on the Gulf Coast and resulted in $200 billion in damages and 103 confirmed deaths in Texas, primarily due to flooding across 11 counties. Thirty-six of the total 68 direct fatalities caused by the hurricane winds and flooding occurred in Harris County (Houston Metropolitan area). The hurricane made landfall as a Category-4 storm with wind gusts up to 212 kph (132 mph) recorded near Port Aransas. The impact area received about 60 inches of rain in a 4-day period. The resulting floods inundated hundreds of thousands of homes, displaced more than 30,000 people, and prompted more than 17,000 rescues leaving 300,000 people without electricity; 48,700 homes affected (1,000 total destruction, 17,000 major damage, and 32,000 minor damage) [15].

Tornadoes were responsible for 14% of the total number of natural disaster-related fatalities in the U.S. from 1960 – 2105 [16]. Texas leads the nation in the average number of tornadoes between 1991-2010 with 155 tornadoes per year followed by Kansas (96), Florida (66) and Oklahoma (62) [17]. Analysis of tornado-induced fatalities and damage in the U.S. between 1880 and 2005 in 2007 identified 1,812 tornado-related fatalities caused by 366 fatal tornado events mostly along the northeastern border of the state [18]. Normalized fatalities and events per 1000 km for Texas tornadoes is in line with the national normalized averages (2.7 fatalities and 0.54 events). The analysis also indicated a relationship between mobile home density and number of fatalities and identified a disproportionate (higher) number of fatalities for middle-aged and the elderly compared to younger people.

Globally, the number of fatalities due to lightning from 1940 to 2015 have steadily decreased [19]. This is also true for the U.S. which had a high number of lightning-related deaths (432) in 1943 which consistently decreased to 28 in 2016 [20]. One possibility for this decrease in lightning-related

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fatalities may be due to exposure to lightning which is more controllable than other disasters such as flooding or hurricanes. Severe thunderstorms associate with lightning are identifiable and could be avoided by moving indoors away from locations where lightning can strike.

The impact of disastrous extreme weather to society is a function of both the climatic and local setting. For example, although both the number of fatalities and the extent of damage to infrastructure have increasing trends from the 1960's to the present, some studies suggest that population growth and demographic shifts play a greater role in the degree of increase than the increase in intensity and/or frequency of the extreme weather that the Earth has been experiencing in the last several decades [21]. It appears feasible that even without any detrimental climate changes, the shifts in U.S. economic development patterns and growth will result in ever increasing losses caused by hydrometeorological disasters. Therefore, it is necessary to recognize spatial and temporal trends of natural disasters to allow for the allocation of resources to the higher risk disasters and their locations.

Supplemental to the intensity of such hazards is the exposure of people in the affected areas. In the last several decades, the U.S. has experienced steady increases in population shifts in rural and coastal development patterns, and economic growth, which have positioned more people in disaster-prone areas [22]. Population density, race/ethnicity, and socio-economic status are key factors that consistently increase social vulnerability. Recent research [23] analyzed the nexus of land development and the responsibility in the context of two development paradoxes: the safe-urban development paradox and the local government paradox. The local land development decisions put people at known risk of losing their property and possibly their lives in during flooding. Their analysis of the October 2015 flood event in Columbia, SC, indicated that considerations for public safety were sometimes secondary to profitable land development. Hurricane research that was published in 2018 analyzed the decision biases of persons affected by the four specific hurricanes: Earl (2010), Irene (2011), Isaac (2012), and Sandy (2012) highlighted five major decision biases that may put communities at greater risk of damage and deaths from a hurricane [24]. Temporal and spatial myopia is a major issue that places at lower priority long-term decisions such as preparation for a pending hurricane than it does on short term routine tasks with the failed intention of addressing the long term need when the disaster event is closer in time.

The purpose of this paper is to study fatality data caused by hydrometeorological disasters in Texas for the period 1959 – 2016. To facilitate the analysis, the natural disasters were categorized into "Flooding", "Heat", "Cold Weather", "Tornado", "Lightning", and "Wind Events". Fatalities due to "Tropical Events" (hurricanes and tropical storms) were either classified as flooding or wind events depending on the cause of fatality. The study examines temporal trends, spatial variations, and demo-graphic characteristics of the victims. The paper concludes with a discussion and commentary of considerations that may influence the number of fatalities with the goal of providing information and perspectives that would help reduce hydrometeorological disaster fatalities.

2. Materials and Method

2.1. Study Area

Texas is the second largest state in the U.S. by population and area, with a population of 27,862,596 and a land area of 695,662 km². The southeast of Texas shares 591 km (367 miles) of coastline with the Gulf of Mexico and is susceptible to hurricanes and coastal flooding. A major topographical feature that affects the number of hydrometeorological disasters in Texas is the Balcones Escarpment that consists of a series of cliffs drop-ping from the Edwards Plateau to the Balcones Fault Line. This outer rim of the Hill Country is the formation point for many large thunderstorms, which frequently stall along the uplift and then hover over this region. The "Flash Flood Alley" includes counties having the fastest population growth rates in Texas [25].

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2.2. Data Source

The hydrometeorological disaster fatality information for Texas reviewed in this study was culled from the NCDC *Storm Data* reports for the period January 1959 through December 2016. Before 1996, the data was only available via PDF files accessible at the NOAA/NWS website [26]. From 1996 forward, all events were available on a searchable database accessible through the website portal. Only fatalities that were classified as being directly caused by the incident are included in the study. *Storm Data* lists each incident with the date, time, the number of people who died in the incident, the number of people injured, and a brief description of the event. The descriptions provided along with each event were used to get information related to the gender, age, activity, mode of transport, and location of the individual who died. In 1996 and after, the database provided an accompanying chart of the victims. The chart listed the victim's age, gender, and location. If there was a disparity between the description and the accompanying table, the information in the description was used since the descriptions were often retrieved from the police report that was filed with the death.

The data in the *Storm Data* Publication relies on self-reporting from individual states and counties and is dependent upon the verification and validation of the reporting agency. The *Storm Data* had some inconsistencies from year to year and county to county in the classification of the causes of fatalities. For example, deaths by lightning are classified as either electrical deaths or lightning deaths. Similarly, wild fires or prairie fires are listed under either wind events or wildfire events in the database. Heat-related deaths from the homeless or illegal immigrants in rural counties also have a potential to be under-reported since the location of the victims may remain undetected. As an example of a potential under-reporting condition, the *Storm Data* indicates that before 2008 there were no deaths due to heat exposure discovered along the border of Texas and Mexico. This is unlikely given that the according to the U.S. Customs and Border Protection, 7,216 people have died from exposure crossing the U.S./Mexico border between 1998 and 2017 [27]. In 2005 alone, more than 500 people died attempting to across the U.S./Mexico border [28]. Texas accounts for 64% (2018 km) of all border miles between the U.S and Mexico.

Fatality information was also reviewed from the Hazards Vulnerability Research Institute (HVRI), U.S Hazard Losses Summary Report (1960-2015), to provide perspective for large scale comparisons of trends between Texas fatalities and national fatalities. But the HVRI data was not used in the numerical analysis of spatial and temporal trends that is the basis of this paper.

3. Results

3.1. Types of Hydrometeorological Disasters

The *Storm Data* reports 55 disaster event types. For purposes of this study the disaster fatalities reported in Texas from 1959-2016 were categorized into one of the following nine hydrometeorological disaster types based on the information provided in the incident report or database [29] (**Table 1**). The definitions are consistent with the general classifications of weather disasters as defined by the National Weather Service.

***Table 1**. Definitions of Hydrometeorological Disaster Types*

Disaster Type	Characteristics
Flooding	Floods and flash floods due to extreme rain caused by *hurricanes, tropical storms, or other rain storm events
**Tornado	Wind event meeting the minimum classification of wind speed and ground contact
Lightning	Natural high voltage electrical discharge from atmosphere striking person or surface in proximity of person
Heat	Prolonged period of time with extremely high average temperature usually accompanied by drought

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Cold Weather	Blizzards, snow storms, ice storms, and prolonged period of time with extremely low average temperatures
Wind	Extreme high winds causing damage but not meeting the minimum criteria of hurricanes or tornados
Other	Hail, water spouts, wildfires, or rain that directly resulted in some major structural damage (e.g. roof collapse)
Rip Current	Coastal specific disaster that includes people killed (drowned) in rip currents. Rip currents have only been tracked as of 1997

** The Saffir–Simpson hurricane wind scale (SSHWS), classifies hurricanes as Western Hemisphere tropical cyclones that exceed the intensities of tropical depressions and tropical storms with sustained winds of at least 74mph (Category 1).*

*** The Enhanced Fujita scale (EF) classifies tornadoes based on wind speed and damage (once they have touch ground) from EF-0 (65-85mph) to EF-5 (> 200 mph)*

Approximately 80% (205 of the 254) counties in Texas reported hydrometeorological fatalities in at least one year during the 58-year study period. Figure 1 shows the primary type of disaster that resulted in fatalities for each Texas county. Seven-ty-seven of the 205 counties that reported fatalities indicated that flooding was the primary disaster in their county. Thirty-one counties had more than one predominant cause of fatality and so were not categorized as primary disaster.

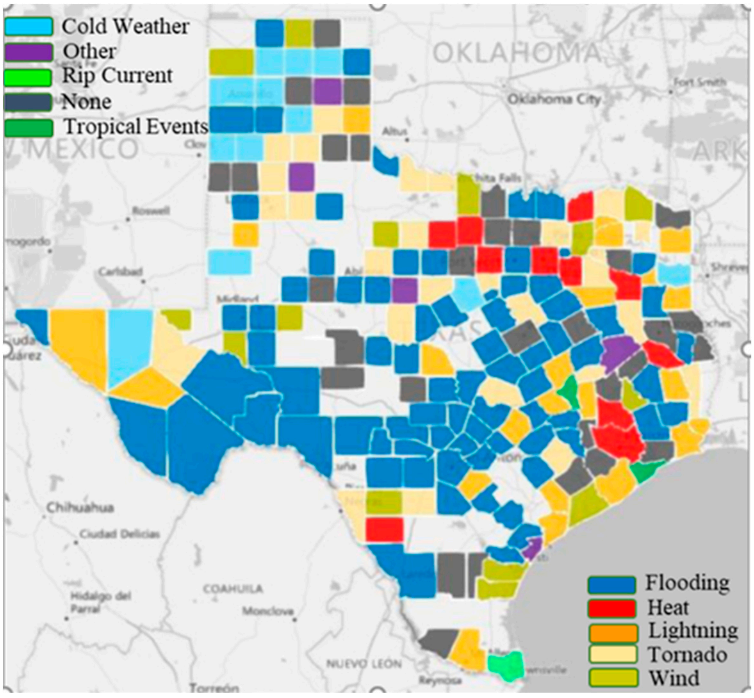

Figure 1. *Primary disaster resulting in largest number of deaths per county. Dark grey = no one predominant disaster. Light grey = No hydrometeorological disaster fatalities reported*

Counties that reported deaths due to flooding as the predominant hydrometeorological disaster are clustered towards the central region of the state and extend west towards Mexico/New Mexico in the region known as Flash Flood Alley. The disasters that caused the greatest number of fatalities along the Gulf Coast of Texas were wind events and lightning (**Figure 1**). Heat-related fatality counties were scattered in 11 counties across Texas and 75% of the cold weather fatality

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counties were in the northwest of Texas (Texas Panhandle) above the 34°N latitude. Fatalities due to tropical events (hurricanes and tropical storms) were all determined to be a result of subsequent flooding and therefore classified as flood-related fatalities. Death due to heat-related events was predominant in Harris County, the most populated county in Texas.

A total of 2,330 natural disaster-related fatalities occurred in Texas from 1959-2016 with 43% due to flooding (991 fatalities) as shown in **Table 2**. The second most frequent cause of fatalities was extreme heat (16%) followed by tornados (14%) and lightning (10%). The single most fatal natural disaster event during this 58-year period was the tornado of April 1979 that struck Wichita and Wilbarger counties killing 54 people and injuring 1,807. This was an EF-4 tornado that had a maximum width of 2.5 km and destroyed a 4 km (2.4 mile) path and also killed four people in the neighboring states of Oklahoma (3 deaths) and Indiana (1 death). Seventy-nine percent (79%) of the total tropical storm-related fatalities were caused by hurricanes (108 deaths).

Table 2. *Hydrometeorological Disaster Fatalities, source: NOAA Storm Data*

Disaster Type	Fatalities	% Total
Flooding	991	42.5
Heat	378	16.2
Tornado	333	14.3
Lightning	222	9.5
Wind	172	7.4
Cold Weather	160	6.9
Other	43	1.9
Rip Current	31	1.3
Total	**2,330**	**100**

**Includes hurricanes and tropical storms*

3.2 Temporal Distribution

3.2.1. Annual Distribution of Fatalities

An average of 42 fatalities per year occurred in Texas from 1959–2016 with a median of 33 fatalities per year and a total of 2,330 hydrometeorological fatalities. The difference between the mean and the median indicates that the annual distribution is positively skewed with long tail in the right direction (towards higher numbers). The raw number of fatalities exhibits a slight increasing trend during the study period. The lowest number of fatalities (6) occurred in 1963 and the highest number of fatalities (118) occurred in 1998 (**Figure 2**). Eleven of the 58 years had an annual number of fatalities greater than the mean plus one standard deviation (40 ± 24).

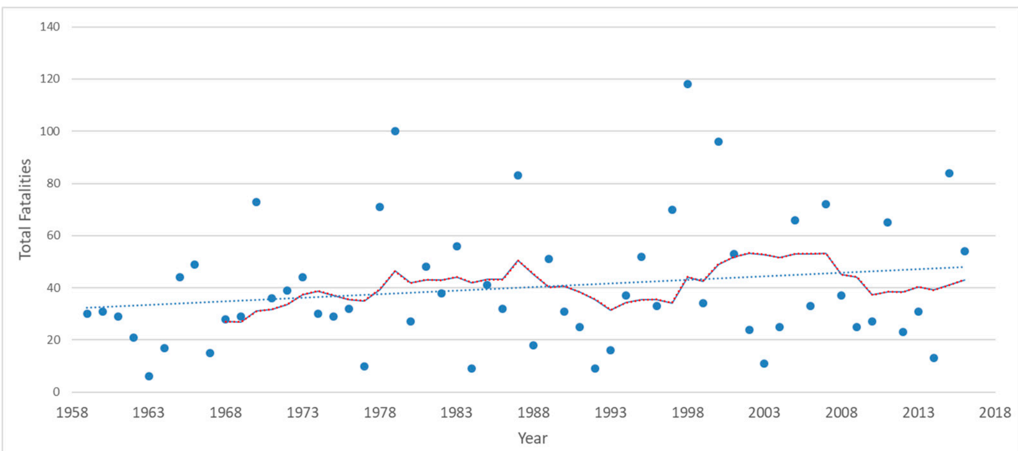

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Figure 2. *Total Fatalities from natural disasters in Texas from 1959–2016 with 10yr rolling average (red dashed line). The solid line represents the linear trend.*

The curve of the cumulative annual fatalities is relatively uniform with two ob-servable spikes in 1978-1979 and 1998 driven by high fatalities resulting from heat and flooding events (**Figure 3**). Specifically, in 1978 Dallas County had 21 heat-related fatalities and 40 flooding fatalities that occurred in several counties in-cluding Bexar, Kerr, Shackelford, Bandera, and Randall counties. From May 1997-Aug 1998 a severe heat event hit the southern region of the United States from Florida through Texas and into Colorado. Conversely, several flooding events in November 1998 resulted in fatalities in Bexar, Val Verde, Caldwell, Guadalupe, and Real counties.

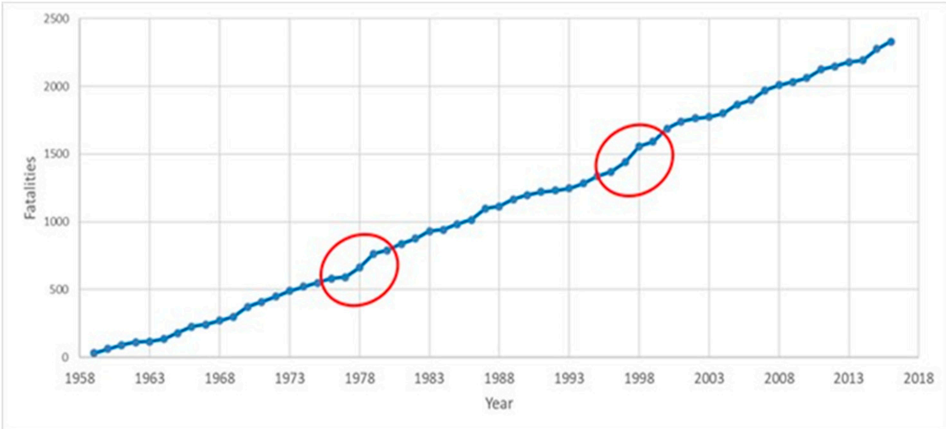

Figure 3. *Cumulative number of fatalities (all disasters)*

However, normalization by population reveals a distinct decreasing trend which correlates to a gradual decrease in the risk of being killed by hydrometeorological events in Texas. The normalized fatality trend can be seen in (**Figure 4**), which shows the number of weather fatalities per 100,000 Texas residents. Public awareness and educational weather safety campaigns in Texas may have contributed to this reduction of risk [13]. Although the rank order of counties by number of raw fatalities aligns with the highest populated urban centers, these regions are not necessarily the most danger-ous. This is evidenced in that several of the counties in immediate proximity to the counties that experienced high fatality have very few fatalities even though the in-tensity and durations of the disasters were probably very similar between the counties.

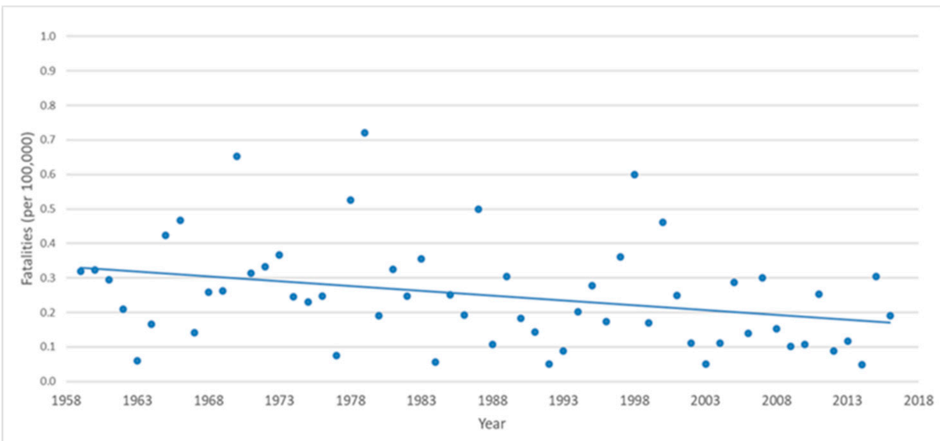

Figure 4. *Normalized Fatalities from hydrometeorological disasters in Texas from 1959-2016. The solid line represents the linear trend*

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For example, Loving county has the highest normalized fatality rate (> 4,000 per 100,000) in the state due to its small and stagnant population and the fact that the county experienced several multi-fatality events of wind and hailstorm that struck the Red Bluff Lake area killing four persons by drowning when their boat capsized in the lake during a squall. Similarly, on June 11, 1965, the city of Sanderson in Ter-rell county was devastated by a flash flood. A wall of water washed down Sanderson Canyon into Sanderson, destroying numerous homes and businesses. Twenty-six people died in the flood. Eleven flood-control dams were constructed to protect Sanderson against another such catastrophe. The town had a population of 1,500 in 1980 and 1,128 in 1990. Reduction of fatality risk in these rural counties will require an increase in awareness through weather-related emergency educational pro-grams and resource assistance (financial and physical) to implement safety systems

The annual distribution of fatalities by disaster type from 1959-2016 for six of the eight disaster types is shown in Figure 5. There seems to be a shift in the number of fatalities at the middle of the study period, especially for tornadoes and lightning. Splitting the study period into two equal parts (1959-1987 and 1988-2016) shows the first half having a greater proportion of the total fatalities for all disasters except for heat-related events. Heat-related events show an increasing trend of 0.45 fatali-ties per year (R^2 =54%) from 1978-2016 with no data available prior to 1978. Eighty-nine percent (89%) of all heat-related fatalities (335 out of 378) occurred after 1994. External factors also may contribute to under-reporting variability of heat fatalities especially along the U.S./Mexico border counties and in the case of chronically ill victims where it is unclear the final cause of death. Immigrant deaths along the border are uncertain due to international policy challenges. Heat deaths may also be under-reported because they depend on the medical condition of the victim. Ex-posure to extreme heat can cause cardiac or respiratory issues that can be fatal. Therefore, the judgment of the medical professional determines the cause of death as exposure to heat or the underlying medical condition.

The difference between the early and the latter half of the study period was high-est for tornadoes with 71% in the first half of the study, followed by 68% for wind, 63% for cold weather, 62% for Lightning, 57% of tropical storms, and 52% for flooding. The other disaster types with at least one fatality per year during the study period are: flooding (57 years), lightning (56 years), wind (47 years), tornado (41 years), cold weather (38 years), heat (26 years), and other (15 years). The year 2011 was the only year that had no reported flood-related fatalities and was also the year that experienced one of the worst droughts in Texas history.

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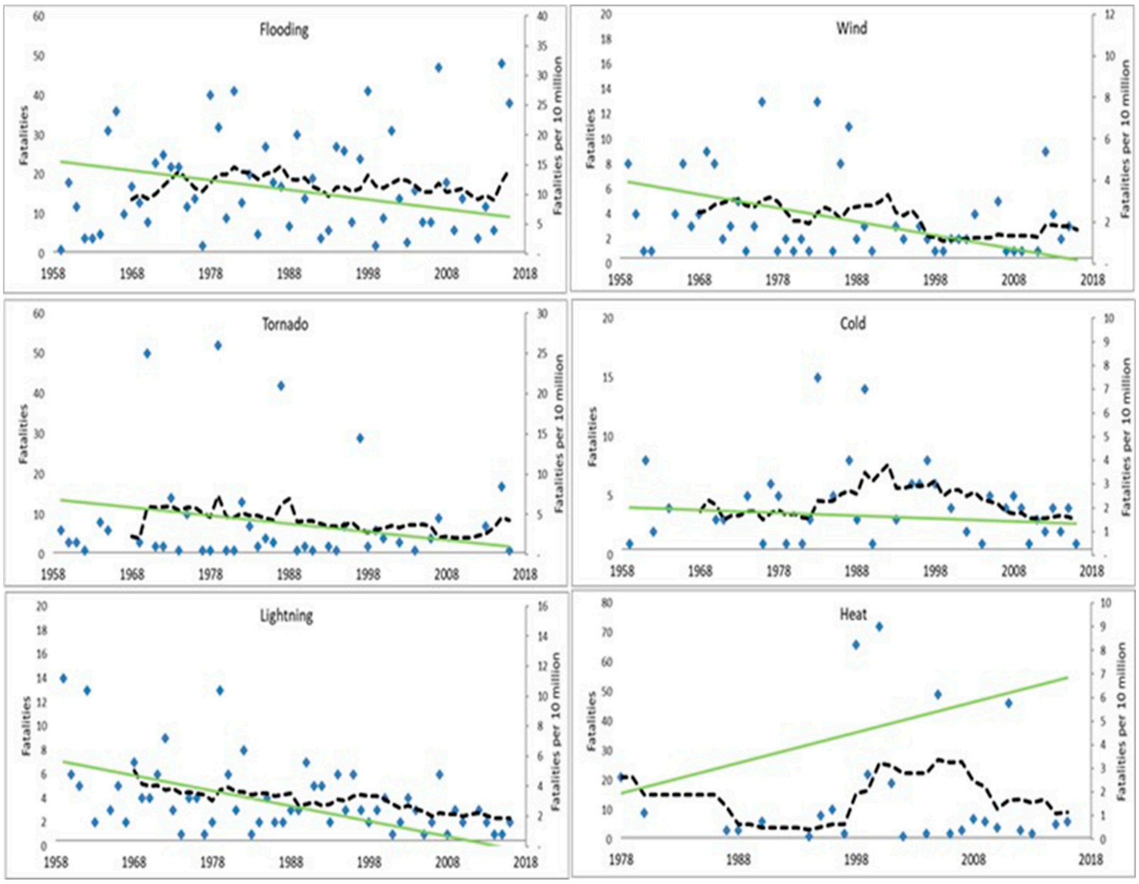

Figure 5*. Annual fatalities in Texas for six disaster types: flooding, wind, tornado, cold, lightning, and heat. Note: Heat fatalities from 1978-2016. 10-yr rolling average (dashed line) and normalized (fatalities per 10 mil-lion) trend line (green solid)*

Fatalities due to tropical events (hurricanes and tropical storms) were mostly due to drowning and therefore were integrated into the flooding fatalities unless there was distinction in the fatality record. Only seven tropical event fatalities occurred during the period 2003 -2007. The disaster category "Other" includes wildfires and other secondary perils that do not frequently result in death, such as hail, water spouts, or rain that resulted in roof collapse. The "Other" disaster category indicated 71% of the years (41 out of 58 years) had zero fatalities with a steady increase in fatalities starting in 2004. Eighty-one percent (81%) of fatalities of this category occurred in 13 years between 2004 and 2016. Rip currents were added to the *Storm data* in 1998. The first reported fatalities occurred in 2007 with two total fatalities at 31 deaths from 2007-2016 with an average of 3.4 per year and a high of 8 deaths in 2011. Five of the 8 deaths were Mexican immigrants visiting the coastal county of Cameron. More years of rip current fatality data is needed to establish any definitive temporal or spatial trends.

3.2.2. Monthly Distribution of Fatalities

The monthly distribution of natural disaster fatalities illustrates the seasonal variability in the number of fatalities for different types of disasters (**Figure 6**). A distinct peak is noticeable in May driven by flooding and tornado fatalities, which are responsible for 80% of the fatalities in the month. During the summer months, most fatalities were due to heat events while spring fatalities result primarily from flooding. Flooding fatalities were highest in the months of May, June, and October with 22%, 17%, and 13%, respec-tively of the total flood-related fatalities. Some disaster-related fatalities are obvi-ously limited to certain seasons such as cold weather fatalities that occur in Winter (85% of all cold weather-related deaths occurred in December, January and

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Febru-ary). Seventy one percent (71%) of all fatalities occurred in spring and summer with an even split between the two seasons.

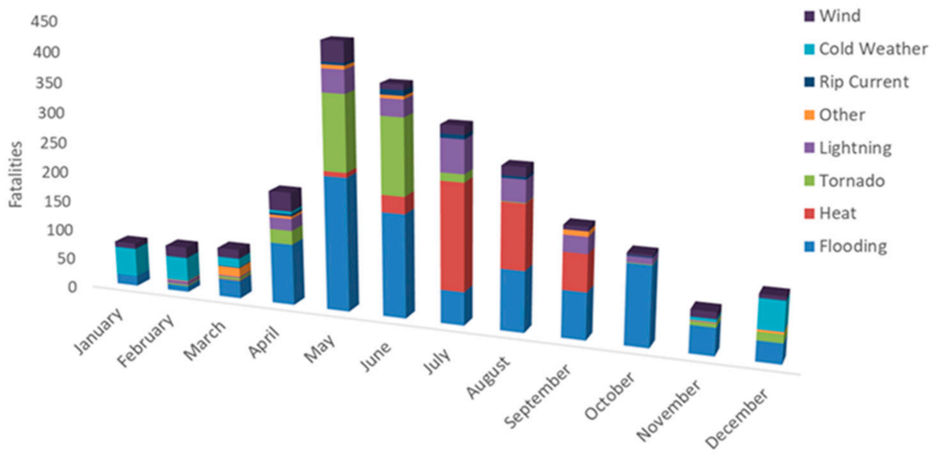

Figure 6. *Monthly distribution of hydrometeorological disaster fatalities (all fatalities)*

A grouping of the months into four seasons, Winter (December, January, February); Spring (March, April, May); Summer (June, July, August) and Fall (September, October, November), highlights the difference in rolling average fatality trends be-tween the first half of the study period to the second half (**Figure 7**). Decreasing av-erage fatalities in spring and winter and increasing averages in summer and Fall with the largest difference in Summer due primarily to an increase in heat-related fatali-ties occurred between 1998 and 2008.

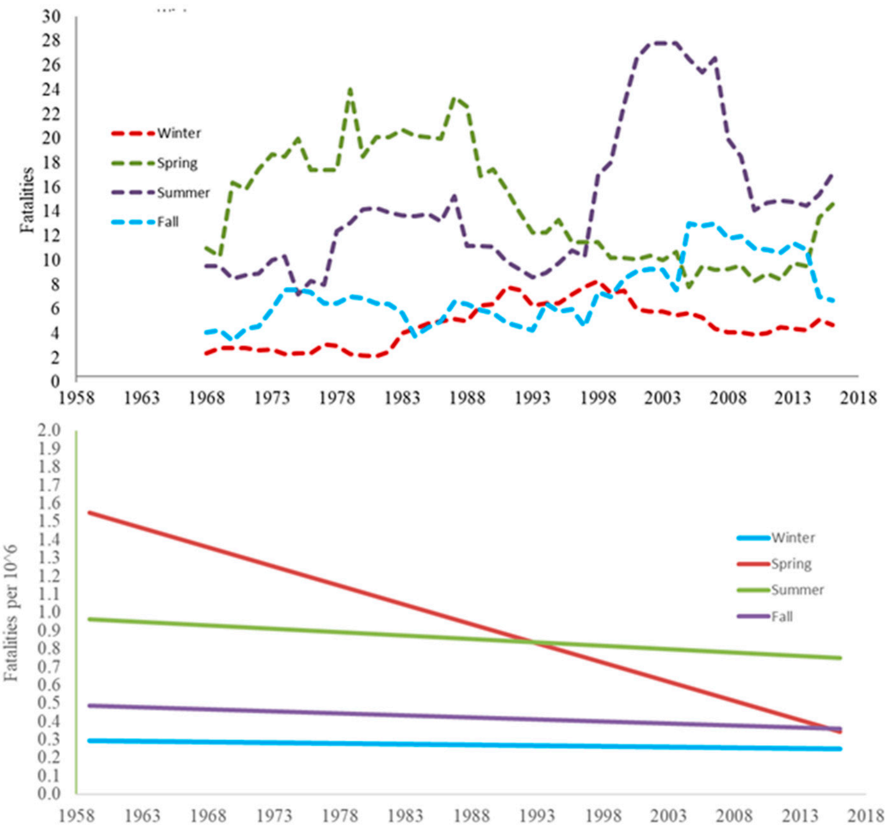

Figure 7. *(Top panel) Number of total fatalities (rolling 10-year averages) by season. (Bottom panel) Normal-ized fatality trends by season.*

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3.2.3. Distribution of Fatalities by Time of Day

The variability of hydrometeorological fatalities by time of the day was examined by assigning the disaster events to one of the four periods in a day-: morning (6am -12pm), afternoon (12pm-6pm), evening (6pm-12am), and night (12am-6am). Time of day was not indicated for 32% of the reported fatalities in *Storm data*. Of the fatalities with the time of death provided, 36% occurred in the afternoon, 26% in the evening, 21% in the morning, and 18% at night. Eighty percent (80%) of the fatalities with unknown time of the day were caused by flooding or heat-related events. Fifty per-cent (50%) of the total fatalities (562) that occurred in the afternoon were due to tornadoes and flooding. Detailed analysis shows that flooding events have a slightly higher chance of causing death at night or in the morning hours. However, tornados are much more likely to fatally strike in the afternoon/evening hours (**Figure 8**).

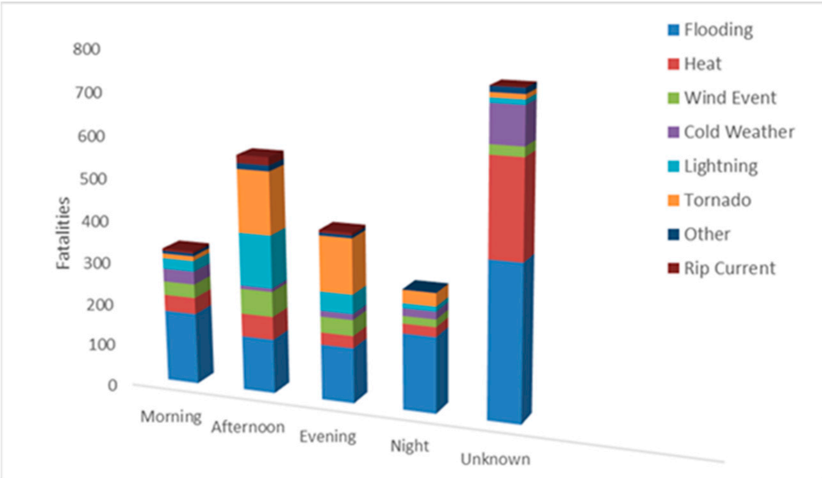

***Figure 8**. Distribution of hydrometeorological disaster fatalities by time of day*

3.3. Spatial Distribution

Most hydrometeorological fatalities occurred in populated counties (Harris (Hou-ston), Bexar (San Antonio), Dallas and Tarrant (Dallas area), Travis and Williamson (Austin) as well as rural counties in west Texas with low populations High fatality numbers are noted in the Flash Flood Alley counties and some coastal counties (**Figure 9**).

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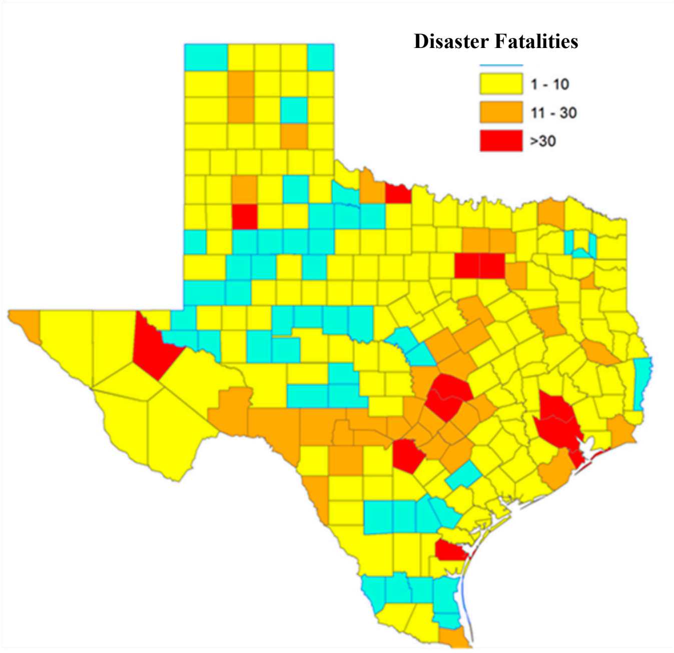

Figure 9. Raw number of hydrometeorological disaster fatalities by county

Table 3 provides the ranking of the top 5 counties with highest number of hydrometeorological ather disaster fatalities which combined, account for 32% of the total hydrometeorological disaster fatalities. Slightly more than 3% of the total reported fatalities did not include county information. Forty-eight percent (48%) of the fatalities in Harris County were caused by heat-related events followed by flooding (33%) and lightning (11%). Heat events also caused the highest percentage of deaths (50%) in Dallas County followed by flooding (65, 29%). Bexar County ranked third with 103 fatalities of which 82% were caused by flooding making Bexar the county the most dangerous in the state for death from flooding (per capita).

Table 3. *Top 5 Texas counties (Raw Fatalities). source: NOAA Storm Data (1959-2016)*

Rank	County	Fatalities
1	Harris	259
2	Dallas	228
3	Bexar	103
4	Tarrant	87
5	Travis	76

The top 5 counties within each hydrometeorological disaster type represent a significant percentage of the overall fatalities within each of the category ranging from a high of 76% of all heat-related fatalities to a low of 28% of all wind event fatalities (**Table 4**). Dallas County is in the top five for six of the eight disaster types (heat, flooding, lightning, cold, wind, and others-not shown in table). Harris is the only county that tops the list for more than one type of disaster and ranks number one for heat, flooding, and lightning fatalities and ranks second in wind fatalities. The top coun-ties with the highest number of fatalities (and most populated counties) identified in **Table 3** also dominate the top 5 ranking of counties in **Table 4** for flooding, light-ning and heat fatalities. Interestingly, although flooding is responsible for 43% of all disaster fatalities in the state, the top five counties only account for 34% indicating that flooding fatalities are extant over a high number of counties.

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***Table 4**. Top 5 Texas counties with highest number of fatalities (and % of total) by hydrometeorological disaster. source: NOAA Storm Data (1959-2016)*

Heat (76%)		Tornado (45%)		Wind (28%)	
Harris	124	Wichita	47	Nueces	16
Dallas	113	Reeves	30	Harris	10
Tarrant	22	Williamson	29	Dallas	8
Montgomery	16	Lubbock	26	Brazoria	7
Travis	12	Donley	17	Denton	7
Flooding (34%)		**Lightning (31%)**		**Cold (30%)**	
Harris	85	Harris	29	Dallas	16
Bexar	84	Jefferson	12	Potter	12
Dallas	65	Dallas	11	McLennan	7
Travis	59	Tarrant	9	Tarrant	7
Tarrant	43	Bexar	8	Castro	6

3.4. Fatalities by Age and Gender

In this study, “Children” is defined as newborns up to 17 years, “Adults” from 18 years to 64 years, and “Elderly” as persons above 65 years of age. Age was pro-vided for only 57% of the total reported deaths (1,333 fatalities) in which “Adults” made up 52%, the “Elderly” 28%, and “Children” 21% of the known fatalities. Adults made up 53% and children made up 27% of all flooding fatalities. This fatal-ity statistic requires more data (age aggregation) and further research into the spe-cifics of the situation before any defensible analysis can be given. On open conjec-ture it can be suggested that flooding is responsible for death of families that either did not evacuate or were killed during the evacuation process on transportation routes. The elderly were mostly at risk for heat events, accounting for 52% of all heat-related fatalities (**Figure 10**).

The gender of the victim was provided in 69% of the reported fatalities. Among those, males made up 68% and females 32% representing an approximate ratio of 9:5. This gender disparity has also been observed in other research, for example in flood-related fatalities [12,13,30,36] and in lightning-related fatalities [31-34]. In all cases there was a high male to female ratio of fatalities. For the current study, the ra-tio of male to female fatalities is approximately 2:1. The greatest disparity was found in wind and lightning fatalities that show a 5:1 ratio of male to female fatalities. Rip currents have only been tracked since 1998 but the data thus far indicates a 30:1 ratio of male to female fatalities.

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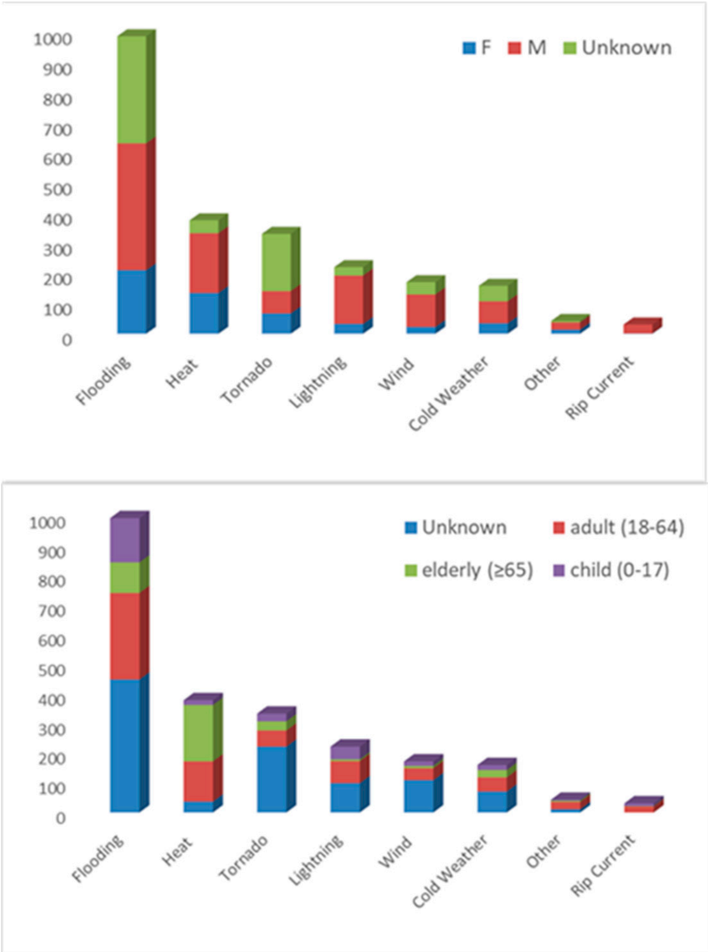

***Figure 10**. Total natural disaster fatalities considered in this study classified by age group (top panel) and gender (bottom panel).*

3.5. Fatalities by Activity Location

The *Storm data* describes 18 potential activity fatality locations. For purposes of this study each of the disaster events reported in Texas from 1959-2016 was catego-rized within one of the following nine locations identified in based on the information provided in the incident reports (**Table 5**).

***Table 5**. Definitions of Hydrometeorological Disaster Fatality Locations*

Location	Definition
In Water	Streams, river, bayous, oceans, floods, etc... and includes activities such as swimming, boating, surfing, and working on oil rigs
By Water	Boat docs, levies, beaches or other types of shoreline appurtenances
Temporary or non-permanent shelters	Tents, car ports, trees, and other temporary shelters that do not have a foundation (excluding umbrellas)

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Outside	People who were outside but not in or near water, people standing in lawns, in construction sites that did not offer shelter, in ball fields, parks, golf courses, etc... People seeking shelter under umbrellas are also included. People standing/sitting near or on top of personal vehicles that are not along a transportation rout are included in outside (e.g. people walking from their home to their car who died before reaching their vehicle, people sitting on top of trucks in fields)
Transportation Route	Roadways, freeways or toll ways, parking lots, sidewalks or air travel routes. People walking along roads who hid behind a vehicle right before the disaster are categorized under transportation routes. Fatalities in vehicles were not assumed to be along transportation routes and were classified as unknown unless the description indicated a transportation route. ***Exclusion:*** People hiking or traveling along non-established routes by foot were not included in this category, and instead were classified as "outside"
Mobile Home	Standard and double-wide mobile homes
Permanent Residence	Domiciles that have a foundation, including but not limited to brick houses, frame houses, and apartment buildings
Public and Permanent Buildings	Schools, restaurants, airports, and other buildings with foundations that are not residences
Other / Unknown	All other locations not described by any of the other location categories listed or if the location was not specified

The location in which the fatality occurred was provided in 75% of the total fa-talities that were reported in Texas from 1959-2016. **Figure 11** shows the stratifica-tion of fatalities by location of occurrence and disaster types considered in this study. Fatalities with known locations, occurred most often (38%) on transportation routes such as roadways, freeways or toll ways, parking lots, sidewalks or air travel routes. Automobile accidents are not categorized as transportation routes unless they were specified as such in the report. Eighteen percent (18%) of known location fatalities occurred in "Permanent Residence", followed by "Outside" and "In Water" at 16% and 15%, respectively. The high incidence of fatalities in and around certain activity locations observed in Texas is also highlighted in research conducted in Switzerland for the period 1946-2015 [35] in which the researcher noted the greatest number of natural disaster fatalities occurring on transportation routes (33%), fol-lowed by in or around buildings and open terrain.

Sixty-five percent (65%) of fatalities on transportation routes were caused by flooding. This percentage is potentially underestimated since 65% of the fatalities in an unknown location were caused by flooding. As noted in other Texas flooding fatality studies [36] driving into flash flooding conditions is a significant occurrence that would make it very difficult to assign a location with no clear transportation route known. Also 25% of tornado fatalities are reported with an unknown location. Forty-eight percent (48%) of heat-related fatalities occurred in permanent residenc-es. Tornados caused 73% of all hydrometeorological disaster fatalities reported in mobile homes. It must not be overlooked that the "Other" category included 11 deaths of children as result of being left in a car unattended and succumbing to heat exposure, a very preventable tragedy.

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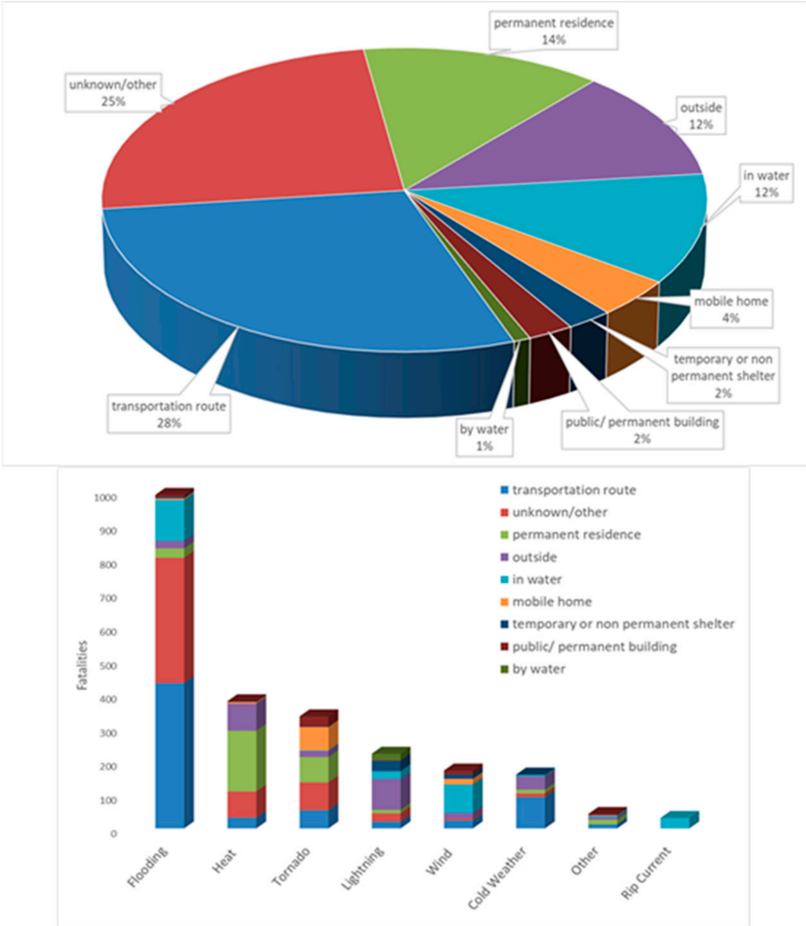

***Figure 11**. Hydrometeorological disaster fatalities classified by reported location of occurrence (top panel) and by disaster type and location (bottom panel)*

4. Discussion

The predominant types of natural disasters in Texas that result in fatalities are those initiated by weather conditions such as flooding, tornadoes, and extreme temperatures. This study is not intended to study the climate conditions that trigger dis-aster events, but rather to analyze the spatial and temporal distribution of fatalities by disaster type. Regardless of the reasons for these changes in hydrometeorological disaster events, the parametric shifts of frequency and intensity can challenge the preparedness and resiliency of a region and in many cases impact the number of fatalities incurred. Analysis of hydrometeorological disaster trends based on historic data can enhance predictability and preparedness planning to reduce the loss of life. Regional mortality and morbidity is also affected by the demographics and behavior of the people in the region of impact, specifically age, gender, and behavior patterns (location) have an observable relationship to the number of hydrometeorological disaster fatalities.

4.1 Population and Fatality Trends

Texas exhibits regional variability in the number of disaster fatalities that is weighted to regions of high population. This suggests that as more people continue to move into populated urban areas or into regions that are at higher risk for hydrometeorological disasters such as flood plains, tornado alleys, or coastal regions, the number of total fatalities will likely increase with or without an increase in the number of disaster events. Highly populated regions are more susceptible to a higher number of natural disaster fatalities than lower populated regions due to the sheer number of persons per area. As the population of Texas and the number of hydrometeorological disasters continues to increase, the result will likely be a continuing increase

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trend in the number of hydrometeorological fatalities. The current population growth rate for Texas is 1.8% which is the third in the U.S. According to the Texas Demographic Center [37], the vast majority of population growth since 1850 has occurred in metropolitan areas while the population in non-metropolitan counties has declined. This urban population increase coincides with an increasing trend of the annual fatalities as noted in ***Section 4.2.1***.

The counties with the highest population density: Harris, Dallas, Bexar, and Travis had the highest number of actual fatalities, but each had a fatality rate below 15 fatalities per 100,000 persons over the study period. In contrast, some counties with lower populations had much higher per capita fatalities (higher risk for fatalities) although they were adjacent to the high population counties and experienced similar hydrometeorological disaster frequency and intensity. For example, Bexar county had 8.7 fatalities per 100,000 while surrounding county of Comal had 188 fatalities per 100,000 people. Harris county had 9.5 fatalities per 100,000 and the surrounding counties of Brazoria Chambers had 55 and 40 fatalities per 100,000 respectively. Figure 12 shows that per capita fatality rates are highest in sparsely populated counties in the southwestern portion of Flash Flood Alley and the Texas Panhandle in the northwestern part of the state.

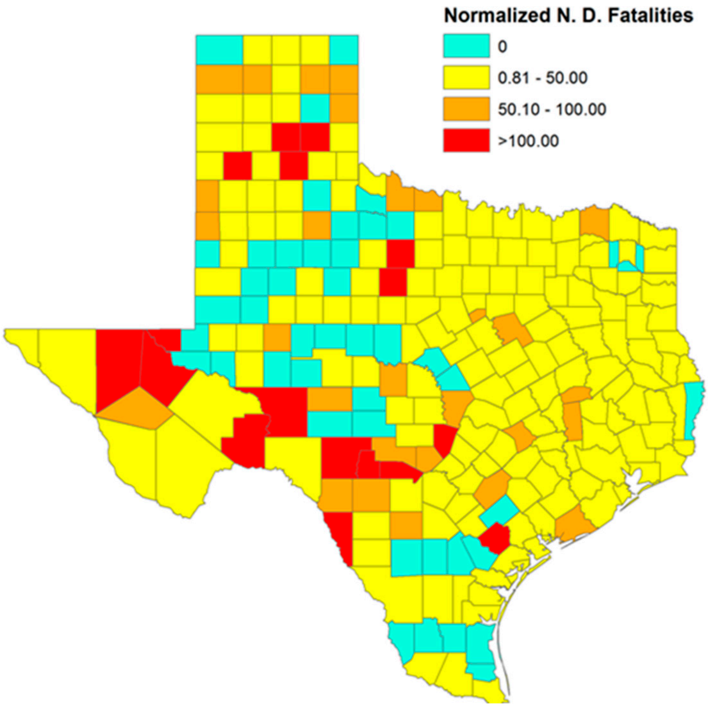

***Figure 12**. Fatalities Normalized by Population (per 100,000)*

4.3. Activity Locations for Fatality Occurrences

Slightly less than 30% of the total number of the reported hydrometeorological disaster fatalities (2,330) identified transportation route as the activity location and 25% of the total number of reported fatalities identified no activity location. With only 75% of the reported fatalities providing an activity location of occurrence there is uncertainty in any trend analysis, but the available data strongly suggests that transportation route is the leading fatality location. Approximately two-thirds (65%) of the fatalities on transportation routes were due to flooding suggesting that driving into flood conditions is a frequent high-risk and activity that likely contributed to many of these deaths. This conjecture is similar to findings of research conducted in the Switzerland study for the period 1946-2015 [35]. Research conducted in 2015 at the University of Texas [13] found that 73% of the flood fatalities in Texas were vehicle related with at least one fatality per year and 16.5% of flood fatalities due to people walking into floodwaters from 1959–2008. The research from this study as well as the current study suggests that flood fatalities are likely underestimated since a large percentage of

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fatalities with an unknown location were due to floods, suggesting probable vehicle related incidents with no clear transportation route documented.

The number of fatalities on transportation routes are directly related to the number of people on transportation routes which is related to the economic development of the affected region and the demographics of the people professionally and personally committed to the transportation routes. Developed economies result in more transportation between place of employment, schools, commercial and recreational destinations. This skew may be offset since regions of greater wealth and communication networks are more likely (have the ability) to evacuate out of harm which reduces the number of fatalities when compared to regions of lower wealth and economic development who are unable or unwilling to evacuate. The employment rate, family structure (dual income/single income), cultural norms, and habits and behavior of the affected population significantly impacts the location of individuals at any given time and thereby impacts the number of fatalities experienced by hydrometeorological disaster events.

4.4. Gender and Age

Although gender and age were not reported for a large number of disaster fatality victims, the available information indicates more male fatalities than female fatalities. The gender gap in hydrometeorological fatalities exhibited a decreasing trend from the early years of the study to the more recent years suggesting a change in exposure possibly due to shifting roles and responsibilities of men and women in society.

Gender and age are two key demographics that are exhibited in lifestyle, behavior and risk tolerance that ultimately affect the fatality rate. Female fatalities due to natural disasters increased significantly from the first to the second half of the study period. The 10-year rolling average more than quadrupled from three deaths in 1969 to 13 deaths in 2016. For the male population, the 10-year rolling average only in-creased (180%) from 10 deaths to 28 deaths during this same period. If it is generally accepted that contemporary (2017) societal gender roles and responsibilities are not the same as they were in 1959, some reasons for this difference may be in changing situational exposure of the workforce coupled with the level of risk accepted by males versus females. Situational exposure is evident in the recent trend which has seen more females taking on historically male work roles (e.g. outdoor, labor) and more roles such as nursing, secretarial and service positions.

The impact of gender and risk tolerance is highest in the rip current fatality numbers culled from a limited time period (1997-2016) with a 30:1 ratio of male to female fatalities. Deaths from rip currents are not due to differences in societal roles but more so to differences in risky activities assumed to be safe when they are not (swimming and water sports in an area and time of rip current activity). Tornado fatalities are an outlier to the general trends exhibiting a higher female to male fatality ratio, but more data is needed since a potential skew may exist since only 50% of all tornado fatalities reported gender.

Risk tolerance also changes with age. Within the fatalities that included age (54% of total fatalities), two high risk groups stand out with the largest number of fatalities; 20-29 yrs. young adult age group and the 70-79 years age group. Changes in priori-ties, family, education, and responsibilities occur for most in this 50-year span and the accepted risk taking from youthful invincibility (such is likely the case for this age group that frequently drive into flash flood conditions), typically progresses to a longer period of more stable (less risky) lifestyle, until the later years when human vulnerabilities of age-related health limitations and immobility issues results in an increase potential for succumbing to hydrometeorological disasters. The limited number of fatality reports with age information available in this study increases the uncertainty within the trend analysis and is an area that warrants further research. But within the confines of the given data, the elderly appear to be most susceptible to hydrometeorological disaster fatalities based on the percentage of total fatalities and the relatively low over-all percentage of the Texas population that is elderly. U.S Census Bureau (2016) statistics indicate that Texas population is 27.3% (<18years, child), 62.4% (18-64years, adult), and 10.3% (≥ 65 years, elderly). The age of the national and state populations overall is increasing and therefore the 2010 census estimates are conservative when

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comparing the fatalities among the age groups from this study taking into account the much smaller number of elderly population versus younger age groups [25].

This study identified that the top two locations for elderly hydrometeorological disaster fatalities occurred in permanent residences (45%) and transportation routes (24%) which suggests a high risk to the homebound elderly segment of the population and to elderly when evacuating a disaster. Heat events and flooding were the top two disasters killing the elderly accounting for almost 80% of all elderly fatalities. The number of heat related fatalities is on the rise across all age groups but is particularly evident in the southwest of the U.S. and is usually combined with an extended drought period. Increasing global temperatures may be a factor in this trend with 2016 having the highest average temperature on record as well as the highest monthly temperatures in eight of the 12 months (Jan-May and July-Sep) [38]. With heat-related deaths heavily weighted towards the elderly that sometimes do not have family or social networks to acknowledge and report their demise, the fatalities may be under-reported

The elderly are not only at risk of heat-related fatalities, but are also very vulnerable to flooding triggered by heavy rains and/or high winds such as exist in hurricane or tropical storm conditions. Flooding fatalities ranked second for the elderly in the study but 45% of all flooding fatalities not reporting age of the victim, there is some uncertainty in this statistic. More certain is that flooding devastates a community on many levels including power interruptions and blockage of transportation routes. Medical attention is a necessity for many elderly whether it is within a medical facility, nursing home or the need to obtain prescription drugs. All these are typically inhibited during a flooding condition. Although there is debate on whether it is safer to evacuate or shelter the elderly in place during a flood, improvement strategies to reduce fatalities should not be stalled until final consensus.

The study also found that flooding was responsible for 53% of the total hydrometeorological disaster fatalities where the victims were known to be children (< 18years). Young children are dependent on the care and good decisions of parents or guardians. Data from this study indicates the top activity location for child flood fatalities is on transportation routes (38%) and seems to support the conjecture.

4.5. Evacuation or Shelter in Place

In response to a pending flood or hurricane event, unless there is a mandatory evacuation order given by the city or county jurisdiction, the critical questions to con-sider is whether it is safer to evacuate by driving or walking to the evacuation location or if there is less risk of harm to shelter in place. For example, although flood fatalities are most likely to occur on transportation routes, all 68 fatalities (except one) during Hurricane Harvey occurred inside homes. Several factors should be considered when deciding to evacuate or shelter in place such as the perceived risk to the specific area of residence, number of children and elderly in the family, health condition and mobility of each family member, condition of the shelter residence, condition and availability of transportation, and evacuation destination distance. The decision to evacuate during a hurricane or flood can be the difference between life and death.

This decision becomes especially critical with regards to the elderly residing in nursing homes and long-term care facilities (LTCF). Research conducted in 2017 by Pierce on disaster preparedness of LTCF [39] found deficiencies in integrated and coordinated disaster planning, staff training, practical consideration before governments order mandatory evacuations, and accurate assessment of the increased medical needs of LTCF residents following a disaster. Previous research on the management of nursing home residents [40] found that, "the decision to completely evacuate, partially evacuate (including transfers of individual residents), or to shelter in place must be based on the integration of real-time data regarding the disaster event, the facility in question, and the clinical profiles of the residents at risk". Similar re-search by Dosa et al. specific to Hurricane Katrina and Rita based on a survey of LCTF administrative directors noted a much higher mortality rate with evacuation actions than with shelter in place that was attributed to lack of governmental assistance,

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unsupported technical and physical requirements for transportation, and difficulty in retaining adequate staff [41].

4.6. Temporal Distribution

The annual trend of raw fatalities is increasing from 1959-2016 with a maximum of 118 fatalities in 1998 due primarily to heat events in the months of July and August and flooding in August and October. Stratification of total fatalities by season indicated that the majority (70%) of all fatalities occurred in spring and summer with floods as the predominant disaster in spring and heat-related deaths in Summer. Monthly variation indicates the highest risk for flooding and tornado fatalities in April and May and the highest risk of heat events in August and September. Within the 68% of the hydrometeorological disaster fatalities that reported the time of day, the data in this study suggests that the afternoon period has the highest risk of fatality from tornado, flooding, or lightning.

Based on the current level of understanding in the relationship between earth sciences and meteorological conditions there is limited scientific predictability of disaster impacts. Predicting hydrometeorological disasters is challenging not only from a scientific basis but also because the number of fatalities is not solely a factor of the type of the disaster but is impacted by societal activities of the region in which the disaster event may occur. In general, hurricanes have some level of temporal probability and typically make landfall at night when the storm strengthens due to the latent heat release in the upper and middle atmosphere (reference?). Tornadoes also tend to occur in the late afternoon and early evening hours, when the atmospheric conditions are most ripe for supercell thunderstorms and are most common from 4pm to 9pm in the evening [42]. Disaster events such as flooding are dependent on the amount and rate of precipitation and location of adjacent bodies of water (coastal, riverine, or inland). The resulting impact of such a disaster is a function of the activities occurring in the community affected at the time of the flood such as transportation density. Other factors include the level of early warning and evacuation, the time of the day of the flooding to accommodate or hinder rescue and transport ef-forts.

Similarly, if tornadoes strike during the day (especially a weekday) more people are at work or school and are in buildings where there are adequate public shelter facilities that typically are more disaster resilient than a private residence. Although one quarter of tornado deaths did not include an activity location, within the known study data, only 12% of the fatalities occurred in public/permanent buildings to support this conjecture. The study data also identified that more than 80% of lightning fatalities occur outside, in or around water and temporary shelters. The extent of fatalities due to lightning is an example of the combined effect of the disaster it-self and the societal activities. Lightning fatalities have decreased significantly on a national and state level in the last several decades as a result of a decrease in expo-sure (outdoor labor, agricultural work) and the strengthening of OSHA (Occupation-al Safety and Health Agency) safety protocols. Children and adults are the high-risk age groups for lightning fatalities and mitigation efforts to reduce the number of fatalities can include increased public awareness in school and at the workplace to move or stay indoors during pending lightning events. An interesting note is that an early morning lightning strike is the most powerful and lethal because the electric charge builds up overnight [43].

5. Conclusions and Recommendations

This study reviewed hydrometeorological disaster fatalities in Texas covering a 58-year study (1959-2016) with the objective of providing perspectives and information to further enhance public awareness, investment in infrastructure improvement, and serve as input to the programs, policies, and mitigation plans such as the State of Texas Mitigation Plan all with the objective to further reduce the number of fatalities for Texas residents. The ability to reduce the number of hydrometeorological fatalities in Texas should not be underestimated. Resources are available but require political will to drive prioritized allocation to ensure weighted coverage in the highest risk areas. Information gleaned from the review of trends from historic hydrometeorological disasters

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such as contained in this study can assist decision-makers in the best allocation of re-sources to provide maximum mitigation potential for high risk disasters and regions.

Flooding, heat, and tornado events rank as the top three causes of hydrometeorological disaster fatalities in Texas. Regions that are prone to flooding are predominantly in the counties within the regions known as Flash Flood Alley and are predominant on transportation routes. Therefore, risk reduction can be supported by investment in roadway flood control improvement including early warning flash flood signage, al-ternate routes in case of emergencies and mandatory evacuation, preemptive public transportation emergency protocols, and public awareness through education pro-grams. Tornadoes occur most often in the northeastern counties of Texas, particularly in the months of April and May, and predominantly affect those in temporary or non-permanent shelter (e.g. mobile homes). Contingency planning for the segment of society that is vulnerable to tornadoes can include more frequent public aware-ness and information campaigns during these months along with practice drills for what to do and where to go in case of a tornado touchdown. Ensuring that emergency shelters in proximity to mobile home communities are available, accessible, and publicized during these high-risk months also has the potential to save lives. Heat fatalities have a strong correlation to counties with high population density as well as disproportionately effecting the elderly segment of the population. Dedicated financial support can improve emergency preparedness for the elderly in nursing homes, long-term care facilities and private residences to ensure backup power, channels of communication, and available transportation to address immobility is-sues for the elderly in the case of mandatory evacuation or the necessity to shelter in place.

Similar basic considerations can also reduce the risk of fatalities for cold weather, wind events and other types of natural hazards. It is imperative that re-search builds on historic data to better understand the synergy between high risk disasters, regions and vulnerable segments of society to reduce the risk of hydrometeorological disaster fatalities in Texas

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Conflicts of Interest: The authors declare no conflict of interest.

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