A GEOGRAPHICAL ANALYSIS OF FLOOD CASUALTIES IN THE UNITED STATES

by

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(Under the Direction of Andrew J. Grundstein)

ABSTRACT

Flood hazards in the U.S. can be observed by both loss of life and property. Every state in the U.S. experiences floods, and consequently, all are vulnerable to their impacts. The purpose of the study is to illustrate flood hazards in the U.S., investigate the correlation between flood magnitude and fatalities, and examine the relationship between flash flood warnings and fatalities.

A comprehensive, nationwide database of the conterminous U.S. was compiled for 1959-2005 in order to complete the objectives of the study. This study finds that flash floods are the leading killer among flood types with the majority of the casualties being male and vehicle-related. Spatially, flood casualties are distributed across the U.S. with notable clusters found along the Interstate 95 corridor in the Northeast, throughout the Ohio River Valley, and along the Balcones Escarpment in south-central Texas.

Secondly, the study examines the relationship between flood magnitude and flood deaths. A low, but significant, relationship was found between the two variables. This low correlation indicates that other factors, especially social characteristics, may help delineate deadly from non-deadly flood events.

Lastly, in examining the relationship between flash flood warnings and flash flood fatalities, it was determined that 40% of all deadly events from 1986-2005 were not warned for in the county of the fatality. A comparison of unwarned events between 1986-1995 and 1996-2005 showed that the percent of non-warned deadly flood events decreased 19% from the first 10 year period to latter 10-year period. A flash flood index map illustrates counties with high actual flash flood deaths relative to the county's potential for flash flood deaths. Counties with a lower potential (or risk) for flood deaths (based on population density and total number of flash flood warnings issued over the 20 years) displayed disproportionately higher actual deaths relative to their potential.

INDEX WORDS: Flood, Hazards, Casualties, Warnings, Geography

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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Introduction

On 28 June 2006, three young adults drowned in floodwaters in western Maryland when their vehicle was overtaken by high water (CNN 2006a, b). On this same day, two youths were reported missing in Maryland after they did not return home from playing near a flooded creek. Another incident occurred just over a month before this recent deadly event; a 4-year old Kentucky girl was found trapped inside a vehicle that was washed away by floodwaters. Two adults in the vehicle were able to escape. Reports similar to these occur too often across the U.S.

Flooding occurs in all 50 states of the U.S. with nearly every community exhibiting some type of flood problem evident by regular flash floods, ice jams, or tropical system floods (French and Holt 1989). The devastating part of these floods comes in the form of human casualties and property damage. Since the 1970s, the loss of life associated with flooding has been higher than that experienced during the early and mid part of the 20th Century (Kunkel et al. 1999), despite advancements and increased sophistication of warning systems. The rise in casualties may be due to the increase in flash floods during the 1970s and 1980s in areas of high orographic relief (Riebsame et al. 1986), an increase in heavy precipitation events (Karl and Knight 1998), or an increase in U.S. population over the 20th Century (U.S. Census 2000).

Flooding can be separated into three types: flash flooding, river flooding, and coastal flooding (French and Holt 1989). Flash flooding is defined by the National Weather Service (NWS 2005a) as "a flood that rises and falls quite rapidly, usually as a result of intense rainfall over a small area, in a short amount of time, usually under 6 hours." Whereas, river flooding is defined as "the rise of a river to an elevation such that the river overflows its natural banks causing or threatening damage" and coastal flooding pertains to "flooding which occurs from storms where water is driven onto land from an adjacent body of water. These can be hurricanes, 'nor'easters,' or tropical storms, but even a strong winter storm or thunderstorm can cause this type of flooding" (NWS 2005a). Globally over the 20th Century, floods have killed approximately 8 million people, but have no doubt affected more (Jonkman and Kelman 2005). Floods also inflict economic loss, cultural damage, and ecosystem damage. Mitchell and Thomas (2001) report that the monetary loss estimates from flooding is almost $4.4 billion annually in the U.S. alone based on data from 1975-1998.

Fatalities and injuries due to floods are partially a result of the rapid movement of the flood waters that are made more powerful with the added burden of boulders, fallen tree limbs, and other debris that are swept into the waters during a flood (French and Holt 1989). The behavior of people is also a contributing factor to the loss of life and injury from flooding. An example of the role of human behavior was seen in the 1977 flash flood of Kansas City, KS, where 25 people were killed (NOAA 2005). A man accompanied by his wife and two children drove their car through window-deep flood water, despite witnessing several cars ahead of him stall in the water. Consequently, all four occupants of the car died. Many such flood-related deaths and injuries can be attributed to careless human choices.

For any given year, 107 people are killed on average in the U.S., although this number can be drastically higher due to fatalities that occur due to a single flooding event (NWS 2005b). An exceptional example of an anomalous year is 1972, and the flood event that occurred on 9-10 June in the Black Hills of South Dakota. Over those two days, a flash flood ravaged the town of

Rapid City, SD killing approximately 230 people and injuring nearly 2,900 (Bryant 2005). Almost 35cm of precipitation fell from a thunderstorm in only six hours: consequently, a dam, built in the early 1930s on Rapid Creek collapsed causing the flood waters to descend upon downtown Rapid City. Other catastrophic events can be seen throughout the 19th and 20th Centuries, especially by floods in less developed parts of the world. For example, in China, the devastating floods of 1887 and 1939 killed approximately 900,000 and 500,000 people, respectively (Knox and Kundzewicz 1997). These historical cases indicate that a single event can prove to be quite devastating to the population of a town or city. As with all hazards, there is the continual need to improve warning practices and mitigation activities associated with floods, while constantly educating the public of the potential vulnerabilities associated with floods.

1.2 Rationale

In addition to the extreme power behind flowing water and human beings' behavior, the location of towns and cities is instrumental in contributing to flood fatalities and damage (O'Connor and Costa 2003). As of the year 2000, more than 3,800 towns and cities were located on floodplains adjacent to rivers in the U.S. (Miller and Miller 2000). Because of these three contributing factors, it is not unexpected to learn that floods are the highest ranking hazard in terms of property loss and second deadliest hazard in the U.S. (Mitchell and Thomas 2001, NWS 2005b).

The average annual number of deaths from floods in the U.S. is approximately 100, although depending on both source and period of record this estimate may vary. The NWS data show that over the 30-year period of 1974-2003, flood-related deaths averaged 107 per year (NWS 2005b). While, Jonkman (2005) reports the average number of deaths in the U.S. is 100 per year based on data from an international database (OFDA/CRED International Disaster Database). Regardless of this discrepancy, deaths from floods are slightly greater than the 93 people who are, on average, killed by lightning strikes per year (Lopez and Holle 1996). While the average number of fatalities remains around 100, there is a disparity in the value across datasets examining flood casualties. Therefore, this research compiles an extensive database of flood casualties in the contiguous U.S. to define and illustrate the geography of flood casualties in the U.S. and, subsequently, examine the relationship between flood deaths and the magnitude of the flood as well as the relationship between flash flood warnings and deaths.

Despite the large number of flood fatalities annually, no single study has examined the flood fatalities over a long period nor thoroughly examined injury statistics. This study examines both flood fatalities and injuries from 1959-2005. Moreover, no study has presented the flood fatalities and injuries geographically for the entire U.S. The spatially explicit approach employed for this research highlights the vulnerability, or potential for loss, of the population of a city or county to flooding (Hill and Cutter 2001).

The following research conducts a comprehensive flood analysis focusing primarily on the hazards of floods as seen by the reported deaths and injuries. This is accomplished by first creating a database of flood-related fatalities and injuries (the term casualties will often be used to refer to both injuries and fatalities) as reported by *Storm Data* for the past 47 years (1959-2005). Subsequently, this research illustrates the geography of flood casualties, investigates the role that flood magnitude plays in creating a deadly flood event, and lastly, examines the relationship between flash flood warnings and flash flood fatalities.

1.3 Research Questions

In order to achieve the overarching goal of this study of flood-related hazards; three objectives are presented each with their own specific research questions. In order to analyze the initial objective of this study, a database of flood fatalities and injuries was manually compiled. No study has analyzed the data over such a long period of record (i.e., 47 years), mapped each fatality, or included injury data. This database includes those casualties from 1959-2005 as reported in *Storm Data* that are exclusively a result of flooding events in the conterminous 48 states of the U.S. This newly constructed database contains such information as: type of flood event (e.g., flash flood) causing the casualty, gender and age of reported casualties, and, a description of activity (or location) of death/injury. It is hypothesized that both physical (i.e., region in U.S., activity) and social (gender, age) characteristics are related to the vulnerability associated with flood casualties in the U.S. The following research questions are posed:

- What is the spatial distribution of flooding casualties in the U.S. from 1959-2005? Are there regions of the U.S. that have a higher frequency of flood-related casualties than other regions?
- What are the annual, seasonal, monthly, and daily patterns of flood-related casualties?
- Do population demographics (e.g., gender, age) increase vulnerability to flood events?
- How are the flood-related casualties distributed across flood types (i.e., flash flood, river flood, tropical system)? Furthermore, are the flood types region-specific?
- What situations are most commonly associated with flood casualties? That is, is the victim within permanent structure, along a stream channel, or within their vehicle?

To date, no study has examined the relationship between flood magnitude and flood fatalities for a single drainage basin or multiple drainage basins in the U.S. Much of the literature provides only information on a single catastrophic rainfall and flooding event typically focusing on either the meteorology of the event or the hydrologic aspects of the event, e.g., peak discharge or return period (Colwick et al. 1973, Maddox and Grice 1986, Smith et al. 2000, Smith et al. 2001, Zhang and Smith 2003, Delrieu et al. 2005). The literature does not include research on the physical disparities between deadly and non-deadly floods. Therefore, the second objective includes an investigation into the relationship between flood magnitude and fatalities in the Guadalupe River Basin in Texas. Moreover, it answers these questions:

- Is there a relationship between the flood magnitude of a river and number of resulting deaths?
- Do floods with higher peak discharges and return intervals typically cause more fatalities?

As a third objective of this study, the relationship between flash flood warnings and flash flood deaths is investigated to determine whether flash floods that are warned result in fewer fatalities than those that are unwarned. Only one study, by French et al. (1983), has examined the association of warnings and flash flood mortality. However, their study was restricted to flash flood "disasters" from 1969-1981 – those events that produced at least 30 deaths or greater than $100 million in property damage. Therefore this study seeks to answer the following questions:

- Are flash floods that cause fatalities being warned well? Are these fatalities occurring in the flash flood warning area?
- Do the flash flood warning areas in the U.S. from 1986-2005 coincide with the distribution of flash flood fatalities?

- Do regions with a high potential for flash flood fatalities observe a high number of actual flash flood fatalities?

1.4 Literature Review

The loss of life associated with flooding has been studied, to a limited extent, from both a nationwide and global perspective (Jonkman and Kelman 2005, Jonkman 2005, Coates 1999, Dittmann 1994, French et al. 1983, and Mooney 1983). Additionally, statistics (e.g., peak fatality months, top ranking fatality states) on natural disasters, including information on floods, have been documented and compiled by Bryant (2005), Mitchell and Thomas (2001), Thomas and Mitchell (2001), Malilay (1997), and Showalter et al (1993).

French et al. (1983) compiled all flash flood reports from 1969-1981 for the U.S. that involved greater than 30 deaths or at least $100 million in property damage using NWS survey reports. During their period of record, 32 flash floods occurred, resulting in 1,185 deaths. Arizona, Texas, and Pennsylvania lead the states in the highest number of flash floods per state, and Arizona had the highest average number of deaths per event. Moreover, French et al. (1983) found that from these 32 flash flood events, 93% of these deaths were due to drowning while 42% of these were vehicular related. Investigating a much shorter time period, Mooney (1983) looked at fatalities associated with flash floods from 1977-1981 using records from *Storm Dat*a. Of the fatalities that included information on how and where they occurred, nearly half occurred in vehicles and those younger than 21 years and older than 60 were the most susceptible to flood events. Coates (1999) found that fatalities are highest among men (80.6%), with majority of deaths occurring when the victim attempted to cross a flooded creek, bridge, or road (38.5%) or was in the victim’s house (31.5%). Zevin (1994) reports that approximately 40% of fatalities occur during stream crossings or in a vehicle.

More recently, Dittmann (1994) has compiled flood-related deaths, including those from flash floods, river floods, dissipated tropical cyclones, and mudslides accompanied by excessive rainfall, for the U.S. and Puerto Rico during the period 1959 to 1991 from *Storm Data* reports. He tallied and analyzed the flood fatalities annually per state per capita. He found that over the 33 years, on average there were 119 deaths per year, although when the database is truncated to the years 1972-1991, the average number of flood-related deaths jumps up to 135.

Jonkman and Kelman (2005) investigated the causes of European and U.S. flood disaster deaths (both direct and indirect) as well as circumstances surrounding those fatalities for a select number of cases using data from the International Disaster Database. Their study was confined to 13 cases with a total of 247 flood deaths in both Europe and the U.S. during 1989-2002 that they asserted were representative of flood disaster deaths. Flood casualties were examined to determine the cause of death, as well as gender and age of the victims. They found that two-thirds of the deaths were due to drowning and 70% of flood deaths victims were male.

Other studies have examined loss of life associated with tropical cyclone flooding (Rappaport 2000, Cerveny and Newman 2000). Flooding from tropical cyclones alone has lead to a large number of fatalities and large property losses in not only the U.S., but other countries as well (Cerveny and Newman 2000). Rappaport (2000) compiled a database of tropical cyclone fatalities using newspapers and NWS publications for the years 1970-1999 and included 600 deaths in the U.S. They found that more male fatalities occurred than female fatalities and a relatively large number (18%) of preteens (12 years or younger) were killed. Vehicle-related deaths accounted for only 23% of the resulting fatalities. This is a lower percentage than that found by Mooney (1983) and Coates (1999) in their research of flood-related deaths.

1.5 Summary

This investigation into national flood-related casualties is a first attempt to examine both flood fatality and injury data geographically, by county, over a long time period. Moreover, no previous study has included injury estimates in their analyses. This study provides information on the town or county's physical and social vulnerabilities to flooding events that leave casualties in their wake. Further, the study investigates whether deadly flood events correspond to high magnitude floods and also examines the relationship between flood warnings and flood deaths. Ultimately, this dissertation provides beneficial information to forecasters (e.g., warning accuracy) and emergency managers (e.g., flood safety education programs) for future risk assessment.

CHAPTER 2

FLOOD CASUALTIES IN THE UNITED STATES[1]

[1] Ashley, S.T. To be submitted to *Natural Hazards*.

ABSTRACT

This study compiles a nationwide database of flood fatalities and injuries for all contiguous states of the U.S. from 1959-2005. The database is compiled from existing monthly *Storm Data* reports issued by the National Climatic Data Center. Such information as location of casualty, age and gender of victim, activity and/or location of casualty, and type of flood event is included for each casualty report. Analysis of the data reveals that the majority of fatalities are caused by flash floods while the majority of injuries are a result of tropical systems. People between the ages of 10 and 29 and the elderly (> than 60 years) are found to be more vulnerable to floods. A large percentage of children (less than 13 years old) perish in floods while either playing in and around the flood waters or when they are driven into the flood waters by their guardian or parent. The findings observable in the fatalities stratified by age indicate that human behavior is integral in causing flood fatalities. These findings also reveal that future structural modifications of flood control designs (e.g., culverts and bridges) may not reduce the number of fatalities nationwide. Spatially, flood casualties are distributed across the U.S. with clusters of high casualties observable along the Interstate 95 corridor in the Northeast, in the Ohio River Valley, and along the Balcones Escarpment in south-central Texas. These distributions are likely driven by both physical vulnerabilities for flooding (e.g., high vertical relief from topography, close proximity to flood control structure) as well as the social vulnerabilities (percent males, age).

2.1 Introduction

Floods, whether originating because of heavy rain, snowmelt, structural failure, or a combination of these factors, are the second (to heat) deadliest of all weather hazards in the U.S. (French et al. 1983, Dittmann 1994, Wisner et al. 2004, NWS 2005b). Kunkel et al. (1999) found that fatalities in the U.S. have generally increased during the past 25 years in comparison to the early and mid part of the 20th Century. Moreover, flood damage costs for the U.S. have been steadily increasing through the 20th Century (Pielke and Downton 2000, Pielke et al. 2002, Downton et al. 2005). Floods that significantly disrupt or incapacitate a society by causing a large number of fatalities and costly damage have primarily been associated with less developed countries, e.g. Bangladesh (Wisner et al. 2004). However, in recent decades, some of the most extensive, damaging, and costly floods have occurred in well developed, wealthy countries. A prime example of this occurred in 1993 in the U.S., along the Mississippi River basin and its major tributaries, where cities and towns located in the floodplain were devastated or entirely destroyed. These "more developed" societies quickly discovered that they were not immune to such natural phenomenon despite governmental attempts to control natural processes through levees, concrete abutments, etc. (Smith and Ward 1998).

Floods are naturally occurring events that are dependent not only on rainfall amounts and rates, but also on the topography of the area, land use of the region, soil type of the watershed, and antecedent moisture conditions (Funk 2006). These periodic events become a detriment to society when people become vulnerable to them. Wisner et al. (2004) state that a combination of factors including the physical environment (e.g., house located on erodible land or low-lying land), the local economy (e.g., low-income neighborhoods), the performance of public actions (e.g., driving through a flooded street) and institutions (e.g., inadequate warning) may contribute to unsafe conditions for the population. They add that specific social pressures such as, economic class and/or gender, also enhance a person's vulnerability. Ultimately, Wisner et al. (2004) state that people with high levels of vulnerability include those who are unable to protect themselves.

Flooding can be separated into three main categories including: flash flooding, river flooding, and coastal flooding (French and Holt 1989). Flash flooding is defined by the National Weather Service (NWS) as "a flood that rises and falls quite rapidly, usually as a result of intense rainfall over a small area, in a short amount of time, usually under 6 hours" (NWS 2005a). Whereas, river flooding is defined as "the rise of a river to an elevation such that the river overflows its natural banks causing or threatening damage" (NWS 2005a). Coastal flooding pertains to "flooding which occurs from storms where water is driven onto land from an adjacent body of water" (NWS 2005a). Coastal flooding can be generated from storm on a variety of scales including a local thunderstorm to large mid-latitude cyclones such as Nor'easters or tropical systems such as hurricanes (NWS 2005a).

Several past investigations have examined U.S. flood-related fatalities (French et al. 1983, Mooney 1983, Dittmann 1994, Coates 1999, Rappaport 2000, Jonkman and Kelman 2005, and Jonkman 2005). Examining fatalities by state for 1959-1991, Dittmann (1994) found that, on average, there were 119 flood deaths per year in the U.S. French et al. (1983) determined that a majority of the flash floods during 1969-1981 occurred during the warm-season spanning July-September, with September representing the peak fatality month. French et al. (1983) also found that 93% of flash flood events were due to drowning and 42% were vehicle-related.

Mooney (1983) examined fatalities during a relatively short time frame (1977-1981) and found that 60% of the deaths in the U.S. occurred in either urban or suburban areas with nearly

75% of the fatalities occurring in the evening or overnight hours. Of the fatality reports that included information on how and where they occurred, nearly half occurred in vehicles. Accordingly, Zevin (1994) reports that 80-90% of annual deaths are caused by flash floods with approximately 40% of fatalities associated with pedestrian stream crossings or vehicles. Jonkman and Kelman (2005) investigated the causes of European and U.S. flood disaster deaths (1989-2002) as well as circumstances surrounding those fatalities. All of the above studies found that fatalities are highest among males and that there is an enhanced vulnerability in the young (< 21 years old) and elderly (> 60 years old). However, Jonkman and Kelman (2005) found an increased vulnerability in people from 20-60 years old.

Other studies have examined loss of life associated with tropical cyclone flooding (Rappaport 2000, Cerveny and Newman 2000). Rappaport (2000) compiled a database using newspapers and NWS publications and found that more male fatalities occurred than female, and a relatively large number (18%) of preteens (<12 years old) were killed in landfalling U.S. tropical cyclones. Vehicle-related deaths only accounted for 23% of the resulting fatalities. This is a lower percentage than that found by Mooney (1983), Zevin (1994), and Coates (1999) in their research of flood-related deaths.

From this limited body of research on flood-related deaths in the U.S., no study has presented a comprehensive national geographic analysis of flood-related deaths and injuries. Past studies have been restricted by the number of years analyzed or by a limited focus on specific flood types. This study is the first to construct a database of casualties associated with flooding events in the U.S., including death and injury data from 1959-2005. Specifically, this study is the first to include the analysis of flood-related injuries in the U.S. Results highlight the specific vulnerabilities associated with floods in the U.S., including social vulnerabilities (i.e., gender, age,) and physical vulnerabilities (i.e., activity leading to casualty, structure where casualty occurred). These data are examined spatially so that regions of the U.S. that are most vulnerable to flood events may be defined. The underlying objective is to improve awareness and education of this hazard to emergency managers, forecasters, and, ultimately, the people of the U.S.

2.2 Data and Methodology

2.2.1 Database Compilation and Storm Data Problems

The database of 1959-2005 flood-related casualties was compiled using monthly reports from *Storm Data*. Although *Storm Data* was first issued in 1950, the information gathered was restricted to tornadic storms until 1959. *Storm Data* is currently the primary source of severe weather event data used by atmospheric and hazard scientists for determining storm location and resulting casualties. Additionally, it is the only such complete and lengthy record available.

Storm Data is an official publication of the National Climatic Data Center (NCDC) and includes such information as storm occurrences or other weather phenomena that cause significant loss of life, injuries, property damage, and/or disruption to commerce (NOAA 2005). Information is gathered primarily through the NWS, although other sources may be used including the media, law enforcement agencies, governmental agencies, as well as private companies and individuals. These sources may at times be unverified by the NWS and therefore, the NWS does not guarantee accuracy or validity of the information provided within *Storm Data.*

For this study, the inaccuracies of the casualty data found in *Storm Data* are assumed to be that of underreporting. Curran et al. (2000) found that for “smaller-impact” events, such as lightning, *Storm Data* typically under-reports the number of casualties. They suggest that this is because these events draw less attention compared to "larger-impact" events (e.g., tornadoes). Thus, many "larger-impact" flood events (e.g., Rapid City, SD, 1972), should be more accurately reported in *Storm Data* because of the considerable number of people that were affected and the high profile nature of the event. However, 85% (95%) of the flood casualty dataset contains flooding events that merely affected a small stream or single town and consequently may have only killed or injured one or two (five) people. Furthermore, the interpretation of injuries is more suspect than fatalities because there is no agreed definition of what constitutes a flood-related injury. Nevertheless, *Storm Data* comprises the nation's best estimate of hazard-event casualty information; however, it is likely that the tallies reported in *Storm Data* and within any analysis of the dataset will produce a conservative estimate of human casualties due to flooding.

Additional problems with *Storm Data* were revealed during the compilation of the dataset that should be addressed. It is important to reveal the problems associated with the *Storm Data* but, unfortunately, it is difficult to ascertain and quantify the effects of these problems on the analysis of flood casualties. These problems are discussed and suggestions for correcting these problems are also provided to benefit future compilation procedures for *Storm Data*. There are instances throughout *Storm Data* where the number of casualties was simply unknown, therefore no number was given. This was an issue primarily before 1987. From 1959-1985 the publication did not provide the casualty reports with the specific activity surrounding the incident (e.g. driving a vehicle, walking through floodwater), although in many instances the activity could be concluded from the description of the event. Starting in November 1985, *Storm Data* began including a code (with age and gender) to describe the activity or location associated with the casualty.

Age and gender of the casualty reports were also routinely absent until the mid-1980s. Before the inclusion of this information, age and gender could be identified in the description of the event, although less reliably than that of the activity. From 1986 onward, the publication becomes much more complete concerning activity, age, and gender of fatality report. From 1986-2005, 92%, 85%, and 91% of the fatality reports have activity, age, and gender information available, respectively.

During the 1960s-1970s, *Storm Data* entries did not appear to follow any criteria for labeling the entry as a single event such as "flash flood" or "high wind." Many times the event label contained multiple events, i.e., "high wind, lightning, rain, flash flood." In many cases the written description of the event could be used to clarify the storm peril type, but in some cases, the description was not sufficient to determine the primary storm peril. Therefore, unless the description had a detailed interpretation of the casualty report, the entry was not included in this study. There were only 48 event entries where it was unidentifiable whether the report was strictly due to flooding (or heavy rain).

In some instances, *Storm Data* did not indicate whether a casualty report from tropical system (i.e., tropical depression, tropical storm, or hurricane) was due directly to flooding or another aspect (e.g., wind) of the cyclone. Therefore, in an effort to include the tropical system casualty data all tropical cyclone reports were added to the dataset. Rappaport (2000) examined the inland threat to life from Atlantic tropical systems from 1970-1999 and found that 80% of all deaths were due to drowning. Of these drowning deaths, 72% (or almost 60% of all tropical system deaths in their database) were due to freshwater flooding and storm surge. Because they found that inland flooding caused a large majority of the tropical system deaths, the decision was made to include all casualties reported due to tropical systems. The inclusion of the reports more accurately portray the distribution of deaths in the U.S. across the different flood types (i.e., flash flood, tropical system flood). It is expected that tropical system casualties are slightly inflated, but the exclusion would substantially underestimate the influence of tropical system flood related casualties in the U.S.

Data from Rappaport (2000, personal communication) was used to verify whether the deaths from 1970-1999 were due to inland flooding. Therefore, any report from *Storm Data* where the cause of death was not determined (either through verification from the Rappaport (2000) dataset or through a detailed entry in *Storm Data*) was included in the dataset, although they were separated out for analysis. This separation can be identified in later figures and are labeled “unidentifiable tropical system” deaths. These fatalities may include deaths due to inland flooding, storm surge, rough seas, tornadoes, or wind. Injuries are handled in a similar fashion, although no reports can be verified by the Rappaport (2000) dataset because injuries were not included in his study.

The majority of the database includes direct casualties, i.e., deaths and injuries that are contributable directly to the flood event (e.g., death due to drowning, death or injury due to physical trauma within water). A small subsection of the database contains indirect casualties due to flooding events and heavy rain events (e.g., death due to electrocution, death due to rain-slicked roads from heavy rain). Each report in the database consists of the following variables:

- State, county, and city (if provided) of the casualty report;
- Date and time (local standard time) of incident;
- Flood event type;
- Activity/location surrounding the incident, i.e., what the person was doing or where the person was located when he/she encountered the flood waters (if provided);

- Demographic information of report (e.g., age and gender; if provided).

Activities or locations surrounding the flooding casualty are often coded in *Storm Data* using a two letter identifier; activities/locations found in this study include camping, in water, mobile home, outside/open air, permanent home, vehicle, and other. For this study, an additional code has been added for hiking. All of the activities/locations are self-explanatory, except, to a degree, "in water" and "outside." For this study, a casualty was labeled "outside" if it could be determined from the description that the victim accidentally fell or was swept into the flood water, while the "in water" category was used for incidences where the victim willingly walked into the water. In the event that no description was available, the activity/location code that was given for the victim was used.

In general, *Storm Data* classifies the flood-related casualties either as "flash floods" or "river floods," therefore each casualty was subdivided by flood type. Through the compilation of data, it was determined that additional categories would be necessary in order to accurately describe the data. Additional categories for fatalities by flood type include: landslides (accompanied by heavy rain), heavy rain, indirect, and unknown flood type. Casualties resulting from heavy rain included those where flooding conditions were not met but the stream or river was at or near bankfull, whereas "indirect" included any casualty that was not a result of drowning or blunt force trauma while in floodwaters. Furthermore, a report was categorized as "unknown" if the description in *Storm Data* was specific enough to know that flooding was occurring, but not detailed enough to know whether it was a flash flood or flood. This typically occurred in the 1960-1970s before standardized methods for report entry were instituted for *Storm Data*. At times, *Storm Data* described that deaths or injuries occurred from two types of relevant events, i.e., flash flooding and resulting landslides, therefore, the actual cause of the casualty could not be determined. Instead of excluding these reports from the dataset, they were categorized as one final category, “two event types.”

Not included in this database were casualties occurring in coastal waters or along shoreline. These reports were excluded since the casualty could be traced back to high winds (i.e., large waves, heavy surf, rip tides). Additionally, casualties that occurred in a boat were subject to exclusion. Unless the description specifically stated that the boat capsized from heavy rain or rough current from flooding, then the report was not included in the database. There were several instances where a boat capsized because of the “storm” because it is unidentifiable whether the boat capsized directly from high winds are strong currents/rain, the report was not included.

Storm Data is not a perfect source for casualty reports. The publication is unique and the only kind of dataset of its type, therefore, it must be used for this type of analysis. The decision on inclusion/exclusion of cases in this study was made as judiciously as possible. Despite this inherent subjectivity, the results should not be significantly altered based on the inclusion or exclusion of a minimal number of reports relative to the total number within the database.

2.2.2 Geographic Analysis

The flood-related fatalities and injuries were classified by each variable in the dataset (i.e., state, year, month, flood type, activity, gender, and age). Additionally, the fatalities and injuries were aggregated by event report and classified in addition to the raw casualty numbers. An excerpt of the compiled dataset is provided in Appendix A. These classifications reveal the temporal distribution of floods in the U.S., the most dangerous type of flood in the U.S., the activities (or structures) that are most vulnerable to flood-related casualties (vehicle vs. home), as well as the demographic characteristics of those most vulnerable to floods in the U.S.

The casualty report data are also spatially represented in a geographic information system (GIS) using the latitude and longitude of the location of the report/event. Generally, a town or city is provided as the location of the report, although, at times, the data is provided by county only. In cases where only the county is reported, the latitude and longitude of the county seat was used. From these maps, the geography of flood-related casualties can be described and any clustering of high or low casualties can be determined. For many tropical system casualty reports, only a state (or multiple counties) was provided because of the large number of casualties associated with the event. Therefore, casualties by state are mapped to include these reports. Lastly, flood type, gender and age classifications of fatalities are mapped to display any regional variations in the data.

Unlike prior studies, the research questions asked in this section of the study are represented spatially. These descriptions are useful in understanding whether there are any geographic controls on hazardous flooding. Additionally, this study includes a much longer period of record and more thorough analysis of how flood casualties occur.

It is hypothesized that there are counties and/or cities that are more often affected by fatal or near-fatal flooding events – e.g., regions along the coasts of the U.S. due to tropical cyclone activity and regions with large vertical relief. The Natural Hazards Research and Applications Information Center (1992) state that streams with steeper gradients will typically produce flash flooding because steeper streams are characterized by higher runoff and higher velocities of stream discharge (Dunne and Leopold 1978).

It is assumed that the primary activity surrounding the casualty is related to the flood type. For example, flash flooding will catch people by surprise; therefore, it is hypothesized that many casualties associated with this flood type occur at home or while driving a vehicle because of lack of warning, hazard appreciation, or response time. It is also hypothesized that there will be a dominance of casualties in children and the elderly. Cutter et al. (1997) report that individuals younger than 18 or older than 65 are more socially vulnerable to hazard events. This is due to their need for special assistance during an event and because they have less ability to recover after a disaster event.

2.3 Results: Descriptive Statistics

During the 47 years of the study, a total of 4,800 fatalities (270 indirect) and 28,442 injuries (721 indirect) occurred from 2,914 relevant *Storm Data* event reports in the contiguous U.S. On average, there are approximately 92 fatalities and 587 injuries per year. Comparatively, the NWS (2005b) computes the average number of fatalities (from a 30-year period) to be 107, while Jonkman (2005) found the average to be 100. The discrepancy in totals reported is due to the differing periods of records examined. The median value for fatalities is 76 per year, while the median value for injuries is 98 per year. The median is more representative in the case of injuries because extreme values inflate the average. Ranking these data by state illustrates that Texas has the most fatalities and injuries for the U.S., while Mississippi and Louisiana follow in ranking for total casualties (Table 2.1). When the data are ranked by fatalities per flood event, it is evident that flash floods (especially those from dam failures) and floods associated with tropical storms are the biggest threat to life in the U.S. (Table 2.2).

2.3.1 Frequency by Year

The number of flood fatalities per year is highly variable with a low of 23 in 1962 to a high of 452 in 1972 (Fig. 2.1). Moreover, no statistically significant trend in fatalities is evident over the period of record. Compared to other weather-related hazards (i.e., lightning, tornadoes) the lack of a decreasing trend is unique. Both lightning and tornado fatalities are found to be decreasing over the second half of the 20th Century (Lopez and Holle 1996, Boruff et al. 2003). This indicates that despite an improved watch-warning system, which has decreased the threat to life from tornadoes and lightning, there has been no significant decrease for flood risk. Deadly events over the same period of record are also variable over the 47 years, although no extreme years are evident.

Of the five anomalously high years regarding flood fatalities, three of the years are characterized by a single large flash flood event. In the first of these three years, 1972, a dam near Rapid City, SD, failed, flooding the entire downtown during the night, killing 237 and injuring 2,932 (Maddox et al. 1977a, Bryant 2005, Carter et al. 2002). Of all single-county flood events in the dataset, this flash flood killed the most people (Table 2.3). This event coincided with a year that was already experiencing a large number of casualties from Tropical Storm Agnes. In 1976, the large number of casualties occurred because of a flash flood in the Big Thompson Canyon, CO, which killed 156 and injured at least 250 (Henz et al. 1976, Maddox et al. 1977b, Albertson et al. 1978, Caracena et al. 1978). In this case, extreme elevation relief and a narrow canyon played an important role in the strength of the current as it moved down slope. Furthermore, in 1977, there were approximately 40 deaths (45 injuries) due to a dam failure and resulting flash flood in Toccoa Falls, GA (Sanders and Sauer 1979, Land 1980). The dam broke at night and the floodwaters washed through downtown Toccoa Falls, the Toccoa Bible College, and a mobile home park.

The other two years with high fatality reports were 1969 and 1973. During 1969, Category 5 Hurricane Camille impacted the Gulf coast, causing a large number of deaths as it came ashore. Additionally, heavy rain, flooding, and landslides were widespread across Camille's inland path: especially hard hit was the western and central portions of Virginia where more than 82 cm of rain fell in Nelson County, VA, in 24 hours (NOAA 1999). In Virginia, 109 people were killed from the combination of flooding and landslides from the remnants of this hurricane nearly matching the fatality total of Alabama, Louisiana, and Mississippi, where Camille made landfall as one of the most intense hurricanes in recorded U.S. history. During 1973 there was no single event responsible for a large fatality frequency; on the other hand, the year contained numerous instances of heavy rain-induced floods and flash floods. A majority of these years with high fatalities can be blamed on either a dam failure or flash flood that occurred at night. Therefore, these difficult-to-predict, short temporal scale events (exacerbated when occurring at night) equate to being the most hazardous.

Examining flood injuries through the period of record, five years stand out as anomalously high injury years, similarly to fatalities (Fig. 2.2a). These years are 1960, 1964, 1969, 1972, and 1998. Three of the five years are anomalously high because of the extremely large estimate of tropical storm injuries. These tropical storms included Hurricane Donna in 1960, Hurricane Hilda in 1964, and Hurricane Camille in 1969. Additionally, in 1964, the Ohio River and many of its tributaries flooded resulting in almost 600 people injured. Once again, the role of dam failures is shown by the number of injuries that occurred with the flash flood in Rapid City, SD (Maddox et al. 1977a, Bryant 2005, Carter et al. 2002). As previously mentioned, 2,932 were injured by the dam failure and resulting flash flood in South Dakota in 1972.

During 1998, there was an especially large number of injuries due to river flooding. Almost 4,500 injuries occurred from the combination of two large flooding events in Texas (CDC 2000). In 1997, there were several events across the nation where 50-100 people were injured by heavy-rain induced floods and flash floods. The four states with the highest numbers of injuries in that year are located in the western U.S.: Arizona, Colorado, Nevada, and Texas. Flood injury events over the 47 years show a significant increasing trend, although this may be due to increased reporting of flood events (Fig. 2.2b).

2.3.2 Frequency by Month

June represents the peak month for deaths from floods in the contiguous U.S., while July and August are also high fatality months (Fig. 2.3). This result differs from French et al. (1983), who found a September peak in fatalities. A reason for this disparity is due to French et al.'s inclusion of 1969-1981 data and their concentration on flash flood events. The high number in June and July can be explained by the prevalence of convective thunderstorms throughout the central and eastern half of the U.S. (Changnon 2001a, Changnon 2001b, Ashley et al. 2003, Brooks et al. 2003, Doswell et al. 2005). The large frequencies in August and also September are mostly from tropical storms in the Southeast, and the "monsoon" rains of the desert Southwest (Higgins et al. 1997). The peak frequency for tropical systems is September (Landsea 1993), yet, the peak frequency for tropical system flood-related deaths is August with 347 injuries in August and 225 in September. Lastly, there is a modest rise in fatalities from December to January, this is due to both rain-on-snow events in northern states (Branick 1997) and heavy rain events along the west coast (CA, OR, WA) resulting in landslides. These landslides along the west coast were responsible for 42% of all flood deaths in January. Fatal flood events show a similar pattern with a peak in June and high event months occurring from May through September.

Flood injuries by month show a peak in the fall (October) with a secondary peak in June (Fig. 2.4) if excluding the estimates from unidentifiable tropical systems. The peak in October is due predominately to the extensive flooding in Texas during this month (CDC 2000). The inclusion of the unidentifiable tropical system injuries causes the secondary peak in injuries to shift to August. Flood injury events peak in the late spring to early fall (May to September), similar to fatal floods.

A regional analysis of flood deaths and injuries as well as the events that caused them shows seasonal differences in casualty occurrences between the six regions delineated (Figs. 2.5a-f and 2.6a-f). The Rocky Mountain (Region 2: MT, ID, WY, NV, UT, CO) and Midwest (Region 3: ND, SD, NE, KS, MO, IA, MN, IL, WI, MI, IN, OH) states have peaks in fatalities during the summer months, while the Pacific Coast states (Region 1: OR, WA, CA) show a peak during the winter months. There is a higher frequency of deaths in the Midwest when compared to both the Rocky Mountain and Pacific Coast states (Figs. 2.5a-c). This extremely high frequency in June for the Midwest is due to the single dam failure flash flood that occurred in South Dakota. The summer maximum for the Midwest and Rocky Mountain states is also due to the propensity of convective storms in these regions. Moreover, the winter maximum for the Pacific Coast states coincides with the region’s climatological high-precipitation season (Koeppen 1936, Robinson and Henderson-Sellers 1999). The fatalities in the Northeast (Region 4: ME, VT, NH, NY, PA, NJ, MA, CT, RI) peaks in the summer with a smaller secondary peak in the fall from the influence of tropical systems (Fig. 2.5d). The southeastern (Region 6: MD, WV, VA, KY, TN, NC, SC, GA, MS, AL, FL, LA, AR) and southwestern (Region 5: TX, OK, NM, AZ) regions have a large number of deaths spread throughout the spring, summer and fall months, although; the influence from tropical systems in the Southeast creates a pronounced peak in the late summer (Fig. 2.5e and f).

Similar monthly distributions are illustrated in the flood injuries graphs by region; although, the frequencies are relatively low compared to that of the Southeast and Southwest (Figs. 2.6a-f). This high frequency in the Southeast is due to the large number of flood-related injuries that occur during tropical cyclone season, while the Southwest has a high peak due to the Texas Great Flood of October 1998 (CDC 2000).

2.3.3 Frequency by Event Type

Storm Data separates "flood" event entries into two main categories: river flood and flash flood. Additional categories were added to accurately display the fatality and injury reports by event type (Fig 2.7 and 2.8a and b). As expected, flash flood deaths and events exceed that of the other categories, although tropical systems are responsible for almost a fifth of all fatalities. Tropical system injuries exceed all other injury classifications, but when excluding the unidentifiable injuries from tropical systems, the leading cause of injuries is river floods and the leading cause of injury events is flash floods.

Indirect casualties and events were included in this study and comprise approximately 5.5% of all fatalities and 2.5% of injuries (Fig. 2.9 and 2.10). Car accidents are the leading contributor of these indirect deaths (72%) and injuries (69%). These accidents either occurred because the driver lost control of the vehicle in blinding rain conditions or on slick roads. The second most prominent contributor of indirect fatalities was heart attack at 10%. Typically these people were either attempting to remove water from their basements and suffered a heart attack or were awaiting rescue/being rescued from a home surrounded by floodwaters and suffered a heart attack. Many injuries (25%) occurred from the collapse of either a roof due to the accumulation of heavy rain or the collapse of a wall (typically a basement wall) from the outside floodwaters. The relatively high percentage is due mostly to roof collapses of commercial establishments, where large numbers of people gather (i.e., supermarket). The events that lead to these indirect fatality and injury show similar distributions among categories.

Because flash floods are a major contributor of flood-related deaths, further investigation is warranted into the exact cause of these events. Out of all flash flood fatalities, the majority of deaths occurred from floods that originated solely from heavy rain in a short amount of time, while fewer than 1% of the deaths were from a combination of heavy rain and rapid snowmelt. The only other cause of flash floods found in this study was from structural failures, including dam and levee failures. These failures were a result of heavy rain and account for approximately 12% of all fatalities. Nine structural failure events resulted in 309 deaths, or an average of about 35 deaths per failure. There was a total 1,028 heavy rain flash flood events with 1,965 fatalities, averaging only two deaths per event. The ratio of deaths to events is much larger for the structural failure events because of their sudden and unpredictable nature. This does not suggest that flash floods from heavy rains alone are a lesser threat, but instead signifies that one structural failure event can impact more people in a single instance. Non-structural events, although typically only affecting one or two people an event, are en masse the primary flash flood killer.

2.3.4 Frequency by Activity/Location

Out of all deaths reported, 64% have known activity or location (e.g., vehicle or permanent structure), while this information is only available for 17% of all injuries. These data show that 63% of fatalities and 67% of injuries with known activities or locations occurred in vehicles (Fig. 2.11 and 2.12). This is a much higher percentage than 42% and 40% previously found by French et al (1983) and Zevin (1994), respectively, as well as the 50% found by Mooney (1983). Other locations with relatively high percentages of casualties include permanent structures and “outside” (i.e., standing on the banks of a flooded stream), which together comprised about 19% (25%) of flood-related fatalities (injuries) with known activities/locations. The frequency of flood fatality and injury events show similar distributions when categorized by activity/location.

After vehicle-related fatalities, deaths occurring outside (14%) and in water (9%) were the leading activities/locations. When a person accidentally fell or was swept into the flood waters the location was labeled “outside”, while “in water” denotes people who intentionally walked through the floodwaters. Out of all of the deaths where people purposely walked through floodwaters, only 16% of them entered the waters in order to evacuate or to rescue someone else. Another 43% walked through the high water to reach some destination (e.g., a house or a car) in the floodwaters. All were of these victims were over the age of 12. Therefore, almost half of these “in water” deaths could have been avoided as they were not going in the water for evacuation purposes or rescue. The remaining deaths in this category were mostly children (<12 years old) that may not have understood the dangers of the waters and either walked into or were playing in the floodwaters. These findings illustrate that people often do not perceive flooding situations as life-threatening (Drobot et al. 2006). This misguided perception or complacency leads to these unfortunate, and often preventable, deaths.

2.3.5 Frequency by Gender and Age

Unfortunately, gender and age characteristics of reports were less frequently reported than that of activity. A majority (63%) of fatalities had unknown age, while nearly half (49%) had unknown gender. Only 4% of injuries had known gender and an even smaller percentage of injuries had known ages, therefore, analysis was restricted to fatalities for this portion of the study.

The percentage of flood fatalities stratified by age category shows that young adults (age 10-19), those in their twenties, and the elderly (> than 60 years of age) have a higher vulnerability to flooding (Fig. 2.13). Each of these age categories shows a high percentage of fatalities compared to the percent of the U.S. population (U.S. Census 2000) in that category and reveals a vulnerability toward these age categories. This is similar to findings reported by Coates (1999), French et al. (1983), and Mooney (1983). Each of these studies found an increased vulnerability in both the young (< 21 years old) and elderly (> 60 years old). Although, children younger than 9 are not found to be highly vulnerable to flooding, they do make up 14% of all the flood fatalities in the U.S. This high percentage of children falling victim to flood events may be explained in two ways. First, many (14% of those killed) children place themselves in danger because they play in and around the floodwater. Consequently, they are swept downstream and are unable to escape the turbid waters. Secondly, many children (31% of those killed) are driven into the floodwaters by their parents or guardians. The vehicle then stalls in the floodwaters, and upon escape, the parents are either unable to unfasten their child’s safety belts/car seats or they are swept from their guardian's grasp in the floodwaters. There is obviously a need for further education of the public on the dangers of driving into floodwaters as 31% of children are driven to their untimely deaths by the people who care for them.

As noted in the literature (Mooney 1983, French et al 1983, Coates 1999, Jonkman and Kelman 2005), the majority of flood deaths with known gender were men. The findings from this longer term study reconfirm this age-specific vulnerability with 35% of those killed between the ages of 10 and 29 (Fig. 2.14). Female deaths by age shows a number of deaths for those younger than 30.

2.3.6 Hurricane Katrina Deaths/Injuries from Louisiana

The exclusion of fatality and injury estimates from Hurricane Katrina and Rita from the state of Louisiana was purposeful. As to date, these values have not been provided by the NWS, NCDC, or reported in *Storm Data*. This is likely because they are still unknown. A Tropical Prediction Center (TPC) report indicated that the number of known fatalities in Louisiana is 1,090 (Knabb et al. 2005). The report states that the fatalities may have been directly or indirectly related to Katrina, but estimate that there were roughly 1,000 directly related deaths due to Katrina. Additionally, the report indicates these fatality numbers are estimates and are "highly uncertain" and the true number "may never be known." This uncertainty arises because complete statistics on causes of death are not available from all counties affected by the storm. At the time the TPC report was written, not all the dead had been recovered, many more were still reported missing, and the causes of death were still being investigated. The report does speculate that a majority of the deaths in Louisiana were directly caused by the widespread surge-induced flooding and its aftermath. This is the last known report issued on Katrina. Until an estimate can be established, the inclusion of these data will only add more uncertainty to the analysis.

2.4 Results: Spatial Analysis

To examine the spatial distribution of flood-related casualties in the U.S., a series of maps have been created aggregating the data at different geographic levels (e.g., state, city). When examining fatality frequency by state, Texas, Pennsylvania, South Dakota, California, and Virginia are the states with the highest fatalities, respectively (Fig. 2.15). Low fatality states (i.e., less than 50 for the 47 year period of record), are found in the northern states from the west coast to Michigan, with the exception of South Dakota. Additionally, the New England region also has low numbers of fatalities. When state fatalities are standardized by population, the top states include South Dakota, Montana, Mississippi, and West Virginia. Injuries by state illustrate a similar pattern as fatalities with high injury states occurring in the eastern U.S. (Figs. 2.16). Several states along the Gulf of Mexico become more prominent when examining injuries mainly due to the influence of tropical systems.

When state fatalities are mapped by flood type, unique spatial distributions can be observed (Figs. 2.17-2.19). High values of flash flood fatalities standardized by population are apparent in the states along the Ohio and Tennessee Rivers as well as in many southwestern states, while high values of river flood fatalities standardized population are seen predominately in West Virginia, Kentucky, Vermont, and Montana. As expected, states with high values of tropical system fatalities standardized by population are seen along the East Coast states and the states bordering the Gulf of Mexico.

Fatalities mapped by city and flood event for the 47 years of the study illustrate that the eastern U.S. has more deaths compared to the western states (Figures 2.20). However, disastrous floods do occur in the western U.S., predominately because of steeper topography of the Rocky Mountains, Cascades, and other mountain ranges in this region.

The high clustering of fatalities in central Texas is unique. Although, no extremely large event occurred, many events with fewer than 20 fatalities occur there regularly. Coinciding with this clustering of cases is the edge of the plateau, the Balcones Escarpment, where elevated topography drops off to the flat lands of the coastal plain. Many of the deaths in this region cluster along this escarpment from the northern extent near the Dallas/Fort Worth area south to Austin and west to Mexico. Floods in the region appear to have shorter lag times between peak discharge and the time centroid of basin-average rainfall (i.e., the time the equally divides the rainfall amount in half) and require much less rainfall and runoff to reach similar peak discharges as floods occurring in the neighboring coastal plains of Texas (Leopold 1991, Smith et al. 2000). Because of its uniqueness, this region is discussed in more detail in the next chapter.

Two additional clusterings of high fatality locations include 1) the Ohio River as it flows along the eastern and southern border of Ohio and 2) the heavily populated I-95 corridor from southern New England south to Washington D.C. Injuries by location and event for the U.S. show a similar distribution as identified with fatalities, although, the clustering along the Ohio River, Interstate 95 corridor, and along the Balcones Escarpment is less pronounced with injuries (Figs. 2.21). Due to lack of county and/or city information provided by *Storm Data*, tropical systems are not well represented in these figures. A majority of the events did not have spatially explicit information on the cities or counties where the deaths occurred, therefore, they could not be mapped at this scale. In an effort to reveal their impact on the spatial distribution of fatalities, the values were included in the state maps (Figs. 2.15 and 2.16).

2.5 Summary and Conclusions

Floods are the second most deadly of all weather hazards in the U.S. (French et al. 1983, Dittmann 1994, Wisner et al. 2004, NWS 2005b), therefore detailed examination that answers where, how, and why these deaths are occurring is imperative. By constructing a new, exhaustive flood dataset for 1959-2005, some of these questions were answered both quantitatively and qualitatively. This investigation was unique in that it 1) provided a much longer period of record in comparison to past research, 2) was the first to specifically address spatial considerations in flood casualties, 3) provided a more refined analysis of casualty types and places of occurrence, and 4) was the first to examine injuries related to floods. The results show that over the 47 years period of record, the impact of a single flash flood event, including those generated by a structural failures, can greatly increase the number of casualties above the yearly average (92 per year). Nevertheless, flash flood events killing one or two persons at a time accumulate over the long period of record to become the largest killer and hazard to the U.S .population.

For the 47 years of the study, 4800 fatalities and more than 28,000 injuries occurred across the contiguous U.S. The casualties were variable from year-to-year, with anomalously high years coinciding with either tropical storm produced floods or sudden flash floods, often associated with structural failures associated with dams and levees. Flash floods from structural failure make an important contribution to fatalities with over 300 deaths occurring just from 9 dam and levee failures. Despite these large casualty events, the database is dominated by single-and two-person events (both fatalities and injuries), similar to that found by Curran et al. (2000) for lightning casualties. This shows the need for flood safety education so that people take responsibility to respond to the threat of flooding.

For all flood types, a majority of fatalities are found to occur in vehicles (63%). This is higher than what has been reported previously in the literature. This dominance of vehicle-related incidences is seen for injuries, as well. An interesting result of this analysis is the percent of “in water” deaths that are attributable to people willingly walking through the flood waters and not as a means of escape to higher ground. This further indicates the need of safety awareness of the dangers of floodwaters. Fatalities examined by age classification reveals that people between the ages of 10-29 and older than 60 years are most vulnerable to flooding. Additionally, a large percentage (30%) of children (younger than 13) die in floodwaters when they are driven into them by their parents or guardians or while playing in or near a flooded stream (14%). The findings in the fatalities stratified by age indicate that human behavior is integral in causing flood fatalities. These findings also reveals that future structural modifications of flood control designs (e.g., culverts and bridges) may not dramatically reduce the number of fatalities.

Spatially, flood deaths and injuries are dominant in the eastern states. It is hypothesized that there are more flood fatalities in the eastern U.S. because they experience a higher percentage of heavy rain producing weather systems (especially those of tropical origin) through a given year compared to the western U.S.; therefore, increasing the number of fatalities. In addition the population density in and along the floodplains of the eastern U.S. is likely greater than the western U.S. The western U.S. is not immune to flood-related casualties as evidenced by the Big Thompson Canyon, CO, flood and the Rapid City, SD, dam failure (Henz et al. 1976, Maddox et al. 1977a, Maddox et al. 1977b, Albertson et al. 1978, Caracena et al. 1978, Carter et al. 2002, Bryant 2005). Many deaths also occur along the west coast from Oregon to southern California during their winter rainy season. These distributions are likely driven by both physical vulnerabilities for flooding (high precipitation amounts, high vertical relief from topography, or close proximity to flood control structure) as well as the social vulnerabilities (percent males, or age characteristics).

Future investigations should examine the types of storms that most frequently cause deadly flooding events by regions in the U.S. Specific regions can be further investigated to determine both their physical and social vulnerabilities to flooding. This study illustrated the problems associated with hazard data and reiterated and provided further evidence for the establishment of set criteria for losses associated with all natural hazards. At present that U.S. does not have one systematic inventory of all hazard events as their associated losses from property or casualties (Cutter and Emrich 2005). Because there is necessary focus in both the meteorological and hazard research communities to reduce the number of lives lost to natural hazards events (e.g., increased warning/watch times), there should be a movement to improve the accuracy of these important sources of data so that precise mitigation systems can be implemented. As suggested by Cutter (2001), Cutter and Emrich (2005), and Changnon (2003) there needs to be a concerted effort to develop a standardized accounting of hazard events and losses for the U.S.

As outlined in this study, *Storm Data* has many inherent problems and limitations. Because this dataset is the only complete severe event data used by atmospheric and hazard scientists for determining storm location and resulting casualties, the need for improvement is imperative. *Storm Data* could improve substantially with 1) set criteria for defining and including direct and indirect deaths, 2) inclusion of county/city where fatality or injury was reported (especially with the proliferation of GPS technology), 3) set criteria for defining and labeling activity surrounding death or injury (e.g., a system similar to the new enhanced-Fujita scale's damage indicators (http://www.spc.noaa.gov/efscale/) could be utilized to classify the specific locations of casualties), 4) a concerted effort to inventory injury reports for events.

In summary, the results of this study indicated that the U.S. population is still unaware of the life-threatening powers of floodwater. This study has attempted to inform emergency managers, forecasters, and most importantly, the public of the severe threat that floods have on the U.S.

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Table 2.1: The frequency of known flood (all types) fatalities, injuries, and casualties with their ranks, for the 48 contiguous states (including District of Columbia) from 1959-2005 (excluding Hurricane Katrina's impact on Louisiana). Gray boxes indicate the top 5 ranking states.

State	Fatalities		Injuries		Casualties	
	Frequency	Rank	Frequency	Rank	Frequency	Rank
Alabama	67	22	40	33	107	29
Arizona	68	21	115	19	183	24
Arkansas	121	15	140	17	261	16
California	241	4	322	9	563	7
Colorado	185	6	333	8	518	9
Connecticut	12	42	3	47	15	45
District of Columbia	4	47	5	44	9	47
Delaware	14	37	13	40	27	41
Florida	75	20	1884	5	1959	5
Georgia	120	16	93	21	213	19
Idaho	4	48	3	48	7	48
Illinois	51	27	41	32	92	30
Indiana	60	24	55	29	115	27
Iowa	45	29	202	15	247	17
Kansas	52	26	33	36	85	31
Kentucky	137	12	623	6	760	6
Louisiana	100	18	5473	3	5573	3
Maine	11	44	2	49	13	46
Maryland	96	19	99	20	195	23
Massachusetts	5	46	62	27	67	35
Michigan	27	35	35	35	62	36
Minnesota	46	28	244	11	290	14
Mississippi	170	7	5711	2	5881	2
Missouri	160	8	45	30	205	21
Montana	45	30	8	43	53	39
Nebraska	14	38	13	41	27	42
Nevada	29	34	80	23	109	28
New Hampshire	12	43	12	42	24	43
New Jersey	45	31	244	12	289	15
New Mexico	60	25	83	22	143	26
New York	125	14	257	10	382	13
North Carolina	154	9	244	13	398	12
North Dakota	13	41	5	45	18	44
Ohio	146	11	61	28	207	20
Oklahoma	102	17	131	18	233	18
Oregon	44	32	31	37	75	34
Pennsylvania	256	2	206	14	462	10
Rhode Island	0	49	4	46	4	49
South Carolina	64	23	467	7	531	8
South Dakota	244	3	2949	4	3193	4
Tennessee	128	13	71	24	199	22
Texas	760	1	6846	1	7606	1
Utah	22	36	36	34	58	37
Vermont	11	45	43	31	54	38
Virginia	236	5	179	16	415	11
Washington	34	33	19	39	53	40
West Virginia	14	39	69	26	83	33
Wisconsin	147	10	21	38	168	25
Wyoming	14	40	71	25	85	32

Table 2.2: Top 10 deadliest multiple county flood events from 1959-2005 in U.S. (excluding Hurricane Katrina's impact on Louisiana).

Rank	Year	State	Month	Type of Flood	Fatalities
1	1972	South Dakota	June	Dam Failure	237
2	1976	Colorado	July	Flash Flood	156
3	1969	Mississippi	August	Hurricane Camille	132
4	1969	Virginia	August	Remnants of Camille	109
5	1977	Pennsylvania	July	Flash Flood	74
6	1972	Pennsylvania	June	Tropical Storm Agnes	50
7	1969	California	January	Flood and Mudslides	41
8	1977	Georgia	November	Dam Failure	39
9	1985	West Virginia	November	Remnants of Juan	39
10	1964	Montana	June	Flood	36

Table 2.3: Top 5 deadliest single county flood events from 1959-2005 in U.S. (excluding Hurricane Katrina's impact on Louisiana).

Rank	Year	State	Month	Type of Flood	Fatalities
1	1972	South Dakota	June	Dam Failure	237
2	1976	Colorado	July	Flash Flood	156
3	1969	Virginia	August	Remnants of Camille	88
4	1977	Georgia	November	Dam Failure	39
5	1985	Ohio	June	Flash Flood	25

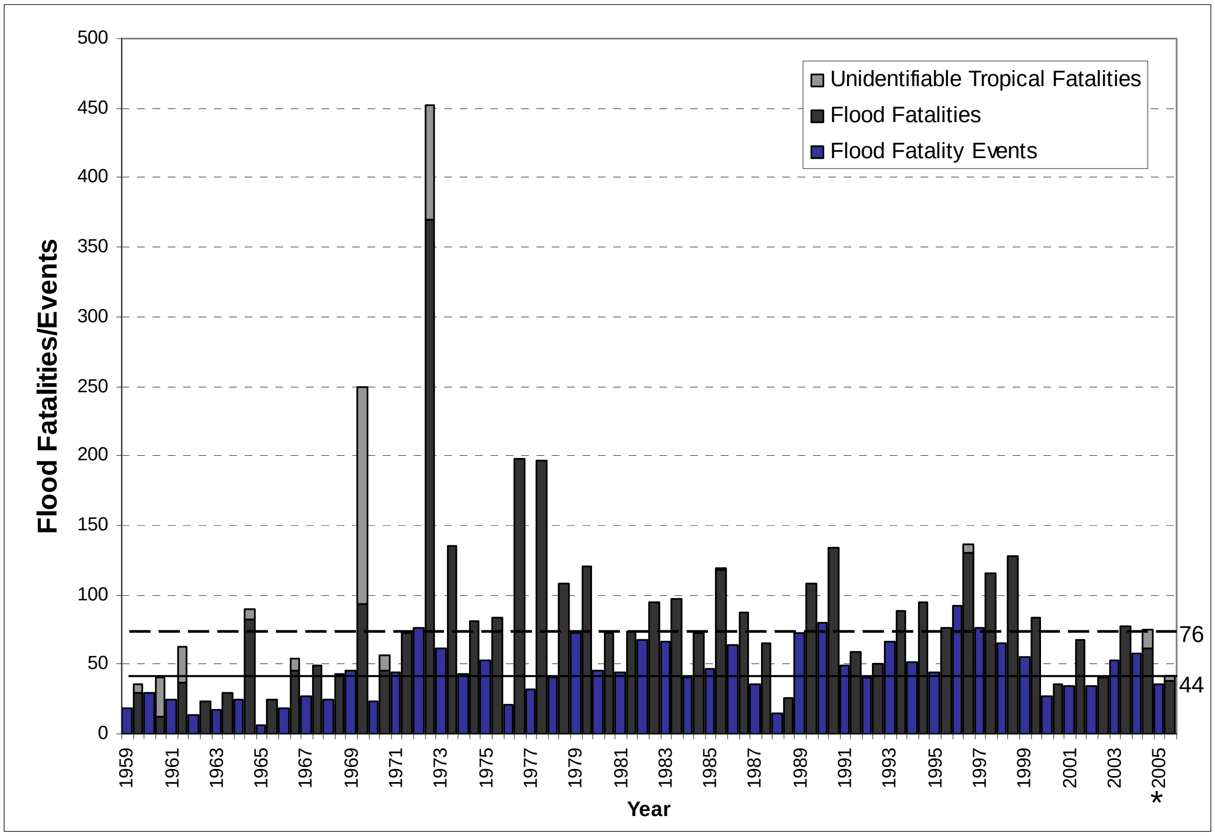

Figure 2.1: The frequency of flood fatalities and fatality events (excluding indirect) from 1959 to 2005. Black bars represent deaths due strictly to flooding for all event types in study. Gray bars represent deaths due to tropical systems but not to flooding alone. Blue bars represent deadly events. Dashed horizontal line represents yearly fatality median and non-dashed horizontal line represents yearly fatality event median. Asterick indicates that 2005 data is preliminary and does not include Hurricane Katrina and Rita fatalities from Louisiana.

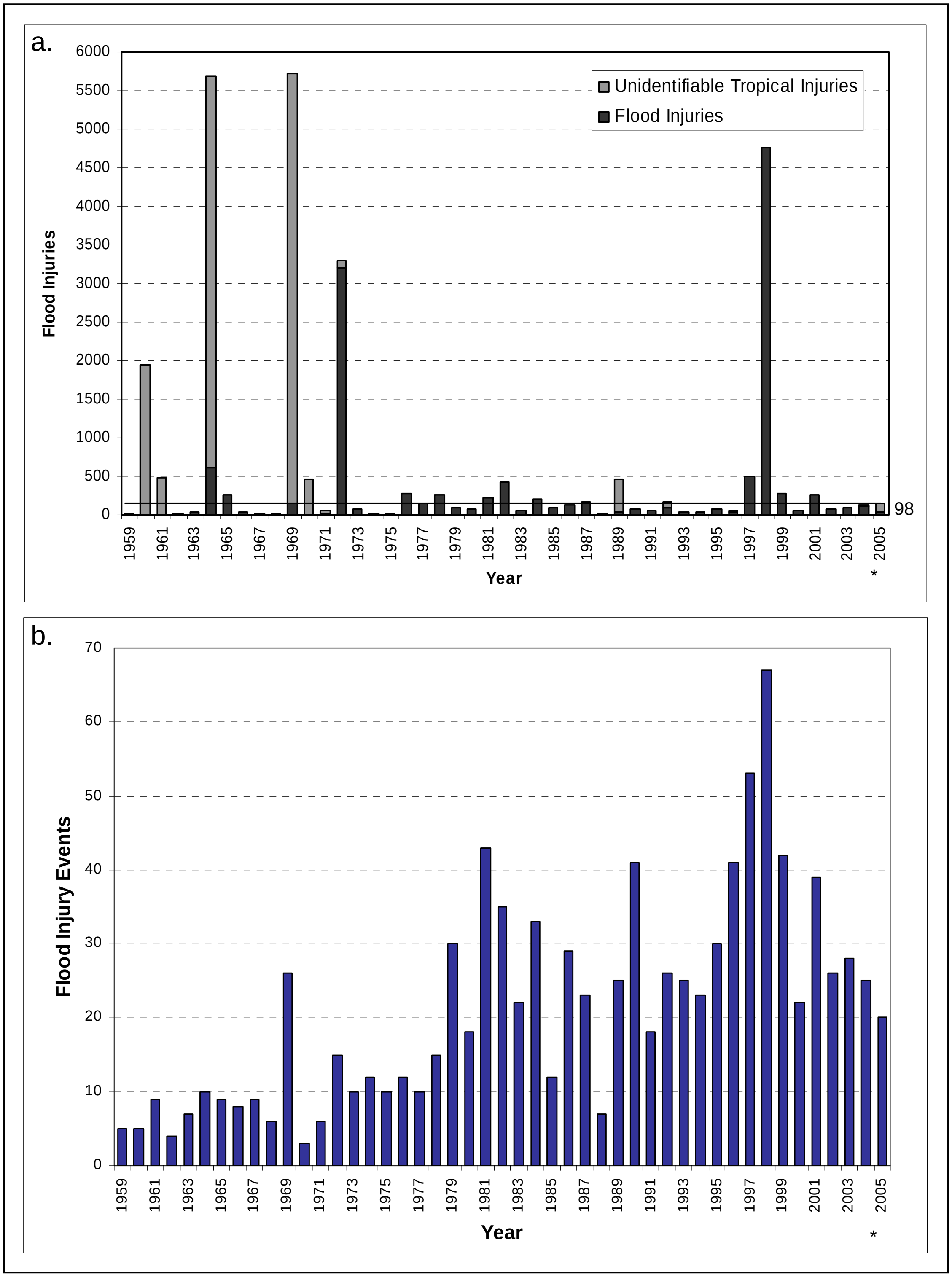

Figure 2.2: a) As in Figure 2.1, except injuries, b) flood injury events from 1959-2005.

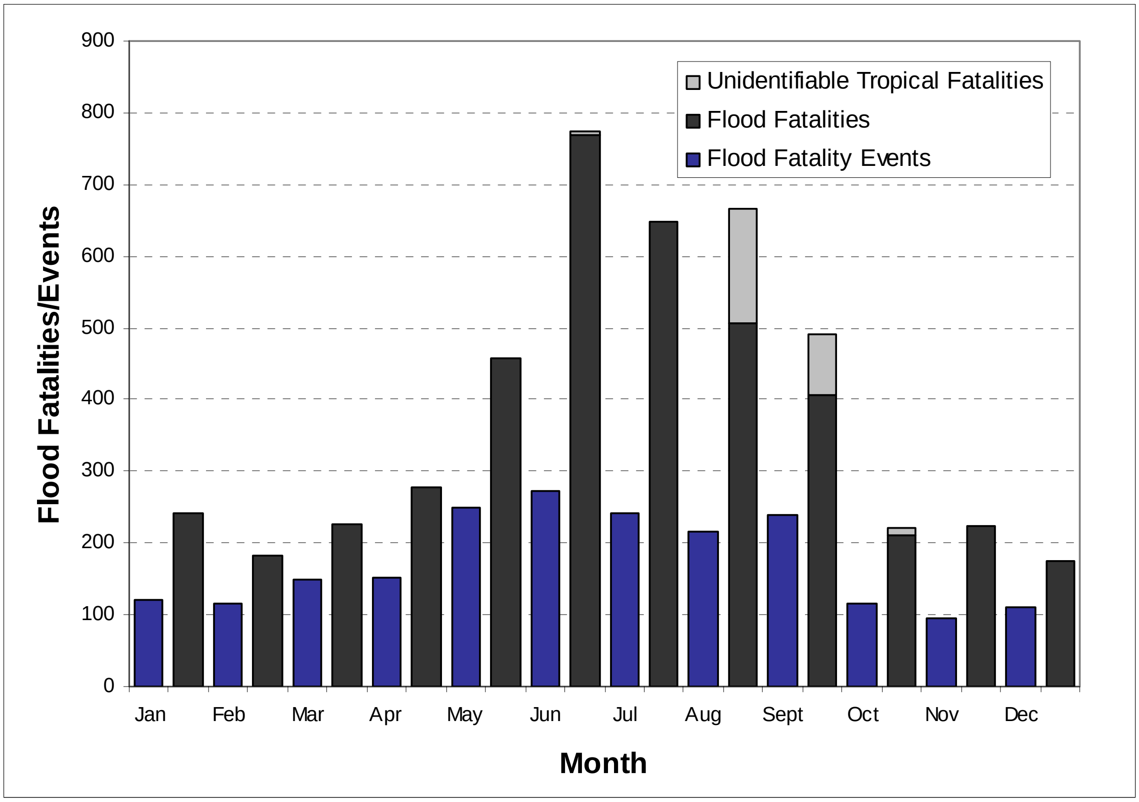

Figure 2.3: The frequency of flood fatalities and fatality events by month (excluding indirect fatalities). Black bars represent deaths due strictly to flooding for all event types in study. Gray bars represents deaths due to tropical systems but not to flooding alone. Blue bars represent flood events with at least one fatality. Excludes Hurricane Katrina's impact on Louisiana.

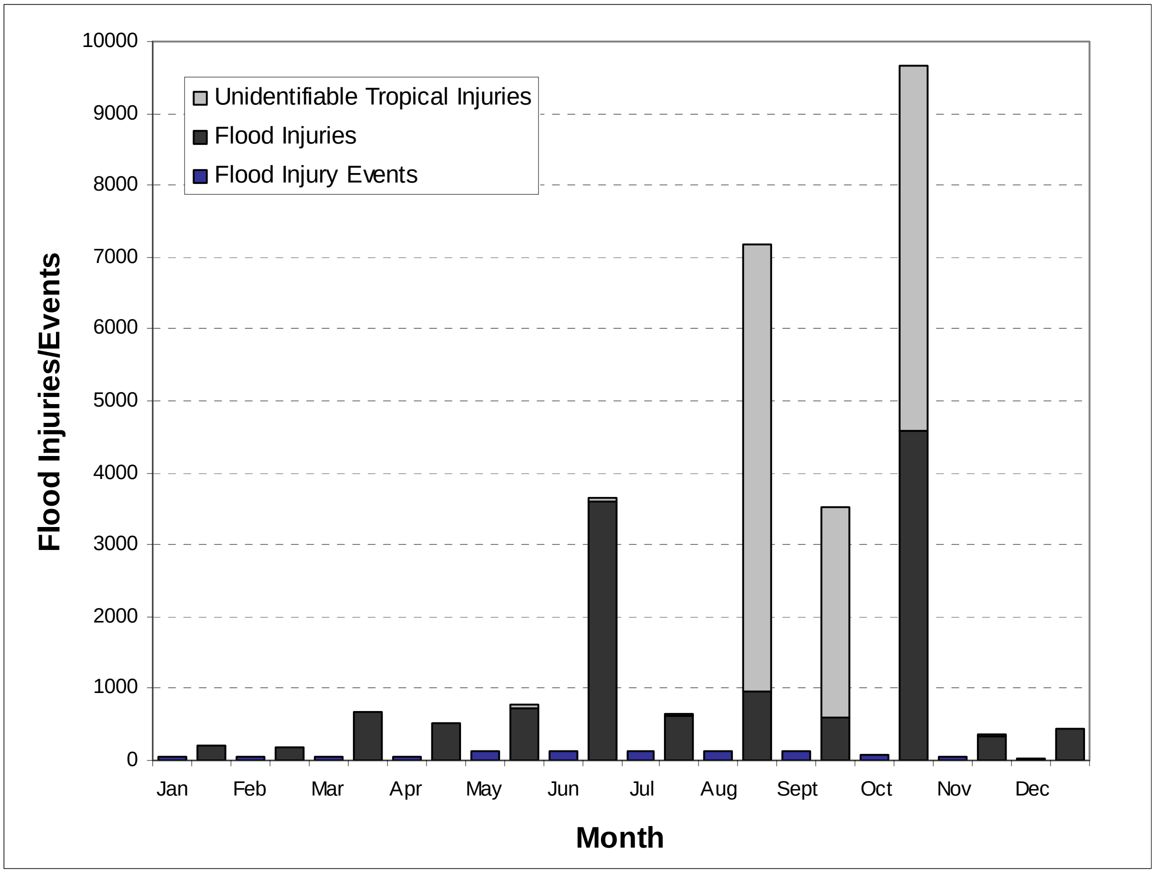

Figure 2.4: As in Figure 2.3 except injuries.

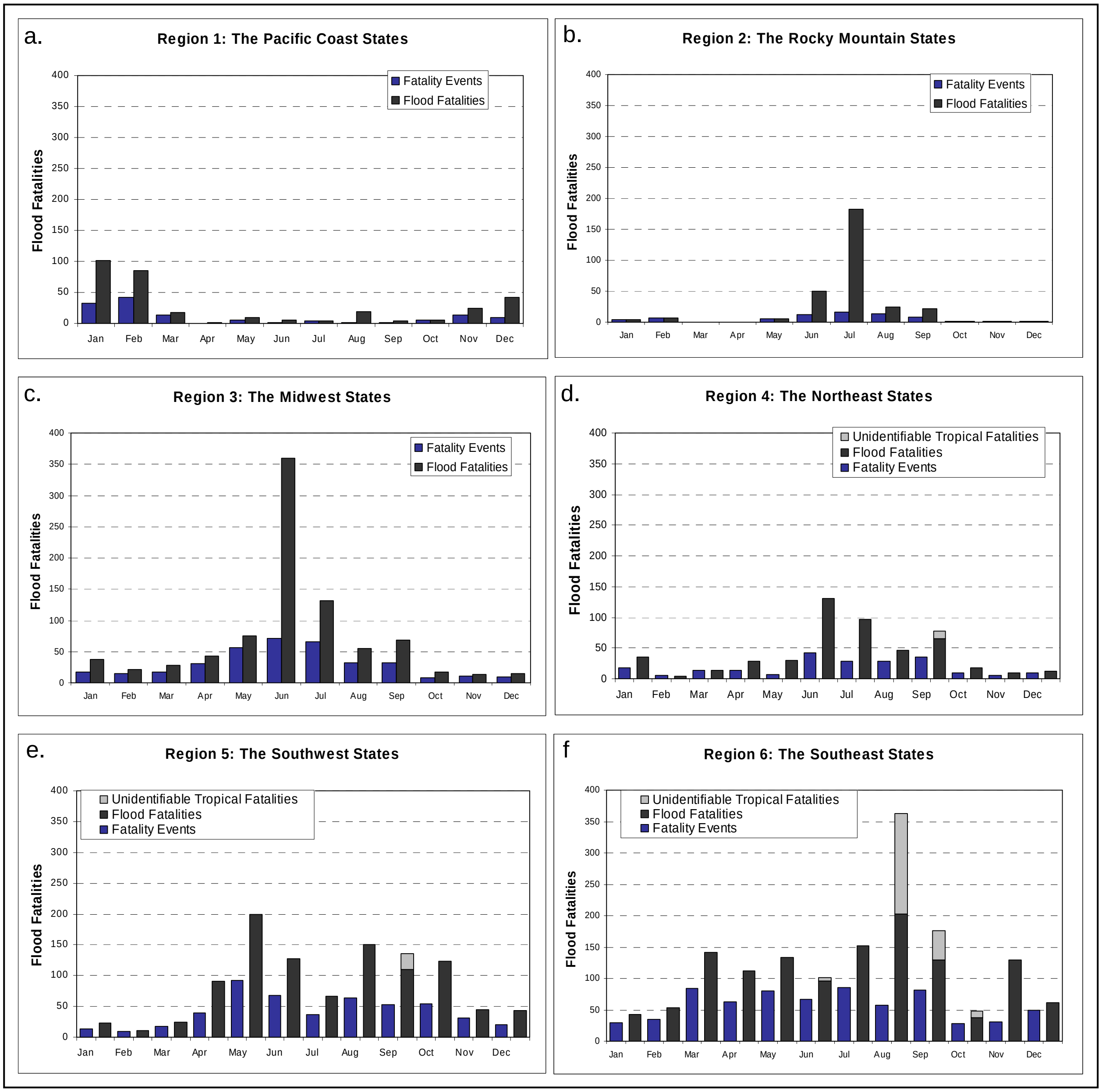

Figure 2.5: The frequency of all flood deaths and fatality events (excluding indirect) by month for six regions of the U.S. (excluding Hurricane Katrina's impact on Louisiana).

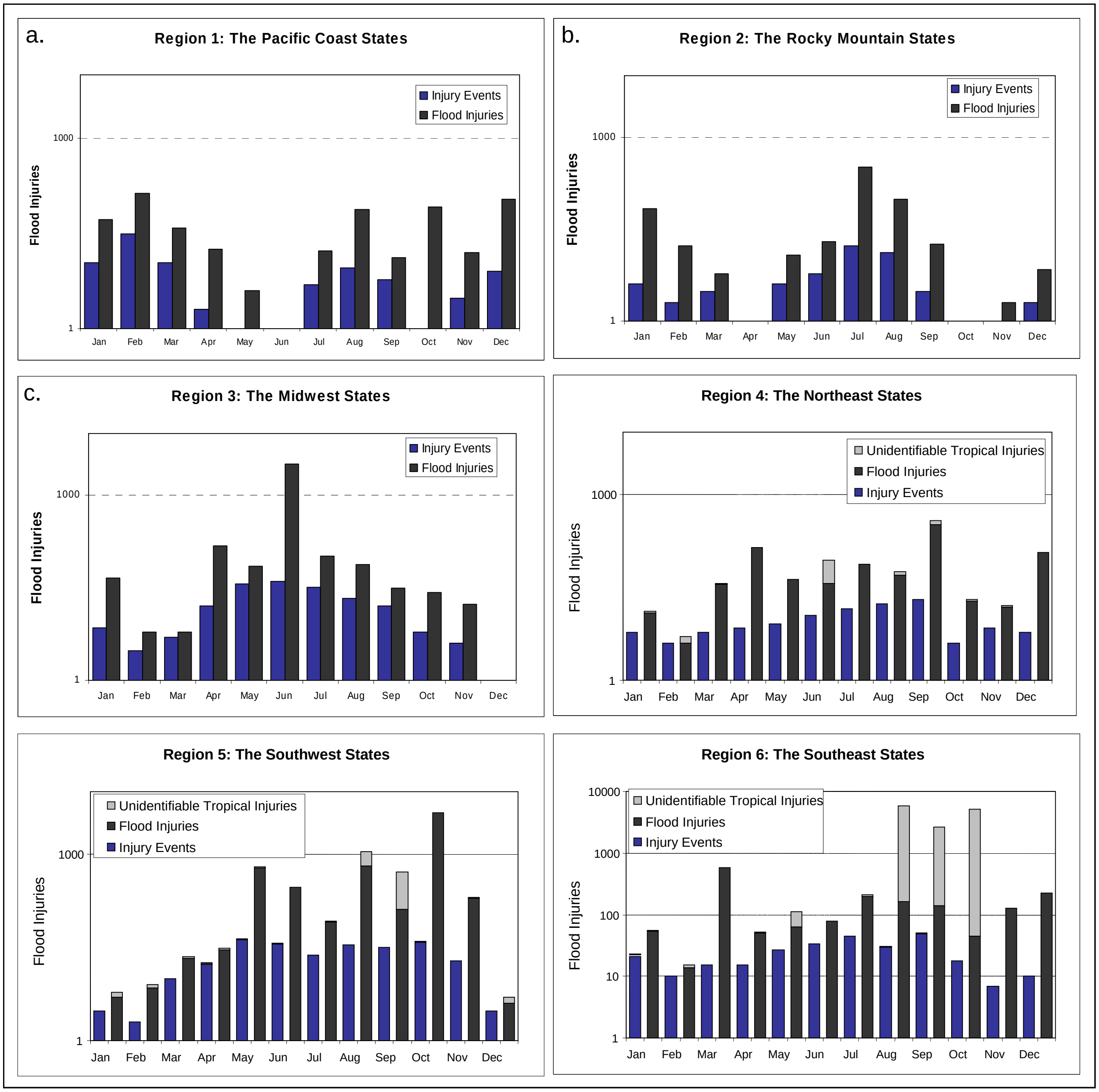

Figure 2.6: The frequency of all flood injuries and injury events (excluding indirect), plotted on a logarithmic scale, by month for six regions of the U.S. (excluding Hurricane Katrina's impact on Louisiana).

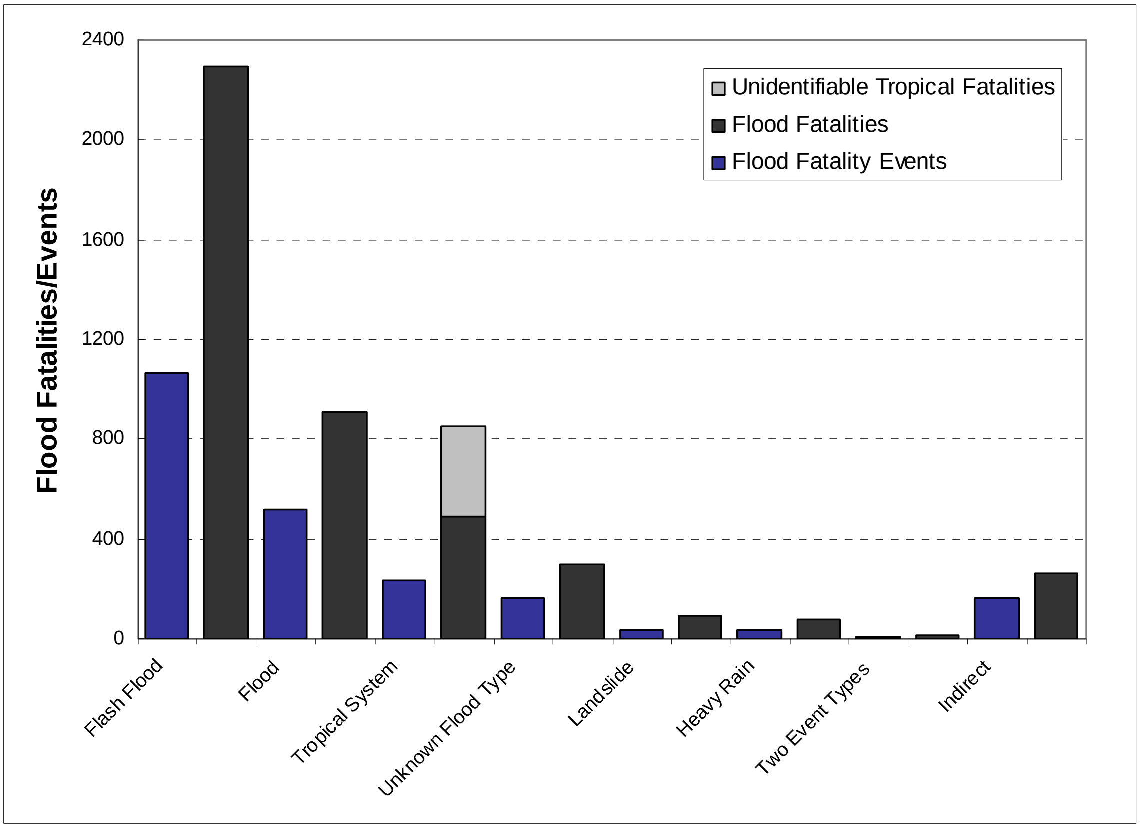

Figure 2.7: The frequency of fatalities and fatal events by flood event type. Black bars represent deaths due strictly to flooding for all event types in study. Gray bar represents the deaths due to tropical systems but not to flooding alone. Blue bars represent flood fatality events. Excludes Hurricane Katrina's impact on Louisiana.

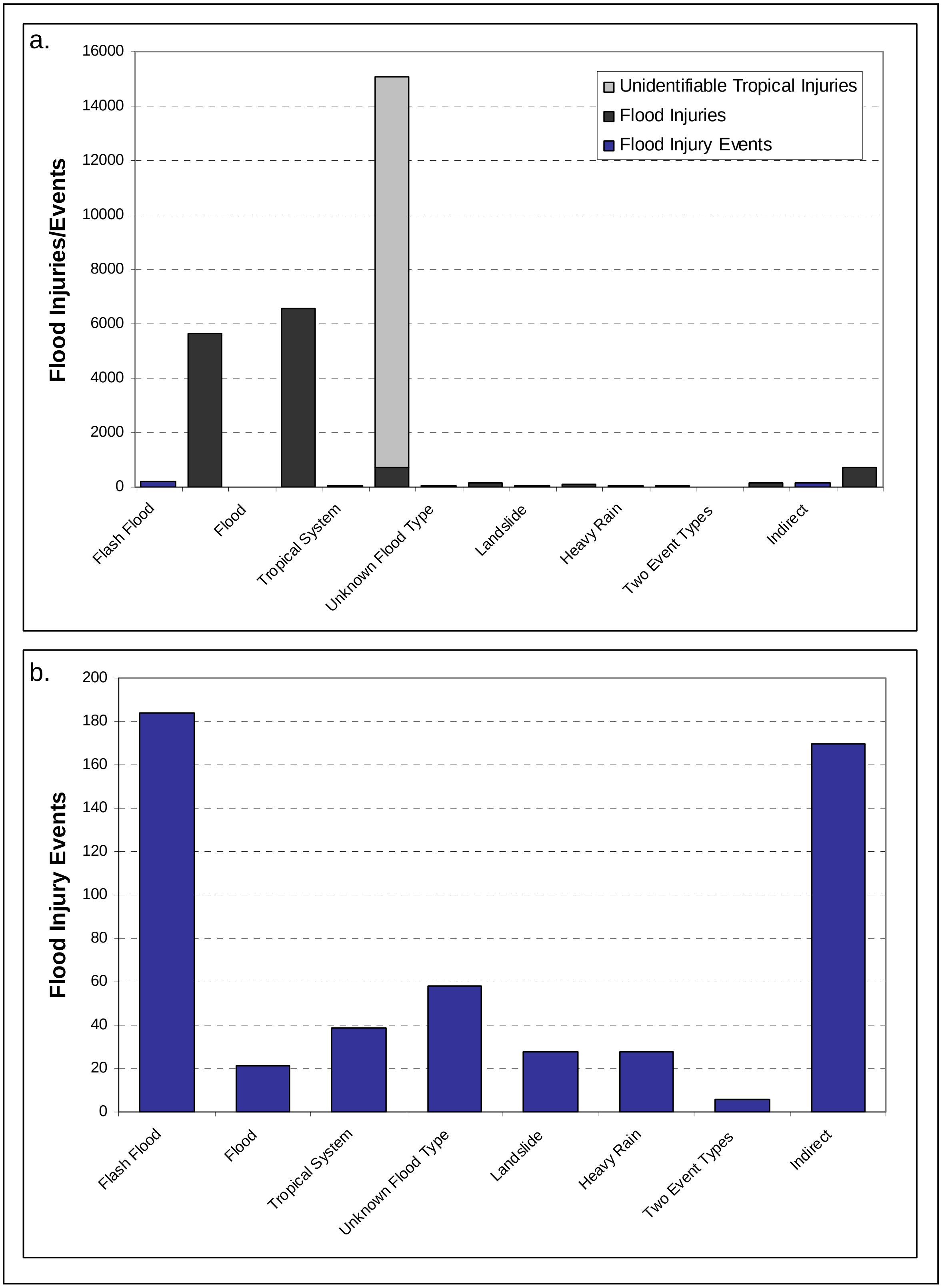

Figure 2.8: a) As in Figure 2.7 except for injuries, b) flood injury events by event type.

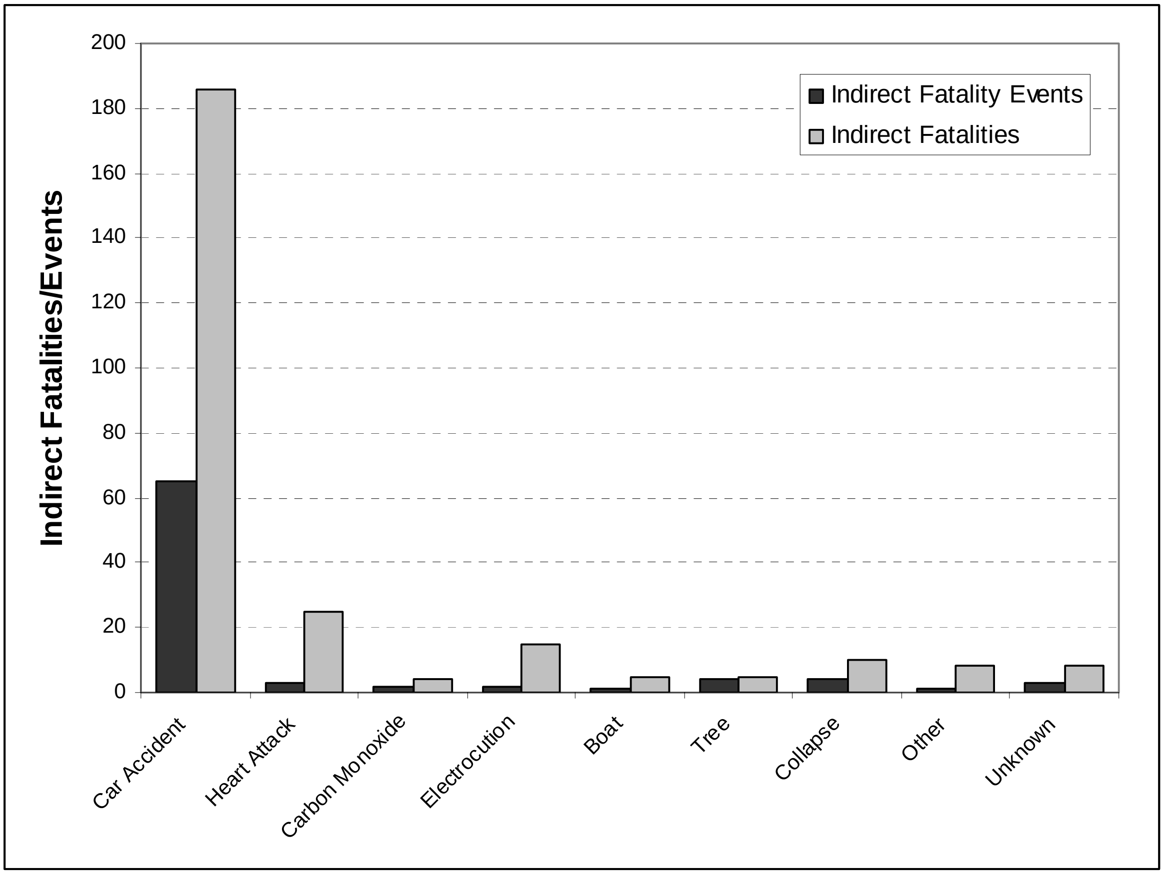

Figure 2.9: The frequency of indirect fatality events (black bars) and fatalities (gray bars).

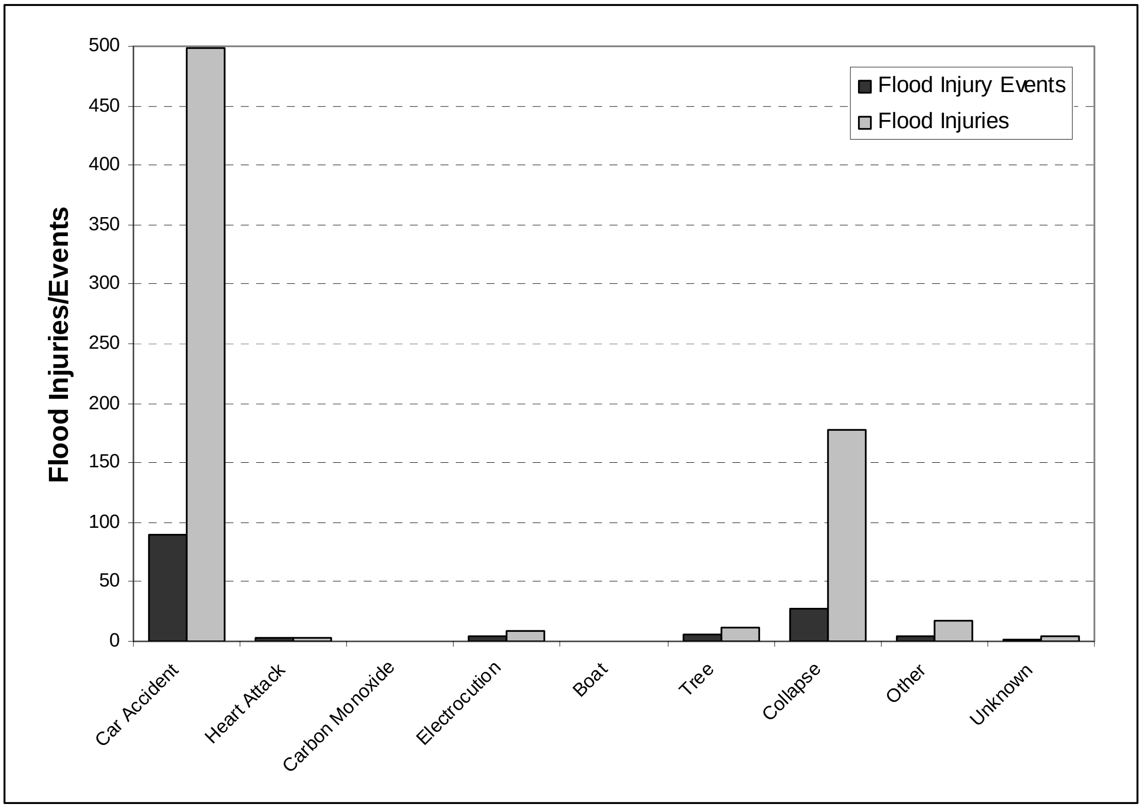

Figure 2.10: As in Figure 2.9 except indirect injury events and injuries.

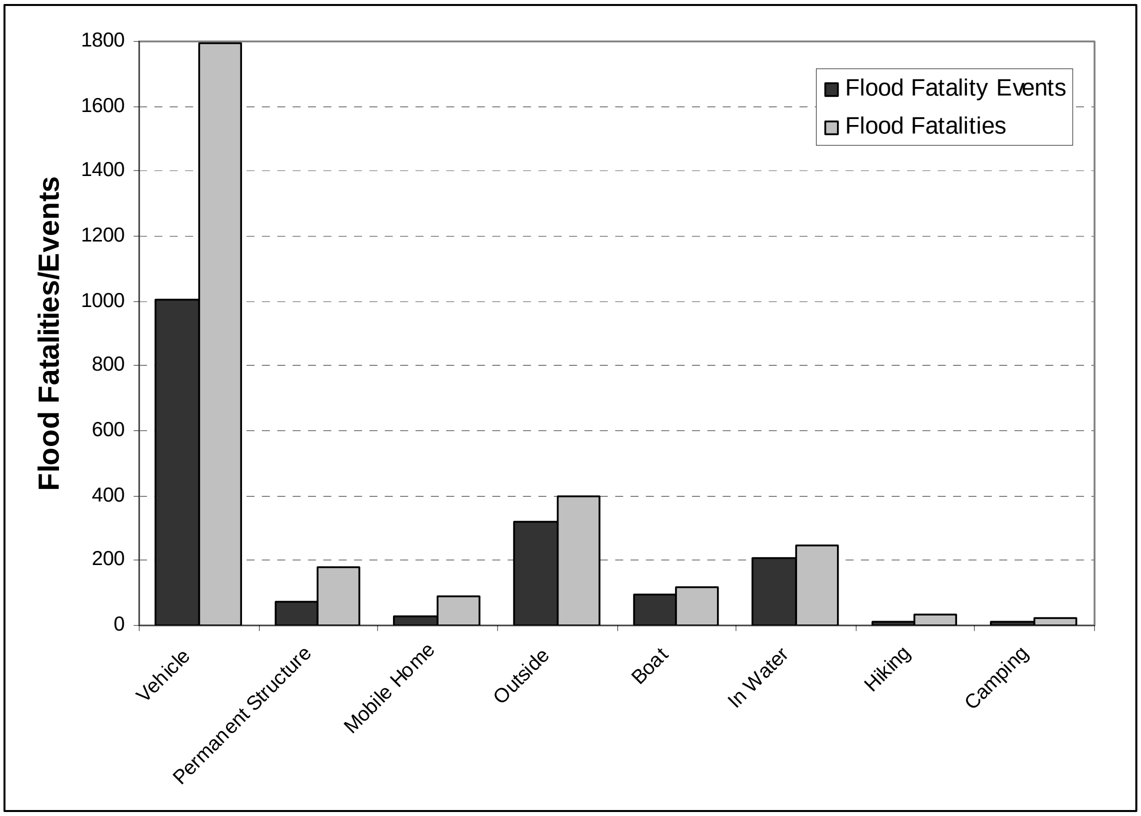

Figure 2.11: The frequency of flood fatality event (black bars) and flood fatalities (gray bars) by activity/location.

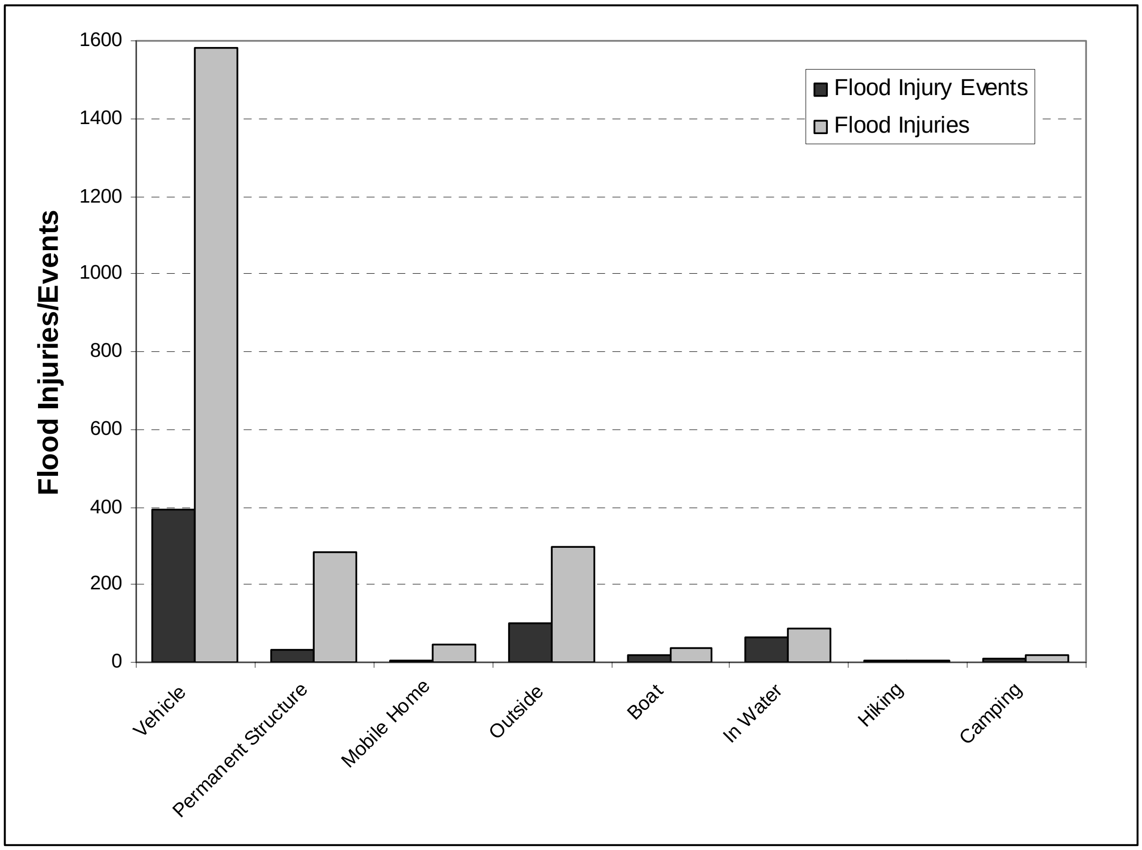

Figure 2.12: As in Figure 2.11 except flood injury events and injuries.

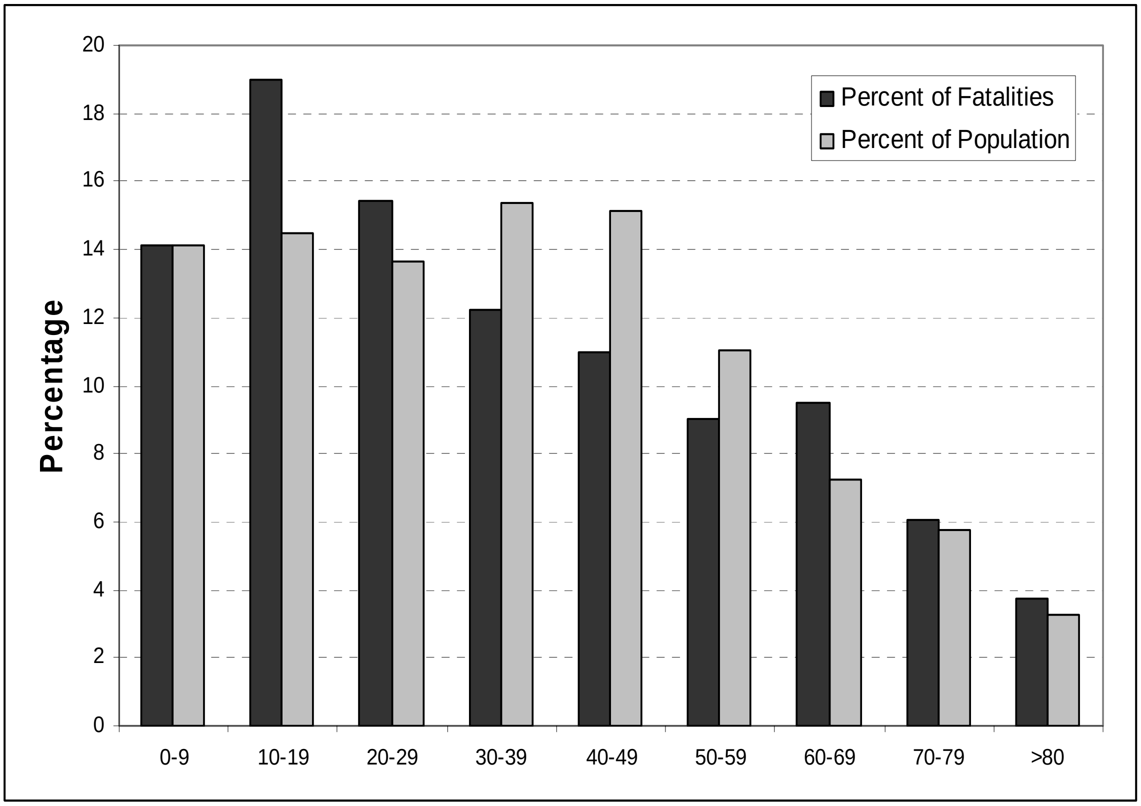

Figure 2.13: The percentage of flood fatalities and population by age classification. Black bars represent the percentage of fatalities in that age category to all fatalities with known ages. Gray bars represent the percentage of the U.S. population in that age category to the total U.S. population (U.S. Census 2000).

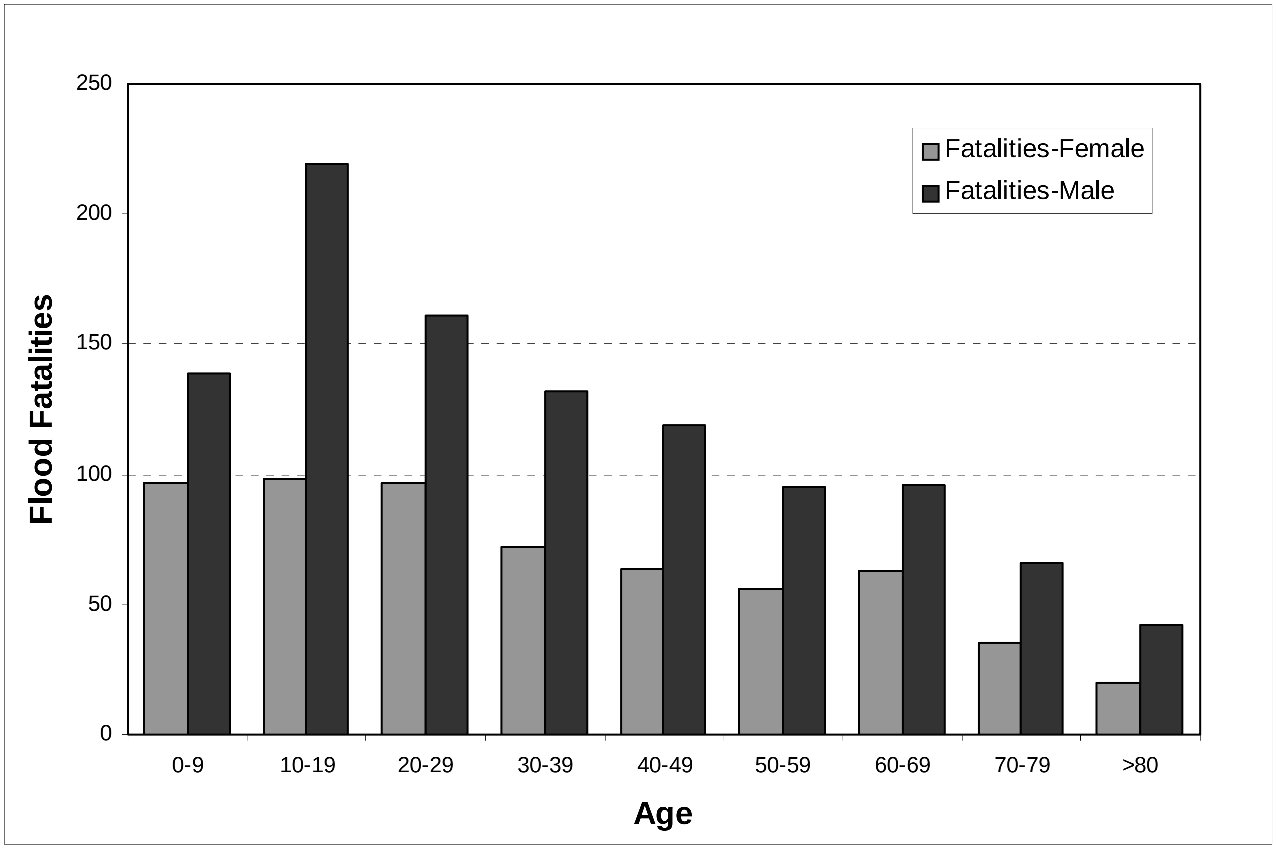

Figure 2.14: The frequency of flood fatalities by gender (female, gray bars; male,black bars) and age classification.

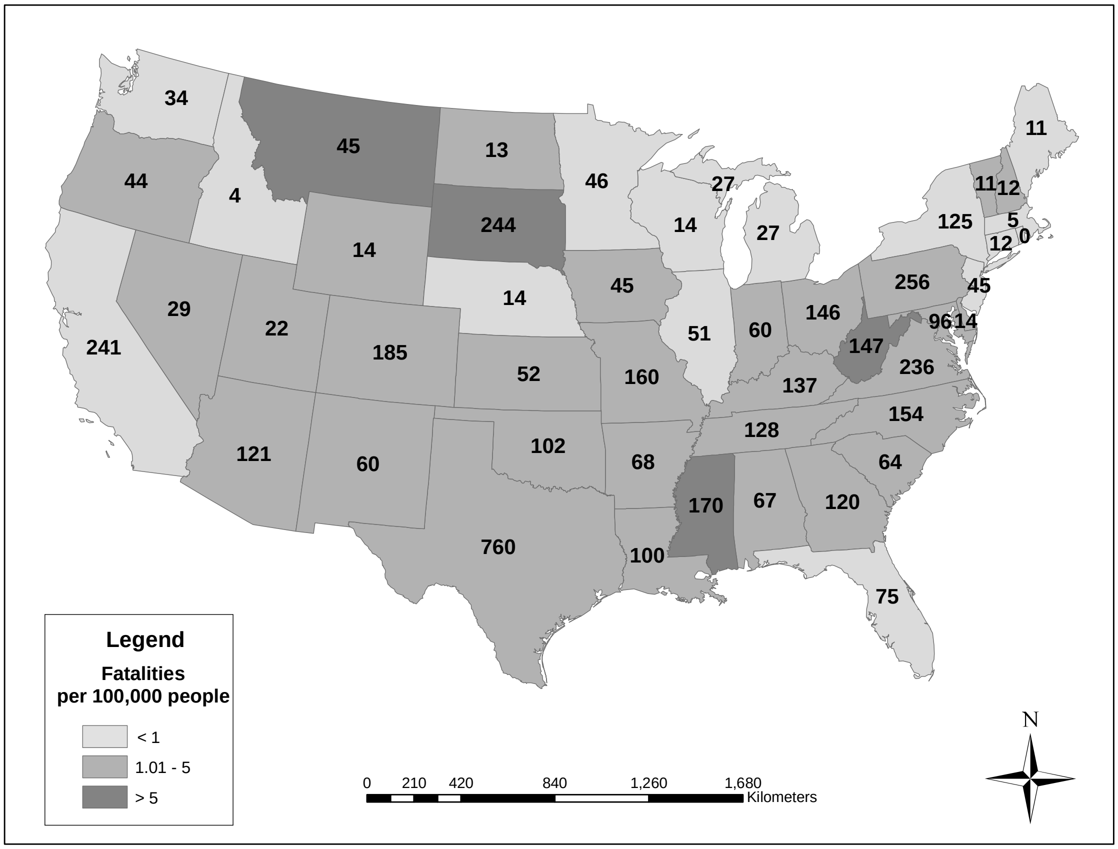

Figure 2.15: U.S. flood fatalities by state standardized by population (per 100,000 people). The number in each state represents the raw number of fatalities from 1959-2005.

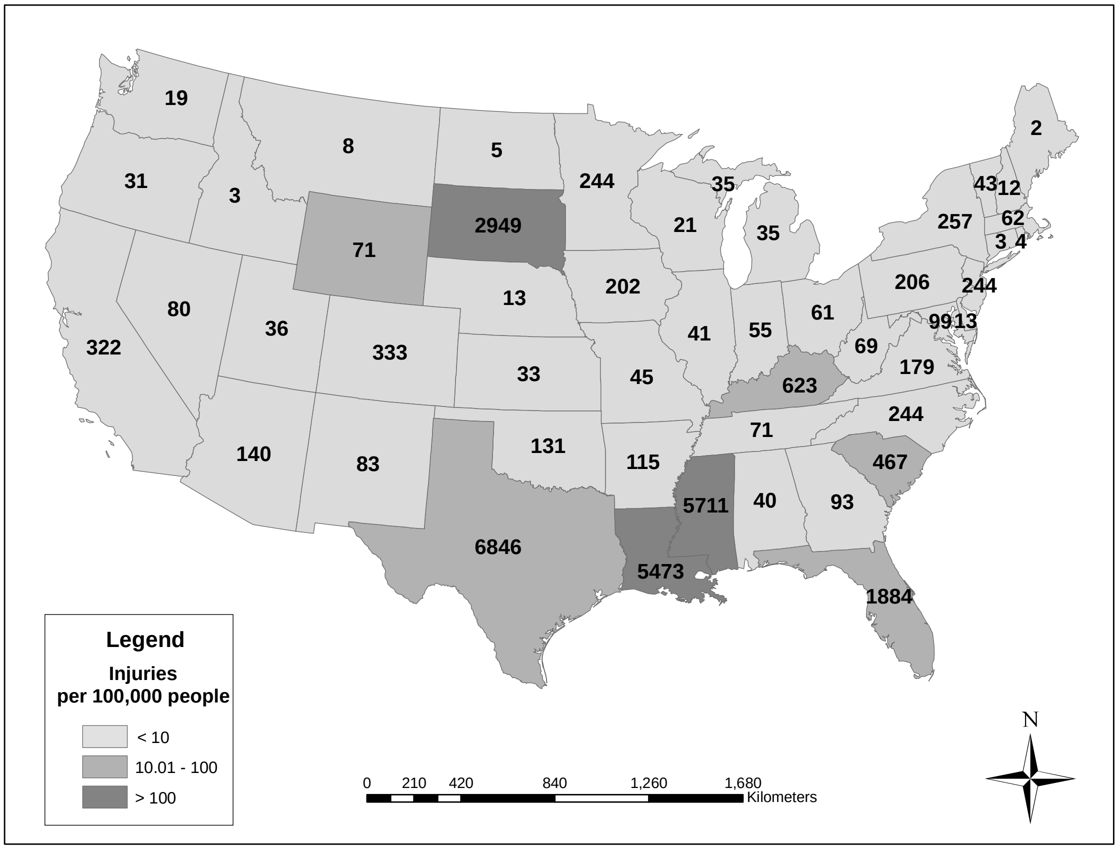

Figure 2.16: Same as Figure 2.15 except for injuries.

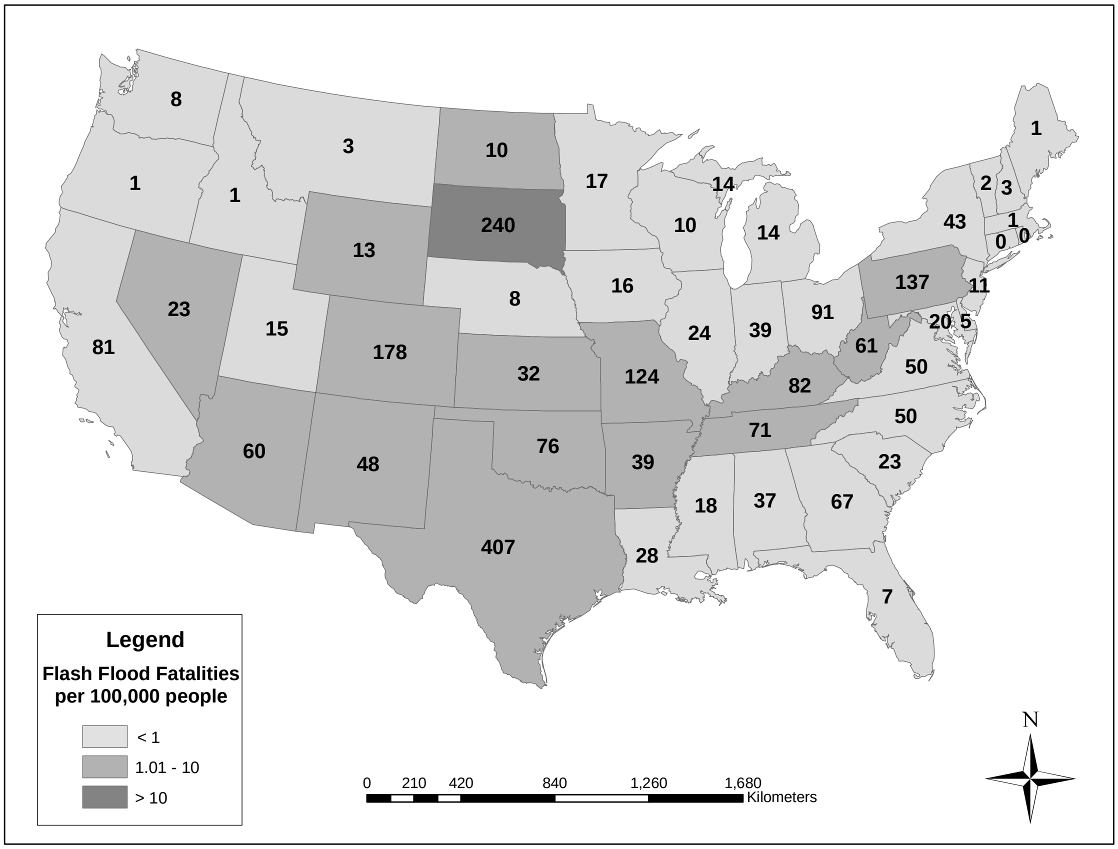

Figure 2.17: All flash flood fatalities by state standardized by population (per 100,000 people). The number in each state represents the raw number of fatalities from 1959-2005.

Figure 2.18: Same as Figure 2.17 except for river floods.

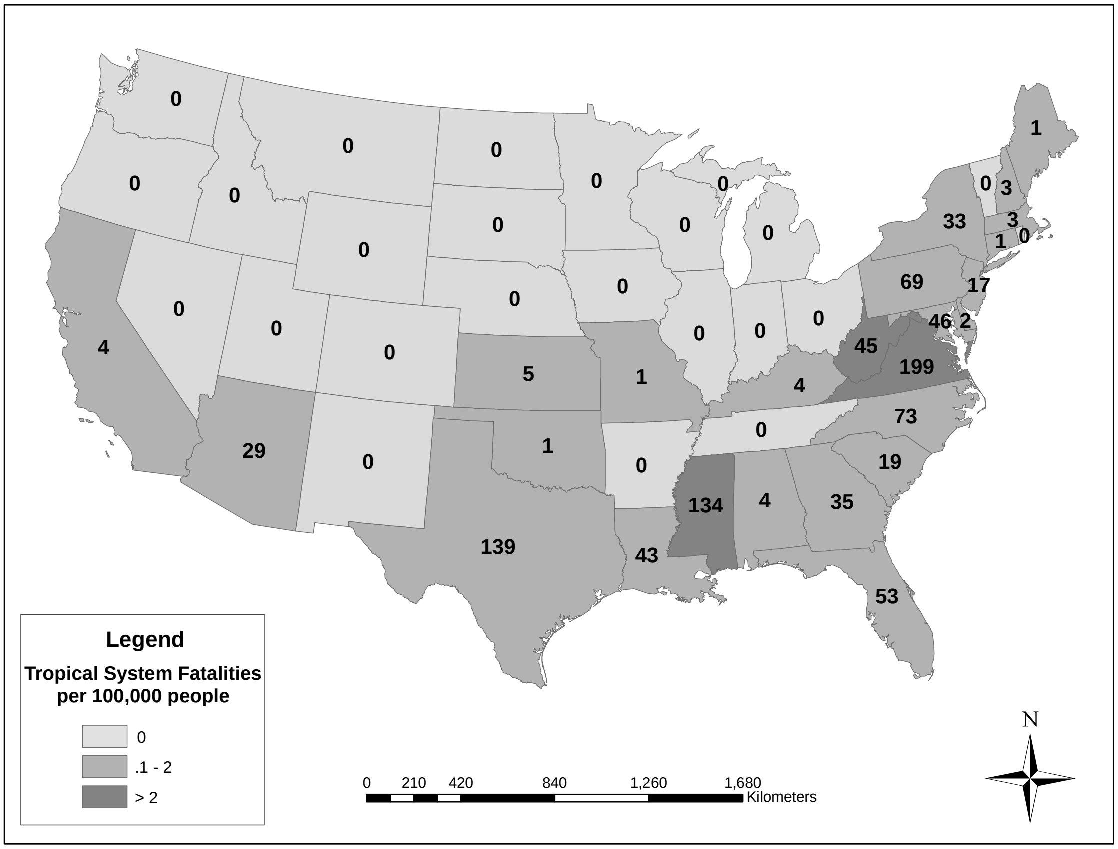

Figure 2.19: Same as Figure 2.17 except for tropical system floods.

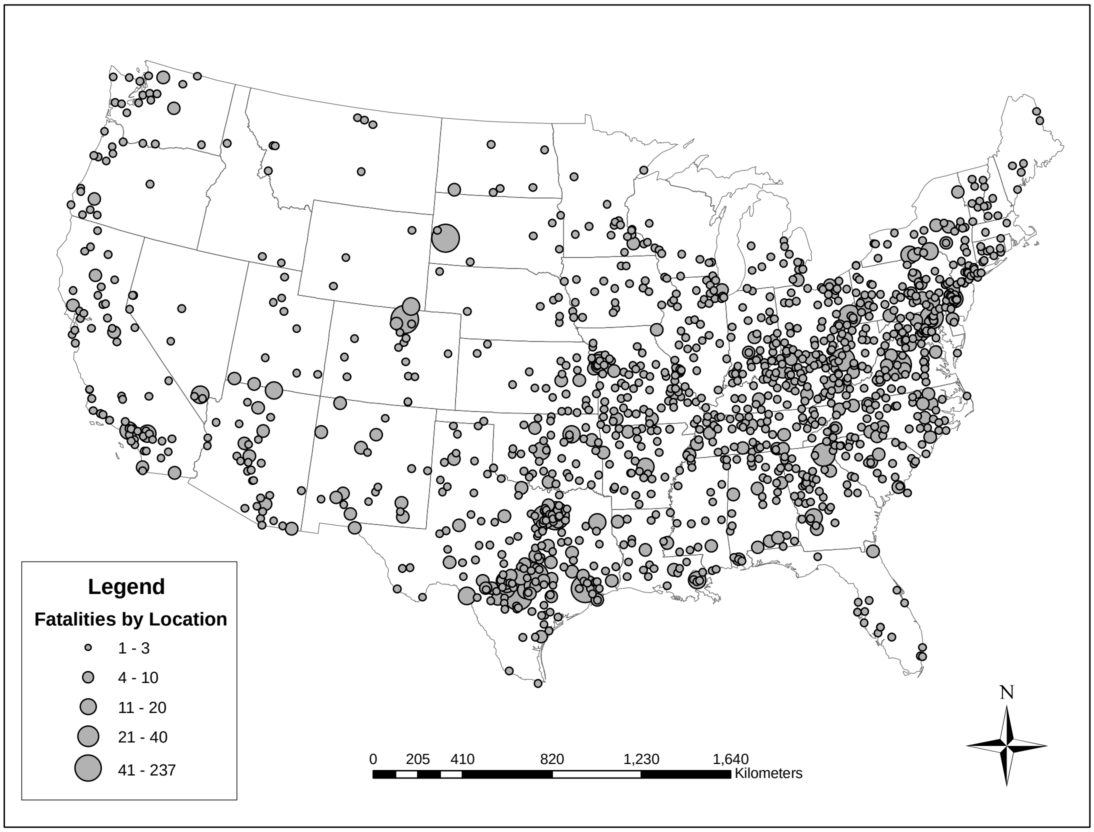

Figure 2.20: Fatalities by city mapped using the latitude and longitude of given city (or county seat if only county was given in *Storm Data*). For each location, one circle represents a flood event; therefore, multiple events for a city will be indicated by multiple circles.

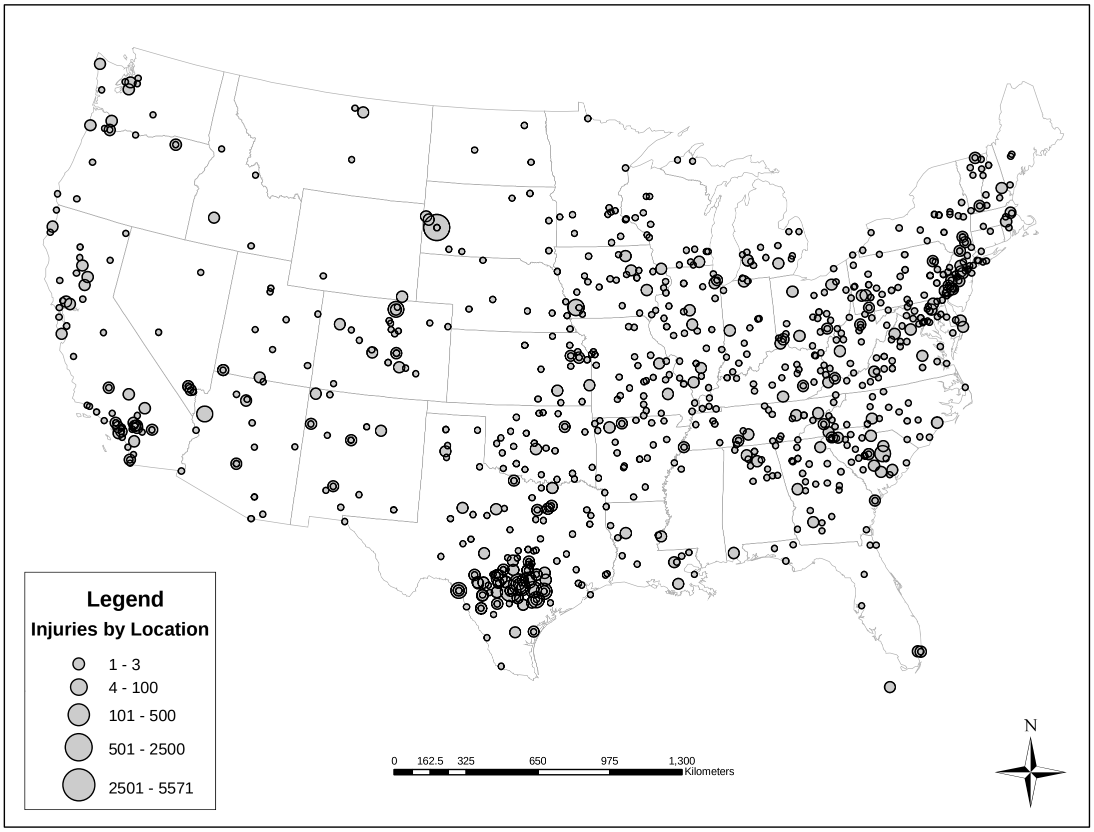

Figure 2.21: Injuries by city mapped using the latitude and longitude of given city (or county seat if only county was given in *Storm Data*). For each location, each graduated circle represents a flood event; therefore, multiple events for a city will be indicated by multiple circles.

CHAPTER 3

THE RELATIONSHIP BETWEEN FLOOD MAGNITUDE AND FLOOD FATALITIES IN THE GUADALUPE RIVER BASIN, TEXAS[2]

[2] Ashley, S.T. To be submitted to *Journal of the American Water Resources Association*.

ABSTRACT

This study investigates the Guadalupe River Basin in south-central Texas in order to provide an understanding of the physical disparities between deadly and non-deadly flood events. Both deadly and non-deadly flood events in this basin from 1959-2005 are examined to reveal the relationship between flood magnitude (i.e., return period) and number of deaths. Over these 47 years, the Guadalupe River Basin experienced 24 deadly flood events and 74 flood fatalities. More than half of the deadly flood events on the Guadalupe River corresponded to flood return periods of five years or less, while many of large magnitude floods (return period of 50 years or greater) caused no fatalities, indicating that high frequency, low magnitude floods may be the most dangerous. Consequently, this examination found that there is low correlation (significant at a 95% confidence interval) between return period and flood fatalities in the Guadalupe River Basin. It is hypothesized that societal factors (e.g., the public's perception of flood dangers) may play an important role in differentiating between deadly and non-deadly floods. A high false alarm ratio (86%) based on floods that occurred in 8 counties of the basin reveal that many flood warnings are not followed by a recorded flood. Therefore, too many warnings may act to increase flood fatalities because people may be more apt to ignore the warning.

3.1 Introduction

Floods are natural phenomena that occur across all 50 states of the U.S., unfortunately, some states experience an above average number of these events and resulting deaths (see Chapter 2). This high rate of floods may be because of the extreme topographical relief of their landscapes, large percent of impervious surfaces from urban centers, and/or high population densities in close proximity to the river channel (Smith and Ward 1998). An excellent example of a state with a high number of flood fatalities from 1959-2005 is Texas. During these 47 years, 772 Texans loss their lives to flooding with a noticeable clustering of fatalities along the Balcones Escarpment (see Chapter 2). The Balcones Escarpment runs from near Dallas/Ft. Worth south through central Texas to San Antonio, Austin, and west to Mexico. The Balcones Escarpment region is one of the most severely flooded landscapes in the U.S. (Beard 1975, Caran and Baker 1986). The flooding in this area can be linked to the intensity of widespread thunderstorms (especially tropical origin) and rapid, high-yield runoff (Baker 1977, Patton and Baker 1976).

The convergence of northern-origin polar air with the warm, moist tropical air transported west from the Gulf of Mexico ensures considerable instability and, therefore, thunderstorms that may be associated with flooding (Caran and Baker 1986). The topography of the region also acts to enhance the precipitation especially when warm, moist air from the Gulf is pushed northward up the escarpment (Caran and Baker 1986). The air then rises rapidly up the several hundred feet of the escarpment because of orograhic lifting (O’Connor and Costa 2003). Consequently, cumulative rainfall along the escarpment is higher than adjacent regions.

In addition to the climatic and topographical factors, the physiographic factors of the landscape also exacerbate the flooding in this region of the state. The escarpment is characterized by steep, sparsely-vegetated slopes, narrow valleys, and thin upland soils on limestone bedrock (Patton and Baker 1976, Baker 1977). These features plus the impervious surfaces that characterize urban centers along the escarpment (e.g., Austin, San Antonio) increase surface runoff and discharge per unit drainage area (Caran and Baker 1986).

A tragic example of severe flooding in Texas occurred in October 1998 when heavy rains fell over south and southeast Texas (NWS 1999, USGS 1999, CDC 2000). A surface front associated with a strong upper-level trough was approaching from the west. Ahead of the surface front, southeasterly flow entrained warm, moist air from the Gulf into the southern half of Texas. Over a two-day period, approximately 55 cm of rain fell causing rapid onset flash flooding followed by extreme river flooding along the many south Texas rivers including (but not limited to) the San Antonio, Guadalupe, Colorado, Brazos, and San Jacinto Rivers. Flash flooding began in the cities of Austin and San Antonio and progressed southward toward the coast as the rain continued. 26 people drowned and an estimated $900 million dollars in property damage occurred (CDC 2000). Flood events that occur under these conditions, especially with onshore flow of warm, moist air, are typical of this region.

One of the major river basins along the Balcones Escarpment where many flooding events have occurred is the Guadalupe River Basin. This basin extends from northwest of Austin and San Antonio perpendicular to the Balcones Escarpment southeast to the Gulf of Mexico (Figure 3.1 and 3.2). The basin has been responsible for a total of 24 deadly flood events that killed 76 people from 1959-2005. The Guadalupe River Basin spans 13 counties including Kerr, Kendall, Blanco, Hays, Comal, Caldwell, Guadalupe, Gonzales, De Witt, Victoria, Goliad, Refugio, and Calhoun. The Guadalupe's major tributaries are the Comal and San Marcos Rivers and collectively the drainage area spans 15,721 square kilometers (TCEQ 2006). This region is one of the most severely flooded regions in the U.S., although not every flood causes a fatality. Moreover, some deadly floods kill only one or two people in this region (Beard 1975, Caran and Baker 1986), while others kill many more people. Is there a relationship between the magnitude of the flood and the number of resulting deaths? Do only large magnitude floods kill? In order to determine whether a flood's physical characteristics (e.g., flood magnitude) are different between deadly and non-deadly events, the Guadalupe Basin is examined because of its unusual number of deadly floods.

To date, no study has examined the relationship between flood magnitude and flood fatalities for a single drainage basin or multiple drainage basins in the U.S. Although many studies investigate a single catastrophic rainfall and flooding event typically focusing on either the meteorology of the event or the hydrologic aspects of the event, e.g., peak discharge or return period (Colwick et al. 1973, Maddox and Grice 1986, Smith et al. 2000, Smith et al. 2001, Zhang and Smith 2003, Delrieu et al. 2005). Due to the void in the literature, this study examined the relationship between the magnitude of the flood and the resulting number of fatalities. As previously mentioned, the study site includes the Guadalupe River Basin in Texas because of the unusual number of fatalities that have occurred there over the last 47 years. This relationship was examined by determining both the flood discharge and return period on the day of the death and correlating these values to the number of fatalities. The return period of a given flood discharge is the inverse of the probability of exceedence. The database consisted of both deadly and non-deadly flood events that have occurred in this basin from 1959-2005. A trend analysis was also completed on all included USGS stream gauges to determine whether flood magnitude has been increasing or decreasing over the 47 years. It is hypothesized that there is a significant relationship between flood magnitude and flood fatalities such that as flood magnitude increases so does the number of fatalities.

3.2 Data and Methodology

A database of deadly flood events for the state of Texas for the years 1959-2005 was compiled based on reports entered into the *Storm Data* publication for the corresponding years. Each report in the publication is reported by the date of the storm event and includes, typically, the city and county where the death occurred. In order to isolate the deaths that occurred in the Guadalupe River Basin, all deadly events that occurred in the counties containing the basin were selected from the dataset. *Storm Data* generally includes a description of the storm event and in the case of flood events the river that flooded is identified. Using the description of the event as well as the city it could then be determined whether the death occurred due to flood waters in the Guadalupe River Basin. Over the 47 years of the study, 26 deadly flood events were determined to have occurred from flooding either on the Guadalupe River or one of its tributaries. For this analysis, a deadly flood event was considered a flood that killed at least one person in a county within the basin either directly by drowning or indirectly through electrocution or heart attack because of the flood waters. Therefore, a flood that travels downstream and crosses county boundaries was counted as separate events in all counties where a death occurred. For example, the Great October Flood of 1998 affected several river basins across south-central Texas, including the Guadalupe basin. Along the Guadalupe River alone, 12 people died in three counties; therefore, a separate event entry was created for each of these three counties. This method was used so that the flood magnitude closest to the fatality could be determined from a United States Geological Survey (USGS) stream gauge.

The city/town of the death was also used to determine the closest USGS stream gauge station. In an effort to accurately represent the magnitude of the flood on the day of the death, the USGS station closest in proximity to each deadly flood event location was used. Mean daily discharge was gathered from each USGS station for the station's entire period of record. In the cases where the data were missing on the day of the death or when the stream gauge station record was less than 20 years, the next closest stream gauge with available data was utilized (Table 3.1). If a fatal event occurred on a small tributary of the Guadalupe River and the closest stream gauge has either less than 20 years of data or missing data on the day of the fatality and there is no other stream gauge to accurate represent the discharge, the event was excluded. There were two events that were excluded for these reasons. Mean daily discharge was used as a surrogate to peak discharge because of its availability from the USGS. It is assumed that the mean daily discharge accurately portrays the magnitude of the flood, although this value is slightly lower than the peak for that day. In all, 11 USGS stations were selected. The Log-Pearson III Distribution is the recommended distribution for defining the annual flood series, therefore this distribution method was selected (USGS 1982). The return period for the discharge on the day of the fatality was then interpreted from the frequency curve (see Appendix B). The resulting database for each deadly event includes:

- Date, location (latitude and longitude of city), and county of flood death;
- Number of fatalities;
- Corresponding USGS stream gauge station with latitude and longitude;
- Mean daily discharge on day of flood death;

- Flood return period on day of the death.

In the event that the date of the death was unknown and a range of two days was given, the highest mean daily discharge was used to determine the return period. There is one flood event in the dataset that occurred just outside the Guadalupe River Basin, along the Cibolo River, which is a tributary of the San Antonio River basin. This event was included in the analysis due to limited information from *Storm Data* on exact location of death in the county. Kendall County (where the event occurred) contains both river basins. The USGS stream gauge station closest in proximity to the assumed locations of the deaths was the Cibolo River, therefore, these two events fall just outside the study basin but are nonetheless included.

To determine the relationship between flood magnitude and flood fatalities, the return period and mean daily discharge on the day of the death are correlated to the number of fatalities. In order to accurately depict this relationship, non-deadly flood events were added to the database using the selected USGS stream stations. Non-deadly events were chosen from the 11 stations by including all discharges greater than the smallest return period that caused a fatality for that station. The resulting database included 483 deadly and non-deadly flood events. Lastly, using the last 20 years of this database, a false alarm ratio for flash flood warnings issued is calculated (Brooks 2004). Flash flood warning data from 1986-2005 were provided by the National Oceanic and Atmospheric Administration (NOAA) (Brenton Macaloney personal communication 2006). These data consisted of all flash floods warnings by county issued during these years with corresponding warning date, begin time, end time, and weather forecast office.

3.3 Results

In the state of Texas from 1959-2005, 772 people died from floods including flash floods (small-scale, rapid-response floods), river floods (large-scale, slow-response floods), and tropical system floods (French and Holt 1989, NWS 2005). In the Guadalupe River Basin, one of the highest frequency flood fatality regions in the U.S., 24 deadly floods were selected for analysis (Table 3.2). In these 24 events, a total of 74 people perished; the deadliest event was a flood in Comal County that killed 17 people on May 1972. This flood, created by 47 cm of rain in four hours from a thunderstorm north of New Braunfels, killed additional people in Guadalupe County (Colwick et al. 1973). Other notable events occurred July 1987 in Kerr County and October 1998 in Comal, Guadalupe, and Caldwell counties. The 1987 flood event, one of the most tragic events in Texas Hill country, caused 10 people (mostly young boys) to drown when their summer camp vehicles became stalled in high waters of the Guadalupe River (NOAA 2005). The latter event, The Great October Flood of 1998, affected many counties and river basins in south-central Texas (USGS 1999, NWS 1999, CDC 2000). In the three counties of the Guadalupe River Basin, 12 people drowned as a result of the flood waters.

Over the 47 years of the study, there is no significant trend in number of fatalities in the Guadalupe River Basin, but the record is marked by several extremely deadly years (Figure 3.3). Other weather hazards (e.g., tornado and lightning) in the U.S. have exhibited a decrease in fatalities over the 20th Century. For example, tornado death rates have declined sharply from 1.8 people per million in 1925 to less than 1.2 people per million in 2000 (Brooks and Doswell 2001, Boruff et al. 2003). A decline in lightning fatalities was also seen over this past century (Lopez and Holle 1996, Curran et al. 1999). On a larger spatial scale (i.e., the contiguous U.S.) this lack of a significant decreasing trend in flood fatalities is also evident (see Chapter 2).

The four most extreme years with respect to flood deaths (1972, 1978, 1987, and 1998) all experienced a single tragic event that caused many deaths. Consequently, these years combined to contribute 69% of all the flood fatalities. The remaining years in the dataset are mostly comprised of drownings of one or two people. Most fatalities in this river basin occurred in May, although July, August, and October all show relatively high frequencies (Figure 3.4). Moreover, the highest frequency of fatal flood events occurred in May with five deadly events occurring over the period of record. Whereas, in other high-frequency months, the deaths occurred from one or two events, e.g., “The Great October Flood” of 1998.

Out of the 24 deadly events alone, 12 flood events resulted in more than one person perishing in a single county. These deadly events were found to have return periods ranging from 100 years to 2 years (Table 3.3). Log-Pearson III Distribution for defining the annual flood series was found to be a reasonable fit for the data at all USGS gauge stations (Appendix B). A Spearman’s Rank Correlation between the two variables, fatalities and return period, returns a coefficient of 0.45, which is significant at a 95% confidence interval. Because this correlation only includes flood events that resulted in at least one fatality, the relationship between fatalities and return period may not present the full picture as a flood with a higher return period may occur and not result in a fatality. Therefore, flood events that resulted in no deaths were added to the database in order to determine the relationship between a flood’s magnitude and number of resultant fatalities.

A Spearman’s Rank Correlation test (Rogerson 2004) was performed between fatalities, return period, and average daily discharge for the day of the death for the 483 events in the database. Fatalities were found to be significantly correlated with return period ($r = .19$, 95% confidence interval). Because it only explains 4% of the variance, it is concluded that that other variables, in addition to flood magnitude, contribute in turning a flood event into a deadly flood event. Other variables may include population density of the cities or town located in the floodplain, the perception of the residences of flood hazards, as well as their level of education concerning appropriate safety measures. This relationship between return period and deadly events for the 483 floods illustrates that the majority deadly floods occur because of lower magnitude, higher frequency floods in the Guadalupe River Basin (Fig. 3.5). Although no category is without a deadly flood, the more common floods (i.e., return period < 5) caused 50% of the deadly events in this basin. These floods may often be ignored by the public until a death occurs. Because of this, future emphasis should be placed on educating the public on these smaller, but more frequent, floods.

The false alarm ratio (floods warned for but not observed relative to the total number of warnings issued) was also calculated for a select number of counties in the Guadalupe River Basin from 1986-2005 (Brooks 2004). The floods selected for this analysis were those that occurred over the last 20 years and recorded at the 11 USGS stations previously selected for this study. The USGS stations were located in 8 counties of the basin and when including only 1986-2005, 188 floods occurred in these counties. Out of the 188 floods, 93 of the events were accompanied by a warning, whereas 95 floods were observed but no warning was issued for the county where it occurred. Furthermore, 591 warnings were issued for these counties. The false alarm ratio for these counties in the Guadalupe River Basin was found to be 86%; therefore, the majority of warnings are not followed by a flood event in this basin. This high percentage of false alarms may act to oppose the positive effects of warnings, in that; too many warnings (especially those that are not followed by a flood) may cause people to ignore future, accurate warnings.

The database was comprised of four events (six deaths) with return periods less than 2 years. The 2-year return period is often assumed to be flood flow or the maximum channel flow (Reed et al. 2002). Therefore, flood with return periods of less than 2 years can be assumed to be channel flow. Of the four deadly events, three of them occurred as vehicles were crossing the Guadalupe River while one death occurred due to recreation in the waters. *Storm Data* does not provide a detailed explanation of the fatality; therefore, it is hypothesized that these deaths in the Guadalupe River Basin may have occurred while crossing fords, which should only be used during low-flow conditions.

3.4 Summary and Conclusions

Texas, which ranks first of all states in the U.S. for total number of flood deaths from 1959-2005, lost 772 people to flood events over this 47 year period (see Chapter 2). Many of these deaths occurred along the Balcones Escarpment that runs north-south through central Texas. Not surprisingly, this region is one of the most severely flooded landscapes in the U.S. because of its location and landscape (Leopold et al. 1964, Beard 1975, Baker 1977, Patton and Baker 1976, Caran and Baker 1986). The Guadalupe River Basin runs perpendicular to the escarpment and over the 47 years has been responsible for 24 deadly flooding events and 74 deaths. Countless non-deadly flood events have occurred in this basin; therefore, this study investigated the relationship between flood magnitude and flood fatalities. Are floods with high magnitudes (e.g., 50 or 100 year return period) what causes an ordinary flood event to turn deadly? To date, no study has attempted to quantify this relationship, although numerous studies have investigated single catastrophic flooding events to understand both the atmospheric and hydrologic components of the flood (Colwick et al. 1973, Maddox and Grice 1986, Smith et al. 2000, Smith et al. 2001, Zhang and Smith 2003, Delrieu et al. 2005).

Through the analysis of 24 deadly flood events and 459 non-deadly flood events in the Guadalupe River Basin, it was determined that an increase in flood magnitude does significantly correlate to an increase in the number of flood fatalities in this basin. Although, these variables were poorly correlated (r = .19), therefore, it is assumed that other variables are important in creating a deadly flood. Half of the deadly events in the basin corresponded with return periods of 5 years or less. This illustrates that high magnitude flood events are not always synonymous with deadly flood events in the Guadalupe Basin. A high false alarm ratio calculated for 8 counties in the basin may indicate that too many warnings are issued prematurely and may work to negate the positive effect of warnings. This, ultimately, may increase flood fatalities because warnings will go unheeded.

The results found for this basin are unique in that this basin is located in a region with extreme flooding potential. First, the basin is located along the Balcones Escarpment which is a region of high topographical relief with steep, sparsely-vegetated slopes and narrow valleys (Patton and Baker 1976, Baker 1977). The basin is also frequented by intense thunderstorms sometimes of tropical origin. These characteristics increase surface runoff and discharge per unit drainage area (Caran and Baker 1986). Expanding on this case study to include more river basins, perhaps in different regions of the U.S., with both deadly and non-deadly flooding events is necessary to corroborate the findings of this study. Further investigation into the social characteristics (e.g., public's perception of the dangers of floods) may aid in understanding what separates a deadly flood from a non-deadly. Additionally, flood safety programs should emphasize the dangers of smaller, higher frequent floods.

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Table 3.1: USGS stream gauge information (including site name and years of data).

Site Name	Period of Record
Cibolo Cr. Nr. Boerne	1962-1997, 36 years
San Marcos Sp. @ San Marcos	1956-2005, 50 years
Guadalupe R. @ Comfort	1939-2004, 66 years
Gaudalupe R. @ Victoria	1934-2005, 72 years
Comal R. @ New Braunfels	1927-2004, 78 years
Guadalupe R. above Comal R. @ New Braunfels	1927-2004, 78 years
Guadalupe R. @ Hunt	1965-2004, 40 years
Plum Cr. @ Lockhart	1959-2006, 54 years
Gaudalupe R. @ Kerrville	1986-2005, 20 years
Guadalupe R. @ Cuero	1964-2006, 42 years
Blanco R. @ Wimberly	1928-2005, 78 years

Table 3.2: Deadly flood events in Guadalupe River Basin, TX.

Event	Year	Month	Fatalities	County
1	1964	September	1	Kendall
2	1970	May	2	Hays
3	1971	August	1	Kendall
4	1972	May	17	Comal
5	1972	May	1	Guadalupe
6	1972	May	1	Victoria
7	1974	Nov	3	Comal
8	1978	August	3	Kendall
9	1978	August	8	Kerr
10	1982	May	1	Caldwell
11	1984	December	3	Kerr
12	1986	May	1	Kerr
13	1987	July	10	Kerr
14	1987	June	1	DeWitt
15	1988	July	2	Kerr
16	1991	December	1	Hays
17	1996	September	1	Kerr
18	1997	June	2	Hays
19	1998	October	2	Comal
20	1998	October	4	Guadalupe
21	1998	October	6	Caldwell
22	2000	November	1	Kerr
23	2001	November	1	Guadalupe
24	2004	November	1	Hays

Table 3.3: Date of deadly flood event in Guadalupe River Basin with corresponding USGS stream gauge information.

Year	Month	Day	Deaths	Site Name	Drainage Area (mi^2)	Mean Daily Discharge (cfs)	Return Period (yrs)
1964	Sept	27	1	Cibolo Cr. Nr. Boerne	68.4	3,830	19
1970	May	15	2	San Marcos Sp. @ San Marcos	48.9	235	2
1971	Aug	11-14	1	Guadalupe R. @ Comfort	839	27,300	11
1972	May	10	1	Gaudalupe R. @ Victoria	5,198	18,500	2
1972	May	12	17	Comal R. @ New Braunfels	130	14,400	100
1972	May	12	1	Comal R. @ New Braunfels	130	14,400	100
1974	Nov	23-24	3	Guadalupe R. above Comal R. @ New Braunfels	1,518	2,230	<2
1978	Aug	2	3	Guadalupe R. @ Comfort	839	74,200	65
1978	Aug	2	8	Guadalupe R. @ Hunt	288	16,300	10
1982	May	13	1	Plum Cr. @ Lockhart	112	3,480	3
1984	Dec	31	3	Guadalupe R. @ Hunt	288	8,540	5
1986	May	26	1	Guadalupe R. @ Hunt	288	195	<2
1987	Jul	17	10	Gaudalupe R. @ Kerrville	510	36,100	20
1987	Jun	5	1	Guadalupe R. @ Cuero	4,934	77,900	10
1988	Jul	11	2	Guadalupe R. @ Hunt	288	5,100	3
1991	Dec	20	1	Blanco R. @ Wimberly	355	17,200	15
1996	Sept	15	1	Gaudalupe R. @ Kerrville	510	1,090	<2
1997	Jun	9	2	Plum Cr. @ Lockhart	112	2,190	3
1998	Oct	17-18	2	Guadalupe R. above Comal R. @ New Braunfels	1,518	37,400	20
1998	Oct	17-18	4	Comal R. @ New Braunfels	130	22,000	>100
1998	Oct	17-18	6	Plum Cr. @ Lockhart	112	19,400	35
2000	Nov	3	1	Gaudalupe R. @ Kerrville	510	2,760	<2
2001	Nov	15	1	Comal R. @ New Braunfels	130	1,260	2
2004	Nov	14-15	1	San Marcos Sp. @ San Marcos	48.9	247	3

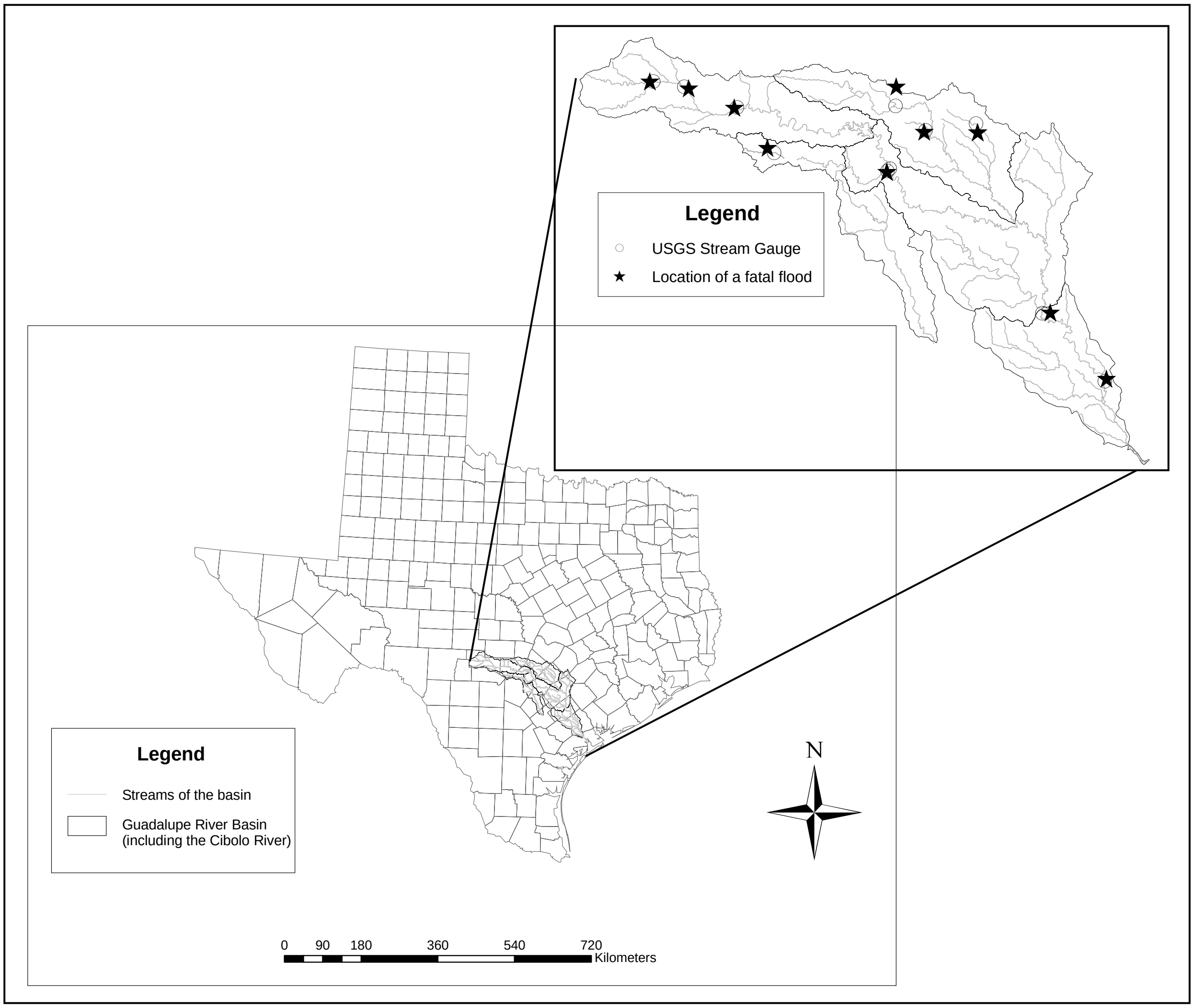

Figure 3.1: Guadalupe River Basin with the inclusion of the Cibolo River Basin in south-central Texas.

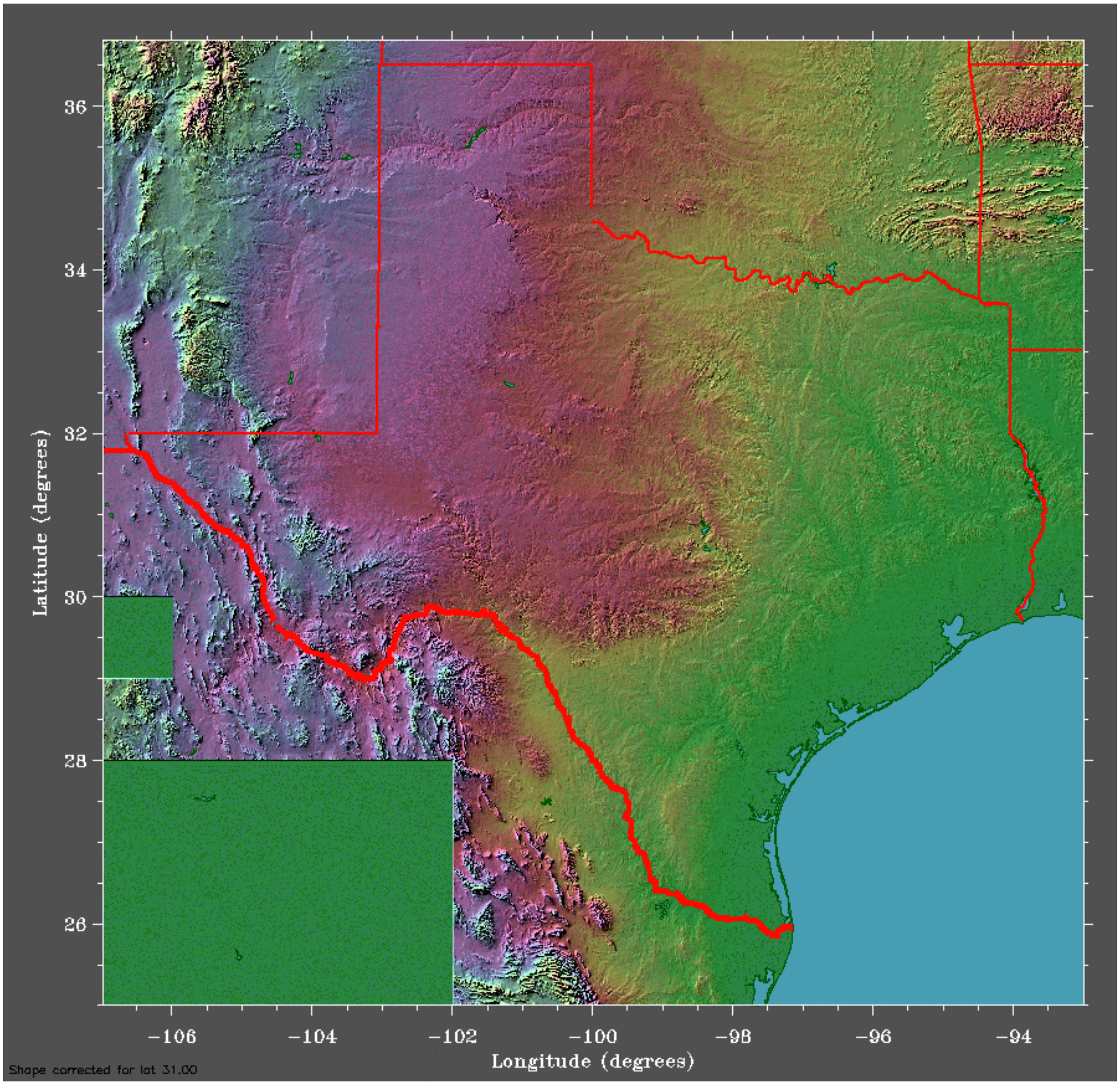

Figure 3.2: Topographic map of Texas (World Atlas 2006).

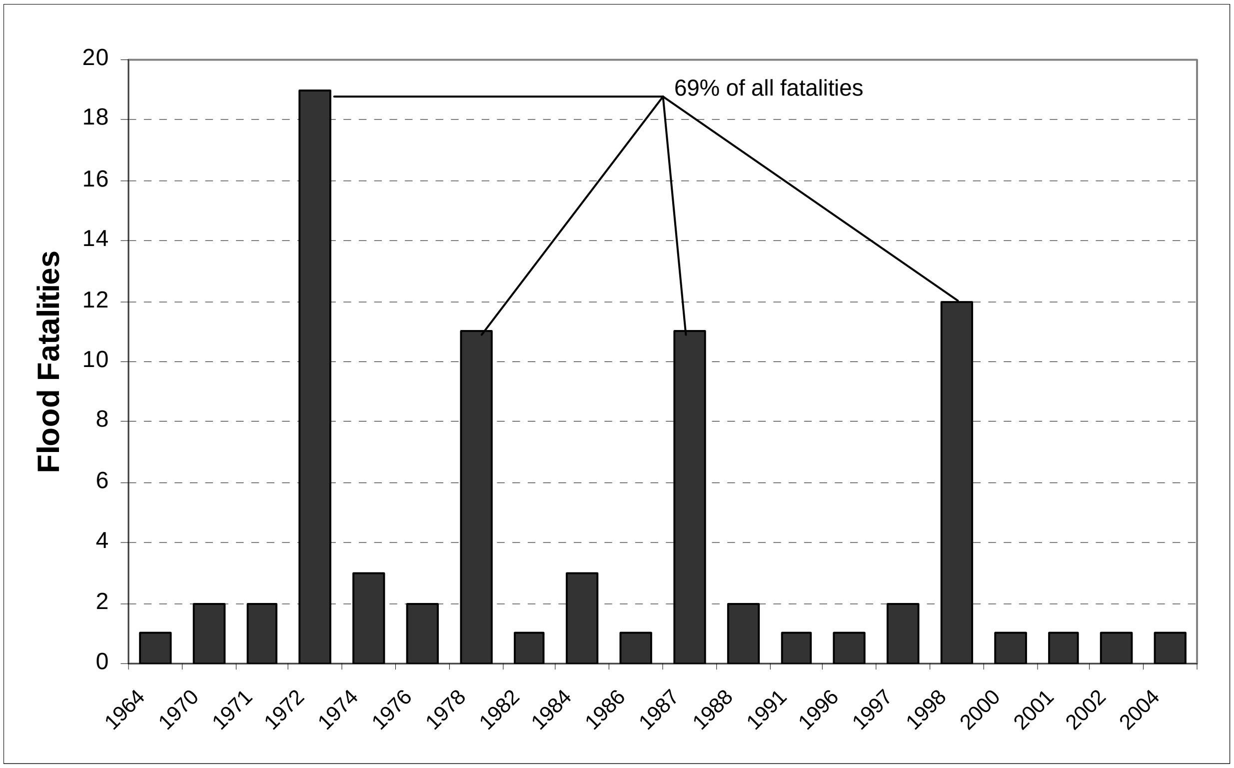

Figure 3.3: Frequency of Guadalupe River Basin fatalities from 1959-2005. There were no deaths in this river basin from 1959-1964 or in 2005 according to *Storm Data*.

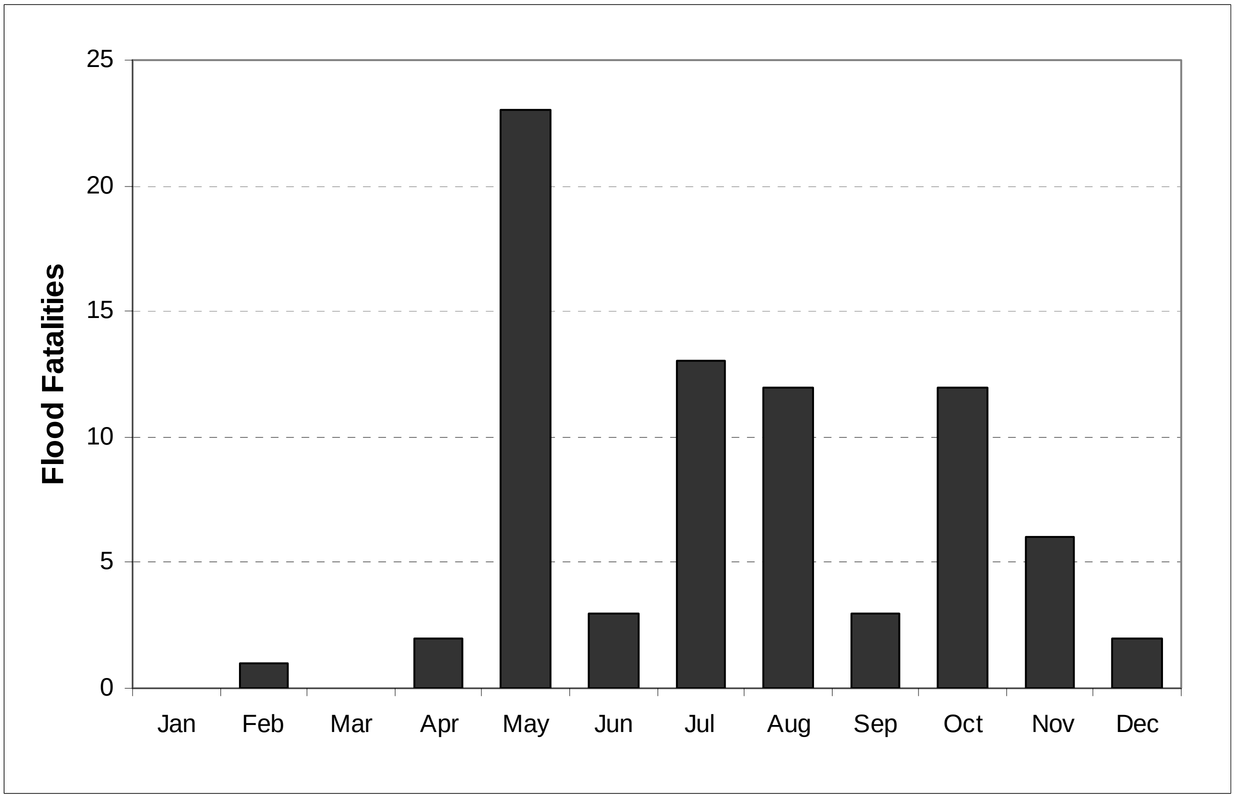

Figure 3.4: Monthly frequency of flood fatalities in the Guadalupe River basin from 1959-2005.

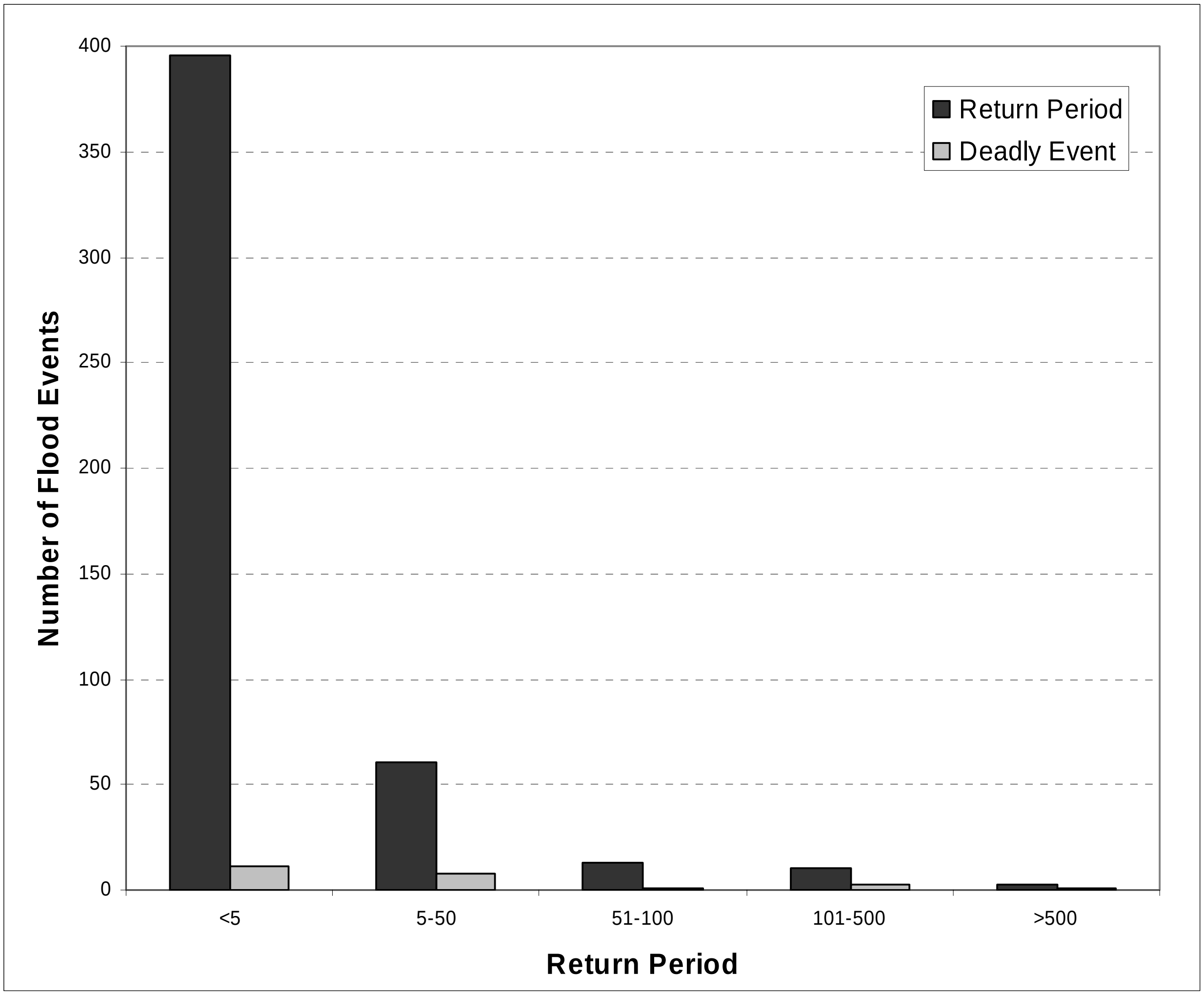

Figure 3.5: Number of events per flood return period class for Guadalupe River Basin in Texas from 1947-2005.

CHAPTER 4

THE DISTRIBUTION OF FLASH FLOOD WARNINGS IN THE UNITED STATES FROM 1986-2005[3]

[3] Ashley, S.T. To be submitted to *Physical Geography*.

ABSTRACT

This study examines the distribution of flash flood warnings in the U.S. for the years 1986-2005 as well as the relationship between flash flood warnings and fatalities. The counties with the highest rates of warnings in the U.S. are found predominately through the Ohio and Tennessee River Valleys, along the Interstate 95 corridor, and in south-central Texas. Over the 20 years investigated, 40% of all deadly flood events went unwarned in the county where the death occurred. During this time period, significant advancements were made in National Weather Service with the installation and implementation of the WSR-88D radar network. The installation was completed by 1995 and a comparison fraction of unwarned deadly floods prior to and post installation reveals that the percent of unwarned deadly floods decreased after the installation. From 1986-1995, 49% of all deadly floods went unwarned, while from 1996-2005 only 30% of all deadly floods went unwarned. Despite this apparent improvement in warnings, flood fatalities did not significantly decrease over the 20 years. Additionally, a flood death index map was created to illustrate counties in the U.S. that observe a high number of actual deaths relative to their potential number of deaths. The county's potential number of deaths is based on its population density and total number of flash flood warnings issued over the 20 years of the study. This map reveals that counties with a high actual number of deaths relative to the potential have a lower risk (or potential) of flash flood deaths. This disproportionately high number of actual deaths to potential may be explained by social factors such as the public's perception of flood dangers, exacerbated by inexperience with floods.

4.1 Introduction

Although the National Weather Service (NWS) issued 84,804 flash flood warnings from 1986-2005 in the U.S., 1,063 people still perished due to the flash floods nationwide. These flash flood fatalities accounted for 65% of all flood-related fatalities that occurred during the 20-year period (see Chapter 2). Despite the fact that floods are natural phenomena, they become hazardous to humans and property once the river channel's adjacent floodplain is encroached upon (Smith and Ward 1998). For example, a town with a physical threat to flash floods because of proximity to the river channel, high topographical relief or a high percentage of impervious surfaces coupled with vulnerable socioeconomic factors (e.g., large number of people living in the low-lying zone, high percentage of elderly unable to cope with disasters) will inevitably raise the likelihood of property loss and casualties caused by the flood event.

The vulnerabilities (e.g., loss of life and property) associated with floods may be reduced through flood forecasting that is translated into an accurate warning for the people at risk. A flood warning that is successful in reducing loss of life and property provides such information as: 1) advance information on the magnitude, location, and timing of the event, 2) nature of the loss-reducing actions to be taken from a targeted group of recipients (Smith and Ward 1998). Lead-times (difference in time between when the warning was issued and the onset of the flood) of flash flood warnings become particularly important in saving lives and property; as little as one-hour of lead-time can reduce losses by 10% (Sweeney and Baumgardner 1999). Because flash floods are rapid onset events, the primary responsibility of these warnings is to save lives. The rapid onset of these events may leave little lead-time for the public to reach safety, and in some instances there is no time for a warning to be issued at all (Smith and Ward 1998, OSHA 2006). Moreover, when forecasters fail to recognize the flash flood threat before the event begins, they tend to inadequately warn the public because of their preoccupation with understanding their mistake (Doswell 1994). In this time spent analyzing their mistake, the flood event may have come and gone.

Flash flood warnings are issued by local NWS warning and forecast offices for an estimated 4,000 U.S. locations with the help of models and real-time data (NOAA 1981, NWS 2006). The Weather Forecast Offices (WFOs) issue these flash flood warnings if rainfall tallies from in situ measurements or rainfall estimates from NWS Doppler Radars exceed flash flood guidance values (Sweeney and Baumgardner 1999). The installation of these 121 Doppler Radar units occurred in the mid-1990s as part of the modernization of the NWS and this national network of radars is used to monitor and forecast severe storms and precipitation (including flash floods).

The WFOs issue a flash flood warning for their county warning area (CWA) based upon the following criteria disseminated from the NWS (NWS 2006): 1) flash flood is reported; and/or, a dam or levee failure is imminent or occurring; and/or, 2) a sudden failure of a natural stream obstruction (e.g., ice jam) is imminent or occurring; and/or, 3) precipitation capable of producing flash flooding is indicated by radar, rain gauge, and/or satellite; and/or, 4) local monitoring and predictions tools indicate flash flooding is likely; and/or, 5) a hydrologic model indicates flash flooding for locations on small streams; and/or, 6) a previously issued flash flood warnings needs to be extended; and/or, 7) flash flooding is imminent or occurring in one or more additional counties.

Once a warning has been issued for a flash flood, the responsibility is then disseminated to the public. Dissemination of flood warnings is largely due to coverage and attention of the local media (AMS 2000) as well as through the National Oceanic and Atmospheric

Administration Weather Radio. Evacuations, flood proofing, and flood fighting initiated by the public must follow the warning in order to reduce the number of fatalities that may potentially occur (Sweeney and Baumgardner 1999). Without these necessary precautions and/or actions, the warning becomes ineffective in saving lives. The behavioral actions of the warning recipients may depend on the size of the household, receipt of warning, past experience with floods, and/or the unwillingness or inability to take action. Behavior varies widely between individual households (Smith and Ward 1998). Unfortunately, the public generally regards rainfall as an ordinary event and, consequently, do not perceive everyday rainfall events to be as deadly as the more menacing events such as tornadoes or hurricanes (Doswell 1997). Moreover, people who are less experienced with floods or perceive themselves as capable of keeping safe in dangerous situations tend to be those who drive through flooded roads (Drobot et al. 2006). Brilly and Polic (2005) and Stewart (2006) also found that people are less likely to worry about future flood events and their impacts if they have never experienced the devastation of a flood. Age may also play a role in different perceptions of floods because young Americans (18-35 years old) are more likely to drive through flood waters than their older (35 years of age an older) counterparts (Drobot et al. 2006, see Chapter 2). Because a majority of flood deaths are associated with vehicle-related accidents, the perception of safety in a vehicle increases the vulnerability and the hazards associated with flood events. In times when no advance warning can be issued, prior flood safety education must be relied upon to protect the inhabitants of the area inundated by the flash flood.

The issuance of warnings is one of the primary tools used by the government in reducing the number of lives lost to flash floods in the U.S. The public's reaction to these warnings is also an important element in this fatality reduction, albeit more difficult to examine and quantify.

Therefore, this study focuses on flash flood warnings and flash flood fatalities in the U.S. from 1986-2005 in order to determine whether there is a relationship between flash flood warnings and flash flood deaths. That is, do the flash floods that are preceded or accompanied with a warning cause fewer deaths as opposed to those that are unwarned? Additionally, this study illustrates the temporal and spatial distribution of flash flood warnings from 1986-2005 across the U.S. Lastly, a county-based flash flood death index is created to illustrate the relationship of a county's actual number of flash flood fatalities to its potential number of flash flood fatalities. The potential number of fatalities is calculated based on the county's population density and number of flash flood warnings the county was issued through the 20-year period. To date, a detailed examination of the relationship between flash flood warnings by county and the number of deaths from these events has not been conducted.

Previous literature has focused primarily on tornadic thunderstorms and not flash flood producing storms when examining the relationship between warnings and fatalities (Galway 1975, Simmons and Sutter 2005). Only French et al. (1983) have examined the effects of warnings on flash flood mortality. However, their study was restricted to flash flood "disasters" from 1969-1981 – those events that produced at least 30 deaths or greater than $100 million in property damage. They determined that warnings encompassing the correct time frame and area had half of the number of deaths than warnings that were issued for general regions and non-specific time frames, i.e., the following day.

Both flash flood and tornado warnings improved with the installation of the WSR-88D radars in the mid-1990s. A study by Simmons and Sutter (2005) attempted to quantify this improvement based on fatalities before and after the installation. They did find that tornado fatalities were lower than expected in the years following the implementation of Doppler radar nationwide. Similarly, a study by Galway (1975) examined the relationship between tornado deaths and severe weather watch areas. He found that almost two-thirds of tornado-related deaths occurred in watch areas.

4.2 Data and Methodology

Flash flood warning data from 1986-2005 were provided by the National Oceanic and Atmospheric Administration (NOAA) (Brenton Macaloney personal communication). These data consisted of all flash floods warnings by county issued during these years with corresponding warning date, begin time, end time, and weather forecast office. Flash flood fatalities from this 20-year period were compiled using reports from *Storm Data* by county for the entire U.S. (see Chapter 2). Over this period there were 1,063 flash flood deaths from approximately 687 *Storm Data* event entries. The study focuses on flash flood fatalities because they are responsible for the majority of all flood fatalities. Moreover, the study is restricted to the past 20 years due to availability of warning data through NOAA.

As an initial objective of the study, the spatial and temporal distribution of flash flood warnings by county from 1986-2005 across the U.S. was examined through the use of a geographic information system (GIS) to determine the regions at highest risk to flash flood occurrences. Furthermore, the corresponding years' fatalities were overlaid on the spatial distribution in order to determine whether the counties that received a high number of warnings also had high numbers of fatalities. Thus, the map was an initial step in determining whether a relationship exists between flash flood warnings and flash flood deaths from 1986-2005. Moreover, the frequency of flash flood warnings was examined by year and month and compared to the temporal distribution of flash flood fatalities during the same period of record.

Each death in the database was examined to determine whether there was a warning issued for that county on the day of the death. For this analysis, all deaths where the specific day was unknown were removed from the study along with deaths where the county was unknown. This criterion reduced the number of fatalities from the 1,063 to 895. From this database, it could then be determined whether there had been a warning issued. It must be noted that only the day of the fatality was examined to determine if a warning had been issued. The time of death could not be matched up with the warning times because in many instances exact time of death was unknown. Therefore, if a warning was issued on the day of the death for the specific county, it was assumed that the warning was issued for the storm that caused the flash flood death. Because of the sudden onset of these types of floods, this is a valid assumption, although it may inflate the number of fatalities that were warned (Smith and Ward 1998). In the event that a death occurred very early in the morning (i.e., prior to 6 AM local time), the previous day was examined to determine if a flash flood warning had been issued within the last 24 hours proceeding the death. In the event that a warning was issued, the death was assumed to have been warned.

Lastly, a flash flood death index was calculated based on the tornado death index introduced by Sims and Baumann (1972). The index is based on a county's area, population, total number of fatalities associated with flash floods from 1986-2005 as well as the total number of warnings issued during the same time period. The index is calculated as follows:

$$\text{Flood Death Index} = \frac{D / A}{(T / A)\,(P / A)} * 100 \qquad (4.1)$$

where D is the number of flash flood deaths in the county from 1986-2005, A is the area of the county in square kilometers, T is the number of flash flood warnings issued in that county from 1986-2005, and P is the population of the county according to the 1999 census. In the original equation provided by Sims and Baumann (1972), T is the number of tornado occurrences (not warnings) in the county; this study used total flash flood warnings as a surrogate for flash flood occurrence. The number of flash flood occurrences was not used because such a database for the entire U.S. by county does not exist. Both of these variables represent the potential for flash flood fatalities in the county. Using flash flood warnings as a surrogate does introduce differences across Weather Forecast Offices (WFOs). Some counties may have higher or lower numbers of warnings depending on the forecast office. In order to determine whether regions of a high threat of flash floods (i.e., high flood death index) are influenced by the WFOs, county warning areas are overlaid with flash flood warnings standardized by area. The use of warnings may also underreport the risk of floods in the western half of the U.S. because of the gaps in Doppler Radar coverage and in situ rain gauge measurements (Maddox et al. 2002). This may be due to either topographic restrictions or low population density. The numerator of this equation provides the county's actual fatalities standardized by county area while the denominator presents the potential number of flash flood fatalities that may occur in a county. Each separate entity of the equation, including the actual amount of deaths and potential number of deaths, were mapped. A final map was created of the flash flood index that incorporated both values to display the relationship between a county's actual number of deaths and the potential number that could occur based on population density and cumulative number of warnings issued over the 20 years. Therefore, a high value computed from this ratio of actual to potential deaths indicates that a county's actual deaths approaches the potential.

4.3 Results

During the period of record, 1986-2005, there have been 1,063 fatalities due to flash floods across the nation. An astounding 84,804 flash flood warnings have been issued during the same time period. Leading the U.S. in both warnings and deaths for this 20-year period is Texas with 14,746 warnings and 212 fatalities (Table 4.1). Following in rank in both warnings and fatalities are Missouri and Ohio. California ranks fourth in state fatalities but has a relatively low total number of warnings for the time period (i.e., ranking 19th). This low number of warnings may be due to the large county area in California as well as the high population density of some of these counties. Therefore, despite the low number of warnings, a large number of people may have been warned because of these two factors. Despite this apparent anomaly, states with high total warnings correspond to states with high total fatalities. Standardizing both warnings and fatalities by state 1999 population redistributes the rankings, causing Wisconsin to top the ranks for warnings per 1 million people and Arkansas for fatalities. Other states ranked high with respect to warnings per 1 million people include Indiana, Kentucky, Missouri, and Kansas, whereas states with high numbers of fatalities per 1 million include Wisconsin, Mississippi, Kentucky, and New Jersey.

4.3.1 Warnings/Fatalities per Year and Month

The total number of warnings per year has increased in the past 10 years compared to the late 1980s and early 1990s (Fig. 4.1). From 1986-1995 there were, on average, 2,309 warnings issued, while the latter 10-year period had an average of 6,171 warnings issued per year. For the entire 20 years of the data, a trend line (not shown) portrays a positive slope and coefficient of determination (r^2) value of 0.65. The r^2 value is significant at a 95% confidence interval revealing that a significant increasing trend in total warnings issued per year has occurred from 1986-2005.

The mid-1990s coincides with technological advancements in the scientific community in understanding and forecasting of high precipitation events including (but not limited to) the implementation of the WSR-88D radar network (Droegemeier et al. 2000) and modernization in the NWS River and Flood Program (Friday 1994, Fread et al. 1995, Crum et al. 1998). The advancements improved the hydrologic models that predict river discharge associated with heavy precipitation events, and therefore, potential flooding events. Additionally, improved reflectivity estimates have assisted in observing areas of excessive rainfall at 1 and 3 hour intervals that are crucial for early detection of flash flood potential (Polger et al. 1994). Because of these improvements, it would be expected that the mean number of flash flood warnings issued after NWS modernization would be significantly greater than the mean number issued before the modernization. Using the Wilcoxon Signed Ranks statistical test, the mean number of warnings before and after can be compared. The results reveal that there were a significantly more flash flood warnings issued post-modernization ($p = .005$).

With such a substantial increase in flash flood warnings in the past 10 years, one might expect a decrease in flash flood fatalities (Fig. 4.2). Although, there has been a decrease in average deaths from 1986-1995 to 1996-2005, the decrease has been minimal. The average over the latter 10 years (51) was down only 4.6 deaths from the average during the first 10-year period (55.6). A comparison of mean number of deaths for the first ten years versus the second ten years using the Wilcoxon Signed Ranks test reveals that there is no significant difference between the two time periods ($p = .760$).

Similarly, over the 20-year period, there is no significant decreasing trend (using a 95% confidence interval) in the number of flash flood deaths ($r^2 = .06$). Over the entire period of record there is much year-to-year variation in both warnings and fatalities. Does this increase in warning frequency with no significant decrease in fatalities mean that there was an increase in false alarms? For the period of record, there were 62,406 county flash flood events where a warning was issued, 355 of these events had at least one death occur. Therefore, over 99% of all warned events did not have a death occur. It is unknown how many false alarms occurred where no flash flood occurred. A study by Polger et al (1994) found that the false alarm rate decreased by 77% with the WSR-88D in operation.

Over a given year, flash flood warnings peak in the summer months with June having the highest frequency (Fig. 4.3). There is a secondary peak from December to January that is due, in part, to snowmelt flash floods in mountainous regions of the U.S. Flash flood deaths show a similar monthly distribution, although May and July are the two highest frequency months (Fig. 4.4). The increase in flash flood deaths from December to January is also evident.

4.3.2 Spatial Analysis of Flash Flood Warnings and Fatalities

Spatially, the distribution of flash flood warnings standardized by area in the U.S. from 1986-2005, illustrates that the Ohio and Tennessee River Valleys, regions of the central Mississippi Valley (namely in Missouri), along the Interstate 95 corridor in the Northeast, and south-central Texas had the highest number of warnings issued by county per 10,000 square kilometers (Fig. 4.5). Warnings per area in the western U.S. were low relative to the eastern U.S. possible due to under-warning in these counties due to a lower density of both Doppler Radars and population. Furthermore, county warning rates did not appear to be influenced by forecast offices (Fig. 4.6). The flash flood fatalities corresponded to counties with high warning rates, although, fatalities did occur in counties with fewer warnings rates. The counties with the highest warning rates were all regions that are characterized by mountainous terrain or high topographical relief, e.g. Ozark Mountains in northern Arkansas and southern Missouri, the Appalachian Mountains in the east, and the Balcones Escarpment in central Texas. Because flash floods are common in mountainous terrain where the water can be quickly channeled downstream, this spatial distribution is expected (Perry 2000). Additionally, the region along the I-95 corridor in the Northeast is a highly urbanized area which is also highly susceptible to flash floods because of the high percentage of impervious surfaces increasing runoff.

Many of the fatalities did occur in the counties with high numbers of warnings issued, although counties within these regions with higher population densities tended to have more clustering of fatalities. A Spearman Rank Correlation test statistic was conducted on county warning totals and county fatality totals in order to determine whether there was a relationship between the two variables. The correlation coefficient value (r) of 0.32 is statistically significant at a 99% confidence interval. The two most noticeable clusters are visible along the Balcones Escarpment in the Dallas/Fort Worth and Austin/San Antonio urban centers. Outside of the eastern U.S., where many of the deaths occurred, many counties in California and Arizona showed moderate numbers of warnings issued per 10,000 sq. km. and clusters of fatalities around their urban centers (Los Angeles, CA, Tuscon and Phoenix, AZ). Correlation tests between number of warnings in a county and population density (using 1999 population) revealed a significant relationship ($r = 0.34$, 99% confidence interval). Moreover, county fatality totals and population density are significantly correlated ($r = 0.19$, 99% confidence interval).

The top 10 ranking counties with respect to total warnings issued over the period of record include counties from Arizona, California, Texas, Arizona, and Nevada (Table 4.2). Pima County, AZ, led the nation in county flash flood warning issues at 415 during the 20 years, although, the county had only seven deaths over the same time. San Bernardino County, CA, was second in the U.S., but had a relatively large number of fatalities (16). This large number can be explained by the county's high population density. Medina County, TX, was 9th in the warning rankings, but had no deaths over the period of record.

Alternatively, with respect to flash flood deaths, Dallas County, TX, led the nation with 26 deaths over the 20 years (Table 4.3). Incidentally, this county had 139 warnings, while the second deadliest county (Belmont Co, OH) had only 95. The only counties that appeared in both tables are San Bernardino Co, CA, Kerr Co., TX, and Bexar Co., TX. Although county warnings and fatalities were correlated, there were counties that exhibited a high value in one category and not the other. In other words, not all high flash flood warning counties corresponded with high flash flood fatality counties. Two hypothesis are introduced to explain these opposing findings. First, counties with a high number of warnings are assumed to be "well-warned" with respect to floods, therefore, fewer fatalities occur because people are aware of the floodwaters and, consequently, avoid them. Alternatively, too many warnings issued may result in higher fatality numbers because the public becomes desensitized to them and, consequently, ignore their message. This results in a county with a high number of warnings and fatalities.

The issuance of warnings is based on the assumption that the public hears the message and heeds its warning. Although, in many instances, the warning may not have been received (by the victim), nor did it initiate a response. A study examining the hazards associated with railroad crossings reveals that drivers that cross under unsafe conditions (approaching train) risked the crossing because cars ahead of them made it safely (Benekohal and Aycin 2004). Obviously, the driver knew of the dangers associated with crossing the tracks, but proceeded anyway. The hazards associated with railroad crossings are in many way analogous with flood hazards in that people see the flood, perhaps know the dangers (or heard the warning), but ultimately attempt to cross because others were successful or because they assume their car can successfully ford the river. The fact that people may proceed across floodwaters, despite a warning, leads to the conclusion that an emphasis should be placed on flood safety education in order to reduce flood fatalities and not necessarily on improving warnings.

In a further examination of whether flash flood deaths have been forecasted by the issuance of a warning, all *Storm Data* event entries with known date and time of death from the dataset were analyzed. Out of the 586 remaining events and 895 flash flood fatalities, 355 of the events were warned, therefore, 40% of the events did not have a warning issued on the day of or the day prior to the death. A comparison between the percent of flash floods warned before and after 1995, shows that the number of deadly events being warned increased after the modernization of the NWS. From 1986-1995, 49% of all deadly flooding events went unwarned (at least in the county where the death occurred), while from 1996-2005 30% of all deadly flooding events went unwarned. (In the event that the deadly flash flood was warned under a flood warning and not a flash flood warning, the flash flood was labeled as not warned.)

4.3.3 The Flood Death Index

The flood death index is an adaptation of Sims and Baumann's (1972) tornado death index that was used to determine the threat of tornadoes across the U.S. In order to determine the flood death index for a given county, both the actual and potential number of fatalities must be established. High values of actual flash flood deaths (per square kilometer) are found predominately across the Ohio Valley, Missouri, and south through central Texas (Fig. 4.7). A similar distribution is seen when actual flash flood deaths are standardized by county population (4.8). The highest potential for flash flood deaths by county based on the number of warnings that were issued over the 20-years and the population density falls predominately in the eastern U.S. (Fig. 4.9). A clustering of high potential counties is found in the Northeast from northern Virginia to extreme southern Maine. Counties along the Ohio and Tennessee River Valleys also illustrate a high potential for flash flood deaths, while other counties with a high potential for flash flood deaths exist along the escarpment in Texas and the California coast.

Because the flood death index is a measure of the agreement between the potential and actual flash flood fatalities counties where actual comes close to meeting the potential are indicated by larger circles (Fig. 4.10). The counties where the actual is approaching the potential are scattered in the western U.S. and clustered in the South and do not coincide with those counties with the highest potential for flash flood deaths shown in figure 4.12. Although the western counties may show a high flood death index due to an underestimate of warnings, as previously stated.

This is similar to the findings of Sims and Baumann (1972) that found a disproportionately higher rate of tornado deaths in the South. They conclude that this disproportionately higher number of tornado deaths does not coincide with the region where the highest numbers of storms occur nor where the population density is the highest. They offer an alternative hypothesis for the unusual pattern by suggesting that this pattern may be found in this region's societal response or perception of tornado hazards. The hypothesis may also relate to the distribution found within this study. These counties exhibiting a high flood death index have a lower potential for flood events (but high actual fatalities relative to the potential), therefore, they are presumably less experienced with flood events. People who have experienced fewer floods are more likely to drive through flood waters and are not as concerned about the possibility of future floods or their impacts (Brilly and Polic 2005, Drobot 2006). These finding may help explain why the there are disproportionately more deaths in counties with a low potential than those with a higher potential.

4.4 Summary and Conclusions

From 1986-2005, over one thousand people died due to the direct impacts of flash flood events across the U.S. During this same time period over 84,000 flash flood warnings have been issued by NWS forecast offices nationwide. Although, flash flood warnings have nearly tripled from 1986-1995 to 1996-2005, mean flash flood fatalities between the 10-year periods decreased by approximately 3 deaths per year. To date, no study has examined the distribution of flash flood warnings in the U.S. for an extended time period in order to determine if there is a relationship between warnings issued and resulting fatalities. A study examining a shorter time frame found that flash floods that were warned adequately (i.e., within the time frame and area that was predicted) resulted in fewer deaths than those where the warning was issued for a region over a broad time frame (e.g., the next day) (French et al. 1983).

The counties with the highest rates of warnings in the U.S. from 1986-2005 were found predominately through the Ohio and Tennessee River Valleys, along the I-95 corridor, and in south-central Texas. Topography and urbanization seem to be contributors to these regions high warning rates. Clusters of flash flood fatalities followed a similar spatial distribution for the 20 years, although many deaths did occur in counties with lower warnings per 10,000 square kilometers than the regions previously mentioned. Over the 20-year period, there was much inter-annual variation in flash flood warnings with considerably more warnings in the last 10 years. This coincides with the NWS modernization and the installation of a national network of WSR-88D radars (Simmons and Sutter 2005).

All flash flood fatalities reported in *Storm Data* and included in this analysis were examined to determine whether a warning had been issued on either the day or the death of one day prior. Out of the 895 fatalities and 586 *Storm Data* entries, 40% of the fatal flash floods were not preceded by a warning for the county where the death occurred. These findings and the fact that flash flood deaths have not reduced even with a dramatic rise in warnings imply that reducing the number of deaths from flash floods may need to be directed to the education of the public on flash flood safety procedures. Obviously, the public does not view flood waters as a dangerous phenomenon especially since a majority (63% of flash flood deaths) drive into them (see Chapter 2).

A flash flood index was created similar to that introduced by Sims and Baumann (1972) and quantifies a county's potential for flash flood fatalities based on population density and number of flash flood warnings and it compares this value to the actual number of deaths per square kilometer. A map illustrating this flash flood index shows that counties outside the high warning regions come closer to meeting their potential indicating that less experience with flash floods may increase vulnerability. Recent studies have shown that people who are less experienced with floods are more likely to minimize their dangers associated with them (Drobot et al. 2006, Brilly and Polic 2005).

Future research should focus on the public's perception of floods at the local scale, so that the issuance of warnings may be more beneficial. The rapid nature of flash floods cause the lead-times to be short or non-existent, therefore, flash flood safety education must also be implemented as well. In addition, future research should examine the relationship between flash flood warning lead times and flash flood deaths in order to determine the optimal lead-time needed to reduce flood deaths nationwide.

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Table 4.1: State rankings of total warnings and fatalities and per 1 million people from 1986-2005. The top five ranking states for each category are bolded.

State	Warnings	Rank	Warnings per 1 million	Rank	Deaths	Rank	Deaths per 1 million	Rank
Alabama	2205	15	503.09	20	28	12	6.39	10
Arkansas	2625	10	736.93	10	19	17	19.16	**1**
Arizona	1885	20	547.98	17	49	6	3.97	22
California	1905	19	57.57	45	63	**4**	1.90	35
Colorado	766	29	189.17	31	12	26	2.96	27
Connecticut	305	41	93.00	40	0	48	0.00	48
District of Columbia	32	49	322.41	27	1	43	5.83	13
Delaware	166	46	42.57	47	3	34	1.33	40
Florida	1012	25	66.74	44	6	31	0.40	42
Georgia	1409	21	180.54	32	23	16	2.95	28
Iowa	1332	22	28.74	48	12	27	0.08	47
Idaho	348	39	369.72	23	1	44	2.69	32
Illinois	2195	18	765.07	9	16	21	8.71	9
Indiana	2196	17	1065.39	**2**	25	15	9.60	8
Kansas	2481	13	936.97	**5**	16	22	6.04	12
Kentucky	3973	**4**	1002.06	**3**	50	**5**	12.61	**4**
Louisiana	2220	14	506.10	19	19	18	4.33	20
Massachusetts	313	40	154.54	36	1	45	0.80	41
Maryland	838	28	161.91	34	14	24	2.70	30
Maine	193	43	50.65	46	1	46	0.16	46
Michigan	693	32	70.24	43	16	23	1.62	37
Minnesota	945	26	198.30	30	8	28	1.68	36
Missouri	4504	**2**	957.86	**4**	73	**2**	5.05	16
Mississippi	2657	9	823.06	7	14	25	13.34	**3**
Montana	484	37	547.38	18	2	37	2.26	34
North Carolina	2541	12	610.32	15	28	13	3.59	25
North Dakota	427	38	276.64	29	3	35	4.40	18
Nebraska	1020	24	156.08	35	6	32	2.50	33
New Hampshire	187	44	104.87	39	3	36	0.24	45
New Jersey	857	27	591.08	16	2	38	10.83	**5**
New Mexico	1037	23	120.96	38	19	19	1.54	38
Nevada	503	35	331.50	26	8	29	3.65	24
New York	2201	16	670.31	13	28	14	4.71	17
Ohio	3995	**3**	355.26	24	68	**3**	6.05	11
Oklahoma	2703	8	800.90	8	34	9	10.07	7
Oregon	255	42	76.63	42	1	47	0.30	44
Pennsylvania	3831	**5**	319.37	28	45	7	3.75	23
Rhode Island	83	48	83.97	41	0	49	0.00	49
South Carolina	682	33	175.51	33	17	20	4.37	19
South Dakota	501	36	677.48	12	2	39	2.70	31
Tennessee	3450	6	627.98	14	29	11	5.28	14
Texas	14746	**1**	732.64	11	212	**1**	10.53	6
Utah	736	30	344.69	25	6	33	2.81	29
Virginia	3110	7	902.57	6	36	8	3.37	26
Vermont	536	34	453.43	21	2	40	5.25	15
Washington	149	47	25.81	49	2	41	0.35	43
Wisconsin	716	31	1433.56	**1**	7	30	17.13	**2**
West Virginia	2594	11	136.35	37	31	10	1.33	39
Wyoming	181	45	375.50	22	2	42	4.15	21

Table 4.2: Top ranking U.S. counties with respect to flash flood warnings. Corresponding flash flood deaths are also shown from 1986-2005.

County	State	Total Warnings	Total Deaths
Pima	Arizona	415	7
San Bernardino	California	363	16
Bexar	Texas	260	12
Val Verde	Texas	222	1
Mohave	Arizona	202	1
San Diego	California	202	1
Kerr	Texas	193	14
Clark	Nevada	191	8
Medina	Texas	187	0
Riverside	California	186	3

Table 4.3: Top ranking U.S. counties with respect to flash flood deaths. Corresponding flash flood warnings are also shown from 1986-2005.

County	State	Total Deaths	Total Warnings
Dallas	Texas	26	139
Belmont	Ohio	25	95
Tarrant	Texas	23	162
Coconino	Arizona	21	127
San Bernardino	California	16	363
Kerr	Texas	14	193
Bexar	Texas	12	260
Alleghany	Pennsylvania	11	148
Jackson	Missouri	10	69
Oklahoma	Oklahoma	10	58

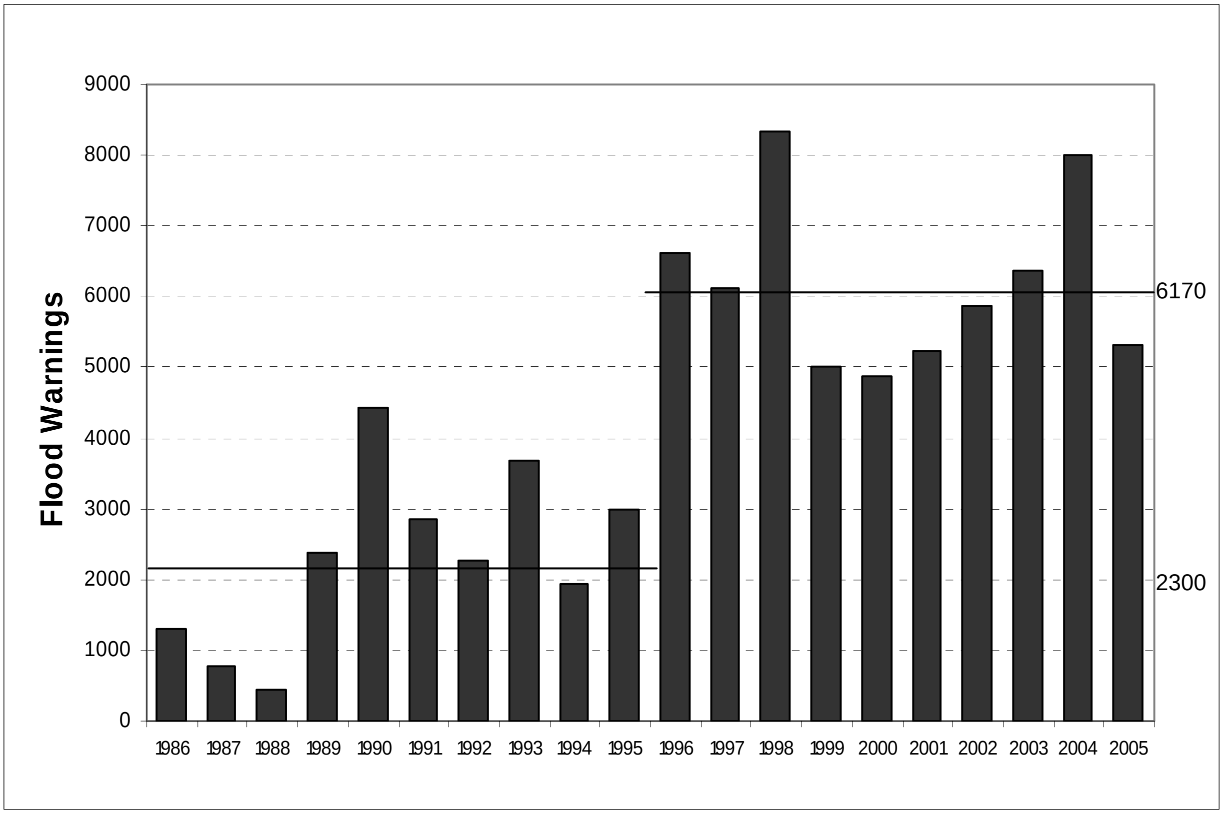

Figure 4.1: Frequency of warnings issued per year from 1986-2005. Values to the right of the graph represent the average number of warnings for the periods 1986-1995 and 1996-2005.

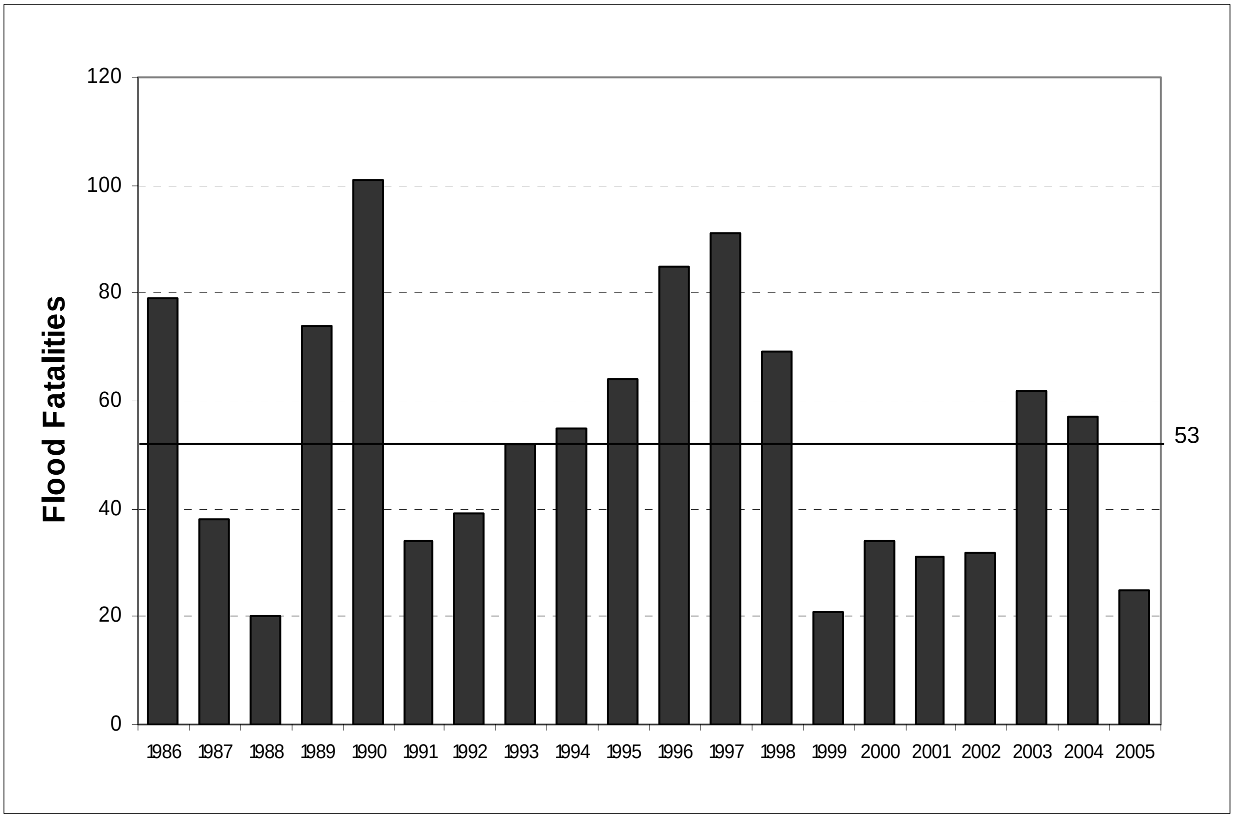

Figure 4.2: Same as Figure 4.1, except flash flood fatalities. Horizontal line represents average from 1986-2005.

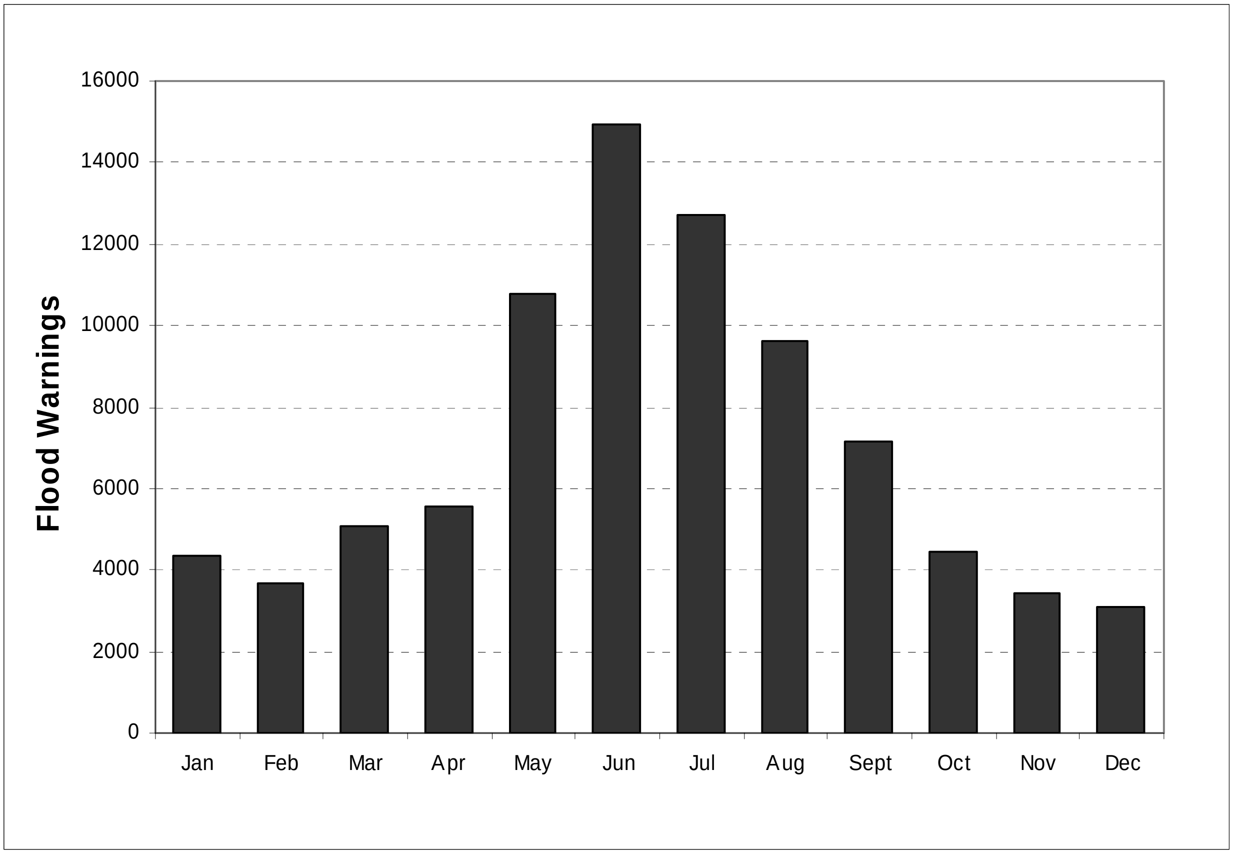

Figure 4.3: Monthly frequency distribution of flash flood warnings in the U.S. from 1986-2005.

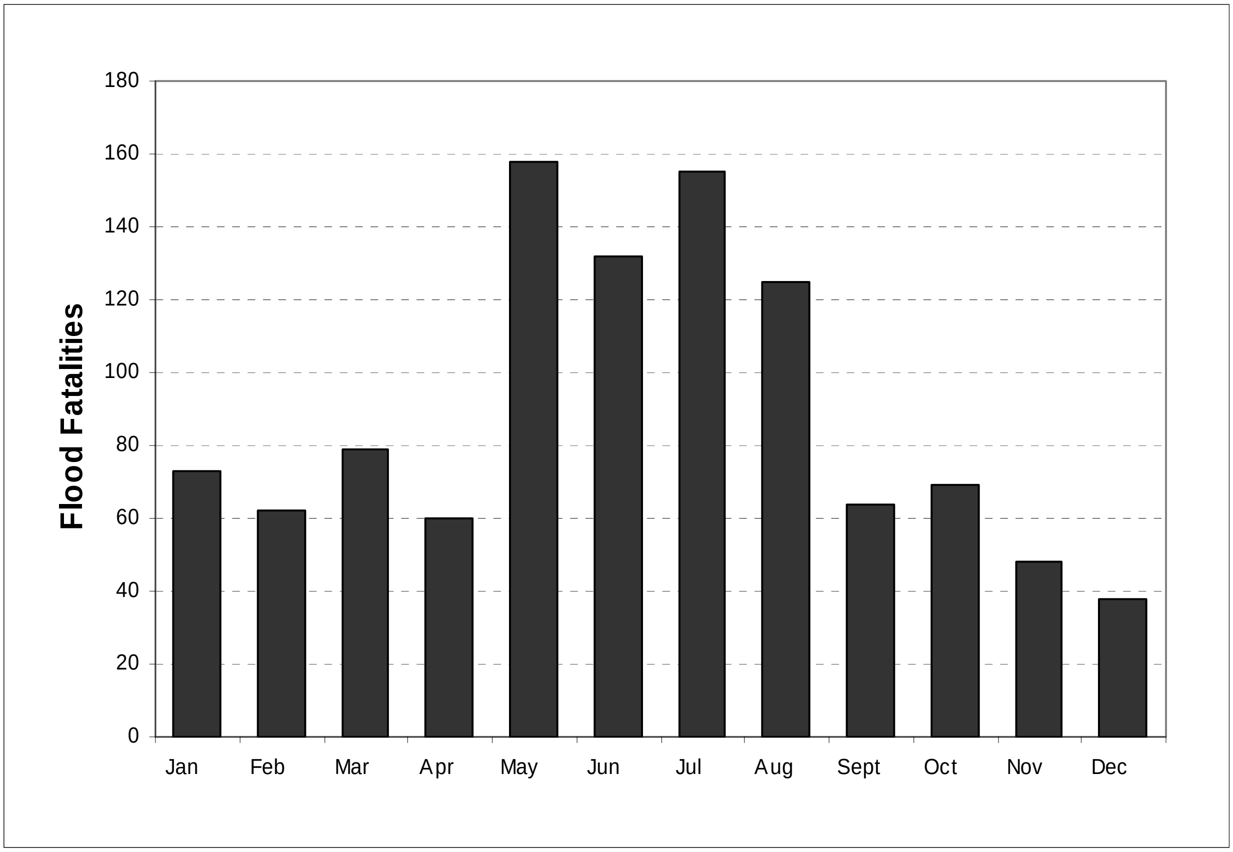

Figure 4.4: Same as Figure 4.3, except flash flood deaths.

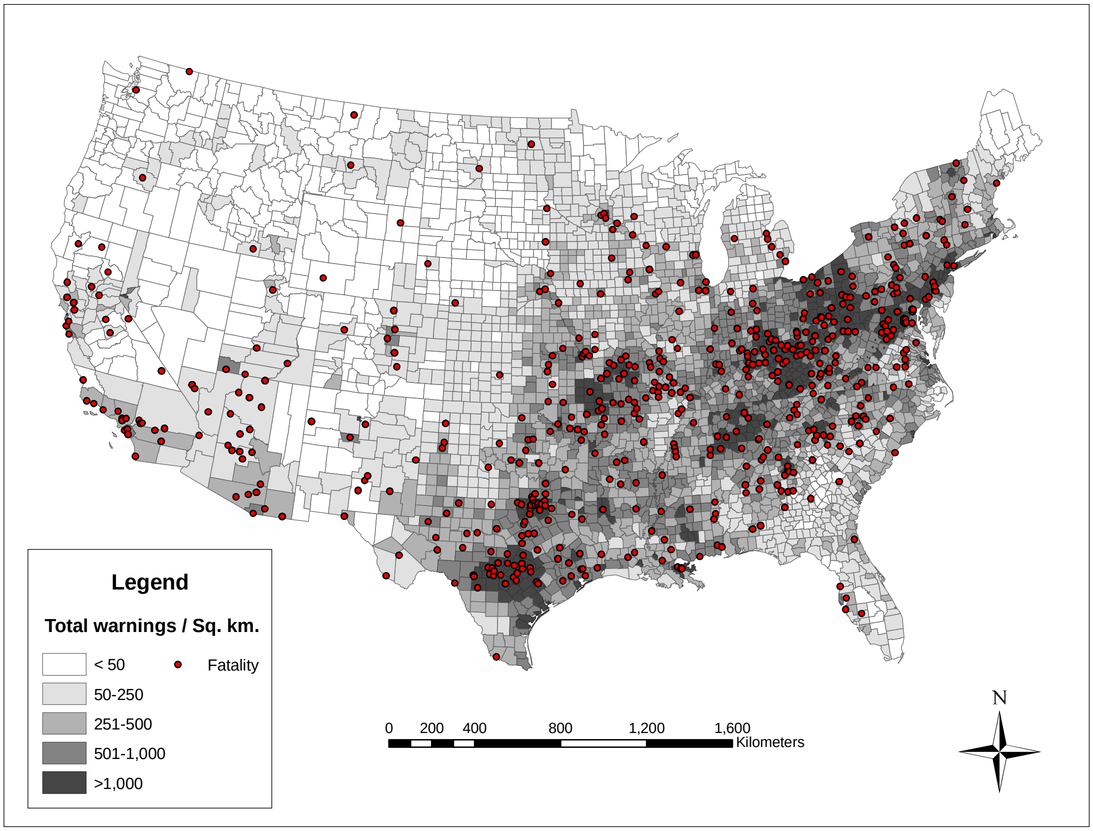

Figure 4.5: Flash flood warnings standardized by area (10,000 km^2) overlaid with flash flood fatalities by city from 1986-2005.

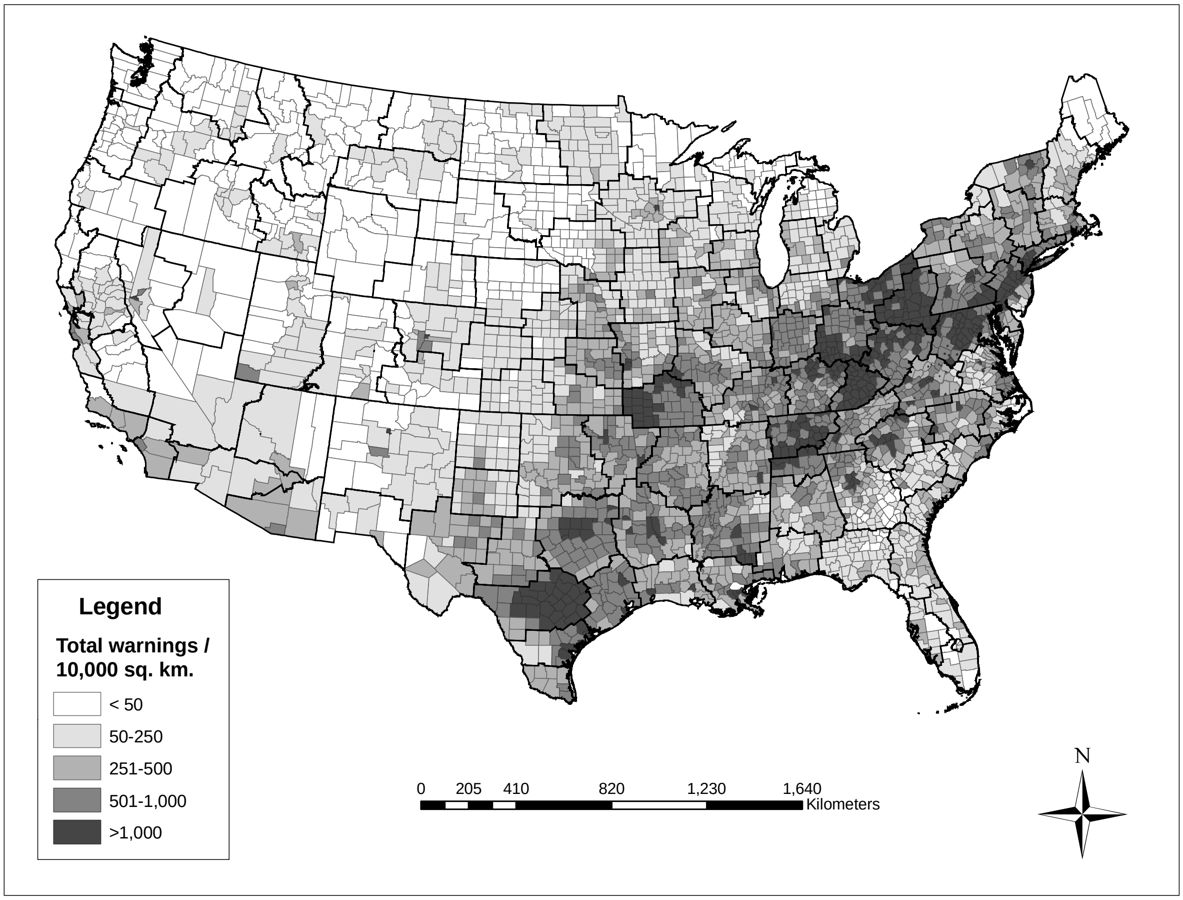

Figure 4.6: Flash flood warnings standardized by area (10,000 km^2) overlaid with county warning area boundaries.

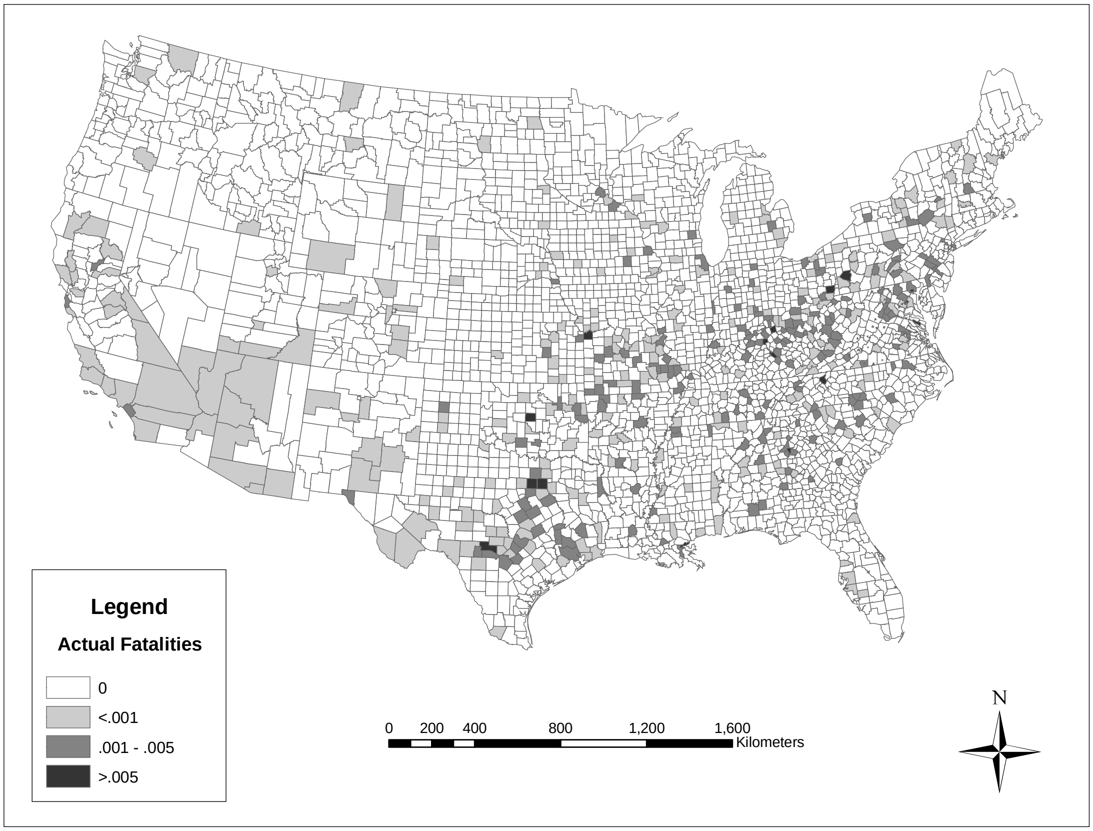

Figure 4.7: Distribution of actual flash flood fatalities (per km^2) from 1986-2005.

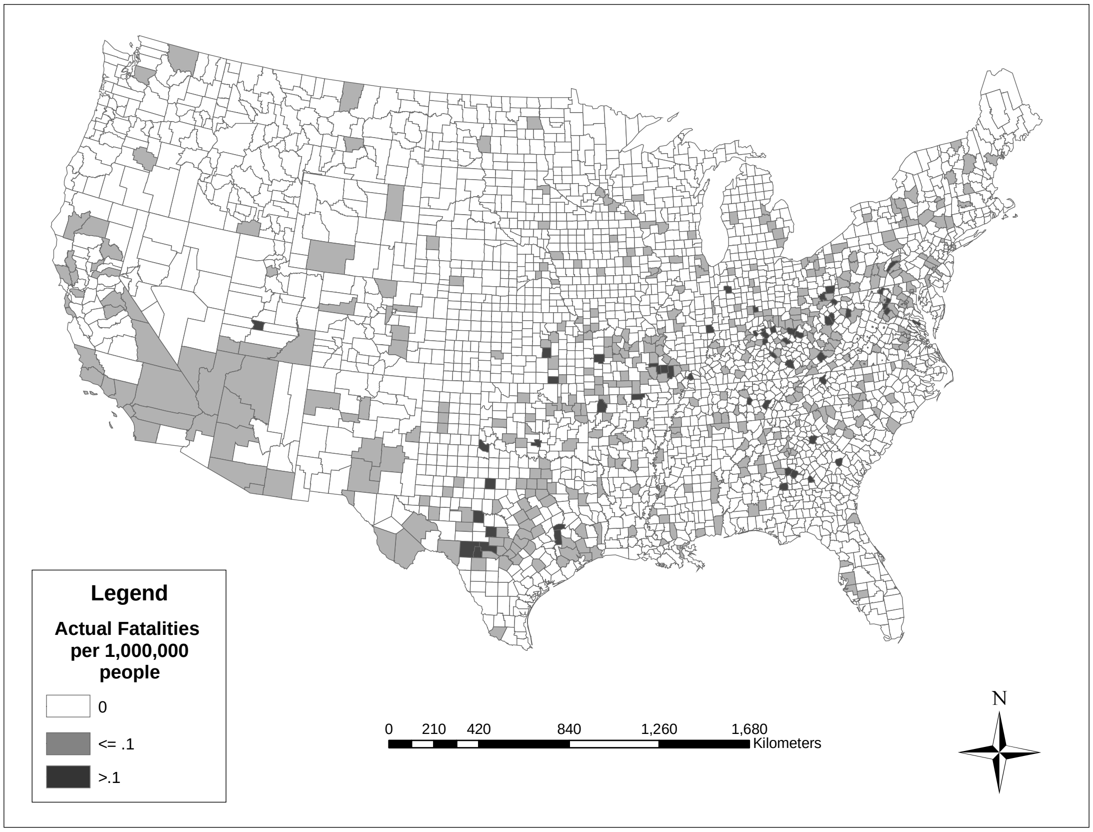

Figure 4.8: Distribution of actual flash flood fatalities (per 1 million people) from 1986-2005.

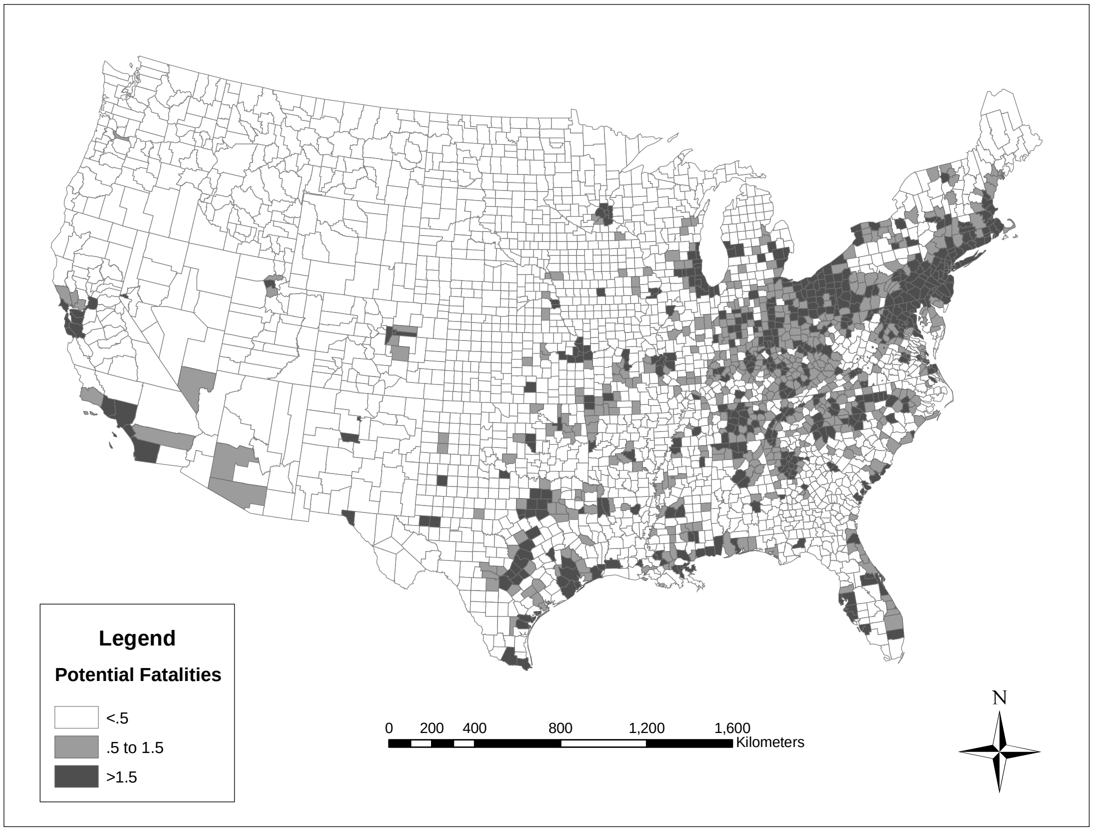

Figure 4.9: Distribution of potential flash flood fatalities (per km^2) from 1986-2005.

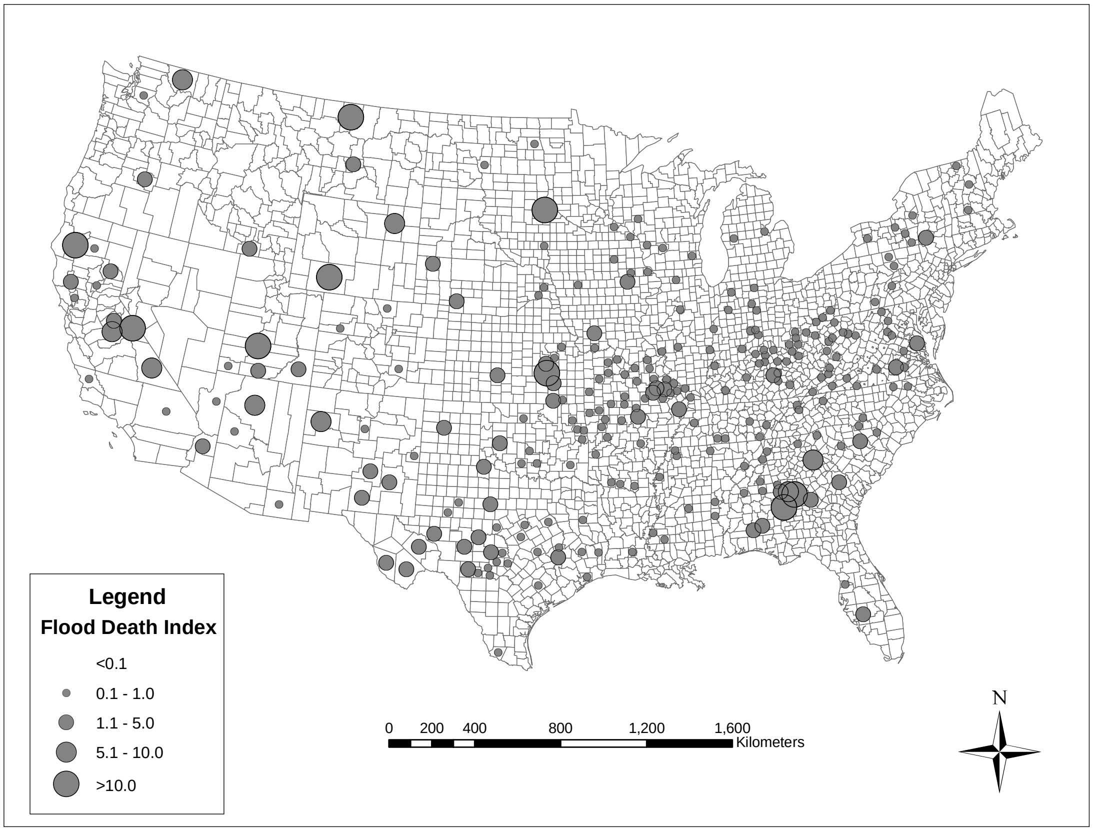

Figure 4.10: Flood death index (by county) – ratio actual deaths per km^2 to potential deaths per km^2 – based on data from 1986-2005.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Overview

Unlike other weather perils, flood fatalities in the U.S. do not show a decreasing trend over the past 50 years. Therefore, an in-depth nationwide investigation into these events is warranted (Lopez and Holle 1996, Curran et al. 2000, Brooks and Doswell 2001, Boruff et al. 2003). In order to complete analyses in this dissertation, an extensive database of flood deaths and injuries in the U.S. from 1959-2005 was compiled using reports from *Storm Data*. Utilizing this database, information on the geography as well as social and physical characteristics of casualties associated with flood events were analyzed and described.

The first manuscript (Chapter 2) analyzed the constructed casualty database to reveal those activities or structures and social characteristics that make people most vulnerable to flood events. Additionally, regions of the U.S. most susceptible to these events are illustrated so that forecasters and emergency managers may better understand this distribution and focus on regions with high rates of fatalities. The second manuscript (Chapter 3) focused on a case study of the Guadalupe River Basin in Texas to help delineate between deadly and non-deadly flood events from a perspective of flood magnitude. Lastly, the third manuscript examines the spatial distribution of flash flood warnings from 1986-2005. Moreover, the study investigated the relationship between the 20 years of county level flash flood warnings and deaths in order to determine whether the fatal floods were adequately warned in advance. A flash flood index was created similar to the tornado death index introduced by Sims and Baumann (1972). A map of this index reveals counties that had a high number of actual fatalities relative to the county's potential for flash flood deaths. The potential value was calculated based on the county's population density and total number of flash flood warnings issued from 1986 to 2005.

5.2 Summary

5.2.1 Flood Casualties

Of the three types of floods examined in this study (i.e., flash floods, river floods, and tropical system floods), flash floods were responsible for the majority (52%) of the flood deaths from 1959-2005. This is likely due to their rapid onset and the inability, at times, to issue a timely warning. Fatalities from tropical system floods rank second to those from flash floods; resulting in 20% of all the deaths nationwide. Moreover, tropical system floods are responsible for the majority (53%) of all injuries. The number one killer activity/location surrounding flood related deaths are those that occur in a vehicle. In many instances, these vehicle-related deaths occurred because the victim drove willingly into flood waters by ignoring either barricades or law officers (NOAA 2005). This lack of judgement may be associated with a person's perception of the dangers associated with flood waters and further investigation is imperative.

Demographic data, including age and gender of the victim, were examined. Those younger than 30 years of age and older than 60 years constituted a large percentage of the deaths. Many children, especially those younger than nine years old, perished in floods when they are driven into the flood waters by their parents or guardians. Moreover, young children (between 6-13 years old) are likely to drown when playing in flooded creeks and streams. Males (especially in age category 10-29 years old) are more likely to perish from a flood than females. These findings indicate the need for more intensive flood safety education program directed toward middle to high school age students in order to reduce the hazards related to flood events in the U.S.

Flood deaths in the U.S. were spatially distributed across all states with clustering in various regions including south-central Texas, the Ohio River Valley, and along the Interstate 95 corridor in the Northeast. Throughout the 47 years of the study there was much yearly variation in total flood deaths with several years of exceptionally high fatalities relative to the average annual value of 92. Years with large numbers of deaths were typically characterized by one or two large impact events (e.g., Hurricane Floyd, The Great October Flood of 1998).

5.2.2 Flood Magnitude

The Guadalupe River Basin is utilized as a case study in order to understand the physical differences deadly and non-deadly flood events. The Guadalupe River was used because of its uniqueness in that it had a large number of fatal events over the 47 years of the study. This unusual clustering of cases is linked to the fact that this region is one of the most severely flooded landscapes in the U.S. (Baker 1977, Patton and Baker 1976). The flooding in this area can be linked to the preponderance of thunderstorms, rapid, high-yield runoff that is typical of steep bedrock slopes in the region, and impervious surfaces due to urbanization along the escarpment.

Both deadly and non-deadly flood events in this basin from 1959-2005 were examined to reveal the relationship between flood magnitude (i.e., return period) and number of deaths in the Guadalupe Basin. More than half of the deadly flood events on the Guadalupe River Basin corresponded to flood return periods of five years or less, while many of large magnitude floods (return period of 50 years or greater) caused no fatalities. Nevertheless, the study found that there was a significant relationship between return period and flood fatalities. The correlation between the two variables was weak (r = .19), therefore, it is concluded that other variables (e.g., people's perceptions of flood dangers) may be important in differentiating a deadly flood from a non-deadly one.

5.2.3 Flash Flood Warnings

Because flash floods are, in aggregate, the deadliest of all floods (Chapter 2), an analysis of the relationship between flash flood warnings issued by the NWS and flash flood deaths was performed from 1986-2005. This analysis helped determine whether storms that produced fatalities were adequately warned. This analysis found that nearly 40% of all floods that killed at least one person did not have a warning issued in the county of the fatality, despite the fact that 18,804 flash flood warnings were issued over the 20 year period. Improvements were made in the NWS with the installation of the WSR-88D radar network during this period. This national network improved significantly the forecasting of flood events (as well as other deadly storm events such as tornadoes) (Friday 1994, Fread et al. 1995, Crum et al. 1998). A comparison of the number of warnings before and after this installation showed that the number of warnings issued increased, but the number of flash flood deaths did not significantly decrease.

An analysis of a county's threat of flash floods illustrated that in regions with a lower potential had a proportionately higher actual number of deaths. Because the residents of these counties are less experienced with flash flood occurrences, this disproportionately high number of fatalities relative to the county's potential may not be surprising (e.g., Brilly and Polic 2005, Drobot et al. 2006, Stewart 2006). People with less experience with flood events are less likely to be worried about their.dangers

5.3 Conclusions

Results from this study contribute to an understanding of the circumstances surrounding flood casualties in the U.S. Of utmost importance is the realization that not just one aspect of a deadly flood (e.g., flood magnitude, local perception of flood dangers) is key to understanding what causes a deadly flood. In order to reduce flood fatalities, research should focus at the local scale and integrate both physical characteristics of the flood and social characteristics of the casualties. Flood forecasters and emergency management personnel can benefit from these findings and utilize them to reduce flood hazards and impacts in the U.S.

Future research should attempt to bring together the results from national studies (such as this one) with regional studies examining localized flood storm types, human perception, and socioeconomic characteristics of flood casualties. In order to accomplish this goal, a concerted effort must be extended toward creating a program to assess and measure the losses from weather events nationwide. Similar suggestions have been voiced by Cutter (2001), Changnon (2003), and Cutter and Emrich (2005) to develop and implement a standardized accounting of hazard events and losses in order to reduce flood-related fatalities in the U.S. In addition, future research and policy dissemination efforts should focus on the local flood safety education programs, or lack thereof, in place across the nation. Although, this study only referenced people's perceptions of flood dangers, the findings indicate that the public's general knowledge of the awareness of flood threats is inadequate. Based on findings in this dissertation, several recommendations to flood policy makers are suggested, including:

- Target specific groups, especially those that may be more vulnerable to flood events than others, with flood safety awareness programs to include local citizen involvement. Educate parents on flood dangers through the parent-teacher groups. Highlight the fact that many children are killed by floods when they are driven into floods by a parent or guardian. Also provide flood safety programs to children within K-12 schools – illustrating the hazards of playing in and around culverts and floodwaters. In addition, target the specific vulnerabilities of the elderly sector of the population through organizations such as the Association for the Advancement of Retired Persons (AARP). This information may be disseminated through their newsletter or via their website (http://www.aarp.org/). These proactive preparedness programs will be useful in reducing flood fatalities (AMS 2000).

- Disseminate information on vehicle-related flood hazards to the American Automobile Association (AAA) and to private and public-sponsored driver education courses required and/or suggested by insurance companies for young drivers. Provide statistics on vehicle-related flood deaths in pamphlets or provide safety education classes through this and similar organizations and/or activities.
- Focus funding and education on high risk regions of the U.S. (e.g., Balcones Escarpment). Implement a program, with the aid of local policy holders, to add flood warning signs to flood-prone roads. In certain regions, such as south-central Texas, local efforts should focus on the redesign of low-water crossings (e.g., fords); in particular, those areas that have witnessed repeat events with casualties. In order to do this, emphasis needs to be places on creating a database with explicit geographic information of when and where the flood fatality occurred (Cutter 2001, Cutter and Emrich 2005, and Changnon 2003). Such a database (i.e., *Storm Data)* could improve substantially with set criteria for defining and including direct and indirect deaths, the inclusion of county/city where fatality or injury was reported (especially with the

proliferation of GPS technology), and set criteria for defining and labeling activity surrounding death or injury.

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APPENDIX A - SAMPLE OF FLOOD CASUALTY DATABASE

Table A.1: Example of dataset compiled from *Storm Data* (FF = flash flood, Dth = death, Inj = injury, CO = location of casualty report; OU = outside, VE = vehicle)

County	Location	Yr	Mth	Day	Time	FF Dth	FF Inj	F Dth	F Inj	M/F (age)	CO
Bartow	Emerson	1989	Oct	1	1030EST		1				
Bartow	Cartersville	1989	Oct	1	1225EST	1				1M-16	OU
Chattooga	Trion	1990	Feb	16	0735EST	1				1M-43	OU
Clayton	Riverdale	1990	Jan	24	1502EST	1				1M-2	OU
Cobb	Smyrna	1990	Feb	17-18	2000-0800EST			1		1M-69	VE
Columbia	5 N Evans	1990	Oct	12	0605EST	1				1M-80	OU
Fannin	5.5 E McCaySville	1990	Feb	16	0620EST		1			1M	
Gordon	Resaca	1990	Feb	17	1600EST			1		1M-78	OU
Henry	McDonough	1990	Mar	17	0345EST	1				1F-39	VE
McDuffie	Countywide	1990	Oct	11-12	2200-1400EST		1			1F	
Stewart	4 SW Lumpkin	1990	Mar	17	0230EST	3				3M 42,34,17	3VE
Talbot	5 N Talbotton	1990	Mar	17	0030EST	2				2M 20,31	2OU
Clayton	2 S College Park	1992	Sept	5	0015-0315EST	1				1F-34	OU
Jefferson	1 N Wadley	1992	Aug	12	0529EST	1				1M-53	VE
Jefferson	Wren	1992	Sep	12	0524EST	1				1F-29	VE
Jefferson	Wren	1992	Oct	12	0625EST	1				1F-46	OU
Jenkins	Millen	1992	Oct	8	2300EST	1				1F 2wks	OU

APPENDIX B - USGS STREAM GAUGE STATION DATA

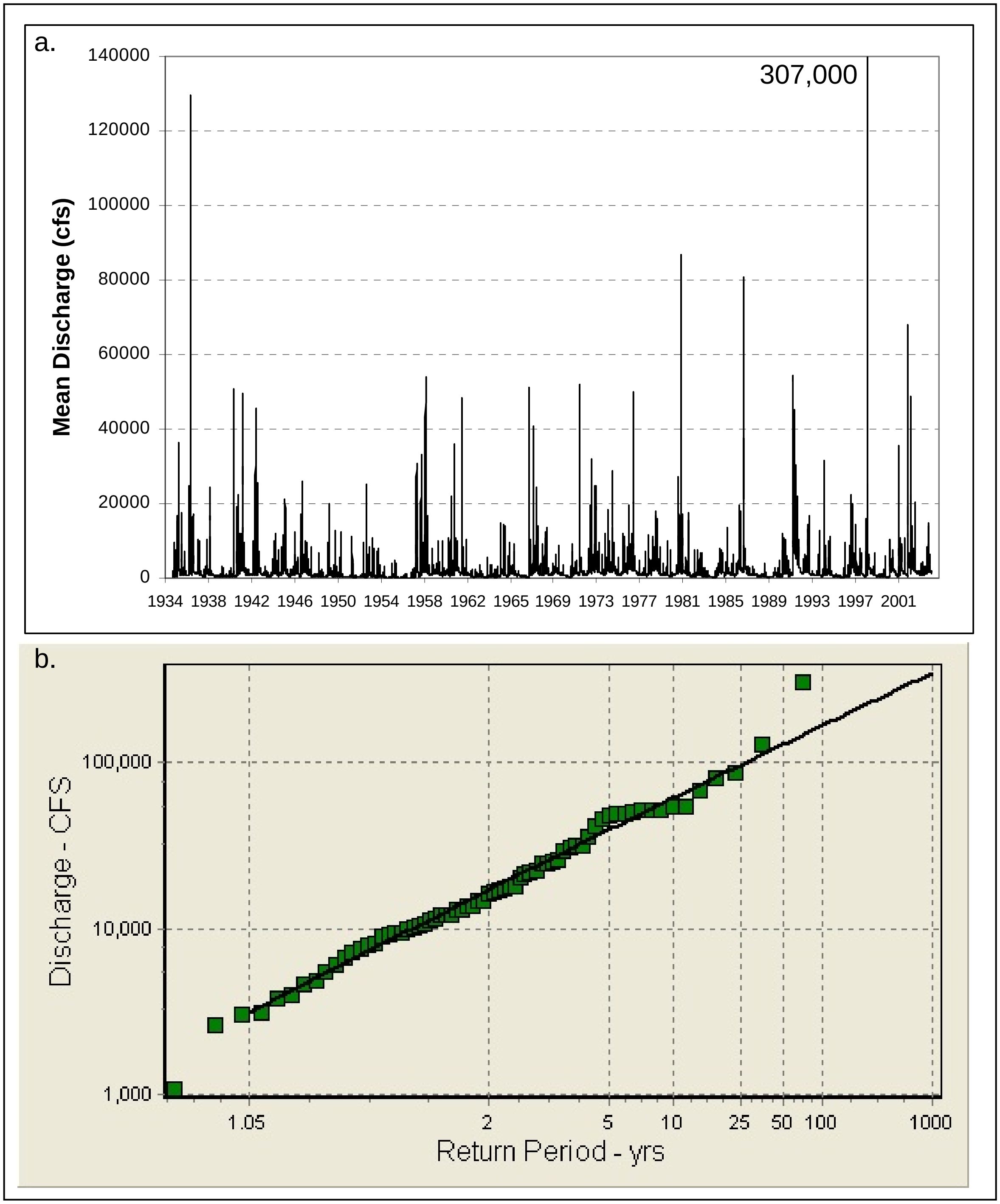

Figure B.1: USGS station: Guadalupe River at Victoria a) mean daily discharge through station's period of record and b) calculated return period based on historical mean daily discharge.

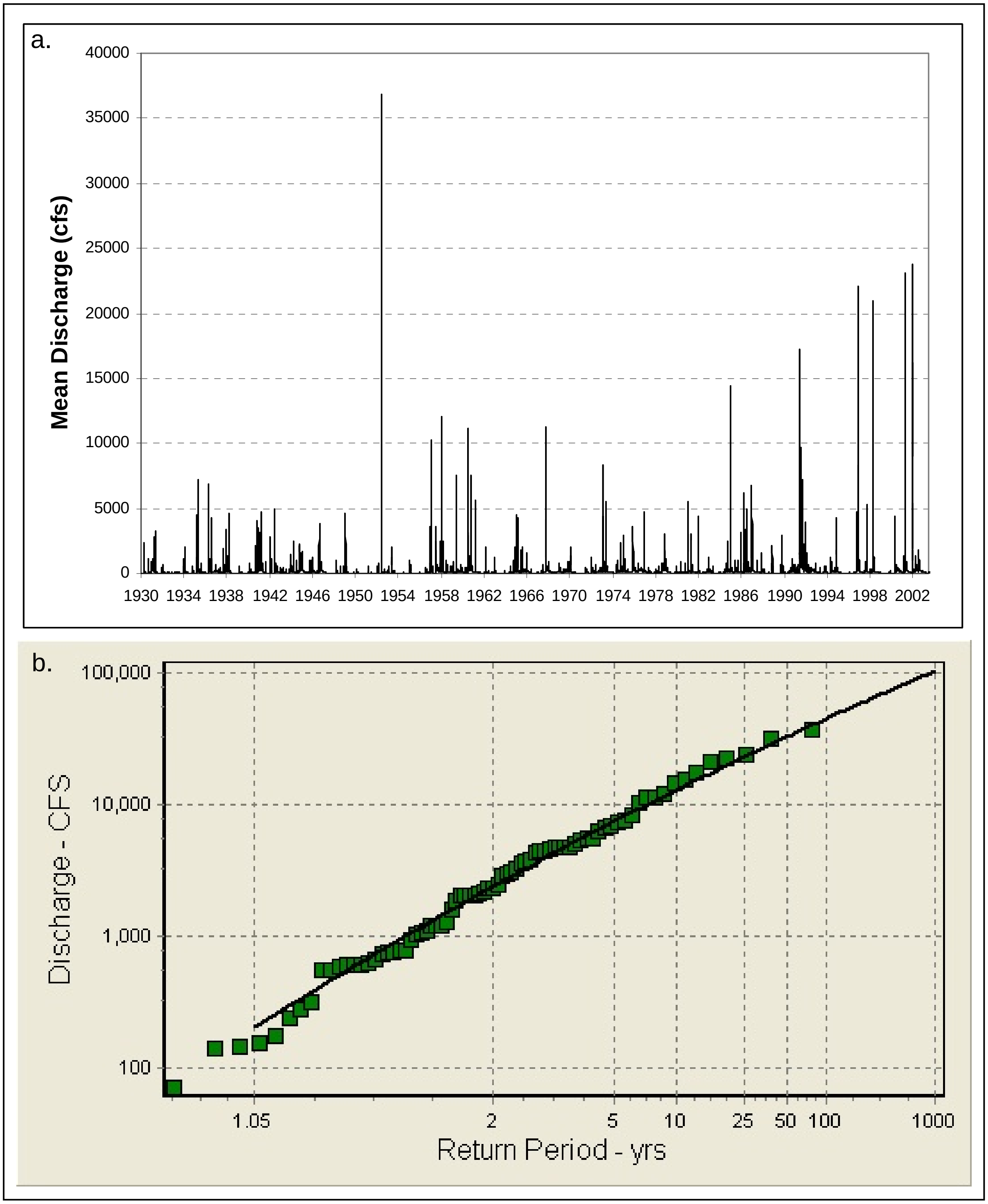

Figure B.2: Same as Figure B.1, except Blanco River at Wimberly.

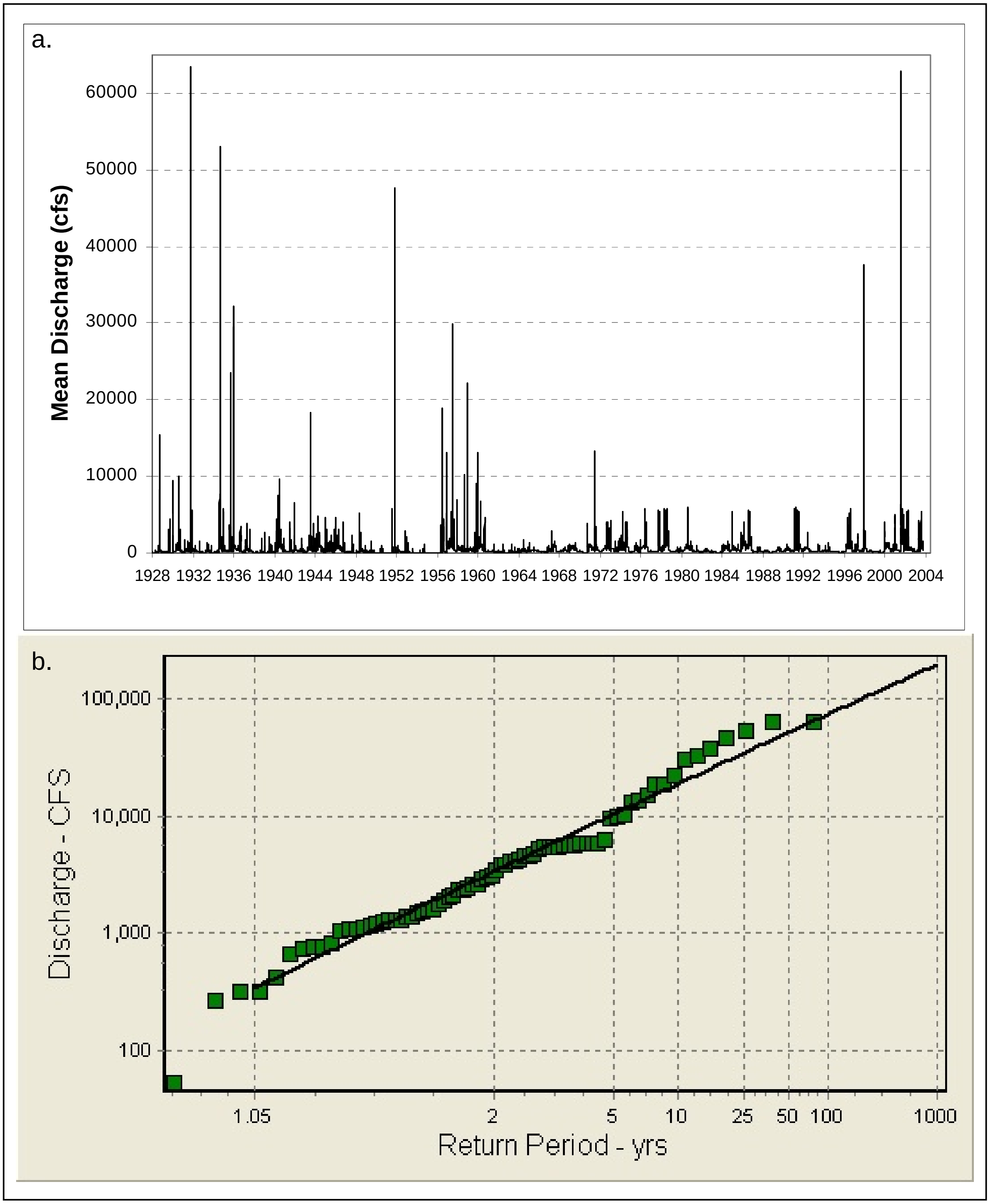

Figure B.3: Same as Figure B.1, except for Guadalupe River at New Braunfels.

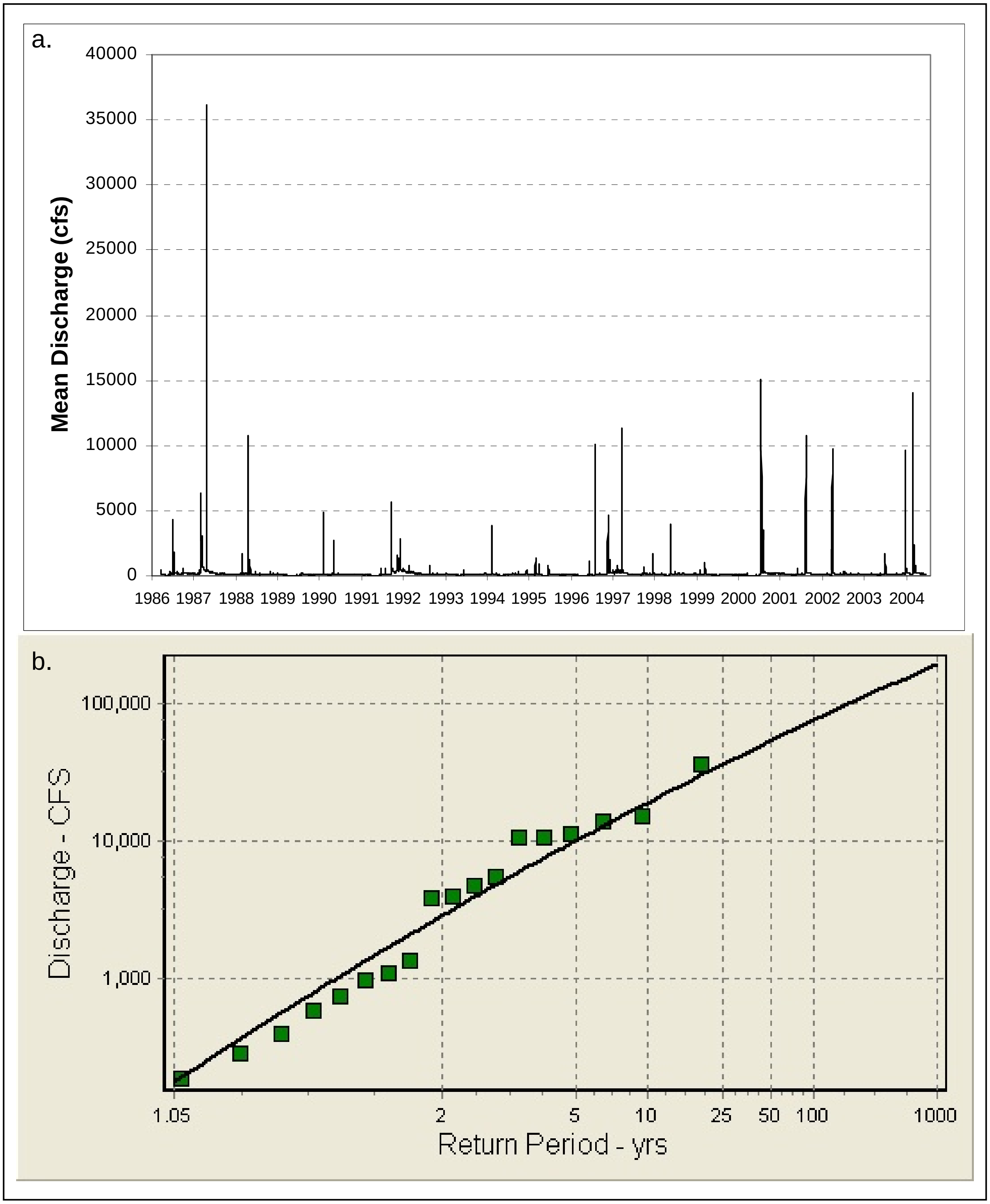

Figure B.4: Same as Figure B.1, except Guadalupe River at Kerrville.

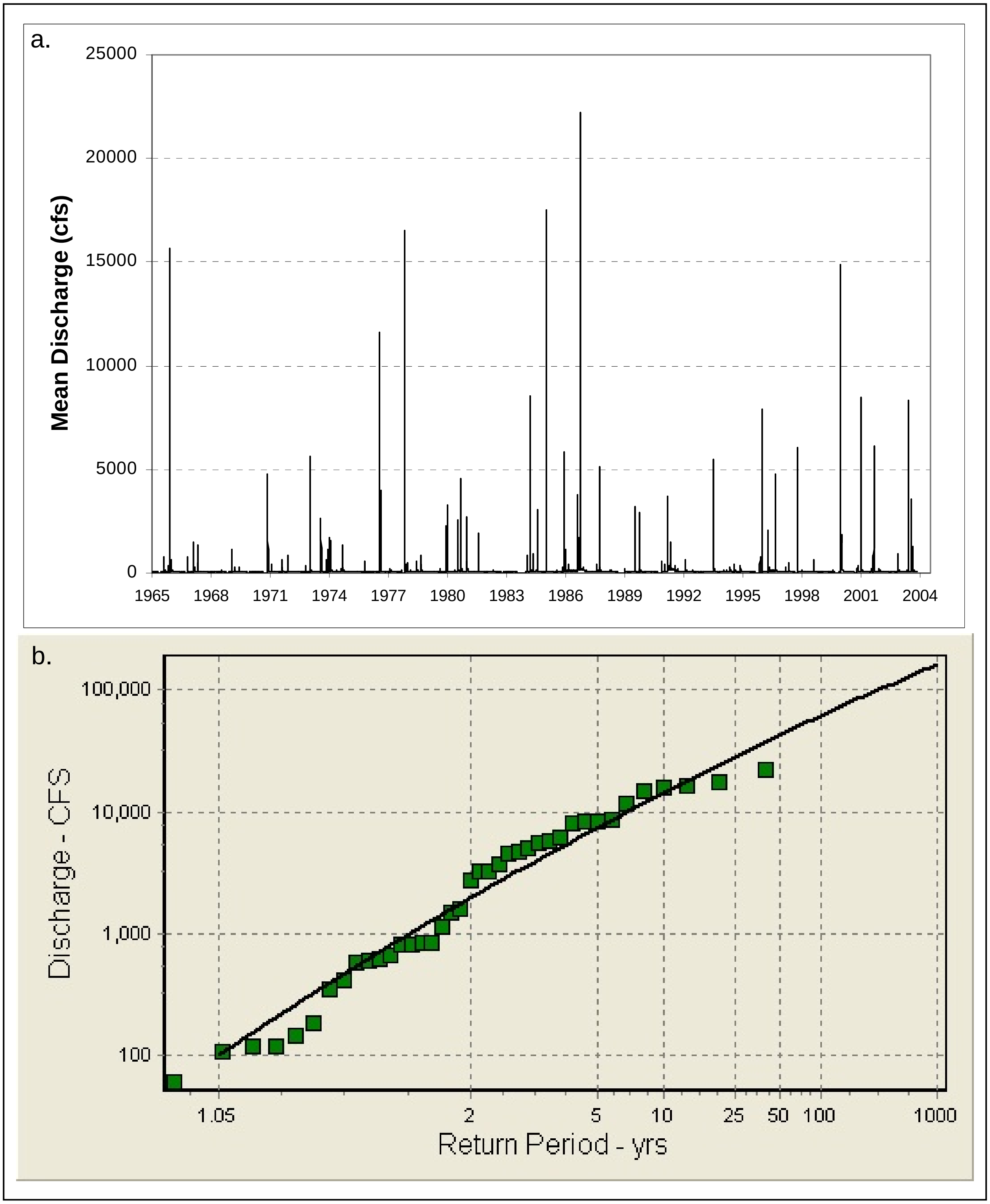

Figure B.5: Same as Figure B.1, except Guadalupe River at Hunt.

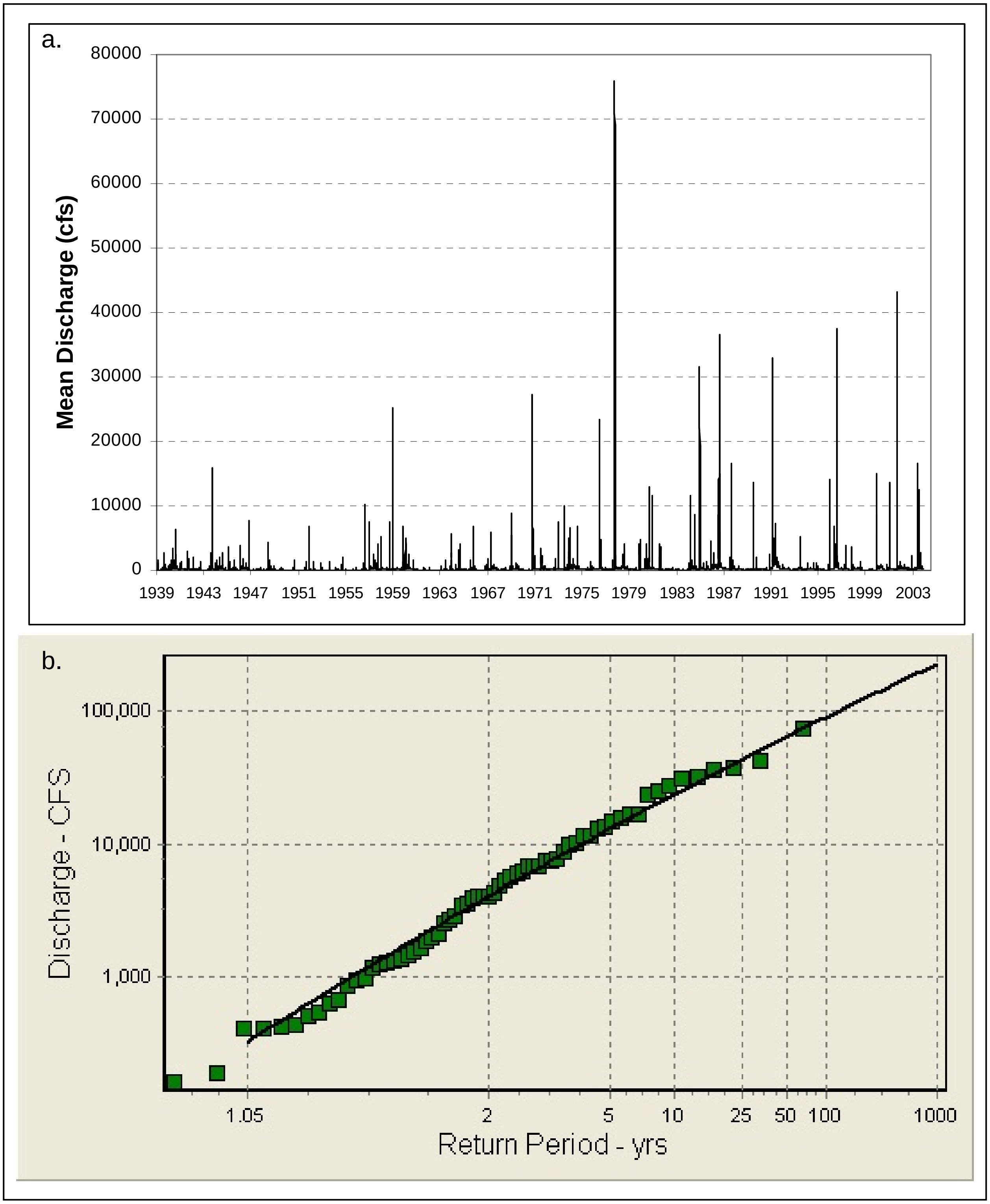

Figure B.6: Same as Figure B.1, except Guadalupe River at Comfort.

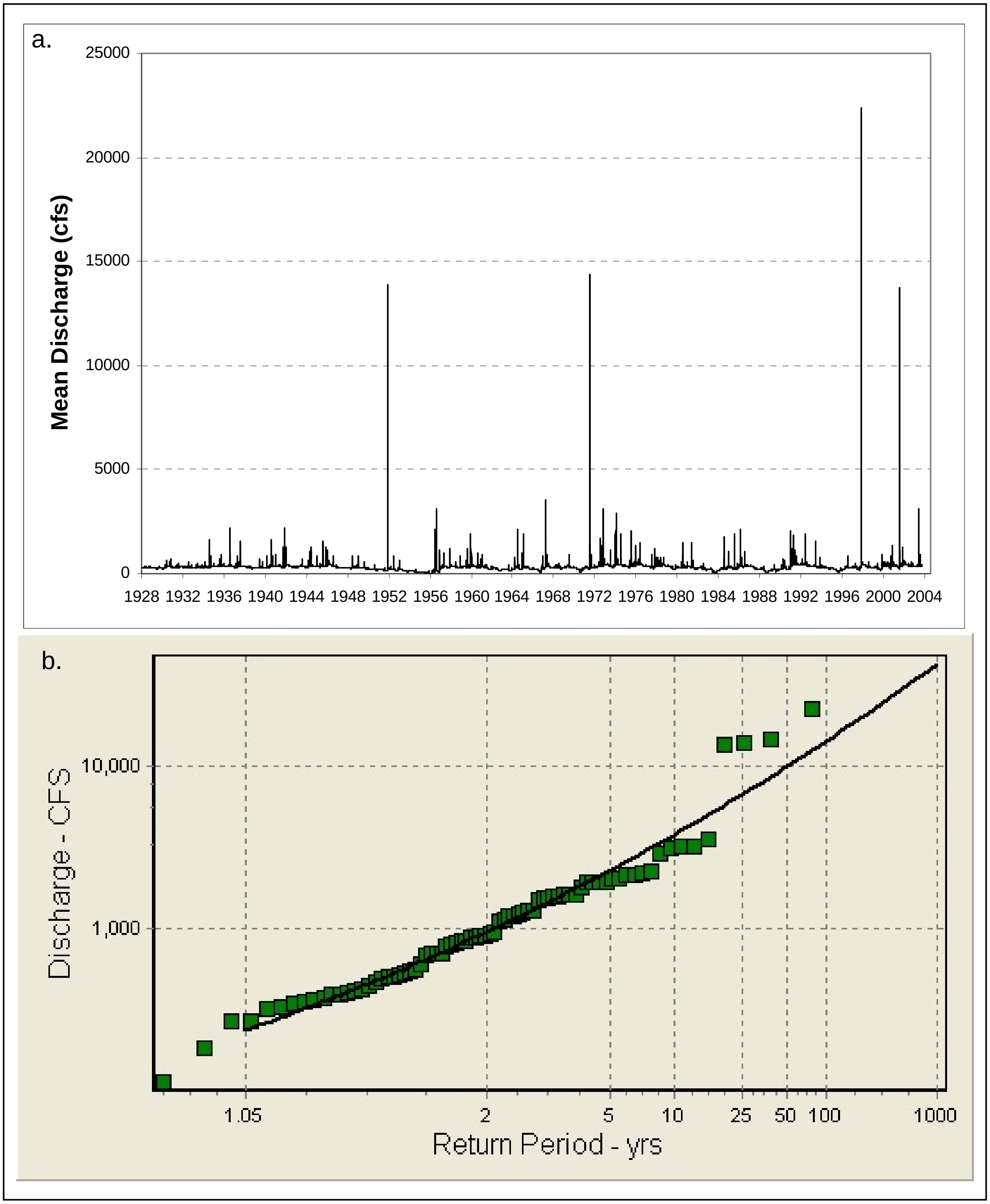

Figure B.7: Same as Figure B.1, except Comal River at New Braunfels.

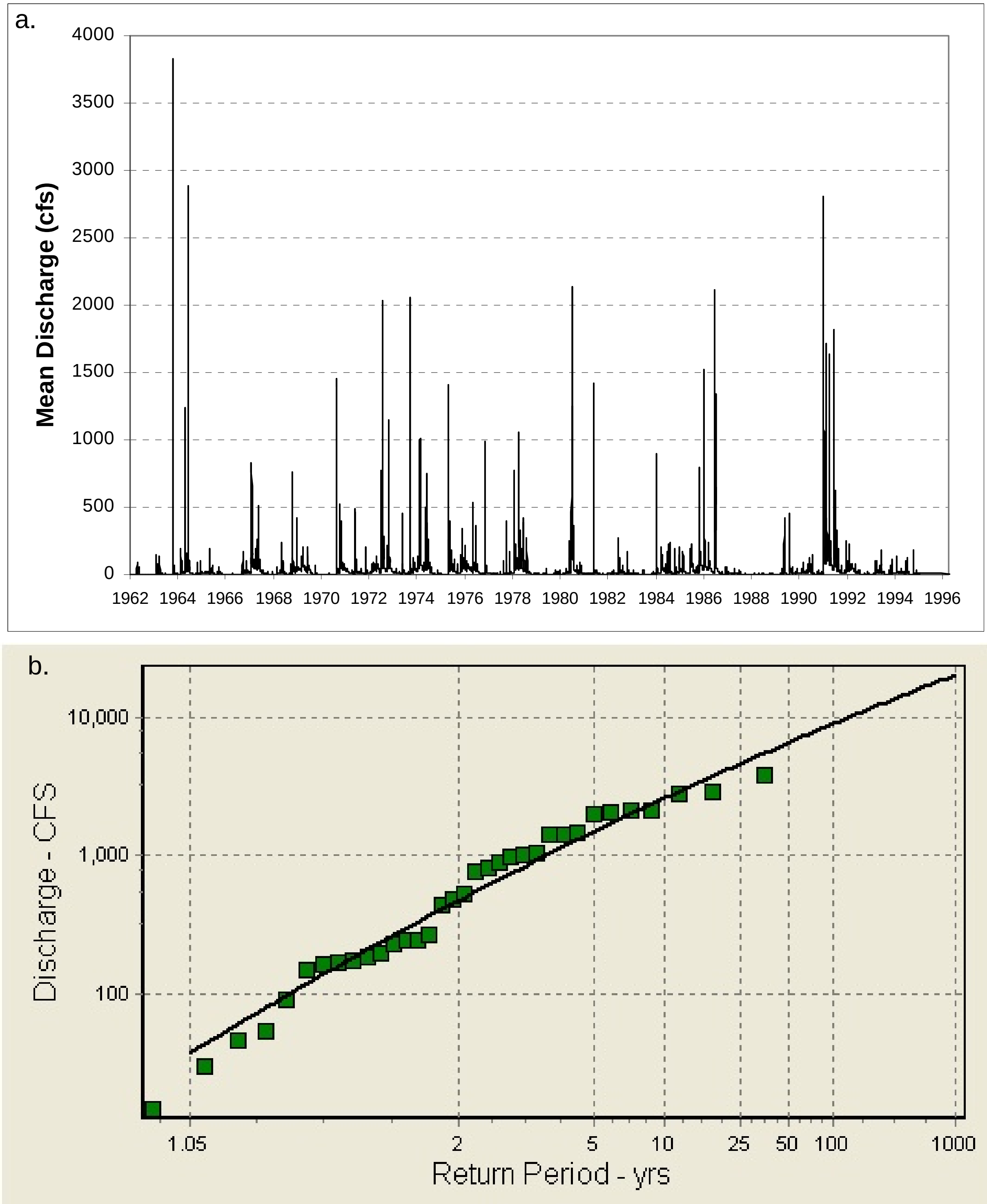

Figure B.8: Same as Figure B.1, except Cibolo River near Boerne.

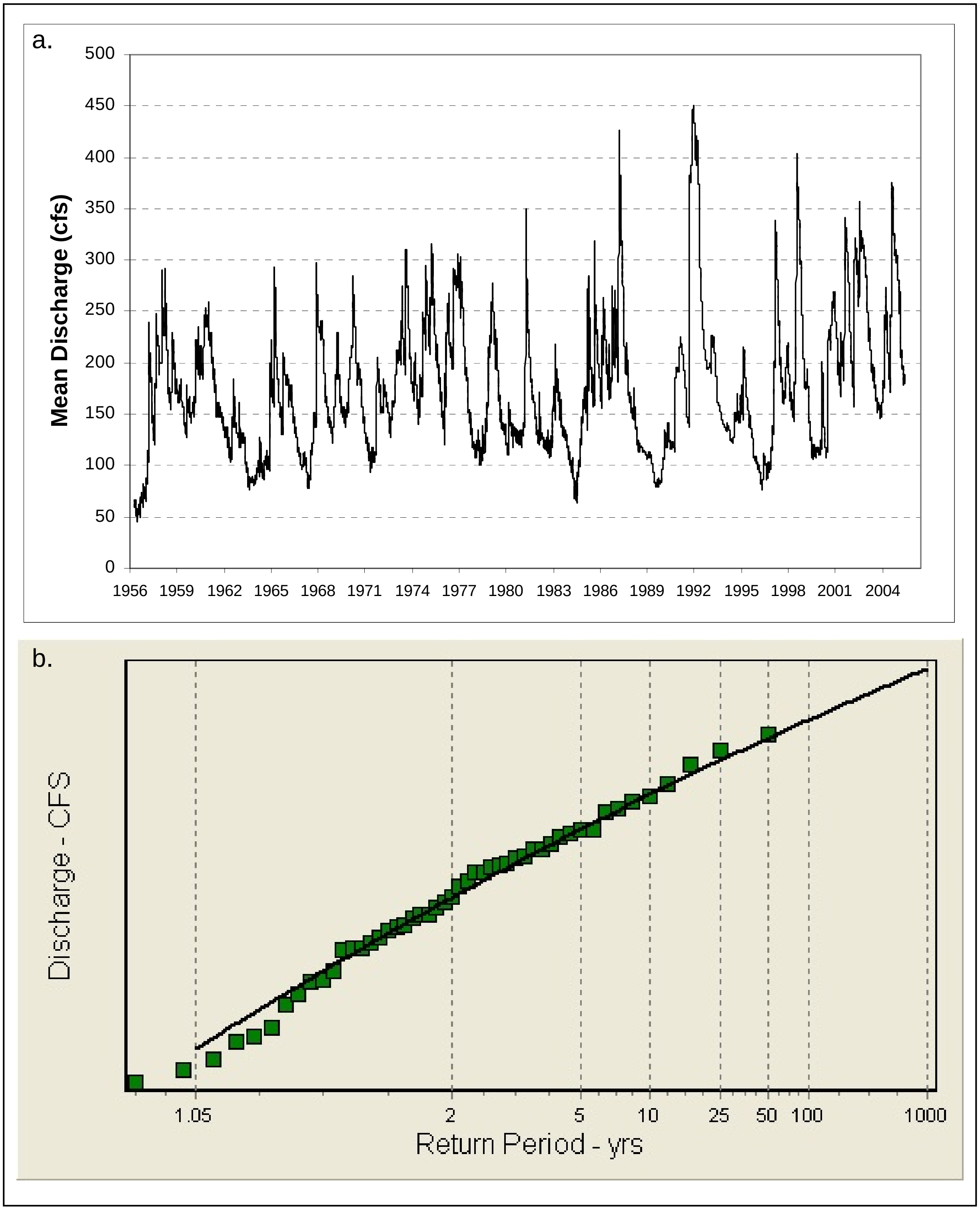

Figure B.9: Same as Figure B.1, except San Marcos Springs at San Marcos.

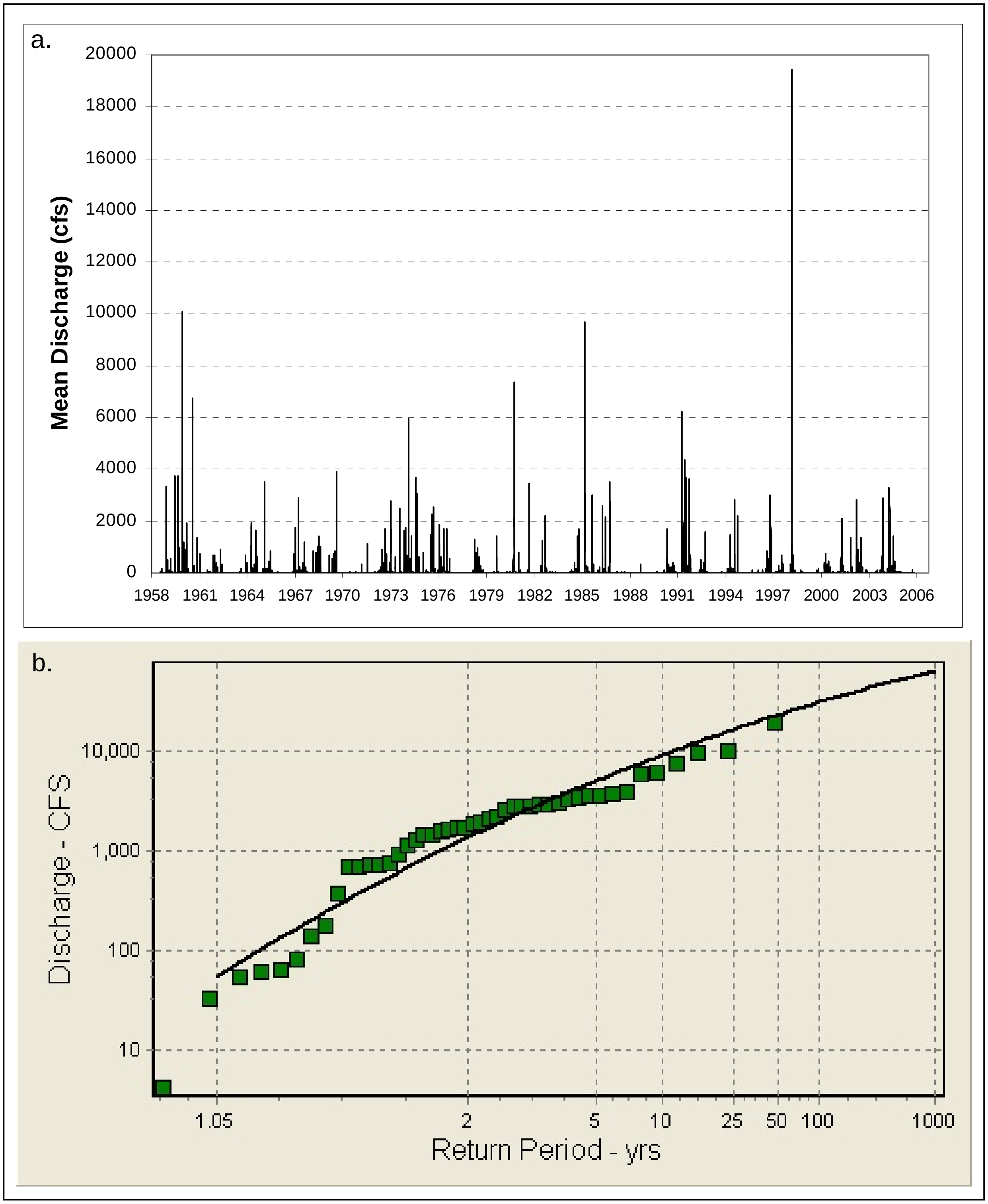

Figure B.10: Same as Figure B.1, except Plum Creek at Lockhart.

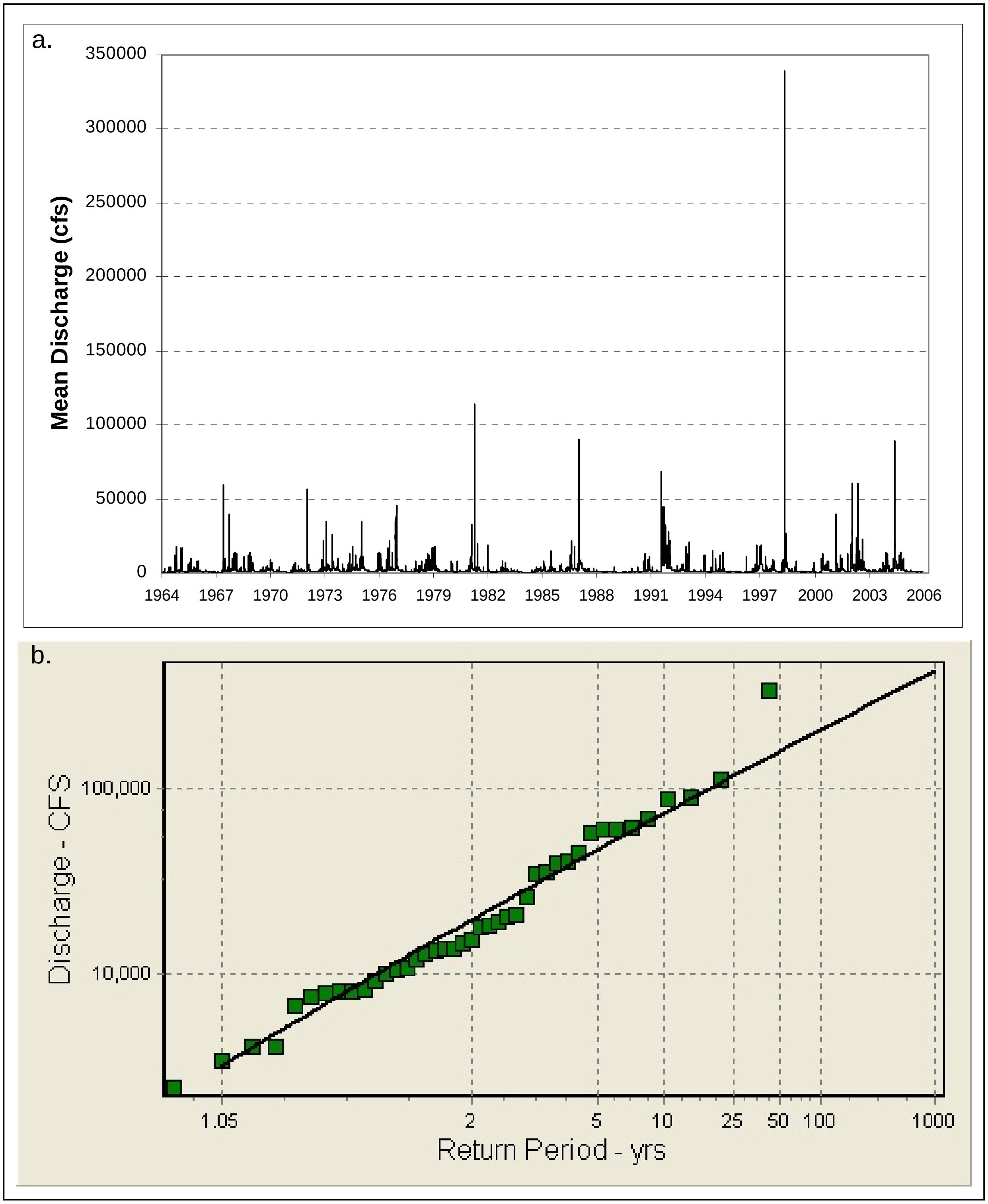

Figure B.11: Same as Figure B.1, except for Guadalupe River at Cuero.